# TSBF Institute

# Annual Report 2002

## VOLUME 1

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**5. Output 1: Biophysical and socioeconomic constraints to integrated soil fertility management (ISFM) identified and knowledge on soil processes improved** (1477 kb)

***Papers***

- BNF: A key input to integrated soil fertility management in the tropics. CIAT-TSBF Working Group on BNF-CP……... 42
- Implications of local soil knowledge for integrated soil fertility management in Latin America. E.Barrios and M.T. Trejo. Geoderma, Special Issue on Ethnopedology (in press) …… ……. 67
- Decomposition and nutrient release by green manures in a tropical hillside agroecosystem. J. G. Cobo, E. Barrios, D. C. L. Kass and R.J. Thomas . Plant and Soil 240: 331-342, 2002. …… 81
- Nitrogen mineralization and crop uptake from surface-applied leaves of green manure species on a tropical volcanic-ash soil. J.G. Cobo, E. Barrios, D.C.L. Kass and R.J. Thomas. Biol. Fert. Soils (2002) 36(2): 87-92……. 96
- Plant growth, mycorrhizal association, nutrient uptake and phosphorus dynamics in a volcanic-ash soil in Colombia as affected by the establishment of *Tithonia diversifolia*. S. Phiri, I.M. Rao, E. Barrios, and B.R. Singh. Journal of Sustainable Agriculture (in press)…….. 105
- Characterization of the phenomenon of soil crusting and sealing in the Andean Hillsides of Colombia: Physical and Chemical constraints. C. Thierfelder, E. Amézquita, R.J. Thomas and K. Stahr. Paper presented to the 12th ISCO Conference, Beijing, China, May 26-31, 2002 …… 117
- Increasing understanding of local ecological knowledge and strengthening interactions with formal science strengthened. J.J. Ramisch and M. Misiko. Report for IDRC 'Folk Ecology' Project…… 123
- "The role of indigenous knowledge in the management of soil fertility among smallholder farmers of Emuhaya division, Vihiga district." *Nelson Juma Otwoma, Student Thesis (submission by end 2003).*……. 127
- Identification of local plants as indicators of soil quality in the Eastern African region. Somoni Franklin Mairura. *Student Thesis (submission by 2004)*……. 129
- Evaluation of current ISFM options by participatory and formal economic methods. JJ Ramisch and I Ekise (2002). …….. 130

- The Competitiveness of Agroforestry-based and other Soil Fertility Enhancement Technologies for Smallholder Food Production in Western Kenya. Julius Mumo Maithya *(Student Thesis, submission in early 2003)*…….. 132
- Assessment of adoption potential of soil fertility improvement technologies in Chuka Division, Meru South, Kenya. Ruth Kangai Adiel. *(Student Thesis, submission by 2004)* ……..…….... 133
- Integrated soil fertility management: evidence on adoption and impact in African smallholder agriculture. F. Place, C.B. Barrett, H. A de Freeman, J.J. Ramisch, B.Vanlauwe. *Submitted to Food Policy*…… 134
- Finding common ground for social and natural science in an interdisciplinary research organisation – the TSBF experience". J.J. Ramisch (TSBF-CIAT), M.T. Misiko (TSBF-CIAT), S.E. Carter (IDRC, Canada). ……. 148
- Modelling nitrogen mineralization from organic sources: representing quality aspects by varying C:N ratios of sub-pools. M E Probert, R J Delve, S K Kimani and J P Dimes.……. 160
- Dynamics of charge bearing soil organic matter fractions in highly weathered soils; World Congress of Soil Science, Bangkok, Thailand, CD-ROM. K. Oorts, R. Merckx, B. Vanlauwe, N. Sanginga and J. Diels; 2002…….…… 174
- Fertility status of soils of the derived savanna and northern guinea savanna and response to major plant nutrients, as influenced by soil type and land use management; *Nutrient Cycling in Agroecosystems* 62, 139-150. B Vanlauwe, J Diels, O Lyasse, K Aihou, E N O Iwuafor, N Sanginga, R Merckx and J Deckers; 2002. ..... 183
- Root distribution of *Senna siamea* grown on a series of soils representative for the derived savanna zone in Togo, West Africa; *Agroforestry Systems* 54, 1-12. B Vanlauwe, F K Akinnifesi, B K Tossah, O Lyasse, N Sanginga, and R. Merckx; 2002……. 201
- Economics of heap and pit storage of cattle manure for maize production in Zimbabwe. H.K. Murwira and T.L. Kudya *Tropical Science, 42: 153-156*……. 218
- Pathways Towards Integration of Legumes into the Farming Systems of East African Highlands. T. Amede. *(Draft Paper)*…….. 221
- Towards Addressing Land Degradation in Ethiopian Highlands: Opportunities and Challenges. T. Amede *(Draft Paper)*…….. 230
- Phosphorus use efficiency as related to sources of P fertilizers, rainfall, soil and crop management in the West African Semi-Arid Tropics. Bationo A., and K. Anand Kumar. …… 237


**6. Output 2: Improved soil management practices developed and disseminated.**
(**Part 1**, 1639 kb; **Part 2**, 494 kb)

***Papers***


- Use of deep-rooted tropical pastures to build-up an arable layer through improved soil properties of an Oxisol in the Eastern Plains (Llanos Orientales) of Colombia. E. Amézquita, R.J. Thomas, I.M. Rao, D.L. Molina and P. Hoyos. *Agriculture, Ecosystems & Environment (in press)*…… 255
- Sustainability of Crop Rotation and Ley Pasture Systems on the Acid-Soil Savannas of South America. E. Amézquita, D.K. Friesen, M. Rivera, I.M. Rao, E. Barrios, J.J. Jiménez, T. Decaëns and R.J. Thomas. Paper presented at the 17th World Congress of Soil Science, Bangkok, Thailand, 14-21, August 2002: Comission: 1…….. 264
- Fallow management for soil fertility recovery in tropical Andean agroecosystems in Colombia. E. Barrios , J.G. Cobo, I.M. Rao, R.J. Thomas, E.Amézquita, J.J. Jiménez. *Agriculture, Ecosystems and Environment (in review)* …… 273
- Sequential phosphorus extraction of a $^{33}$P-labeled oxisol under contrasting agricultural systems. 2002. S. Buehler, A. Oberson, I.M. Rao, E. Frossard and D.K. Friesen. *Soil Science Society of America Journal* 66: 868-877 ……..... 288

- Constructing an arable layer through chisel tillage and agropastoral systems in tropical savanna soils of the Llanos of Colombia. S. Phiri, E. Amézquita, I.M. Rao, and B.R. Singh. *Journal of Sustainable Agriculture* (in press) …… 306
- Networks of Agricultural Information Dissemination in Emuhaya, Western Kenya. Michael Misiko (TSBF-CIAT), J.J. Ramisch (TSBF-CIAT) and Leunita Muruli (University of Nairobi). *Submitted to the IIED.*…….. 323
- Decision Support Systems for Integrated Soil Fertility Management. J.J. Ramisch and M. Misiko. *Draft paper*…….. 336
- *Mucuna pruriens* and *Canavalia ensiformis* legume cover crops: Sole crop productivity, nutrient balance, farmer evaluation and management implications. Delve, R.J. and Jama, B. …… 339
- Farmer participatory evaluation of legume cover crop and biomass transfer technologies for soil fertility improvement using farmer criteria, preference ranking and logit regression analysis. Nyende, P. and Delve, R. J……. 349
- Evaluation of cowpea and Lablab dual-purpose legumes. R. Delve and P. Nyende *(Draft paper)* …….. 360
- Mineral nitrogen contribution of Crotalaria grahamiana and Mucuna pruriens short-term fallows in eastern Uganda. Tumuhairwe, J.B., B. Jama, and R. Delve , M.C. Rwakaikara-Silver (2002). *(Submitted to African Crop Science Journal)*…….. 363
- The effect of green manures, Mucuna, Lablab, Canavalia and Crotalaria on soil fertility and productivity in Tororo District, Uganda. Matthew Kuule. *(MSc. Thesis)*.. 364
- Financial benefits of Crotalaria grahamiana and Mucuna pruriens short-duration fallow in eastern Uganda. Tumuhairwe, J.B., B. Jama, and R. Delve, M.C. Rwakaikara-Silver. (Draft paper to be submitted to Journal of Agricultural Economics or African Crop Science Journal) …….. 365
- Impacts of land management options in western Kenya and eastern Uganda. Delve, R. J. and Ramisch, J. J. (Synthesis paper presented at Regional Workshop)…… 367
- Contending with Complexity: The Role of Evaluation in successful INRM. B. Douthwaite, R. Delve, J. Ekboir and S. Twomlow. Presented at INRM Workshop, 2002…… …….. 371
- Organic resource management in sub-Saharan Africa: validation of a residue quality-driven decision support system; Agonomie; In Press. B. Vanlauwe, C.A. Palm, H.K. Murwira and R, Merckx; 2002. *Agronomie (in press)*…… …… 396
- Using decision guides on manure use to bridge the gap between researchers and farmers. H.K. Murwira, K. Mutiro and P. Chivenge. *Agriculture & Human Values (submitted)* …….. 410
- Efficacy of soil organic matter fractionation methods for soils of different texture under similar management. P. Chivenge, H.K. Murwira and Ken E. Giller. *Draft*. ..... 418
- Nitrogen mineralization from aerobically and anaerobically treated cattle manures. J. K. Nzuma and H. K. Murwira. *Draft* ……. 426
- Influence of tillage management practices on organic carbon distribution in particle size fractions of a chromic luvisol and an areni-gleyic luvisol in Zimbabwe. P.P. Chivenge, H.K. Murwira and K.E. Giller. *Draft* …….. 434
- Towards addressing land degradation in Ethiopian Highlands: Opportunities and Challenges. T. Amede. *Draft.*…… …….. 444
- Soil fertility management for sustainable land use in the West African Sudano-Sahelian zone. A Bationo, U. Mokwunye, P.L.G. Vlek, S. Koala and B.I. Shapiro. *(AfNet 8 Proceedings: In Press)* …… 451
- Soil Fertility Management and Cowpea Production in the Semi-Arid Tropics of West Africa. Bationo, A., B.R. Ntare, S. Tarawali and R. Tabo. *(World Cowpea Conference IITA: In press)* ……. 483

- Sustainable intensification of crop livestock systems through manure management in Western and Eastern Africa: lessons learned and emerging research opportunities. Bationo, A., Nandwa, S.M., Kinyangi, J.M.; Bado, B.V.; Lompo, F.; Kimani, S.; Kihanda, F. and S. Koala. *Draft* …… 522

**7. Output 3: Ecosystem services enhanced through ISFM** (705 kb)

***Papers***

- Carbon and nutrient accumulation in secondary forests regenerating from degraded pastures in central Amazônia, Brazil. T.R. Feldpausch, M.A. Rondón, E.C.M. Fernandes, S.J. Riha and E. Wandelli. *Journal of Ecological Applications (in press)* 546
- Slash-and-char – a feasible alternative for soil fertility management in the central Amazon? J. Lehmann, J.Pereira da Silva Jr, M.A. Rondon, M. da Silva Cravo, J. Greenwood, T. Nehls, C. Steiner, and B. Glaser. *Proceedings Chinese Soil Science Society Meeting 2002* …… 563
- Effects of Land Use Change in the Llanos of Colombia on Fluxes of Methane and Nitrous Oxide, and on Radiative Forcing of the Atmosphere. M.A. Rondón, J.M. Duxbury and R.J. Thomas. *Agriculture, Ecosystems and Environment (in review)*….. 573
- Carbon Storage in Soils from Degraded Pastures and Agroforestry Systems in Central Amazônia: The role of charcoal. M.A. Rondon, E.C.M. Fernandes, R. Lima, E. Wandelli. *Proceedings LBA Meeting, Manaus, 2002* …… ……. 597
- Biodiversity and ecosystem services in agricultural landscapes – are we asking the right questions? M.J. Swift, A-M.N. Izac[2] and M. van Noordwijk. *Agriculture, Ecosystems and Environment (accepted for publication)*…….. 601

**8. Output 4: Research and training capacity of stakeholders enhanced** (125 kb)

- Integration of local soil knowledge for improved soil management strategies. E. Barrios, Delve R.J., Trejo M.T. and Thomas R.J. 17th World Congress of Soil Science, Bangkok, Thailand - August 2002. Symposium: 31 …… … 625
- The African Network for Soil Biology and Fertility (AfNet). A. Bationo. ……... 634
- Soil fertility Management in Africa: A Regional Perspective. M.P. Gichuru, A.Bationo, H.C. Goma, S.K. Kimani, P.L. Mafongoya, D.N. Nugendi, H.M. Murwira, S.M. Nandwa, P. Nyathi, M.J. Swift. *African Academy of Sciences (in press)*…….. 641
- List of Acronyms…… 648

# TSBF Institute Description

**Objective:** To develop and disseminate to clients strategic principles, concepts, methods and management options for protecting and improving the health and fertility of soils through manipulation of biological processes and the efficient use of soil, water and nutrient resources in tropical agroecosystems.

**Outputs:** 1) Biophysical and socioeconomic constraints to integrated soil fertility management (ISFM) identified and knowledge on soil processes improved, 2) Improved soil management practices developed and disseminated, 3) Ecosystem services enhanced through ISFM and 4) Research and training capacity of stakeholders enhanced.

**Gains:** Guidelines for selecting productive and resource-use-efficient crop and forage components. Guidelines for identifying profitable options to manage organic and mineral inputs, crop residues, and green manure, and for controlling erosion and improving soil structure. Site-specific guidelines for optimum management of combined use of inorganic and organic resources. Soil-quality indicators to assist farmers and extension workers in assessing soil health. Decision-support systems for resource conservation and productivity enhancement. Strengthened capacity of NARS by use of decision guides for integrated soil fertility management.

**Milestones:**

2003 Decision-making tools available for managing soil erosion, nutrient cycling and maintenance of an arable layer. Correlations established between local soil quality indicators and scientific measurements.

2004 Innovations for establishing an arable layer available. Soil management strategies to improve soil structure available for hillsides. Indicators of soil fertility, biological health, and physical quality used for decision making in hillsides and savanna agroecosystems.

2005 A soil quality monitoring system developed and tested by partners. Decision making tool available for combined management of organic and inorganic resources. List of soil quality indicators available to NARS to monitor land degradation. Farmers adopting improved system components, including crops and soil management technologies.

**Users:** Principally small-scale crop-livestock farmers and extension workers in tropical agroecosystems of sub-Saharan Africa, Latin America and south-east Asia

**Collaborators:** NARS: CORPOICA (Colombia), DICTA (Honduras), EMBRAPA (Brazil), IAR (Nigeria), IER (Mali), INERA (Burkina Faso), INRAB (Benin), INRAN (Niger), INTA (Nicaragua), ITRA (Togo), KARI (Kenya), NARO (Uganda), SRI (Ghana); AROs: CIP, IFDC, ICRAF, IITA, ICRISAT, IRD (France), ETH (Switzerland), JIRCAS (Japan); Universities: Kenyatta (Kenya), Makerere (Uganda), Nacional (Colombia), Nairobi (Kenya), Sokoine (Tanzania), UNA (Nicaragua), UNA and Zamorano (Honduras), Uberlandia (Brasil), Zimbabwe (Zimbabwe), Leuven (Belgium), Paris (France), Bayreuth and Hohenheim (Germany), SLU (Sweden), AUN (Norway), Cornell (USA), Ohio State (USA).

**CGIAR system linkages:** Enhancement & Breeding (10%); Crop Production Systems (20%); Protecting the Environment (40%); Saving Biodiversity (10%); Strengthening NARS (20%). Convener of Systemwide Program on Soil, Water & Nutrient Management (SWNM), and contributes to the Ecoregional Program for Tropical Latin America, the African Highlands Initiative and the Alternatives to Slash and Burn Programme.

**CIAT project linkages:** Integrated soil fertility and soil pest&disease management (IP-1, PE-1), acid-soil adapted components received and adaptive attributes identified for compatibility in systems (IP-1 to IP-5), strategies to mitigate soil degradation (PE-3, PE-4, PE-6), agroenterprise alternatives to improve profitability of soil management options (SN-1), and strengthening NARS via participation (SN-3).

# Log Frame Work Plan for the TSBF Institute

**Area:** **Natural Resources**
**Director:** **Michael J. Swift**

| Narrative Summary | Measurable Indicators | Means of Verification | Important Assumptions |
|---|---|---|---|
| **Goal**<br>Empowering farmers to conduct sustainable agroecosystem management by increasing capacity for integrated soil fertility management through the generation and sharing of knowledge and tools across multiple scales. | • Yields in farmers fields increased.<br>• Land degradation halted/reduced.<br>• Yields per unit area and input increased.<br>• Land use changed | • Farmers surveys.<br>• Regional/national production statistics.<br>• Land use surveys (satellite imagery, rapid rural appraisal). | • Land survey data available<br>• Farmers adopt new technologies<br>• Socioeconomic conditions are favorable for achieving impact<br>• Adequate resources available for soils research |
| **Purpose**<br>To develop and disseminate to clients strategic principles, concepts, methods and management options for protecting and improving the health and fertility of soils through manipulation of biological processes and the efficient use of soil, water and nutrient resources in tropical agroecosystems. | • Technologies for soil improvement/ management developed.<br>• Limiting soil-plant-water processes identified.<br>• Compatible plant components identified for low fertility soils in crop-livestock systems.<br>• Guidelines, manuals and training materials for integrated soil fertility management produced. | • Scientific publications<br>• Soil and crop management guidelines published<br>• Decision support systems developed<br>• Annual reports | • Economic analysis of options available<br>• Effective linkages within CIAT and partners in S.S.Africa, LA and S.E. Asia<br>• Socio-economic inputs available from other projects (e.g., PE-3, BP-1)<br>• Field sites accessible |
| **Output 1.** Biophysical and socioeconomic constraints to integrated soil fertility management (ISFM) identified and knowledge on soil processes improved. | • Soil, water, nutrient and knowledge constraints to sustainable production defined, and the understanding of the role of soil biota, multipurpose germplasm, and organic and inorganic resources for sustainable management of land resources improved. | • Annual Report/ publications<br>• Reviews published<br>• Documents of synthesized results<br>• Detailed tables published in Annual Report.<br>• Decision guides for ISFM developed. | • Sufficient operational funds for soil and plant analyses.<br>• Literature on constraints available<br>• Farmers continue to participate.<br>• Projects SN-2, PE-3 and PE-4 actively participate.<br>• Collaboration of participatory research project (SN-3), RII and NARS. |
| **Output 2.** Improved soil management practices developed and disseminated: | • Relevant knowledge, methods and decision tools for improved soil management to combat soil degradation, increase agricultural productivity and maintain soil health provided to land users in the tropics. | • Annual reports/ publications.<br>• Management guidelines and decision trees published and available to farmers, NARs, NGOs.<br>• Training manual for use with tools.<br>• Maps published.<br>• Simulation models used to assess alternative management of organic resources for ISFM<br>• A policy brief for ISFM produced. | • Sufficient operational funds available for chemical analyses.<br>• Continuity of long-term experiments.<br>• Modeling expertise available from partners e.g. Michigan State Univ. USA, IFPRI, CSIRO.<br>• Soil biology expertise from IRD/Univ. of Paris available. |

| | | | |
|---|---|---|---|
| **Narrative Summary** | **Measurable Indicators** | **Means of Verification** | **Important Assumptions** |
| **Output 3.** Ecosystem services enhanced through ISFM: | • The soil's capacity to provide ecosystem services (global warming potential, water quality and supply, erosion control, nutrient cycling) and maintain soil biodiversity in the face of global change in land use and climate enhanced. | • Annual reports/ publications.<br>• Internationally accepted standard methods for characterization and evaluation of below-ground biodiversity (BGBD), including set of indicators for BGBD loss agreed (GEF funded special Project).<br>• Methods for assessing impacts of land management on soil microbial and faunal diversity tested<br>• Workplan developed to evaluate interactions between soil management practices and soil-borne pests and beneficial organisms. | • Collaboration from partners.<br>• Information from questionnaires synthesized comparisons made with available PE-3 results.<br>• Collaboration with PE-3 on soil erosion in CA.<br>• Collaboration with SN-2, PE-4, PE-3 and SWNM Program.<br>• Collaboration with PE-4 on land quality indicators at reference sites. |
| **Output 4.** Research and training capacity of stakeholders enhanced**:** | • Research and training capacity of stakeholders in the tropics in the fields of soil biology, fertility and tropical agroecosystem management enhanced through the dissemination of principles, concepts, methods and tools. | • Scientific information (theses, publications, workshop reports, project documents) disseminated to network members and all stakeholders<br>• Network trials planned and implemented with partners<br>• Degree-oriented and on-the-job personnel trained (Farmer, NARS, NGO's) | • Continued interest/participation of NARS and ARO partners, and national and international universities.<br>• Continued support for collaborative activities e.g. systemwide SWNM program. |

## EXECUTIVE SUMMARY

### *3.1 List of Staff*

*A. TSBF Institute Africa Programme*

**Senior Staff:**
Director: Mike Swift (Soil biology)
Bernard Vanlauwe (Nutrient Cycling Management)
Andre Bationo (AfNet Coordinator)
Herbert Murwira (Soil Scientist)

**Senior Research Fellows:**
Robert Delve (Soil Fertility Management)
Joshua Ramisch (Anthropologist)
Tilahun Amede (African Highlands Initiative)

**Consultants:**
Prof Nancy Karanja (BGBD Project)
Dr Stephen Nandwa (SWNM Project)

**Research Assistants:**
Catherine Gachengo – Kenya
James Kinyangi – Kenya
Isaac Ekise – Kenya
John Mukalama – Kenya
Michael Misiko - Kenya
Joseph Kimetu - Kenya
Paul Nyende - Uganda
Killian Mutiro – Zimbabwe
Pauline Chivenge – Zimbabwe

**Technical Staff:**
Wilson Ngului,(Laboratory Technician)
Benson Muli (Laboratory Assistant)
Margaret Muthoni (Assistant Lab. Attendant
Francis Njenga (Manual Worker)

**Administration Staff:**
Charles Ngutu (Finance/Administration Officer)
Alice Kareri (Personal Assistant to Director)
Juliet Ogola (AfNet Secretary)
Caleb Mulogoli (Assistant Account / I.T. Assistant)
Henry Agalo (Driver / Field Assistant)
Elly Akuro (Driver / Field Assistant)

*B. TSBF Institute Latin America Programme*

**Senior Staff:**
Project Manager: Edmundo Barrios (Soil Ecology)
Edgar Amézquita (Soil Physics)
Miguel Ayarza (Agronomy) MIS Coordinator (SWNM) - Honduras
Idupulapati M. Rao (Plant Nutrition)

**Senior Research Fellow**
Marco Rondón (C sequestration/GH gases)

**Postdoctoral Fellows**
Axel Schmidt (Soil Fertility/Forages)
Erik Sindhoj (Landscape/Soil Fertility)

**Consultants:**
Myles Fisher (Climate change)
Phanor Hoyos (Crop-livestock systems)
Eloina Mesa (Biometrics)

**Research Associates**
Neuza Asakawa

**Research Assistants**
Gonzalo Borrero
Luis Fernando Chávez
Irlanda Isabel Corrales (Carimagua)
Juan Guillermo Cobo
Diego Luis Molina (Villavicencio)
Gloria Isabel Ocampo
Jenny Quintero
Jaumer Ricaurte
Mariela Rivera
Gloria Marcela Rodríguez
Helena Velasquez
Juan Andrés Ramírez
Katherine Tehelen
Marco Tulio Trejo (Honduras)

**Specialists:**
Jesús Hernando Galvis
Edilfonso Melo
José Arnulfo Rodríguez

**Secretaries:**
Carmen Cervantes de Tchira
Cielo Núñez P.

**Technicians:**
Arvey Alvarez
Pedro Herrera H. (Villavicencio)
Jarden Molina

Martín Otero
Maryori Rodríguez
Gonzalo Rojas (Villavicencio)
Gloria Constanza Romero
Hernán Mina
Amparo Sánchez
Flaminio Toro (Villavicencio)
Carlos Arturo Trujillo (Cauca)

**Workers:**
Nixon Bethancourt (Carimagua)
Joaquin Cayapú (Cauca)
Dayro Franco (Cauca)
Adolfo Messu
Jaime Romero
Josefa Salamanca
Luis Soto
Héctor Julio Unda (Carimagua)

### *3.2 Linkage with institutions in the region and advanced research organizations*

*A. TSBF Institute Africa Programme*

**AROs:**
CDR, Denmark: Esbern Fris-Hassen
Centro Nacional de Pesquisa de Soja (CNPSO), Brazil: George Brown
CSIRO-APSRU, Australia: Merv Probert
FAO, Rome
Foundation for Advanced Studies in International Development (FASID, Tokyo).
IDRC, Canada: Guy Bessette
IDRC, Kenya: Luis Navarro
IFDC, Togo: Constant Dangbenon, M.Wopereis, A.Mando
Instituto de Ecologia, A.C., Mexico: Isabelle Barois, Dan Bennack, Carlos Fragoso
International Center for Insect Physiology and Ecology (ICIPE), Nairobi, Kenya
IRD, University of Paris: Patrick Lavelle
World Bank: Beverely Macyntree

**Universities:**
Alemaya University, Alemaya, Ethiopia
Amadou Bello University, Zaria, Nigeria: E. Iwuafor
Catholic University of Leuven (K.U.Leuven), Leuven, Belgium
Cornell University, Ithaca, USA
Egerton University, Tegemeo Institute, Kenya
Exeter University, UK: Jo Anderson
University of Reading
Jawaharlal Nehru University, India: KG Saxena
Kenyatta University: Daniel Mugendi, Ruth Kangai, Monicah Mucheru and James Kinyua
Makerere University, Uganda: Mary Okwakol, Mary Silver
Mekelle University, Ethiopia;
Sokoine University of Agriculture: Susan Ikerra
Université de Cocody: Yao Tano
Université Federal de Lavras, Brasil: Fatima Moreira
University Lampung, Indonesia: FX Susilo, Muhajir Utomo
University of Abidjan-Cocody, Côte d'Ivoire: Y. Tano,
University of Agricultural Sciences: DJ Bagyaraj
University of Nairobi: Leonita Muruli, Isaac Nyamongo, Lydia Kimenye, Richard Mibey
University of Reading: Geoff Warren
University of Zambia
University of Zimbabwe: Paul Mapfumo and Florence Mtambanengwe
Wageningen Agricultural University, Wageningen, The Netherlands
Cornell University: Chris Barrett
University of London, Queens Mary College, UK: David Bignell

**CGIAR Centers**
CIMMYT, Kenya: Hugo de Groote
CIP, Kenya: Charles Crissman
ICRAF, Kenya: Frank Place, Steve Franzel, Noordin Qureish, Bashir Jama
ICRISAT, Kenya: Ade Freeman
ICRISAT, Mali: Tabo
ICRISAT, Niger: Aboudoulaye, Abdoulaye and Mahamane

ICRISAT, Zimbabwe: John Dimes
IITA Research Station, Ibadan, Nigeria- Abdou
ILRI, Kenya: Patti Kristjanson, Steve Staal, Philip Thornton, Mario Herrero, Dannie Romney

**NARES:**
ARS, Chilanga, Zambia: Moses Mwale,
Agricultural Policy Research Unit of Bunda College, Malawi
AHI-Ethiopia: Tilahun Amede
AHI-Tanzania: Jeremiah Mowo, Juma Wickama
Areka Research Centre, Ethiopia
Awassa College of Agriculture, Awassa, Ethiopia
Chidetze, Malawi: Webster Sekala
CRRA Niono, Mali: M. Bagoyoko
DR&SS, Zimbabwe: Nhamo Nhamo, Tarasai Mubonderi
Ethiopian Agricultural Research Organization (EARO), Addis, Ethiopia
Holeta Research Center, Holeta, Ethiopia
INERA, Burkina Faso: V. Bado
Institut National de Recherche Agronomique (INRA), Togo- B.K. Tossah
Institut National des Recherches Agricoles du Benin (INRAB), Cotonou, Benin
Institut Togolais de Recherche Agronimique (ITRA), Lome, Togo
Institute for Agricultural Research (IAR), Zaria, Nigeria: E. Iwuafor
KARI-Embu: Alfred Micheni, Francis Kihanda
KARI-Kakamega, Kenya: Rueben Otsyula, David Mbakaya, Martin Odendo
KARI-Muguga, Kenya: Stephen Kimani
KARI-NARL: Nairobi: Stephen Nandwa
KEFRI, Kenya
Ministry of Agricultural and Livestock Development (MoALD), Kenya
Ministry of Agriculture, Kenya, Ethiopia, Malawi and Uganda
Ministry of Health, Israel: Dorit Kaluski
NARO, Uganda: John Byalebeka
NSS, Mlingano, Tanga, Tanzania: Susan Ikerra and Atanasio Marandu,
Salien Agricultural Research Institute, Lushoto, Tanzania
Soil Research Institute, Kwadaso, Kumasi, Ghana: E. Yeboah

**Non-Governmental Organizations:**
Africa 2000 Network (A2N), Uganda
Africare, Zimbabwe
AREX, Zimbabwe: W.Mpangwa, J.Nzuma
AT (Uganda)
Bunda College of Agriculture, Malawi
CARITAS, Uganda
CNFA
DARTS, Malawi: W.Sakala
DR&SS, Zambia: M.Mwale
Farmer Groups in Vihiga, Siaya, Busia, Teso, and Kakamega districts of western Kenya and Meru South district of central Kenya, Tororo and Mayuge districts of Uganda; farmer groups in Lushoto (Tanzania), Togo and Benin.
Forestry Research Institute (FORI), Uganda
FOSEM, Uganda
KWAP (Kenya Woodfuel and Agroforestry Project)
PLAN International, Uganda

SDARMP, Zimbabwe: D.Saunders
SG2000 Agriculture Programme, Uganda
Smallholder Flodplain Development Project, Malawi: J. Chisenga
System-wide Livestock Program (SLP)

*B. TSBF Institute Latin America Programme*

**NARS:**
CORPOICA – Bogotá, Colombia: Juan Jaramillo
CORPOICA – Bucaramanga, Colombia: Hernando Méndez
CORPOICA – Espinal (Tolima), Colombia: Pedro Pablo Herrera
CORPOICA– La Libertad (Villavicencio), Colombia: A. Rincón, J.J. Rivera, C.J. Escobar, Jaime H. Bernal, Diego Aristizábal, José E. Baquero, Emilio García, Rubén Valencia, Carmen R. Salamanca
CORPOICA – Macagual, Colombia: Carlos Julio Escobar
CORPOICA – Medellín, Colombia: Alvaro Tamayo
CORPOICA – Obonuco (Pasto), Colombia: Luis F. Campuzano, Bernardo García
CORPOICA – Palmira, Colombia: Jorge Peña, Gloria Ortiz, Carlos Arturo Rincón, Ferney Salazar
CORPOICA – Tibaitatá, Colombia: Inés Toro, Margarita Ramírez
CORPOICA – Turipaná (Montería), Colombia: Nora Jiménez, Sony Reza, Socorro Cajas, Carlos Sánchez, Joaquín García
DICTA – Directory of Science and Technology, Honduras.
EMBRAPA– Agrobiologia, Brazil. Bob Boddey, Avilio Franco.
INTA – National Institute for Agricultural Technology, Nicaragua. Elbenes Vega, Lilliam Pavón.
MAG-FOR– Ministry of Forestry and Agriculture, Nicaragua. Eduardo Marín.

**Non-Governmental Organizations:**
ASOGRANDE, Caicedonia, Colombia: Roberto Tiznes Mejía
CARTON DE COLOMBIA, Cali: Bayron Orrego
CENICAFE, Chinchina: Horacio Rivera, Siavash Sadeghian, Alveiro Salamanca
CENIPALMA, Bogotá: Fernando Munévar, Pedro León Gómez
CETEC: Kornelia Klaus, Aníbal Patiño
CIPASLA, Pescador: Rodrigo Vivas
CIPAV: Enrique Murgueitio, María Cristina Amézquita, Maria Elena Gómez
COLCIENCIAS, Bogotá: Oscar Duarte, Jaime Jiménez
CORPOTUNIA: William Cifuentes
COSMOAGRO, Palmira: Antonio López
CRC (Corporación Regional del Cauca), Popayán: Jesús A. Chávez
CVC (Corporación del Valle del Cauca), Cali: Eduardo Varela, Enrique A. Torres, Alvaro Calero
FEDEARROZ, Ibagué: Alvaro Salive, Armando Castilla
IPF (Instituto de Fósforo y Potasio), Ecuador: José Espinosa
MONOMEROS COLOMBO-VENEZOLANOS, Bogotá: Ricardo Guerrero, Alberto Osorno
PALMAS DE CASANARE, Villavicencio: Juliana Betancourt
SERTEDESO, Honduras: Saúl San Martín

**Specialized Institutions:**
IFDC, USA; D. Friesen
FAO, Honduras, L.A.Welchez
College on Soil Physics, Trieste, Italy: Miroslav Kutilek
ETH, Zurich, Switzerland; Prof. E. Frossard, A. Oberson
FAO-Lempira Sur, Honduras: Luis A. Welchez
IGAC (Instituto Geográfico Agustín Codazzi), Bogotá-Colombia: Dimas Malagón

IIAP (Instituto de Investigaciones Ambientales del Pacífico), Quibó (Chocó), Colombia: Eduardo García Vega, Luis Carlos Pardo Locarno, Jesús Eduardo Arrollo Valencia
IICA, Bogotá-Colombia: Fabio Bermúdez
IRD, Bondy, France: P. Lavelle
Sociedad Colombiana de la Ciencia del Suelo-SCCS, Bogotá-Colombia: Francisco Silva Mojica
USDA-ARS – Jornada, New México, USA: Jeff Herrick

**Universities:**
Agricultural University of Norway, Norway: B.R. Singh
CATIE, Costa Rica: John Beer, Muhammad Ibrahim, Francisco Jiménez, Bryan Finegan
Cornell University: John Duxbury, Erick Fernandes, Johannes Lehmann, Janice Thies
CURLA – Unversity for the Atlantic Region, Honduras: Manuel López.
Escuela Agrícola Panamericana Zamorano, Honduras: Carlos Gauge
ESNACIFOR (National School of Forestry), Honduras: Samuel Rivera.
Instituto de Educación Técnica Profesional, Roldanillo, Colombia: José A. Rodríguez, Gustavo A. Ramírez, Alma L. Obregón
Instituto Técnico Agropecuario-ITA, Buga, Colombia: Manuel Amaya Navarro
North Carolina State University, USA: Jot Smyth
Ohio State University, USA. Rattan Lal
Swedish Agricultural University, Uppsala: Olof Andren
University of Bayreuth, Germany: Wolfgang Wilcke.
Universidad de Caldas, Colombia: Franco Obando, William Chavarriaga
University of California-Davis, United States: Donald Nielsen
Universidad Centro Americana (UCA), Nicaragua: Alfredo Grijalva
Universidad Distrital de Bogotá, Colombia: Miguel Cadena
Universidad Central de Venezuela (UCV): Deyanira Lobo
Universidad de los Andes, Mérida, Venezuela: Lina Sarmiento, Dimas Acevedo
Universidad de la Amazonía, Colombia: Bertha Ramírez
University of Chile: M. Pinto
Universidad de Córdoba, Montería, Colombia: Iván Darío Bustamante
Universidad de Costa Rica: Alfredo Alvarado
University of Freiburg; E. Wellmann
University of Ghent, Belgium: Donald M.Gabriels
University of Gottingen, Germany, N. Claassen
University of Hohenheim, Germany: R. Schulze-Kraft, D. Leihner, K. Stahr
Universidad de Lleida, Spain: Idelfonso Pla-Sentis
Universidad de Nariño, Colombia: Hugo Ruíz, Jesús A. Castillo, Germán Arteaga, Javier García.
Universidad del Pacífico, Colombia: Carlos Castilla, Alfredo León, Arnulfo Gómez-Carabalí
University of Paris, France: Patrick Lavelle
Université de Rouen, Rouen, France: Thibaud Decaëns
Universita di Trieste, Italy: Giancarlo Ghirardi
Universidade de Uberlandia, Brazil:
Universidad del Valle, Colombia: Patricia Chacón, James Montoya, Martha Páez
Universidad Javeriana, Bogotá, Colombia: Amanda Varela
Universidad Jorge Tadeo Lozano, Bogotá, Colombia: Abdón Cortez
Universidad Nacional de Agricultura (UNA), Honduras: José T. Reyes
Universidad Nacional Agraria (UNA), Nicaragua: Matilde Somarriba
Universidade de Sao Paulo, Brazil: Klaus Reichardt
Universidad Tecnológica de los Llanos: Jorge Muñoz, Gabriel Romero, Obed García, Julio C.Moreno
Universidad Tecnológica de Pereira: Alex Feijoo
Wageningen University, The Netherlands: Ken Giller, Peter Buurman.

### *3.3 Financial Resources*

**Complementary and Special Projects**

Research activities reported have been supported from a number of donors

*TSBF Institute Africa Programme*

**List of Current TSBF Projects**

| Donor / Project | Duration | Total Pledge (US$) |
|---|---|---|
| **The Rockefellefer Foundation**<br>Soil Biology and ecology as a component of integrated soils management in African farming systems | **2002 - 2004** | 1,200,000 |
| **The Rockefellefer Foundation**<br>Collaborative Initiative on Soil Biology for African Agriculture: Exploration of Methods for the Integrated Management of the Soil Biota | **1999 - 2002** | 100,000 |
| **The Rockefellefer Foundation**<br>Collaborative research with the Department of Agricultural Economics and Extension, University of Zimbabwe on the economics of using animal manure for soil fertility management by poor farmers in resettled communal lands of Zimbabwe | **2000 - 2003** | 32,034 |
| **The Rockefellefer Foundation**<br>Expansion of TSBF AfNet acitivities to address the problem of soil nutrient depletion facing smallholder farmers in West Africa | **2002 - 2004** | 181,000 |
| **The Rockefellefer Foundation**<br>Soil fertility improvement technologies in the Tororo district of Eastern Uganda | **2001 - 2002** | 41,000 |
| **The Rockefellefer Foundation**<br>Support for Scientists from East and southern Africa to attend a conference on African soil fertility degradation at Bellagio Study and Conference Centre, March 2002 | **2002** | 9,000 |

| Donor / Project | Duration | Total Pledge (US$) |
|---|---|---|
| **IFAD via IFDC**<br>Development of sustainable intergrated soil fertility management strategies for smallholder farmers in Sub-saharan Africa | **2001 - 2004** | 559,193 |
| **Systemwide Livestock Project: SLP/ILRI**<br>Improving Crop-Livestock Farming Systems in the Dry Savanna of West and Central Africa. | **2001 - 2002** | 29,900 |
| **United Nations University**<br>Publication and Printing of TSBF Book entitled: "Fighting Poverty in Sub-Saharan Africa: The Multiple Roles of Legumes in Integrated Soil Fertility Management" | **2001 - 2002** | 20,000 |
| **DANIDA - UNESCO**<br>Managing Soil Biodiversity for improved ecosystem services | **2002 - 2003** | 43,500 |
| **BMZ/CGIAR/CIAT**:<br>Soil Water Nutrient Management | **2002** | 29,126 |
| **GEF via UNEP**<br>Conservation and Sustainable Management of Below Ground Biodiversity, Phase I | **2002- 2007** | 5,300,000 |
| **DfID via CIAT**<br>Integrated Resource Management in Crop-Livestock Farming Systems of Sub-Saharan Africa | **2001 - 2004** | £ 421,620 |
| **IDRC - Nairobi**<br>Community-Based Interactive Farmers Learning Processes and their Application on Soil Fertility Management (Kenya) | **2001 - 2004** | 334,940 |
| **Food and Agriculture Organization of the UN**<br>Soil Productivity Improvement - Farmer Field School Programme (SPI-FFS) in East and southern Africa | **2002** | 12,240 |
| **Technical Centre for Agricultural and Rural Co-operation**<br>Production and Printing of "Soil Fertility Management in Africa: A Regional Perspective" | **2002** | 22,979 |

*TSBF Institute Latin America Programme*

**List of donors of Complementary and Special Projects:**

| Donor/Project | Duration | Total Pledge (US$) |
|---|---|---|
| **ACIAR**<br>Integrated nutrient management in tropical cropping systems: Improved capabilities in modelling and recommendations. | 1999 - 2002 | 434,130 |
| **BMZ-GTZ**, Bonn, Germany<br><br>An integrated approach for genetic improvement of aluminium resistance of crops on low-fertility acid soils | 2001 - 2003 | 690,244 (Euros) |
| **DFID, United Kingdom**<br>Integrated Resource Management in Crop-Livestock Farming Systems of Sub-Saharan Africa. | 2000-2003 | 602,916 |
| **European Commission (EC**), Brussel, Belgium<br><br>Characterization of South American genotypes of bean for optimal use of light under abiotic stress | 2001-2004 | 831,261 (Euros) |
| **PRONATTA, Colombia**<br>Strategies for building up productive arable layer in Altillanura soils/ | 2001-2004 | 153,000 |

## *3.4 Main highlights of research progress in 2002*

**Output 1. Biophysical and socioeconomic constraints to integrated soil fertility management (ISFM) identified and knowledge on soil processes improved**

- Relationships of organic input quality to fertilizer equivalency values established
- Quantification of lignin and polyphenols in different organic materials
- Nutrient monitoring (NUTMON) approaches introduced at two sites in West Africa
- Optimum management for combined use of organic and inorganic resources established
- Green manures and grain legumes do not work everywhere but there are niches where they could do well on-farm.
- Grain legumes have a much higher likelihood for adoption by farmers due to their multiple benefits and often high profit margins.
- High legume biomass and the consequent high amounts of N incorporated in soil do not always translate to high cereal crop yields because the soil systems are leaky though this can be minimised by manipulating timing of incorporation of the green manures.
- Building on previous progress the modelling work this year involved revising the APSIM SoilN and MANURE modules so that the three fpools that comprise FOM can have different C:N ratios.
- Similarly, following the work in Year 2 a similar approach was taken for the release of plant available P from organic inputs, so that P release depends on the pools having different C:P ratios. In Year 3 changes were also made to the APSIM SoilP and Maize modules to modify the uptake of P and its partitioning within the crop.
- A linked soil-crop simulation model, ruminant livestock simulation model, household model and linear program module developed
- Farm level crop-livestock integration scenarios in four countries developed
- Extension of the preliminary dataset testing fertilizer equivalency value – organic resource quality relationships with data from the AfNet 2001 meeting and West Africa revealed that the original hypothesis put forward by Palm et al. (2001) are valid; the N fertilizer equivalency values were found to be linearly related to the N content of the organic resources for resources with a N content above 2.4% and the slope of the relationship between both characteristics was substantially lower for materials containing a large amount of soluble polyhenols.
- Resource flow maps, drawn in various sites across East Africa, confirm the very diverse range of soil management options implemented by small scale farmers and point towards various potential options to improve the use efficiency of add organic and mineral nutrient sources for various farmer wealth classes and overall biophysical and socio-economic conditions.
- Community meetings generated a baseline of “folk ecological” knowledge in four communities of Western Kenya, along a gradient from high population density Vihiga district, through Busia, to lower population density Teso district. Culturally this gradient also extends from predominantly Luyia (Bantu) to Teso (Nilotic) speakers. Considerable common local knowledge was identified and characterised in local reports. Local soil taxonomies are quite detailed, describing soil quality as a function of topsoil colour and texture, location within the topography, and the presence or absence of signs of degradation (erosion, excessive weediness or stoniness). Since soil ‘fertility’ is perceived only through indirect means, such as the presence / absence of certain indicator plants or the vigour of crop growth, it is usually conceived of in very holistic terms (i.e.: fertility, weed and pest dynamics are strongly interrelated in local vocabulary). One of the key knowledge gaps identified is that, while many farmers recognise various crop leaf discolorations as signs of ‘low fertility’ there is not widespread understanding of there being multiple different nutrients in the soil which could be affecting crop performance. Many of the older women, who are frequently the farm managers, were not aware of the different nutrients provided by different commercially available fertilisers.

- Seminars held to share findings between the sites led to community-level mapping of the soil types and transect ground-truthing exercises to further refine and verify the local soil classifications, as well as to discuss examples of various forms of soil alteration through management or neglect. Older participants revealed than many of the soil types seen today are degraded forms of older soil types, whereas younger farmers assumed the soils of today had also existed in the past and that 'a soil cannot change itself'. The locally recognised diversity of soils is greater than that depicted on scientific soil maps of the study regions. As a result, local farmers complained that experimental plots for new technologies are often not situated on enough of the local soil types for people to draw inferences about where (or if) they would be appropriate.
- Key informants have been selected and interviewed to gather their knowledge of soil fertility processes, indicators of soil fertility status changes, and the evolution of their soil management practices. Many older farmers' felt that they cannot really apply their knowledge of how to match crops with suitable soils or agro-ecological niches because land sizes today are too small, demands for annual maize production are relentless, and access to different niches is limited now that the landscape is fully settled. One unexpected finding has been that local knowledge of soil fertility is not any less amongst younger farmers, in part because those who have stayed in the area are those who by intent (or lack of alternative options) have a commitment to agriculture. They also tended to have better understanding of soil nutrients and of potential new technologies.
- Multiple studies of the distribution and extent of knowledge on local indicators of soil fertility status and changes conducted in Teso, Busia, Siaya, and Kakamega districts conducted.
- Ethnobotanical study of plant species indicating soil fertility status and changes initiated in Meru South and adjacent districts of Central Kenya as companion study to work conducted in Latin America. (MSc student)
- Evaluation of local decision-making related to concepts of 1) high vs. low quality residues and 2) soil nutrients, using community-based demonstration plots in Western Kenya. Initial round of plots completed and follow-up activities with farmers in progress.
- Farmers, extension, and KARI-Kakamega field staff were trained in participatory monitoring and evaluation methods. Several forms of farmer recording keeping were introduced in 2001 to monitor and evaluate progress with the soil fertility management technologies. However, lack of funds has limited follow-up, which has lead to widely varying levels of farmer interest and disparate standards of data collection.
- A baseline survey of soil fertility management practices and socio-economic conditions was completed and analysed for 314 farmers in the West Kenya site. The methodology was shared with the Ugandan and Tanzanian sites. These data will now be compiled and analysed along with comparable studies conducted at the other BMZ project sites in West Africa (Togo and Benin) to produce a scientific paper relating soil fertility management practices to the contrasting socio-economic and agro-ecological conditions of the sites.
- A formal economic survey of on-farm use of organic and inorganic resources has been designed for the BMZ sites in Kenya, Tanzania, Uganda, Benin, and Togo, and will be implemented at the end of 2002 / early 2003.
- Public and private benefits and costs of different ISFM options evaluated using the policy analysis matrix (PAM) technique. This approach is particularly useful for examining the role of transaction costs and market failures in influencing profitability of new technologies. (MSc student)
- Evaluating whether the soil fertility management and livelihood enhancement needs of different classes of farmers are being met with the ISFM options currently available to them, by contrasting the profitability of different options (using gross margin analysis). (MSc student)
- Evidence for the external constraints (such as the mis-functioning of input and output markets) on adoption and use of ISFM options documented and explained. For example, the bumper harvest reported in Kenya and Uganda in the 2001 short-rain season led to sale prices of maize that were often below production costs. In such situations, farmers face the prospective of losing money if they

sell their maize to generate cash, but there is also no incentive for them to invest in their agricultural enterprises given the policy environment they operate within. Clearly, innovations need to address food security and livelihood sustainability, not just increased production as a good in its own right. Policy interventions that would rationalise input and output markets, and buffer smallholders from their volatility, should have as their goal a) increasing farmers' opportunities to innovate, and b) making investments back into agriculture attractive. (Paper presented to ILRI-IFPRI conference on "Policies for Land use management in highland East Africa".)

- Review of African smallholder experiences with integrated soil fertility management practices found growing use, both indigenously and through participation in agricultural projects. Patterns of use vary considerably across heterogeneous agro-ecological conditions, communities and households. The potential for integrated soil fertility management to expand markets for organic inputs, labour, credit, and fertilizer explored. Markets for organic markets are hampered by inherent constraints such as bulkiness and effects on fertilizer markets are conceivably important, although no good empirical evidence yet exists on these important points. (Paper submitted to Food Policy for special issue on "Input use and input markets in sub-Saharan Africa")
- Proposal submitted to FASID (Foundation for Advanced Studies in International Development) to examine the links between improved agricultural technologies and practices and productivity change and poverty reduction in smallholder communities and households. Agricultural technologies considered will include crop, livestock, and natural resource management innovations. Technological change is taken to be improvements in productivity of existing resources and enterprises (e.g. adoption of input packages leading to higher yields of crops) as well as the shifts in the composition of resources or enterprises (e.g. adoption of higher value added crops).
- The changing theoretical and methodological approaches of integrating social science into TSBF's research activities over the past decade were examined, and strategic lessons relevant to INRM research identified. The interdisciplinary "experiment" of TSBF has steadily taken shape as a shared language of understanding integrated soil fertility management. While individual disciplines still retain preferred modes of conducting fieldwork (i.e.: participant observation and community-based learning for "social" research, replicated trial plots for the "biological" research) a more "balanced" integration of these modes is evolving around activities of mutual interest and importance, such as those relating to decision support for farmers using organic resources. Since TSBF is working constantly through partnerships with national research and extension services, it has an important role in stimulating the growth of common bodies of knowledge and practice at the interface between research, extension, and farming. To do so requires strong champions for interdisciplinary, collaborative learning from both natural and social science backgrounds, the commitment of time and resources, and patience.
- The proportion of legumes in the farming systems is very low, and integration of legumes into system is constrained mainly by socio-economic factors
- Legumes with multiple benefits were accepted by farmers than legume cover crops
- The biophysical indicators used by farmers for selection were firm root system, early soil cover, biomass yield, decomposition rate, soil moisture conservation, drought resistance and feed value as important criteria.
- The socio-economic indicators that dictated integration of legumes into systems were depended on land productivity, farm size, land ownership, access to market and need for livestock feed.
- A draft decision guide was developed by combining the biophysical and socioeconomic indicators
- The CIAT-TSBF Working Group prepared a position paper on "BNF: A key input to integrated soil fertility management in the tropics" as part of the Pre-Proposal preparation for BNF Challenge Program.
- Case studies in Latin America show that there is a consistent rational basis to the use of local indicators of soil quality and their relation to improved soil management.

- Initial plant quality parameters that best correlated with decomposion were neutral detergent fibre (NDF) and *in vitro* dry matter digestibility (IVDMD) could be useful lab-tests during screening of plant materials as green manures.
- Green manures that decomposed and released N slowly resulted in high N uptake when they were used at pre-sowing in a tropical volcanic-ash soil.
- When *Tithonia diversifolia* is to be used as a fallow species, the use of plantlets as compared to the stake method of establishment was associated with better for nutrient acquisition and use efficiency.
- Annual application of high amounts of chicken manure can lead to surface sealing and crusting in volcanic-ash inceptisols in Colombian hillsides which is reflected in reduced water infiltration and air permeability and high superficial values of shear strength.
- Extension of the preliminary dataset testing fertilizer equivalency value – organic resource quality relationships with data from the AfNet 2001 meeting and West Africa revealed that the original hypothesis put forward by Palm et al. (2001) are valid; the N fertilizer equivalency values were found to be linearly related to the N content of the organic resources for resources with a N content above 2.4% and the slope of the relationship between both characteristics was substantially lower for materials containing a large amount of soluble polyhenols.
- Resource flow maps, drawn in various sites across East Africa, confirm the very diverse range of soil management options implemented by small scale farmers and point towards various potential options to improve the use efficiency of add organic and mineral nutrient sources for various farmer wealth classes and overall biophysical and socio-economic conditions.

**Output 2: Improved soil management practices developed and disseminated**

- Biological analysis of ISFM options conducted in collaboration with System wide Livestock Programme (SLP)
- Participatory economic analysis of current ISFM options conducted at benchmark sites
- Hill placement of small quantities of fertilizers evaluated at four sites on-farm
- Establishment of credit systems to increase farmers' access to external inputs at one site in the Sahel of West Africa.
- The APSIM model over-predicts the effects of fertilizer N only for the organic-inorganic N combinations and under-predicts release of nutrients from cattle manure.
- Manure decision guides have been developed and tested with farmers in Zimbabwe Current efforts are being made to evaluate the usefulness of these guides as communication tools to enhance uptake of soil management options.
- Farmers' categorizations of manure quality correlate well with laboratory indices and can be linked to use strategies of different types of manure.
- A District co-ordinated and run soil productivity enhancement program established in Tororo District. More than 3000 farmers accessing new and improved sources of information and technology options. Project funded successfully raised for 2003-4.
- Improved dual-purpose legume and improved fodder germplasm evaluated in Uganda
- Legume cover crops and biomass transfer species for maize production in Uganda evaluated
- Economic analysis of Legume cover crops and biomass transfer species for maize production in Uganda conducted
- Updated and new extension leaflets produced
- Studies of social capital and dissemination pathways completed
- Impact of policy on land management options investigated.
- Various dual purpose grain legumes are found to perform very well in terms of BNF and biomass production in Western Kenya. A certain level of variation in access to low available soil P between the various accessions was also noted.

- Significant rotational benefits were observed on maize after both herbaceous and dual purpose grain legumes, but most of the time only when P had been applied to the legumes. A minimal amount of N fertilizer applied to the cereal following a legume led to equal or higher yields compared to the maize-maize treatment receiving a recommended dose of N fertilizer.
- Twenty farmers participated in resource flow mapping (RFM) exercises in Emuhaya sub-location, the AHI/BMZ site in Western Kenya. The objective was to characterise their soil fertility management practices for the 2000-2001 cropping seasons. The participant selection was stratified on the basis of their wealth ranking in PRA's conducted earlier. Partial nutrient balances are in the process of being calculated using NUTMON. Initial results (from both West Kenya and work in Uganda) suggest that wealth class *per se* is not a good predictor of how well the soil will be managed. Higher wealth class households may use more externally purchased inputs, but their overall nutrient balances are also frequently lower than less resource endowed households.
- Following visits by Emuhaya farmers to other regions of Kenya, local initiative has led to the creation of three farmer field schools. These groups have a broader membership than the original farmer research groups, and have stimulated considerable interest in soil fertility management using high quality manure, marketable vegetable crops (particularly kales) and improved maize and bean germplasm.
- A community resource centre begun with the Ministry of Agriculture and Livestock Development (MOALD) in Emuhaya currently lacks materials. Renovation is to start after the long rains are finished (July/August 2002) and at this time community involvement will help develop the centre in directions that meet local needs. It is proposed that decision aids and other potential extension tools generated through local research will be disseminated and tested through this centre, to better understand the potential channels of information sharing. Links are also being explored with local NGO's active in soil fertility management (SCODP) and input traders and stockists in the private sector.
- Principles for conducting research to integrate local and scientific understanding of soil fertility processes are being compiled for development of a Field Manual to support trainers, farmer leaders, and scientists.
- Draft publication on the role of social networks in the generation and sharing of agricultural information has been submitted to the International Institute for Environment and Development (IIED) for inclusion in their Gatekeeper Series.
- A decision support plot was planted in March 2002 in Emuhaya to demonstrate concepts of both a) resource quality and b) nutrient deficiency. Follow up meetings at top-dressing have generated some interest with farmers who have not previously taken part in research activities. However, a better effort at labelling and visually explaining the demonstration site will improve its potential to communicate.
- Collective activities at the harvest evaluated which organic material classes should be considered 'high' quality and identified additional local or exotic materials that could be collectively tested on the plot next season. Recommendations on new experimental designs and site locations were made and will be incorporated in next season's activities, which will also include several of the 'folk ecology' project sites.
- Land degradation in East African Highlands is at an alarming stage, and yet soil conservation practices are not well accepted as there the technologies did not participate the communities in decision making.
- Four major steps were outlined to reverse the trend of land degradation namely, participatory characterization of the determinants of land degradation, community-led soil-water conservation practices, intensification of the system through integrated soil fertility management, and enhanced collective action to address communal resources.
- Deep-rooted tropical pastures can enhance soil quality by improving the size and stability of soil aggregates when compared with soils under monocroping.

- Increasing intensity of production systems resulted in improved soil physical conditions but decreased soil organic matter and macrofauna populations with the exception of agropastoral systems evaluated where a general improvement was observed.
- Improved fallows with species such as *Tithonia diversifolia* under slash and mulch management can contribute to the rapid restoration of soil fertility that has been exhausted by continuous cassava cultivation with little or no inputs.
- Determined the influence of contrasting agropastoral systems and related P fertilizer inputs on size of P fractions in soil and their isotopic exchangeability and showed that organic P dynamics are important when soil Pi reserves are limited.
- Showed that the use of vertical tillage and agropastoral treatments can contribute to the build-up of an arable layer in low fertility savanna soils of the Llanos of Colombia as indicated by improved soil physical properties and nutrient availability.

**Output 3: Ecosystem services enhanced through ISFM**

- The first Phase (2002-2004) of the project on 'Conservation and sustainable management of below-ground biodiversity' (BGBD) was endorsed by the Council and Chief Executive Officer of the GEF for $5 million. TSBF-CIAT is the Executing Agency on behalf of partners in seven countries ie. Mexico, Brazil, Cote d'Ivoire, Uganda, Kenya, India and Indonesia. A successful start-up workshop was held in Wageningen in August, hosted by BOT member Ken Giller
- TSBF undertook the quantification of biological nitrogen fixation using isotope dilution technique and samples are sent to IAEA in Vienna for 15N analysis.
- The chemical analysis of samples from the long-term trials are in progress.
- Yield from the long-term trials can be increased up to five fold when organics and inorganics are used in combination in a legume cereal rotation system.
- The significant effect in a cereal rotation is not only due to the nitrogen effect of the legume but more on the change in biological soil properties.
- Food deficit in Africa is not only the function of food shortage but also quality.
- The barley-based systems offer a considerable quantity of calorie and zinc, but deficit in vitamin A and calcium.
- It was possible to suggest a balanced human nutrition by reallocation of the land through optimization models using the existing resources.
- Tropical Secondary forest regrowth following pasture abandonment in Central Amazonia rapidly sequesters C in the soil where there is greatest potential for long-term C gains.
- The slash-and-char technique that involves charcoal additions to the soil significantly increased biomass production of a rice crop in comparison to a control on a Xanthic Ferralsol from the Central Amazon and opens new possibilities to enhance C sequestration in soils in areas where burning is a common management practice.
- Introduction of improved pastures with deep rooting abilities can convert savannas from a net source to a net sink of methane. Soils under gallery forests, covering 10% of the area of the Colombian savannas, are responsible for 48% of total methane sinks. For a 20-year time horizon, the global warming potential of the Colombian savannas region under current land use distribution constitutes a very small fraction of estimated global planetary radiative contribution.
- Agroforestry systems can lead to net C accumulation in soils close to total C stocks in the primary forest; however, charcoal derived-C found to 1 m depth can account for as much as 15% of total soil C and needs to be quantified when comparing the effect of land use change on soil organic C.

**Output 4. Research and training capacity of stakeholders enhanced**

- Long-term management of phosphorus, nitrogen, crop residue, soil tillage and crop rotation in the Sahel undertaken
- Maintenance of soil fertility under continuous cropping in maize–bean rotation evaluated
- Long-term management of manure, crop residues and fertilizers in different cropping systems in the Sahel of West Africa conducted
- Optimum combination of organic and inorganic sources of nutrients in seven African countries
- Equivalency of fertilizer value of legume-cereal cropping established in four sites
- Phosphorus (P) placement and P replenishment with Phosphate rock established in West Africa
- Placement of phosphorus and manure evaluated
- Farmers' evaluation of soil fertility restoration technologies at two sites in the Sahel of West Africa
- TSBF Institute webpage launched
- Training manual for identifying and classifying local indicators of soil quality developed, used and incorporated into University curriculum
- Facilitated participatory M&E training at BMZ/AHI site
- Reviewed proposals and assisted the refining of social science papers presented at the AfNET-8 meeting in Arusha, May 2001.
- On-going promotion of AfNET to social scientists working in Kenyan, Ugandan, Ethiopian, and Tanzanian universities and NGO's. Economists are the largest social science constituency interested in AfNET, but the input of sociologists, geographers, and anthropologists will also help broaden the relevance of ISFM research in the region
- A participatory methodology has been developed that facilitates consensus building about which soil related constraints should be tackled first. Consensus building is presented as an important step prior to collective action by farming communities resulting in the adoption of improved soil management strategies at the landscape scale.
- 12 field days were organized in Cauca and 3 training courses were organized in the Colombian Llanos.
- Prepared and/or published 34 articles for refereed journals, 3 books, 18 book chapters and 15 articles for conference proceedings most of which which are coauthored with other institutional partners.
- 72 students are associated with the project (24 Ph.D. theses).
- Established and maintained collaborative links with NARS and ARO partners.

## *3.5 Progress towards achieving output milestones of the project logframe 2002*

**Output 1. Biophysical and socioeconomic constraints to integrated soil fertility management (ISFM) identified and knowledge on soil processes improved**

- *Relationships of organic input quality to fertilizer equivalency values established; multiple benefits of organic resources quantified and incorporated into the ORD; optimum management of organic and inorganic resources established*

Information related to N fertilizer equivalency values obtained in W-Africa has been added to the information obtained in E and S Africa and was presented during the Nitrogen meeting in September 2001 in France.

Trials on the 'optimum management of low quality organic resources' were established in several sites in East and West Africa. The major objective is to determine the immediate and residual response of various cereals (maize, rice, sorghum) to application of low to medium quality materials (manure, maize

stover, rice straw, etc) combined or not with various rates of urea. Preliminary results of the first season show significant responses to N in most of the sites and limited impact of the organic resources. The immediate response of these materials was rather neutral in most places, except in the Sahel where strong responses were observed. Currently, the first residual year is being determined. The trials also look at the P supply potential of various organic resources. Moderate applications of manure were observed for supply all the P required by a maize crop in Nigerian and W Kenya. This observation could not be explained in terms of amount of P supplied alone; effects on the P sorption dynamics are likely to have contributed to the observed effect.

Trials on the 'optimum N and P management in legume-cereal rotations' were established in several sites in East and West Africa. The trials look at the impact of grain and herbaceous legumes on soil fertility status. Treatments are a herbaceous legume (most of the time Mucuna) and a grain legume (mostly soybean or cowpea) followed by maize with and without application of mineral N. The legume is treated or not with TSP, and significant responses were observed to P application in most sites.. The impact of previous legumes and application of P to the legume on the need for N and P of a subsequent maize crop will be evaluated.

Trials on organic/mineral interactions are being established in 2 sites in Ethiopia (Ginchi, Mekelle). Legume species used include local species and improved varieties of 'exotic' species. The work in Mekelle is part of the PhD thesis of Kiros Habtegebriel, in Ginchi of Balesh Tulema.

The NUTMON approach was introduced at two sites in Sadore (Niger) and Samanko (Mali) to install capacity to monitor nutrient inputs and outputs from cropping systems. The packages consist of two data collection questionnaires, which were translated into French for ease of use and the NUTMON Toolbox model kit. At both sites, the work was undertaken in collaboration with ICRISAT with funding support from the system wide livestock project. Data wil be analysed in 2002.

Following the installation of NUTMON toolbox, farmer input and output inventory survey data has been collected in Mali and Niger. These data are now being logged into the model together with monitoring season data that are being recorded during the current crop and livestock activity season. The initial farm NPK balance output will be available later in 2002.

In July 2002 the ICRISAT laboratory supervisor based at Sadore in Niamey visited TSBF for training in resource quality analysis. Currently, several samples of manure and crop residue input materials used in the 2002 season network trials have been analysed for %N, % Lignin, and % Polyphenols.

- *Optimum management for combined use of organic and inorganic resources established*

Several network experiments were established at benchmark locations in different agro-ecological zones of West and East Africa to look at N fertilizer equivalencies of organics. The input materials are low quality cattle manures and crop residues (rice and maize stover). The most important research highlight is that whereas the fertilizer equivalency values of low quality manure were very poor in the Sub-humid and humid zones, their values were very high (>250%) in the semi-arid zones. Indicating that the critical value for immobilization and mineralization is site specific.

- *Soil, water, nutrient and knowledge constraints to sustainable production defined and the understanding of the role of soil biota, multipurpose germplasm, and organic and inorganic resources for sustainable management of land resources improved.*

Most of the work focussed on integrating legumes into farming systems looking at where some of the legumes could work best and analyzing the reasons why the perform best under the sets of conditions.

Legume work was established in the 2000/01 season to screen legumes in two areas, Murewa (annual rainfall 800-1000mm) and Shurugwi (annual rainfall 600mm). Results in the first season showed that the three green manures, Crotalaria grahamiana, Crotalaria juncea and Mucuna pruriens produced high biomass and added higher amounts of N to the soil compared with the grain legumes, Vigna

unguiculata and Glycine max. Of the green manures, Mucuna pruriens was found to give the highest biomass and N addition to the soil on some of the sites while Crotalaria grahamiana gave higher biomass yield and N addition to the soil at some of the sites. Biomass yields were as high as 6000 kg $ha^{-1}$ with N addition of up to 200 kg $ha^{-1}$. Vigna unguiculata gave higher biomass and grain yields than Glycine max with biomass as high as 2000 kg $ha^{-1}$ and 1000 kg $ha^{-1}$ of grain. In the second season, Crotalaria grahamiana had the highest maize yields of up to 2000 kg $ha^{-1}$ even on the sites where Mucuna had higher biomass yields in the first season. Early incorporation gave higher yields than late incorporation. There were however no treatment differences in maize yields because of the drought that was experienced during the season causing low yields.

Experiments were setup in the 2001/02 season to establish the biophysical boundary conditions under which different legumes perform in Malawi, Zambia and Zimbabwe (Murewa and Shurugwi). Biomass yields of the legumes were generally high in the clay soils than in the sandy soils. The correlation between clay content and biomass yield was however poor probably because of the drought experienced causing moisture to be the most limiting factor. Similar trends were observed for pH, CEC, %C and available P content with biomass yields. Generally, higher biomass yields were observed for green manures than grain legumes in Zambia and Zimbabwe. There was crop failure in southern Zambia while biomass yields of up to 16 000 kg $ha^{-1}$ of Crotalaria juncea were observed in the northern parts of the country where rainfall was high. This experiment will be repeated on the sites where biomass yields were low and maize will be planted on the sites where legume biomass yields were greater than 2500 kg $ha^{-1}$.

A PRA was conducted with farmers from Shurugwi to establish how smallholder farmers prioritise legumes in their farming system, establish factors determining the area allocated to legumes, farmer perceptions on legumes and green manures introduced through farmer participatory research trials and identify opportunities for increasing the role of legumes and green manures in soil fertility management. Farmers identified legumes as the second major crop in the smallholder farming system after maize. Farmers grow legumes mainly for cash and food. More than 90% of the farmers were aware of the potential of legumes especially groundnuts in improving soil fertility. Diseases and limited land available limit opportunities for expanding area under legumes. Green manures were identified as very important in reclaiming poor soils were maize yield responses, even with fertility inputs, is limited and as fallow crops. Farmers identified green manures with multiple uses as more appropriate and likely to be adopted. Multiple benefits and labour requirements were identified as the most important criteria for identifying green manures for adoption. Farmers ranked mucuna highly for its potential in improving soil fertility, controlling weed growth, controlling striga, its use as a coffee bean and that it is easier to incorporate compared to sunhemp and crotalaria. On grain legumes, groundnut was ranked first as it is the main cash crop for most smallholder farmers. Soyabeans appeared to have a much higher likelihood for instant adoption by most farmers due to its multiple benefits and high profit margins. A benefit cost analysis revealed that cowpeas had the most attractive gross margin per hectare compared to the green manure legumes. The value of the other cowpea benefit as a relish, though very important, was not included in computing the margins per hectare. The Net Present Values (NPV) for all the green manures were negative. Cowpea had a positive NPV. The biomass produced by the green manures may not have been large enough to raise the fertility status of the soils to achieve the desired yield levels for maize in the second year.

- *Soil, water, nutrient and knowledge constraints to sustainable production defined and the understanding of the role of soil biota, multipurpose germplasm, and organic and inorganic resources for sustainable management of land resources improved.*

Soils at our Central America reference sites in Honduras and Nicaragua appeared to be both N and P limited thus responding best to the combined application of N and P. One Post-Doctoral Fellow started

studies in Nicaragua on "farm resource and nutrient flows" in the Wibuse watershed at the San Dionisio Reference Site in Nicaragua following training with TSBF colleagues in Africa.

In the hillsides of the Cauca department-Colombia, we made progress in the identification of some biophysical mechanisms that are related to crust formation. We found that excessive application of chicken manure as an organic fertilizer on Andean volcanic ash soils leads to soil crusting and sealing due to physical dispersion, chemical dispersion, and the interaction of soil physical and chemical characteristics.

For the Llanos of Colombia, field studies conducted at Carimagua and Matazul (Savannas) contributed to define lime and nutrient requirements for acid soil tolerant varieties of rice, maize, cowpea and soybeans in rotational production systems on heavy-textured Oxisols. Field and glasshouse studies on crop and forage components indicated that forage legumes are more efficient in acquiring P per unit root length. Comparative studies of a forage grass (*Brachiaria dictyoneura* CIAT 6133) and a legume (*Arachis pintoi* CIAT 17434) demonstrated that the legume could acquire P from relatively less available P forms from oxisols of Colombia.For the Llanos of Colombia….

The increasing attention paid to local soil knowledge in recent years is the result of a greater recognition that the knowledge of people who have been interacting with their soils for long time can offer many insights about sustainable management of tropical soils. Case studies show that there is a consistent rational basis to the use of local indicators of soil quality. Biological indicators (native flora and soil fauna) were shown to be important local indicators of soil quality related to soil management. Although benefits of local knowledge include high local relevance and potential sensitivity to complex environmental interactions, without scientific input local definitions can sometimes be inaccurate to cope with environmental change. It is argued that a joint local/scientific approach, capitalizing on complementarities and synergies, would permit overcoming the limitations of site specificity and empirical nature and allow knowledge extrapolation through space and time.

Field research in Cauca showed that decomposition and nutrient release rates by green manures of contrasting chemical composition or quality were significantly correlated with initial quality parameters often used by animal nutritionists in the lab like neutral detergent fiber (NDF) and *in vitro* dry matter digestibility (IVDMD). This observation highlights potential usefulness of these lab-based measures as screening methods for large numbers of potential green manure materials in relatively short time. Glasshouse studies showed that at pre-sowing surface application of low-quality green manures (i.e. *Calliandra calothyrsus*) and/or surface application of high quality green manures (i.e. *Indigofera constricta*) during periods of high crop demand could be seen as alternative nutrient sources for hillside farmers cropping volcanic-ash soils. We also investigated the effects of establishment in *Tithonia diversifolia*, from bare root seedlings (plantlets) and vegetative stem cuttings (stakes), because this plant has the ability to sequester nutrients from soil in its tissues, including P, and has been shown to be useful for cycling nutrients via biomass transfer and improved fallow. Nutrient uptake efficiency (μg of shoot nutrient uptake per m of root length) and use efficiency (g of shoot biomass produced per g of shoot nutrient uptake) for N, P, K, Ca and Mg were greater with plants established from plantlets than those established from stakes (is it right). Improved nutrient acquisition could be attributed to relief from P stress and possibly uptake of some essential micronutrients resulting from mycorrhizal association.

Field research carried out at Carimagua showed that both native savanna and introduced pastures develop deep root systems compared to field crops such as maize. Studies on root distribution of maize showed that most of the roots are in top 20 cm of soil depth. Application of higher amounts of lime did not improve subsoil-rooting ability of maize but contributed to greater nutrient acquisition. Cultivation with disc harrow (8 passes) markedly improved maize growth and nutrient acquisition. We made progress in demonstrating the importance of deep-rooted tropical pastures to enhance soil quality by improving the size and stability of soil aggregates when compared with soils under monocropping. The concepts and strategies developed from this work are relevant to different areas of the Llanos for improving soil quality and agricultural productivity.

- *Decision guides for ISFM developed; a strategy for the wider use and dissemination of the ORD and decision guides developed and implemented*

Resource flow maps were drawn calculated for various farms belonging to various wealth classes in Lushoto (Tanzania), Western Kenya, Iganga (Uganda), Mekelle (N Ethiopia), Ginchi (W Ethiopia), Hirna (E Ethiopia), and Areka (S Ethiopia). Currently the partial nutrient balances are being calculated and evaluated with the NUTMON toolbox. The partial nutrient balance calculations need to be completed and the impact of wealth and overall economic environment evaluated. Idea is to get a paper out on this topic in the framework of the current projects. Follow-up NUTMON data processing meeting in Addis (planned somewhere in February 2003).

- *Contribution of SOM to crop production as influenced by organic resource quality evaluated*

Preliminary relationships between OM Q and SOM characteristics are being investigated in existing medium-to-long term trials (Meru, Kabete, Nyabeda) where organic resources of varying quality have been applied (all trials contain Tithonia and Calliandra applications). The delta 13C technique will be used. The SOM status (quantity and quality) of soils will be related to a set of specific soil properties essential for proper crop growth in an attempt to 'valorize' SOM. The use efficiency of mineral fertilizer is being determined using 15N labeled fertilizer, in a set of treatments of the trials (control, Calliandra, Tithonia) to determine relationships between SOM status and fertilizer use efficiency. The soil properties to include in the evaluation work will be decided upon and preliminary relationships between SOM status and these properties will be evaluated. The samples from the microplots will be analyzed before the end of the year and preliminary N recoveries calculated. These activities are implemented through MSc projects of M Kirunditu and B Waswa.

As set of trials looking at relationships between organic matter quality, environment, and soil organic matter quantity/quality have been established in Embu and Machanga (Kenya) and or going to be established near Kumasi (Ghana) and in Zimbabwe. Inputs are: Tithonia or Crotalaria, Leucaena of Calliandra, maize stover, sawdust, and manure. The organic resources are applied sole and in presence of N fertilizer. The trials are expected to run for at least 5 years. Further back-stopping of the trials in Kenya, Ghana and Zimbabwe.

**Output 2: Improved soil management practices developed and disseminated**

- *Biological analysis of ISFM options conducted*

In 2001 TSBF was partner in the project of improving crop-livestock systems in the dry Savannah of West Africa with funding from the System wide Livestock Programme (SLP). The activities of this project were established in different sites in Nigeria, Niger and Mali. Most of the activities of TSBF were undertaken in Niger to evaluate on-farm best bet integrated soil fertility management following a rainfall gradient from 400 mm to 800 mm. The best bet options identified are the use of small quantities of fertilizers (4 kg P/ ha) hill placed at planting time, the combination of organic amendments such as manure and crop residue with mineral fertilizers and the increase of cowpea in the cropping systems due to the very positive effect of rotations of cowpea with cereals. The effect of crop residue use as mulch is more critical in the drier zone than in the high rainfall zone. Although the rotation of cereal with cowpea can double the succeeding cereal yield and cowpea is an important cash crop, farmers are not enthusiastic to adopt this option. The adoption of the hill placement of small quantity of fertilizer can double crop yields.

Trials looking at the impact of cut-and-carry systems on nutrient balance were established in 2 sites (a poor and a fertile soil) in Nyabeda, Western Kenya in August 2001. Treatments are Tithonia, Calliandra, and natural fallow. The aboveground biomass production in these treatments is to be cut continuously and applied to a maize and kale crop. As such, the nutrient status under the shrubs and its effect on the quality of the aboveground biomass can be evaluated, together with the response of two important crops to organic matter application. Tithonia biomass production was about double as much on the fertile compared to the poor soil. No other data are available yet as the trials are just recently established. Evaluation of the response of maize and kale to the application of Tithonia and Calliandra residues.

Trials looking at the impact of grain and herbaceous legumes on soil fertility status were established in East and West Africa during the first or second season of 2001. Treatments are a herbaceous legume (most of the time Mucuna) and a grain legume (mostly soybean or cowpea) followed by maize with and without application of mineral N. The legume is treated or not with TSP, and significant responses were observed to P application in most sites.

Various classes of legumes (herbaceous, fodder, tree, grain) are being screened in Ginchi (W Ethiopia) and Mekelle (N Ethiopia) for their potential to accumulate biomass and supply N to the soil. No data are available yet as the trials are just recently established.

Demonstration trials to evaluate with farmers the organic resource quality concept were established in BMZ benchmark villages. No data are available yet as the trials were just recently established (April 2002).

- *Participatory economic analysis of current ISFM options conducted at benchmark sites*

A PhD student at the economic department of Purdue university used the field data collected to write his PhD dissertation with John Sanders and thesis is already published.

Collaborative research continue with ICRISAT and FAO in Niger on the removal of the barriers to the adoption of soil fertility restoration technologies through the introduction of the Warrantage Credit Facility in the Sudano Sahelian zone and a progress has been prepared. The Warrantage Credit Facility was initiated to remove barriers to the adoption of soil fertility restoration. It provides access to cash credit to enable farmers to purchase external inputs such as fertilizers, while using storage of crops to enable farmers to get higher prices during the period when market supply begins to decline. In Karabedji, a village of western Niger, fertilizer consumption increased 10 fold from 350 to 3600 kg due to the warrantage system.

- *Relevant knowledge, methods and decision tools for improved soil management to combat soil degradation, increase agricultural productivity and maintain soil health provided to land users in the tropics*

APSIM was used to simulate manure technologies, improved manure storage and organic-inorganic N combination technologies. The model failed to simulate trends that were observed in the field for the improved manure storage systems. The model predicts high maize yields in the season of manure application for both high and low manures followed by yield decreases in the subsequent seasons, and this trend was true for high quality manure. The model under-predicts maize yields for high quality manure in the three seasons while for low quality manure the model over-predicts yields in the first season and under-predicts in the second and third seasons. In the field however, there were yields were low in the first season followed by yield increases in the second and third seasons for the low quality manure. For the organic-inorganic N combinations, APSIM over-predicts the effects of fertilizer N only.

Manure decision guides have been developed and tested with farmers in Zimbabwe (see attached paper). Current efforts are being made to evaluate the usefulness of these guides as communication tools to enhance uptake of soil management options. There are, however, still a lot of issues that need to be covered to simplify the farmer decision guide and make it easier to use, for example determining the quality parameters and ranges for the different manures available to the farmers.

A follow up PRA exercise was carried out to correlate the farmers' quality parameter and laboratory indices on manure quality three districts of Zimbabwe (see attached paper). This was followed by field trials with manures from different categories to test their effects on maize yield. Low maize yields were observed because of the drought, resulting in no treatment differences. Maize will be planted in the second season to test the residual effects of the manures. Use strategies were linked to manure quality however, there is need to explore these aspects further.

Other farmer participatory experiments on manure and mineral fertilizer combinations, and soil moisture and nutrient conservation were not successiful. Differences in treatments on the trials were not observed due to the drought. Farmers expressed great interest in having these trials established again for the 2002/3 season.

A logit model was used to analyse the determinants of adoption of pit storage system by smallholder farmers. The variables considered for the analysis were the age of the household head, number of cattle owned, educational status of the household, interaction of the household with extension agents, labour availability, experience of using manure and the total household income. Most of these factors were not statistically significant in explaining adoption of the pit storage system. The age of the household head and the number of cattle owned were significant in explaining the adoption of the pit storage system at 5%. Younger farmers were found to have a higher probability of adopting the pit storage system compared to the older farmers. This could be explained by the fact that young farmers have a lower risk aversion and that they are still able bodied and able to cope with the additional labour demands associated with pitting manure. Farmers with large heads of cattle had a lower probability of adopting pit storage system. Those farmers with larger heads of cattle were able to compensate for the poor quality of the manure by applying higher rates of manure per hectare. This could also be a reflection of the labour demands for storing large quantities of manure in a pit. The experience of using manure was statistically significant in explaining adoption at 10%. Farmers with experience using manure were in a better position to accurately assess the risk and returns of pit storing manure compared to heaping the manure.

- *Relevant knowledge, methods and decision tools for improved soil management to combat soil degradation, increase agricultural productivity and maintain soil health provided to land users in the tropics*

The concept of building an 'arable layer' has developed from the limited success of introducing intensive as well as no-till systems into acid-soil savannas in Colombia. In practice, this involves vertical tillage practices to overcome physical constraints, an efficient use of amendments and fertilizers to correct chemical constraints and imbalances, and the use of improved tropical forage grasses, green manures and other organic matter inputs such as crop residues, to improve the soil's "bio-structure" and biological activity. The use of deep-rooting plants in rotational systems to recover water and nutrients from subsoil is also envisaged in this scheme.

Intensification of agricultural production on the acid-soil savannas of south America (mainly Oxisols) is constrained by the lack of diversity in acid (aluminum) tolerant crop germplasm, poor soil fertility and high vulnerability to soil physical, chemical and biological degradation. Out of a suite of croppings system options including monocropping, rotation with grain legumes, green manures and agropastoral systems compared with native savanna, only agropastoral systems (including maize/*Panicum maximum+legume cocktail = Arachis pintoi, Centrosema acutifolium, Glycine wightii, Stylosanthes capitata) and rice/Brachiaria humidicola + legume cocktail*,) were able to simultaneously improve the physical, chemical and biological properties of the soil.

We investigated the effect of land-use systems and P fertilizer inputs on size of P fractions and their isotopic exchangeability. Differently managed Colombian Oxisols were labeled with carrier free $^{33}P$ and sequentially extracted after different incubation times. The recovery of $^{33}P$ in the two soils with annual fertilizer inputs and large positive input-output P balances indicated that resin-$P_i$, Bic-$P_i$ and NaOH-$P_i$ contained most of the exchangeable P. The organic or more recalcitrant inorganic fractions

contained almost no exchangeable P. In contrast, in soils with low or no P fertilization, more than 14% of added $^{33}P$ was recovered in NaOH-$P_o$ and HCl-$P_o$ fractions two weeks after labeling, showing that organic P is involved in short term P dynamics.

In the Andean hillsides we have shown that an improved fallow with species such as *Tithonia diversifolia* in a slash and mulch system can contribute to the rapid restoration of soil fertility that has been exhausted after years of cropping with little or no inputs. Increased biomass production, greater accumulation and recycling of plant nutrients, especially phosphorus, with introduced fallow species are the reasons for the observed increases in soil fertility and biological activity. *Tithonia* has been shown to increase the pool of plant-available phosphorus.

**Output 3: Ecosystem services enhanced through ISFM**

- *The soils capacity to provide ecosystem services (global warming potential, water quality and supply, erosion control, nutrient cycling) and maintain soil biodiversity in the face of globl change in land use and climate enhanced*

In a unique study for tropical savannas we have shown that the introduction of improved pasture species with deep rooting capacities can convert the agroecosystems of the savannas from a net source of global warming potential (total greenhouse gas emissions of carbon dioxide, nitrous oxide and methane) into a net negative potential or sink. The study is the first to collect data on all greenhouse gas emissions from different land management practices (cropping and pastures) and develop an overall global warming potential based on current and projected land use.

**Output 4. Research and training capacity of stakeholders enhanced**

- *Research and training capacity of stakeholders in the tropics in the fields of soil biology, fertility and tropical agroecosystem management enhanced through the dissemnation of principles, concepts, methods and tools.*

A participatory approach in the form of a methodological guide has been developed and used in Latin America and the Caribbean (Honduras, Nicaragua, Colombia, Peru, Venezuela, Dominican Republic) and Africa (Uganda, Tanzania) in order to identify and classify local indicators of soil quality related to permanent and modifiable soil properties. This methodological tool aims to empower local communities to better manage their soil resource through better decision making and local monitoring of their environment. It is also designed to steer soil management towards developing practical solutions to identified soil constrains, as well as, to monitor the impact of management strategies implemented to address such constraints. The methodological approach presented here constitutes one tool to capture local demands and perceptions of soil constraints as an essential guide to relevant research and development activities. A considerable component of this approach involves the improvement of the communication between the technical officers and farmers and *vice versa* by jointly constructing an effective communication channel. The participatory process used is shown to have considerable potential in facilitating farmer consensus about which soil related constraints should be tackled first. Consensus building is presented as an important step prior to collective action by farming communities resulting in the adoption of improved soil management strategies at the landscape scale.

- *Optimum combination of organic and inorganic sources of nutrients*

In 2002, network experiments were conducted at 7 benchmark locations across 7 countries to investigate the nitrogen and phosphorus contribution of different low quality organic materials that are available for direct use by farmers. The sites include: Banizoumbou, Niger (*Interaction of N, P and manure; Biological nitrogen fixation; Combining organic and inorganic plant nutrients for cowpea production);* Maseno,

Western Kenya; Kogoni, Mali; Farakou Ba, Kou Valley, Burkina Faso; Zaria, Nigeria; Kumasi, Ghana; Davie, Togo; Kabete, Kenya.

- *Fertilizer equivalencies of legume-cereal cropping*

For establishing equivalency of fertilizer value of legume-cereal cropping, experiments were established at Maseno in Western Kenya, Zaria in Nigeria, Kumasi in Ghana and Davie in Togo.

Other aspects evaluated are Phosphorus (P) placement and P replenishment with Phosphate rock, Placement of phosphorus and manure, and farmer evaluation of soil fertility restoration technologies (Karabedji and Sadore).

## 4. Indicators

### Appendix A: List of Publications

### *4.1 Refereed journals*


Amézquita, E., R. J. Thomas, I. M. Rao, D. L. Molina and P. Hoyos. 2002. The influence of pastures on soil physical characteristics of an oxisol in the eastern plains (Llanos Orientales) of Colombia. Agriculture, Ecosystems and Environment (in press).

Barrios E. and Trejo M.T. (2002) Implications of local soil knowledge for integrated soil fertility management in Latin America. Geoderma (in press)

Barrios, E., J. G. Cobo, I. M. Rao, R. J. Thomas, E. Amézquita and J. J. Jiménez. 2002. Fallow management for soil fertility recovery in tropical Andean agroecosystems in Colombia. Agriculture, Ecosystems and Environment (in press).

Bationo A. and Buerkert A (2001). Soil organic carbon management for sustainable land use in the Sudano-Sahelian West Africa. Nutrient Cycling in Agroecosystems 61:131-142.

Bationo, A., and Ntare, B.R. (2000). Rotation and nitrogen fertilizer effects on pearl millet, cowpea and groundnut yield and soil chemical properties in a sandy soil in the semi-arid tropics, West Africa. Journal of Agricultural Science 134: 277-284

Bielders, C.L., Michels, K., and Bationo, A. (2002). On-farm evaluation of ridging and residue management options in a Sahelian millet-cowpea intercrop. 1. Soil quality changes. Soil Use and Managemnet 18

Buehler, S., A. Oberson, I. M. Rao, E. Frossard and D. K. Friesen. 2002. Sequential phosphorus extraction of a 33-P labeled oxisol under contrasting agricultural systems. Soil Science Society of America Journal 66: 868-877.

Buerkert, A., Bationo, A., and Piepho, H.P. (2001). Efficient phosphorus application strategies for increased crop production in sub-Saharan West Africa.Field Crop Research 72: 1-15.

Buerkert, A., Piepho, H.P. and Bationo A. (2002) Multi-site time trend analysis of soil fertility management effects on crop production in Sub-Saharan West Africa. Expl. Agric 38: 163-183.

Burkert, A., Bagayoko, M., Alvey, S., and Bationo, A. (2001). Causes of legume-rotation effects in increasing cereal yields across the Sudanian, Sahelian and Guinean zone of West Africa. Developments in Plant and Soil Sciences 92: 972-973

Cobo J.G., Barrios E., Kass D.C.L., Thomas R.J. (2002a) Decomposition and nutrient release by green manures in a tropical hillside agroecosystem. Plant and Soil 231:211-223.

Cobo J.G., Barrios E., Kass D.C.L., Thomas R.J. (2002b) Nitrogen mineralizatio and crop uptake from surface-applied leaves of green manure species on a tropical volcanic-ash soil. Biol.Fert. Soils 36:87-92.

Delve, R.J. and Jama, B. *Mucuna pruriens* and *Canavalia ensiformis* legume cover crops: Sole crop productivity, nutrient balance, farmer evaluation and management implications. (Submitted to Biology and Fertility of Soils)

Koutika LS, N Sanginga, B Vanlauwe and S W Weise 2002 Chemical properties and soil organic matter assessment under fallow systems in the forest margins benchmark. Soil Biology and Biochemistry 34, 757-765.

Murwira, H.K. and T.L. Kudya.2002. Economics of heap and pit storage of cattle manure for maize production in Zimbabwe. Tropical Science, 42: 153-156.

Nyende, P., and Delve, R.J. Farmer participatory evaluation of legume cover crop and biomass transfer technologies for soil fertility improvement using farmer criteria, preference ranking and log it regression analysis in eastern Uganda. (Submitted to Experimental Agriculture)

Oberthur T., Barrios E., Cook S., Usma H. and Escobar G. 2002. Helping soil scientists and Andean hillside farmers to see the obvious about soil fertility management. Agriculture, Ecosystems and Environment (in review).

Phiri, S., E. Amezquita, I. M. Rao and B. R. Singh. 2002. Constructing an arable layer through chisel tillage and crop-pasture rotations in tropical savanna soils of the Llanos of Colombia. Journal of Sustainable Agriculture (in press).

Phiri, S., I. M. Rao, E. Barrios, and B. R. Singh. 2002. Plant growth, mycorrhizal association, nutrient uptake and phosphorus dynamics in a volcanic-ash soil in Colombia as affected by the establishment of *Tithonia diversifolia*. Journal of Sustainable Agriculture (in press).

Place, F.P., Freeman, A., Ramisch, J.J., Vanlauwe, B., Barrett, C., 2003. "Integrated soil fertility management: evidence on adoption and impact in African smallholder agriculture." *Food Policy.*

Ramisch, J.J. "Whose soil degradation counts? Nutrient balances and soil fertility policy for Africa" submitted to *Land-use Policy.*

Ramisch, J.J., [revised and resubmitted] "Inequality, agro-pastoral exchanges and soil fertility gradients in Southern Mali." *Agriculture, Ecosystems, and Environment*.

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Swift, M.J. 2002. Steering Committee Member and Participant 4th INRM Taskforce Meeting, Aleppo, Syria.

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### *4.6. Working Papers, Other Presentations or Publications*

Amede, T., E. Amézquita, J. Ashby, M. Ayarza, E. Barrios, A. Bationo, S. Beebe, A. Bellotti, M. Blair, R. Delve, S. Fujisaka, R. Howeler, N. Johnson, S. Kaaria, S. Kelemu, P. Kerridge, R. Kirkby, C. Lascano, R. Lefroy, G. Mahuku, H. Murwira, T. Oberthur, D. Pachico, M. Peters, J. Ramisch, I. Rao, M. Rondon, P. Sanginga, M. Swift and B. Vanlauwe, 2002, Biological Nitrogen Fixation: A key input to integrated soil fertility management in the tropics, CIAT-TSBF Working Group on BNF-CP.

Delve, R.J., Nyende, P., Jama, B., and Kabuye, F. Mapping improved fallows in Tororo district, Uganda: lessons learnt. Poster presentation at the Advancing impact of Agroforestry research and Development in the ECA Region - Regional Technical and Planning Workshop, Nairobi, 3rd-8th February 2002.

Esilaba, A.E., Byalebeka, J.B., Nakiganda, A., Mubiru, S., Ssenyange, D., Delve, R.J., Mbalule, M. and Nalukenge, G. December 2001. Integrated nutrient management in Iganga District, Uganda: Diagnosis by participatory learning and action research. CIAT Africa Occasional Publication Series, No. 35 (Working Paper)

Misiko, M.M., Ramisch, J.J., and L. Muruli. *Networks of agricultural information dissemination in Emuhaya, Western Kenya.* IIED Gatekeeper Series. IIED, London.

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Tumuhairwe, J.B., R.J. Delve, B. Jama, M. Rwakaikara-Silver. Nitrogen fertiliser values of leguminous fallows in eastern Uganda. Poster presentation at the Advancing impact of Agroforestry research and Development in the ECA Region - Regional Technical and Planning Workshop, Nairobi, 3rd-8th February 2002.

Vanlauwe, B. Book review for Agricultural Systems of' Sustainable management of soil organic matter', 2002, Eds RM Rees, BC Ball, CD Campbell, CA Watson, CAB International, Wallingford, UK.

Vanlauwe, B. Book review for Geoderma of 'Dynamics and diversity – soil fertility and farming livelihoods in Africa', 2002, Ed I Scoones, Earthscan Publications, London, UK.

**Other publications:**

Amézquita, E., L.F. Chávez, J.H. Bernal. 2002. Construcción de una "capa arable" en suelos pobres: conceptos esenciales aplicados en la altillanura. Folleto Divulgativo. Colaboración Colciencias, Ciat, Corpoica.

***Agroecology Highlight bulletins on:***

1. Integration of local soil knowledge for improved soil management strategies
2. Farmers evaluations and innovations with legume cover crops
3. Going to scale with improved fallow options: More benefits, more people, more quickly
4. Resource flows and nutrient balances in smallholder farming system in eastern Uganda

**Appendix B: Research training capacity of stakeholders enhanced**

| Name | Nationality | Education | Institution | Research theme |
|---|---|---|---|---|
| D. Fatondji | Nigerian | Ph.D. | University of Bonn, Germany | Interaction between water harvesting and soil fertility |
| Vincent Bado | Burkinabe | Ph.D. | Laval University in Quebec, Canada | Interaction between organic and inorganic nutrient sources in different cropping system in the Sudano sahelian zone of West Africa |
| Shamie Zingore | Zimbabwean | Ph.D. | Wageningen University, Netherlands | Evaluation of the nutrient use effciencies of resource management options in smallholder crop-livestock farming systems in Zimbabwe |
| Chris Nyakanda | Zimbabwean | Ph.D. | University of Zimbabwe | Effects of Sesbania sesban and cajanus cajan improved fallows on soil moisture and nutrient dynamics and on maize performance in medium rainfall areas of Zimbabwe |
| Nhamo Nhamo | Zimbabwean | Ph.D. | University of Zimbabwe | An avaluation of the efficacy of organic and inorganic fertilizer combinations in supplying N to crops |
| Jean Nzuma | Zimbabwean | Ph.D. | University of Zimbabwe | Manure management options for increasing crop production in smallholder farming systems of Zimbabwe |
| Bonaventure Kayinamura | Rwandan | Ph.D. | University of Zimbabwe | Potential use of three plant species: Glycine Max, mucuna pruriens and crotalaria grahamiana as soil fertility ameliorants in smallholder farming systems in Zimbabwe: synergistic improvements of water and nutrient use efficiencies |
| Fredrick Ayuke | Kenyan | Ph.D. | University of Nairobi, Kenya | Assessing diversity and population dynamics of macrofauna (earthworms and termites) as influenced by land-use change and impact on soil properties |
| Margaret Mwangi | Kenyan | Ph.D. | University of Nairobi, Kenya | Soil functional groups: evaluation of ecosystem engineers and soil fertility management within agro forestry ecosystems |

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|---|---|---|---|---|
| Susan Ikerra | Tanzanian | Ph.D. | Sokoine University, Tanzania | Effect of organic materials on MPR dissolution on an Ultisol in Morogoro, Tanzania |
| Kiros Habtegebriel | Ethiopian | Ph.D. | Norway Agricultural University | Development and evaluation of site-specific integrated nutrient management practices for wheat on Vertisols in semi-arid Northern Ethiopia |
| Jane Kapkiyai | Kenyan | Ph.D. | Cornell University, USA | Effects of Legume Green Manures on Crop Productivity and Nutrient Cycling in Maize-based Cropping Systems of Western Kenya |
| John Ojiem | Kenyan | Ph.D. | Wageningen University, Netherlands | Management of legume green manures in Western Kenya |
| Mercy Kamau | Kenyan | Ph.D. | Wageningen University, Netherlands | Socio-economic evaluation of legume-based systems in Western Kenya |
| Twaha Atenyi | Ugandan | Ph. D. | Agricultural University of Norway | Soil phosphorus transformations and organic matter dynamics |
| Nelson Castañeda | Colombian | Ph.D. | University of Gottingen | Genotypic variation in P acquisition & utilization in *A. pintoi* |
| Brigit Krucera | German | Ph. D. | University of Freiburg | Characterization of bean genotypes for abiotic stress adaptation |
| Alvaro Rincon | Colombian | Ph.D. | National University | Integration of maize with forages to recuperate degraded pastures in the Llanos of Colombia |
| Karen Tscherning | German | Ph.D. | University of Hohenheim | Simultaneous evaluation of tropical forage legumes for feed value and soil enhancement |
| Elena Velásquez | Colombian | Ph.D. | National University/ IRD | Biological indicators of soil quality based on macroinvertebrate communities and relationships with soil functional parameters |
| Armando Torrente | Colombia | Ph.D | U.Nacional, Palmira | Soil-water movement in Magnesic soils |
| Christian Thierfelder | Germany | Ph.D. | Univ.Hohenheim, Germany | Development of soil preserving land use systems in the tropics |
| Martha Ligia Castellanos | Colombia | Ph.D. | U.Nacional, Palmira / U. of the Guajira | Discussion in a new topic of research |

| Name | Nationality | Education | Institution | Research theme |
|---|---|---|---|---|
| Yolanda Rubiano | Colombia | Ph.D. | U.Nacional, Palmira | Soil degradation indicators for the Llanos |
| Ruth Kangai Adiel | Kenyan | M.Sc. | Kenyatta University, Kenya | Assessment of the adoption potential of soil fertility improvement technologies in Chuka Division, Meru South, Kenya |
| Monicah Mucheru | Kenyan | M.Sc. | Kenyatta University, Kenya | Enhancement of soil productivity using low-cost inputs |
| James Kinyua | Kenyan | M.Sc. | Kenyatta University, Kenya | Nutrient management by use of agroforestry trees for improved soil productivity |
| Joseph Kimetu | Kenyan | M.Sc. | Kenyatta University, Kenya | Nitrogen fertilizer equivalencies based on organic input quality |
| John Baptist Tumuhairwe | Ugandan | M.Sc. | Makerere University, Uganda | Effect of short-duration C*rotalaria grahamiana* and *Mucuna pruriens* fallows on soil productivity in southeastern Uganda |
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| Dennis Wafula | Kenyan | M.Sc. | Jomo Kenyatta University, Kenya | The contribution of different feeding guilds of termites to nutrient cycling in soil |
| Pamela Pali | Ugandan | M.Sc. | Makerere University, Uganda | The acceptance and profitability of biomass transfer and legume cover crops in Tororo district, Uganda |
| Ali Lule | Ugandan | M.Sc. | Makerere University, Uganda | The role of social capital in adoption of soil fertility technologies |
| Abas Isabirye | Ugandan | M.Sc. | Makerere University, Uganda | Communication flow between service providers and farmers |
| Paul Bagenze | Ugandan | M.Sc. | Makerere University, Uganda | Linking farmers preferences and GIS for targeting of soil fertility technologies |
| Patricia Namwanda | Ugandan | M.Sc. | Makerere University, Uganda | Techniques and criteria for extrapolation of soil fertility technologies: From farm to the regional level |

| Name | Nationality | Education | Institution | Research theme |
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| Eria Bulega | Ugandan | M.Sc. | Makerere University, Uganda | Extrapolation domains for countrywide targeting of legume cover crop technologies |
| A.N. Other | Ugandan | M.Sc. | Makerere University, Uganda | Utilization of dual-purpose live barriers for soil water conservation and increased household income |
| John Mutihero | Zimbabwean | M.Sc. | University of Zimbabwe | An assessment of profitability of cattle manure use and the relative impacts on rural farming households in Mangwende communal area, Zimbabwe |
| U. Chipfupa | Zimbabwean | M.Sc. | University of Zimbabwe | The potential of decision guides as an extension tool in improving adoption of integrated soil fertility management options |
| Charles Nhemachena | Zimbabwean | M.Sc. | University of Zimbabwe | Comparative analysis of grain legume production and domestic consumption trends in Zimbabwe' s dual farming sector and the policy challenges for the post land reform era |
| Julius Mumo Maithya | Kenyan | M.Sc. | University of Nairobi | The Competitiveness of Agroforestry-based and other Soil Fertility Enhancement Technologies for Smallholder Food Production in Western Kenya |
| Somoni Franklin Mairura | Kenyan | M.Sc. | Kenyatta University, Kenya | The Competitiveness of Agroforestry-based and other Soil Fertility Enhancement Technologies for Smallholder Food Production in Western Kenya |
| Pablo Tittonell | Argentina | M.Sc. | Wageningen University, Netherlands | Farmer-induced soil fertility gradients and their impact on soil processes affecting the efficiency of nutrient capture in smallholder farming systems in East Africa |
| Mercy Karunditu | Kenyan | M.Sc. | Kenyatta University, Kenya | Nitrogen fertilizer use efficiency as affected by soil organic matter status in Eastern, Central, and Western Kenya |
| Boaz Waswa | Kenyan | M.Sc. | Kenyatta University, Kenya | Soil Organic Matter Status under Different Agroforestry Management Practices in Three Different Sites in Kenya |

| Name | Nationality | Education | Institution | Research theme |
|---|---|---|---|---|
| Adriana Arango | Colombian | M.Sc. | National University | Identification of candidate genes for aluminium resistance in *Brachiaria* |
| Oscar Molina | Colombian | M.Sc. | National University | Effect of residual P fertilizer and organic manure application on mycorrhizal association of maize-bean rotation in P-fixing Andisol in Cauca, Colombia |
| José Trinidad Reyes | Honduran | M.Sc. | National University | Potential influence of mycorrhizal external mycelia on the recuperation of degraded soils in Cauca, Colombia |
| Ivonne Valenzuela | Colombia | M.Sc. | U.Nacional, Palmira | Relationship between free soil water and its composition in Vertisols |
| Jaime Lozano Fernández | Colombia | M.Sc. | U.Nacional, Palmira | Variability of soil physical properties in CIAT Experimental Station |
| José Augusto Rodríguez | Colombia | M.Sc. | U.Nacional, Palmira | Influence of some a amendments in some physical, chemical and biological characteristics of a magnesium soil. |
| Mariela Rivera | Colombia | M.Sc. | U.Nacional, Palmira | Chemistry of tropical soil |
| Maryory Rodríguez A. | Colombia | M.Sc. | U.Uberlandia, Brazil | A comparison between Colombian and Brazilian Oxisols |
| Maria E. Baltodano | Ncaragua | M.Sc. | Universidad de Guatemala | Methods to assess the economical value of environmental services |
| Pauline Chivenge | Zimbabwean | M.Phil | University of Zimbabwe | Tillage effects on soil organic matter fractions in long term maize trilas in Zimbabwe |
| Killian Mutiro | Zimbabwean | M.Phil | University of Zimbabwe | Adoption of improved manure storage systems by smallholder farmers in drought prone and high potential areas of Zimbabwe |
| Nelson Juma Otwoma | Kenyan | MA | University of Nairobi | The role of indigenous knowledge in the management of soil fertility among smallholder farmers of Emuhaya division |
| L. Rusinamhodzi | Zimbabwean | B.Sc. | University of Nairobi | Linking farmer criteria and laboratory indices for on-farm prediction of manure quality in smallholder farming areas of Zimbabwe |

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| German Manrique | Colombian | B.Sc. | National University | Screening of common bean genotypes for aluminium resistance |
| Luisa F. Escobar | Colombian | B.Sc. | Javeriana University | Symbiotic potential of native rhizobia under different land use systems in Cauca, Colombia |
| Lorena Parra Lopez | Colombian | B.Sc. | University of Valle | Screening methods for aluminium resistance in common bean |
| Enna Diaz Betancourt | Colombia | B.Sc. | Fund. Universitaria de Popayán | Soil physical characterization in Cauca Paramo soils |
| José Manuel Campo | Colombia | B.Sc. | U. Nacional, Palmira | Evaluation of some crop systems in relation to erosion in Volcanic Ash Soils (Pescador) |
| Liliana Paz Betancourt | Colombia | B.Sc. | Fund. Universitaria de Popayán | Soil physical characterization in Cauca Paramo soils |
| Lina María Gaviria | Colombia | B.Sc. | U.Suramericana, Neiva | Characterization of surface biogenic structures under different cassava treatments in Santander de Quilichao |
| Rafael Andrés Jaramillo O. | Colombia | B.Sc. | U.Nacional, Palmira | The influence of the intensity of soil management in some physical conditions in CIAT Station |
| Roberto Arturo Viveros A. | Colombia | B.Sc. | U.Nacional, Palmira | The influence of the intensity of soil management in some physical conditions in CIAT Station |
| German Manrique | Colombian | B.Sc. | National University | Screening of common bean genotypes for aluminium resistance |
| Maria E. Butrago | Colombian | B.Sc. | University of Valle | Screening of *Brachiaria* hybrids for aluminium resistance |
| Orlando Mejia | Honduras | B.Sc. | MSEC Consortium | Training in the use of the PCARES model |

## Output 1. Biophysical and socioeconomic constraints to integrated soil fertility management (ISFM) identified and knowledge on soil processes improved

Challenge Program – Biological Nitrogen Fixation: Position Paper prepared by CIAT-TSBF Working Group for "International Workshop on Biological Nitrogen Fixation for Increased Crop Productivity, Enhanced Human Health and Sustained Soil Fertility". ENSA-INRA, Montpellier, France (10-14 June 2002).

# BNF: A key input to integrated soil fertility management in the tropics

CIAT-TSBF Working Group on BNF-CP[1]

*Centro Internacional de Agricultura Tropical (CIAT), A. A. 6713, Cali, Colombia*
*Tropical Soil Biology and Fertility Programme (TSBF), P. O. Box 30677, Nairobi, Kenya*

[1]The CIAT-TSBF working group on BNF-CP includes Drs. T. Amede, E. Amézquita, J. Ashby, M. Ayarza, E. Barrios, A. Bationo, S. Beebe, A. Bellotti, M. Blair, R. Delve, S. Fujisaka, R. Howeler, N. Johnson, S. Kaaria, S. Kelemu, P. Kerridge, R. Kirkby, C. Lascano, R. Lefroy, G. Mahuku, H. Murwira, T. Oberthur, D. Pachico, M. Peters, J. Ramisch, I. Rao, M. Rondon, P. Sanginga, M. Swift and B. Vanlauwe.

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*Abbreviations and acronyms:* AABNF, african association for biological nitrogen fixation; AfNet, african network for soil biology and fertility; BNF, biological nitrogen fixation; CGIAR, consultative group on international agricultural research; CIAT, centro internacional de agricultura tropical; CNDC, combating nutrient depletion consortium; CP, challenge program; DSSAT, decision support system for agrotechnology transfer; ECABREN, eastern and central africa bean research network; FPR, farmer participatory research; FYM, farm yard manure; GIS, geographical information systems; ICARDA; ICRAF, international center for research on agroforestry; ICRISAT, international crops research institute for the semiarid tropics; IITA, international institute for tropical agriculture; INM, integrated nutrient management; INRM, integrated natural resource management; ISFM, integrated soil fertility management; MIS, integrated management of soils; NARS, national agricultural research systems; NGOs, nongovernamental organizations; OM, organic matter; ORD, organic resource database; PABRA, pan-african bean research alliance; PRGA, participatory research and gender analysis; Profrijol, Regional bean network for central America, Caribbean and Mexico; QTL, quantitative trait loci; SROs, specialized research organizations; SWNM, soil, water and nutrient management; TSBF, tropical soil biology and fertility; TSP, triple super phosphate; UNDP, united nations development program.

## Abstract

It is widely recognized that biological nitrogen fixation (BNF) by the legume-rhizobium symbiosis is an important component of productivity in tropical agriculture, especially in farmland which is marginal either in terms of distance from the markets, or small farm size and poverty of the farmers.

This position paper starts out by describing, the importance of BNF to tropical agriculture, the evolution of BNF paradigms, progress in creation of strategic alliances to combat soil fertility degradation, and past accomplishments of BNF-related research at CIAT-TSBF in collaboration with partners. Based on lessons learned, the paper suggests that BNF research should not be conducted in isolation but that a holistic-multidisciplinary-systems approach is needed to integrate BNF-efficient and stress adapted legumes into smallholder systems of the tropics. The paper proposes a number of research and development priorities for the BNF-CP to address for achieving improved contributions of BNF through integrated soil fertility management (ISFM) in the tropics. ISFM is the adoption of a holistic approach to soil fertility that embraces the full range of driving factors and consequences – biological, physical, chemical, social, economic and political – of soil degradation.

BNF research on common bean and tropical forage legumes at CIAT started in the 1970s. CIAT maintains a collection of 5,628 *Rhizobium* strains. Lessons with BNF research in bean can be summarized as follows. BNF has not been a panacea, neither on the side of strain selection nor breeding of the host, but modest progress has been registered. On the one hand, even if response to inoculation is not dramatic, the technology is so inexpensive that any response at all is economically viable. On the other hand, the environment is at least as limiting on BNF as is the strain and the host. Therefore the benefits of BNF are best expressed in the context of an agronomic management system that addresses other components of the crop, especially phosphorus supply, drought stress and not infrequently starter N. Selection for BNF capacity under physiological stress has revealed genotypes (and possibly genetic systems) that are worth exploiting more fully and which could hold keys to broader progress. Research efforts on BNF in tropical forage legumes indicated that the main constraints to the widespread adoption of forage legumes include a lack of legume persistence, the presence of anti-quality factors such as tannins, variable *Bradyrhizobium* requirements and a lack of acceptability by farmers. The main problem identified is that there is not enough work done on participatory evaluation of legumes with farmers to identify their criteria for acceptability and feed this information forward into germplasm screening. What is needed here is better collaboration among stakeholders to really get legume adoption under way in the tropics.

In other research programmes, it was confirmed that there is little scope for using legumes as an entry point to address soil fertility decline, but that there are various opportunities using multipurpose germplasm to indirectly improve the soil fertility status while providing the farmer with immediate products.

TSBF researchers in collaboration with partners made substantial progress in creating an organic resource database and using it to construct a decision support system (DSS) for organic matter management based on organic resource quality. Analysis of organic resource data indicated a hierarchical set of critical values of nitrogen, lignin and polyphenol content for predicting the "fertilizer equivalence" of organic inputs. This decision tree provides farmers with guidelines for appropriate use of organic materials for soil fertility improvement. On-going TSBF network experiments are now addressing the organic/inorganic nutrient interactions to allow the refinement of the recommendations to farmers. TSBF and CIAT with a wide range of partners are also developing methods for disseminating ISFM options through processes of interactive learning and evaluation among farmers, extensionists and researchers.

BNF-related research should proceed along the process-component-systems continuum and lead to demand-driven, on-farm problem-solving. Addressing farmers' problems in a systems context generates management options better suited to their local needs. Developing adoptable legume-BNF technologies to combat soil fertility degradation remains to be a major challenge. Research and development efforts are needed to integrate BNF efficient and stress-adapted grain and forage legume germplasm into production systems to intensify food and feed systems of the tropics. Several key interventions are needed to achieve greater impact of legume-BNF technologies to improve livelihoods of rural poor. These include: (a) integration of stress-adapted, BNF-efficient, grain and forage legume cultivars in rotational and mixed cropping systems, (b) development of management options aiming at optimal use of the legume-N in combination with strategic applications of mineral fertilizers to maximize

nutrient cycling and soil organic matter replenishment, (c) adoptable strategies of soil and water conservation, (d) integrated pest/disease/weed management through the use of biotic stress resistant germplasm with minimum pesticide/herbicide applications, (e) marketing strategies that are economically efficient, and (f) development of an appropriate policy and institutional environment that provides incentives to farmers to adopt legume-based BNF technologies.

## 1. Introduction

It is widely recognized that biological nitrogen fixation (BNF) by the legume-rhizobium symbiosis is an important component of productivity in tropical agriculture, especially in farmland which is marginal either in terms of distance from the markets, or small farm size and the poverty of the farmers (Giller, 2001). In such resource-poor, smallholder systems the application of large quantities of inorganic fertilizers such as urea is not economically feasible. The use of management techniques that increase the contribution of N to the system through the legume-rhizobium symbiosis, would improve crop-livestock production levels and their stability. A major challenge for BNF research is developing strategies to integrate BNF-efficient and stress-adapted legumes (grain/forage/greenmanure/cover/fallow) into local cropping systems for the crucial transition of smallholders in the tropics from subsistence agriculture to mixed-enterprise, market-oriented production systems because it is only through this development that spiraling declines in poverty, food insecurity and land degradation may be addressed.

The central issues of the BNF-CP are: (1) managing factors that determine integration of legumes into agricultural systems; and (2) realizing the benefits of legumes through effective BNF. Developing adoptable legume-BNF technologies could markedly improve livelihoods of rural poor in a variety of ways. Legumes can contribute directly to food security and human and animal nutrition. They can also contribute to income generation where markets for legumes exist or where enhanced soil fertility via BNF permits production of high value commercial crops. When legumes substitute for purchased fertilizer inputs, households can save scarce cash. Finally, for both economic and socio-cultural reasons, legumes may be particularly suited to reaching women and the poor. Because of their critical role in food production, especially legume production, women should be at the core of any strategies to ameliorate soil fertility via BNF. This is especially important in sub-Saharan Africa, where women produce up to 70-80% of the domestic food supply, and they also provide, on average, 46% of the agricultural labor (Gladwin et al. 1997). Realizing these livelihoods gains, especially for the poor and marginalized, is the ultimate objective of the BNF-Challenge Program (CP).

Although significant advances were made in BNF research during 20$^{th}$ century, impact of this research to improve productivity of smallholdings in the tropics through N input has been small, e.g., less than 5 kg N per hectare per year (Giller, 2001). Recently, Giller (2001) has analysed the likely impact of future BNF research. He put forward the view that the amounts of BNF in tropical agriculture could be improved enormously if current understanding was put to more effective use via simple agronomic practices on-farm. Beyond this the most rapid additional gains are likely to come from adapting legume germplasm to different agroecological niches in cropping systems. Other approaches such as genetic engineering are likely to take much longer to yield benefits.

This position paper starts out by describing the evolution of BNF paradigms, importance of legume-BNF to tropical agriculture, progress in creation of strategic alliances to combat soil fertility degradation, and past accomplishments of BNF-related research at CIAT-TSBF. Based on lessons learned, the paper suggests that BNF research should not be conducted in isolation but that a multidisciplinary systems approach is needed to integrate BNF-efficient and stress adapted legumes into smallholder systems of the tropics. The paper proposes a number of research needs and challenges for BNF-CP to address for achieving improved BNF through integrated soil fertility management (ISFM) in the tropics.

### 1.1 Importance of legume-BNF to tropical agriculture and soil fertility

Various BNF technologies addressinng the problems of food insecurity, poverty and land degradation can be identified with various potentials for BNF (Table 1). Legume-rhizobium symbiosis can sustain tropical agriculture at moderate levels of output, provided all environmental constraints to the proper functioning of the symbiosis have been alleviated (see later). Legumes can accumulate up to 300 kg N $ha^{-1}$ in 100 to 150 days in the tropics (Table 1). Rhizobial inoculation in the tropics can enhance yield of grain legumes when phosphorus availability in soil is not a major limitation.

Legume-cereal intercrops or rotations are widely practiced in the tropics to minimize the risk of crop failure and to provide households with improved diets. Traditionally, the main contribution of BNF in these systems is to improve household food security and human nutrition rather than improved soil fertility. Table 1, however, indicates various other niches for legumes in croppnig systems, each with their own specific contributions to improvement of food security, or land restoration.

## 1.2 Evolution of BNF paradigms

The African Association of biological nitrogen fixation (AABNF, 2001) summarized the first paradigm for BNF research of the 20th century as *"the upper limits of BNF may be steadily increased by the collection and evaluation of ever-more effective $N_2$-fixing micro organisms and their hosts because the distribution of this elite germless will necessarily accrue benefits following their introduction to production systems"*. This paradigm during the 20th century faced a major challenge that greater knowledge over time was not accompanied by improved BNF in the field. The widening gap between scientific advance of BNF and opportunities realized from their application is leading to the evolution of a new paradigm for BNF research. The 21st Century Paradigm designed by AABNF for greater BNF impacts may be summarized as *"research in biological nitrogen fixation must be nested into larger understandings of system nitrogen dynamics and land management goals before the comparative benefits of $N_2$-fixation may be realistically appraised and understood by society-as-a-whole"*. It is critical to note that this assumption does not reduce the importance of nitrogen-fixing organisms and their products, but rather repositions them from a central auto ecological focus into a more integrated component of a larger, more complex task. The rationale behind this new paradigm is that it is not biologically-fixed nitrogen alone which sets the standard for successful contribution to social needs, but rather the products realized from more resilient and productive ecosystems that are strengthened through BNF.

## 1.3 TSBF-CIAT

The former Tropical Soil Biology and Fertility Programme (TSBF), an international institution devoted to integrated soil fertility management (ISFM) research, has joined with the International Center for Tropical Agriculture to form the TSBF Institute of CIAT. This brings together TSBF's expertise in ISFM with that of CIAT in soils and land management as well as the complementary areas of germplasm improvement, pest management, GIS and participatory research. This merger builds on the strong collaboration between CIAT and TSBF in soil fertility research in East Africa that has developed within the CGIAR Systemwide Programme on Soil Water and Nutrient Management (SWNM) for which CIAT is the convening centre.

ISFM is the adoption of a holistic approach to soil fertility that embraces the full range of driving factors and consequences – biological, physical, chemical, social, economic and political – of soil degradation. There is a strong emphasis in ISFM research on understanding and seeking to manage the processes that contribute to change. The emergence of this paradigm, very closely related to the wider concepts of Integrated Natural Resource Management (INRM), represents a very significant step beyond the earlier, narrower, nutrient replenishment approach to soil fertility enhancement.

Table 1. BNF interventions for income generation and food security, their social benefits, target systems and potential. Adapted from AABNF (2001).

| *BNF Interventions* | Social benefits (0, 1 to 5) | | | | | Land Use system | *Geo. range* | Pot. BNF (kg/ha) | Current BNF (kg/ha) | Pot. Impact | Specifics |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Income generation | Food security | Land cons./rest | *C* | *Bio* D | | | | | | |
| Crop related | | | | | | | | | | | |
| Soybean rotation (Parasitic weed supp.) | 5 | 2 | 3 | 1 | 1 | S to L | SA to H | 150 | < 50 | high | Germplasm imp.<br>Agron. Practices<br>***P inputs***<br>Screening germ<br>.<br>Marketing<br>Post -harvest |
| Cowpea rotation/int | 3 | 4 | 3 | 1 | 3 | | SA to SH | 70-80 | <40 | high | |
| Groundnut rot/int | 3 | 3 | 2 | 0 | 1 | S to L | SA to H | 80 | ~ 60 | high | |
| Pigeon pea int. | 2 | 3 | 4 | 2 | 1 | S | SA to SH | 150 | <50 | Med-high | |
| Phaseolus beans int. | 3 | 4 | 0 | 0 | 2 | S | SA to SH (MA/HA) | 70 | <10 | med | |
| *Livestock related* | | | | | | | | | | | |
| Woody fodder banks | 4 | 2 | 4 | 3 | 2 | S | MA to HA | 300 | 30-50 | high | Calliandra etc. |
| Herbaceous fodder banks | 3 | 2 | 3 | 2 | 2 | S to L | SA to SH | 150 | 50 | high | Stylosanthes, Aeschynomene, etc. |

Table 1 contd…

| *BNF Interventions* | Social benefits (0, 1 to 5) | | | | | Land Use system | *Geo. range* | Pot. BNF | Current BNF | Pot. Impact | Specifics |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Income gen. | Food sec. | Land cons./rest | *C* | *Bio* D | | | | | | |
| Dune stabilisation | 0 | 0 | 5 | 5 | 3 | Waste. | A | 120 | 60 | High | Casuarina |
| Woodlots | 3 | 0 | 5 | 4 | 2 | Degraded Low N soils | SA to SH | 150-300 | 50 | High | Acacia spp |
| Afforestation | 0 | 0 | 5 | 5 | 4 | | SA to SH | | 50 | | Numerous sp |
| Woody fallows | 1 | 0 | 4 | 3 | 2 | S to L | SH to H | | 50 | | P solubilisation |
| Herbaceous fallows | 1 | 0 | 4 | 3 | 2 | S to L | SH to H | 200 | 50 | Med | Mucuna, Pueraria, S. rostrata |
| Mixed woody/herbaceous | 1 | 2 | 4 | 4 | 4 | S to L | SH to H | 300 | | Med | Numerous |
| Woody parkland | 1 | 0 | 2 | 2 | 2 | S to M | SA to SH | 100 | 50 | Med | [thorny] Acacia spp |
| Boundary trees | 1 | 0 | 3 | 3 | 2 | S to L | SH to H | 60 | 30 | High | Numerous |

Land Use Systems: S=small land holdings; L=large holdings; W=wasteland.
Geo range: SA=semi-arid; SH=subhumid; H=humid; A=arid; MA=mid-altitude; HA=highland.

1.4 Strategic alliance to combat soil fertility degradation through holistic approach (CIAT-TSBF-ICRAF)

Soil fertility degradation has been described as one of the major constraints to food security in developing countries, particularly in Africa. Despite proposals for a diversity of solutions and the investment of time and resources by a wide range of institutions it continues to prove a substantially intransigent problem. The rural poor are often trapped in a vicious poverty cycle between land degradation, fuelled by the lack of relevant knowledge or appropriate technologies to generate adequate income and opportunities to overcome land degradation. Three international institutions, CIAT, TSBF and ICRAF, have joined together to form a strategic alliance, the goal of which is 'to improve rural livelihoods in Africa through sustainable integrated management of soil fertility' (Figure 1). The three partners have made significant contributions to combating soil fertility degradation over the past decade and have also a long record of collaboration through joint research projects. The alliance will go further however by building on existing networks and partnerships to implement a fully integrated programme of research and development activities. This triple alliance is regarded as the first step in a wider partnership consistent with the process of integration of international, and national, agricultural research activities.

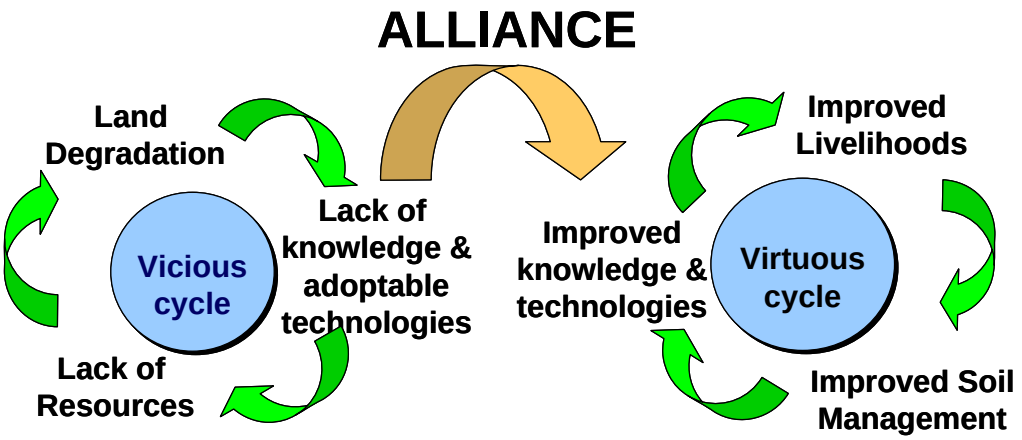


*Figure 1:* Combating soil fertility degradation: generating ISFM knowledge to improve rural livelihoods.

1.5 Ecoregional alliance (CIAT-IITA-ICRISAT-ICARDA) on legumes

The ecoregional alliance, formed in 2000 by CIAT, ICARDA, ICRISAT and IITA, reinforces the regional and global dimension of the evolving research and development paradigm. The alliance represent a unique concentration of multidisciplinary expertise in legume research, with over 65 qualified scientists working on various aspects of legume production and utilization (genetic resources and breeding, agronomy and microbiology, plant protection, quality and post-harvest processing, and socio-economics). This ecoregional alliance sees achieving synergy in legume research as a key opportunity to make progress in improving food security, combating environmental degradation and alleviating poverty in developing countries. A BNF-CP would be an important axis of collaboration among the ecoregional alliance centers for all of whom legumes are a high priority. The BNF-CP would not, however, be the only area of collaboration on legumes research among the four centers. The ecoregional alliance will continue to explore other avenues for collaboration on legume genomics, adaptation to biotic and abiotic constraints, agroecosystem health, and rural innovation.

1.6 Systemwide Program on Soil, Water and Nutrient Management (SWNM)

SWNM is a systemwide global program of CGIAR created in 1996 to help multiple stakeholders rise to

the challenge to reverse degradation of soils through the development of sustainable practices for managing soil, water, and nutrients. Operating through four complementary research consortia (combating nutrient depletion, optimising soil water use, managing sloping lands for erosion control, and integrated soil management), the SWNM program has developed a series of decision support tools and methodologies that are being tested across the different regions in Africa, Asia and Latin America covered by the program. SWNM program could serve as an important vehicle to test, promote and deliver BNF-efficient legume technologies to improve rural livelihoods of farmers in the tropics.

1.7 Systemwide Program on Participatory Research and Gender Analysis (PRGA)

PRGA is a CGIAR systemwide program on participatory research and gender analysis for technology development and institutional innovation. The PRGA program develops and promotes methods and organizational approaches for gender-sensitive participatory research on plant breeding and on the management of crops and natural resources. PRGA is cosponsored by CIAT and three other CGIAR centers (ICARDA, CIMMYT and IRRI). A recent review carried out by the PRGA program found very little relevant experience in ISFM research with attention to gender-related needs or constraints (Kaaria and Ashby, 2001). This lack of a client-oriented, gender sensitive approach to the basic design of ISFM technologies has contributed not only to poor adoption but also to inequity. As a result the PRGA is currently supporting research to test novel approaches to pre-adaptive research for ISFM which are incorporating client-oriented participatory research methods, such as gender and stakeholder analysis, into very early stages of technology design. PRGA currently supports research on gender-differentiated approaches to developing technology for integrated nutrient management being conducted by CIAT's parricipatory research team. Linking BNF-CP with PRGA program could markedly enhance the ability to develop appropriate and adoptable legume technologies in the tropics. PRGA, together with ICRISAT, conducted a study on impact of participatory methods in the development and dissemination of legume soil fertility technologies and identified lessons that will be useful in BNF work (Snapp, 1998; 1999a, b; Snapp et al., 2001; Johnson et al., 2001). TSBF is a partner in implementation of a subsequent project on the use of participatory approaches in research on natural resource management to improve rural livelhoods for women farmers in risky environments.

## 2. BNF-related research accomplishments of CIAT-TSBF on grain legumes and multipurpose legumes

BNF research at CIAT started in the 1970s. Several scientists including Peter Graham, Judy Kipe-Nolt, Douglas Beck (Beans) and Dick Date, Jack Halliday, Rosemary Bradley, Richard Thomas (Tropical Pastures) and others made significant contributions to developing practical ways to enhance BNF in legumes. CIAT maintains a collection of *Rhizobium* strains of 5,628 strains.

### 2.1 Grain legumes

#### *2.1.1 Genetic improvement of BNF efficiency in grain legumes: Common bean as a case study*

BNF research in common bean (*Phaseolus vulgaris* L.) has spanned the range of strain selection, host improvement, and agronomic management, and recently QTL (quantitative trait loci) studies have been initiated (Graham, 1981; Graham and Temple, 1984; Kipe-Nolt and Giller, 1993; Kipe-Nolt et al., 1993). Thus, the case of bean illustrates both some of the successes and failures of BNF research. An important attribute of common bean, justifying its inclusion in low input systems, is the ability to fix atmospheric N and thereby reduce the depletion of soil resources. Beans in tropical environments are capable of fixing from 50 (CIAT, 1987) to 80 kg N $ha^{-1}$ (Castellanos et al., 1996). Yet, actual $N_2$ fixation in bean cultivars is generally low when compared with many other grain legumes. Early research in the late 1970s indicated that this poor BNF is not due to an intrinsic inability of beans to nodulate because profuse nodulation can occur in controlled conditions in the greenhouse and in some soils. Although poor nodulation is frequently observed, soils in most bean growing areas contain large numbers of compatible and effective rhizobia. Selection of adapted *Rhizobium* strains for beans sown directly in pots of soils

containing large populations of indigenous, compatible rhizobia has resulted in yield increases when these strains were tested in the field.

Graham and coworkers field tested more than 600 cultivars of common bean under short-day subtropical conditions and found greatest $N_2$ fixation in the indeterminate, climbing beans (Graham and Rosas, 1977; Graham, 1981; Graham and Temple, 1984). A very active program of breeding for improving BNF in beans (crossing and recurrent selection) in the early 1980s in small-seeded bush beans generated a number of advanced lines (designated as RIZ lines). Field evaluation of these RIZ lines in the late 1980s in Colombia indicated that the RIZ lines generally nodulated better and fixed more $N_2$ than their parents (Kipe-Nolt and Giller, 1993). However, when compared with other CIAT bred lines, RIZ lines were no better in $N_2$-fixation than some other bred lines that were not specifically bred for BNF potential, in particular BAT 477 (see below). A major lesson learned from this breeding effort was that the field sites used for breeding -- for better BNF -- in Colombia are rich in N supply thus the selection pressure was not adequate. These results are in contrast to field evaluation efforts of bean germplasm on infertile soils in Africa, which met remarkable success in identification of several genotypes with superior adaptation to low N supply (Wortmann et al., 1995). These genotypes improved grain yield on farmers' fields, at least in part due to superior BNF.

Research work done in the late 1970s and most of the 1980s indicated that environmental constraint(s) limit $N_2$ fixation in the field. Phosphorus deficiency -- which affects 60% of bean growing area -- was considered to be the main factor limiting $N_2$ fixation in the field. In the early 1990s specific research into P x BNF interactions in beans was conducted in close collaboration with INRA, France. Extensive effort has been dedicated to seeking sources of bean germplasm tolerant to low P with regard to BNF and to identifying the respective genes. The selection parameter used in breeding for greater BNF was total N accumulation. This work resulted in identification of cultivars and strains that fix N more efficiently in low P soils. Among them BAT 477 is an unusual bred line in several respects. It is one of the most widely adapted drought-tolerant lines found to date. It has demonstrated unusually high general combining ability among lines within race Mesoamerica. With regard to BNF potential, it has been shown to be one of the best $N_2$ fixing genotypes under unstressed conditions in different soil types as well as stressed conditions of both drought and low P. This suggests that the BNF genes of BAT 477 are especially stable, and therefore are of particular interest for intensive study, and for deployment in bean cultivars.

In the late 1990s, recombinant inbred lines (RILs) of BAT 477 x DOR 364 were used to identify QTLs for BNF under low P stress conditions in collaboration with INRA, France (Ribet et al., 1997; Valdez et al., 1999). Results obtained indicated that most QTL contributing to greater total N and/or dry weight (DW) proceeded from BAT 477 in the F5 generation, although one QTL that contributed to total N proceeded from DOR 364. It is no surprise that, for a trait as ubiquitous in *Phaseolus vulgaris* as is nitrogen fixation, some positive QTL are found where not expected. Yet, in its development, BAT 477 was never selected consciously for nitrogen fixation.

In the late 1980s to early 1990s, a collaborative program between CIAT and NARS to select bean rhizobia strains adapted to specific areas and cultivars has been successful in Cuba and Cajamarca, Peru. In Cuba it has been possible to reduce N applications on bean by 80% through inoculation, and a BNF "package" of strain, genotype and low levels of P inputs gave yields equal to the standard variety with high inputs. The most productive strains are now produced commercially and used by farmers in these two countries. In the majority of cases, however, successful inoculation response trials in Latin America and Africa have been sporadic at best. But in Central America a regional collaborative project tested the benefits of inoculation with selected strains and found an average of 14% yield increase over 39 trials. CIAT maintains rhizobia strain collection and database. In the early 1990s research on *Rhizobium* focussed on two activities: 1) evaluation of strain $N_2$ fixation effectiveness and strain x cultivar interactions; and 2) evaluation of factors affecting rhizobial competitiveness. The latter was approached through development of strains genetically transformed to express glucuronidase in nodules, enabling easy wide scale analysis of inoculation events. This work was aimed to identify strains capable of high levels of $N_2$ fixation across a broad range of cultivars and a high degree of competitiveness under prevailing

environmental constraints. CIAT has developed a group of 20 strains transformed with the *gus* gene while maintaining the symbiotic and competitive characteristics of the wild type. These genetically modified strains could serve as valuable tools to evaluate competition x environment interactions.

Another valuable tool that was developed in 1990s was a series of non-nodulating lines. Mutagenesis was employed to create a mutant with a total lack of nodules. The non-nodulating gene in turn was backcrossed into a series of elite lines, to have at hand a ready tool for estimating the amount of nitrogen fixation in any given situation, by comparing non-nodulating and wild type paired lines.

*2.1.2 Lessons learned*: In summary, lessons with nitrogen fixation in bean can be summarized as follows. BNF has not been a panacea, neither on the side of strain selection nor breeding of the host, but modest progress has been registered. On the one hand, even if response to inoculation is not dramatic, the technology is so inexpensive that any response at all is economically viable. On the other hand, the environment is at least as limiting on BNF as is the strain and the host. Therefore the benefits of BNF are best expressed in the context of an agronomic management system that addresses other components of the crop, especially phosphorus, drought and not infrequently starter N. Selection for BNF capacity under physiological stress has revealed genotypes (and possibly genetic systems) that are worth exploiting more fully and which could hold keys to broader progress.

## 2.2 Tropical forage legumes

### *2.2.1 Selection of rhizobial strains and development of BNF technologies for forage legumes*

BNF research on tropical forage legumes initiated in the late 1970s and continued throughout the 1980s and 1990s (Date and Halliday, 1979; Sylvester-Bradley et al., 1983, 1988, 1991; Sylvester-Bradley, 1984; Thomas, 1993, 1995; Thomas et al., 1997). Taking into account the wide range of forage legume genera being evaluated, about which very little information concerning BNF was available, the main priority was initially to determine need to inoculate. After improving the methodology for evaluation of need to inoculate, specifically by ensuring that the presence of mineral N was not interfering with the evaluations, by using different methods to immobilize mineral N, it was found that a surprisingly large proportion of the legumes showed responses to added N. This indicated that the naturally occurring rhizobial populations were inadequate, either numerically or in nitrogen fixing capacity under the given soil conditions. A program was developed whereby rhizobium strains which a) were able to compete with the native rhizobial population and b) would be effective on as wide a range of legume species as possible, were selected. A new method for strain selection, viz. the screening of large numbers of strains in undisturbed soil cores, was developed, and proved to be highly successful. Many statistically significant responses to rhizobial inoculation in the field were obtained.

With funding from the UNDP, a network of scientists was established in the mid 1980s to evaluate legume-rhizobium symbioses in 14 countries of Latin America. The findings of this network were brought together at a workshop held at CIAT in 1987 where appropriate strain recommendations were made, and continue to be revised as a result of field evaluation by network members. The proceedings of this workshop were published in 3 volumes entitled “The legume-rhizobium symbiosis, proceedings of a workshop on evaluation, selection and agronomic management”. A list of recommended *Rhizobium* strains for herbaceous and shrubby legumes is available. In addition, a manual of methods for legume-rhizobium studies plus an accompanying audio-visual package has been available for interested researchers in national programs.

The marked responses to rhizobial incoulation observed in these trials led to the realization that a new way of inoculating the seeds of legumes was needed, so that the technology would be more available to farmers. In view of the fact that vaccines for both humans and animals are vital in tropical countries, and that the infrastructure for making them available is being developed in many areas, it was considered that this technology might also be useable for rhizobial strains. Traditional peat-based inocula need a large refrigerated storage space, and even if stored under refrigeration have a shelf life of only 6 months. Several different strains of rhizobia are needed for the different legume species being selected for pasture-based production systems, which complicates even further the possibility of supplying good quality

traditional peat-based inoculants to farmers. CIAT therefore initiated a project to develop freeze-dried rhizobial inocula, also with funding from the UNDP. This project demonstrated that such inocula could survive for several years in vacuum-sealed vials, and that they can be suspended in water and applied to the seeds with high survival rates. This technology could well be a realistic alternative for supplying forage legume seeds and rhizobial inocula to farmers.

Work on quantification of $N_2$ fixation using $^{15}N$ dilution studies was carried out in the late 1980s through a Swiss Development Corporation funded project (Cadisch et al., 1989, 1993). This project demonstrated the need to maintain adequate levels of both P and K for legume-based pastures that rely on biologically fixed N to supply the N requirement of the pasture.

CIAT researchers were also the first to demonstrate fungal/bacterial inhibitory role of *Bradyrhizobium* strains isolated from tropical forage legumes (Kelemu et al., 1995). Screening of 15 strains of *Bradyrhizobium* from CIAT collection with *in vitro* tests showed that *Bradyrhizobium* can inhibit mycelial growth, reduce or prevent sclerotial formation, and inhibit sclerotial germination in *Rhizoctonia solani*. In addition, cell-free culture filtrates of three strains of *Bradyrhizobium* had inhibitory effects on the growth of the bacteria *Escherichia coli* and *Xanthomonas compestris*. The antifungal/antibacterial property may increase the competitiveness of *Bradyrhizobium* strains and enhance the chance of nodule occupancy and other beneficial responses with compatible forage legumes. Further research is justified to determine the impact of *Bradyrhizobium* strains on integrated disease and pest management in crop-livestock systems.

*2.2.2 Role of legume-BNF in crop-livestock systems (Latin America)*

As the objective of selection for improved $N_2$ fixation was mostly achieved, research in 1990s broadened from $N_2$ fixation *per se* to the role of the legume and N in productive and sustainable pasture and crop-pasture systems (Thomas, 1992; 1995). This work showed that tropical forage legumes have the capacity to meet the requirements to balance the N cycle of grazed pastures. It also showed that the actual amounts required could depend on the rate of pasture utilization and the efficiency of recycling via litter, excreta and internal remobilisation. The efficiency of $N_2$ fixation (%of legume N derived from fixation) was found to be usually high in tropical pastures (> 80%) and is unlikely to be affected by inorganic soil N in the absence of N fertilizer application. This work resulted in a recommendation that an estimate of the amounts of N fixed by tropical forage legumes could be obtained from simple estimates of legume biomass provided tissue levels of P and K are adequate for plant growth.

In an on-going and long-term crop-pasture rotations experiment in tropical savannas of Colombia, N dynamics were studied under cereal monocultures and rotations with greenmanure legumes with the objective to determine the use efficiency and fate of N derived from inorganic and organic sources (Friesen et al., 1998). Results indicated that N recovery by crops from residues was low (7-14%) while recovery from fertilizer was far greater (26-50% in biomass). Sequential measurements of soil profile mineral-N concentrations indicated a large accumulation of nitrate content to 1-m depth through the dry season and substantial nitrate movement through the soil profile during the wet season under both rotations and monocultures. Thus in a high leaching environments of humid tropics, poor N supply-demand synchrony can result in substantial leaching of nitrate below the crop rooting zone and eventual contamination of the ground water. Use of deep-rooted crop, forage and fallow components could minimize N losses from legume-based systems in the tropics.

*2.2.3 Lessons learned:* It was realized that the main constraints to the widespread adoption of forage legumes include a lack of legume persistence, the presence of anti-quality factors such as tannins, variable *Bradyrhizobium* requirements and lack of acceptability by farmers. But “lack of legume persistence” is not really a limitation if the seed is cheap enough. The legume seed can be broadcast into an already established pasture. Seed can cost as little as $4/kg and only 3 kg of Stylosanthes are needed per hectare. The problem is that there is not enough work done on participatory evaluation of legumes with farmers. What is needed here is better collaboration among stakeholders to really get legume adoption under way in the tropics.

2.3. Organic resource database and organic matter management

In areas where access to adequate quantities of mineral fertilizers is beyond the reach of low resource endowed farmers, organic sources of nutrients of animal and plant origins e.g. legumes will continue to be a critical source of nutrients (Palm et al., 1997). Organic materials influence nutrient availability (i) by nutrients added, (ii) through mineralization-immobilization patterns, (iii) as an energy source for microbial activities, (iv) as precursors to soil organic matter, and (v) by reducing the P sorption of the soil. The TSBF-SWNM (CNDC) organic resource database (ORD) with over 2000 data entries has been used to construct a decision support system (DSS) for organic matter management based on contents of nitrogen, polyphenol and lignin. Most studies indicated a linear response between N content and fertilizer equivalency values (FEQ) of the material with an increase of 8% FEQ for every increase of 0.1% N. In a recent study on evaluating FEQ of *Tithonia diversifolia*, *Tephrosia, Sesbania* and pigeon pea, yield increases up to 48% were recorded. This decision tree provides farmers with guidelines for appropriate use of organic materials for soil fertility improvement. On-going TSBF network experiments are now addressing the organic/inorganic nutrient interactions to allow the refinement of the recommendations to farmers. A systematic framework for investigating the combined use of organic and inorganic nutrient sources includes farm surveys, characterization of quality of organic materials, assessment of the FEQ value based on the quality of organics, and experimental designs for determining optimal combinations of nutrient sources. The desired outcome is tools that can be used by researchers, extensionists and farmers for assessing options of using scarce resource for maintaining soil fertility and improving crop yields (Palm et al., 1997). With the recent success of CIAT scientists with their partners in linking of the DSSAT crop models with the CENTURY soil organic matter model (Gijsman et al., 2002), the nutritive value of organic substrates for crop production can be analyzed under a range of climatic and soil conditions and for many different crops. The combined DSSAT-CENTURY also proved to be an excellent tool for evaluating the SOM pattern under low-input systems.

A combination of resource flow mapping, ORD and FEQ has helped farmers to identify options for enhancing farm productivity and sustainability. Analysis of organic resource data indicated a hierarchical set of critical values of nitrogen, lignin and polyphenol content for predicting the "fertilizer equivalence" of organic inputs. TSBF and CIAT with a wide range of partners are also developing methods for disseminating ISFM options through processes of interactive learning and evaluation among farmers, extensionists and researchers.

2.4 Legumes in smallholder systems in Africa: Lessons learnt from experiences of other institutes and initiatives

The potential for legumes is increasing for many smallholder farming systems in Africa as soil fertility declines and livestock management is intensified (Wortman and Kirungu, 2000). These two researchers summerized lessons from several cases where legumes have been promoted for soil improvement or forage. The cases included Mucuna in Benin, Sesbania and Tephrosia in Zambia, Calliandra in Kenya, improved fallows and green manures in Rwanda, Stylosanthes in west Africa, Tephrosia in eastern Uganda, best-bet niche options in central and eastern Uganda, and Lablab in western Kenya. These cases included those where the practice was well adopted by farmers, as well as cases of unconfirmed promise, and adoption failure.

Over 15 years of work in West Africa with leguminous trees in alley cropping systems and *Mucuna* cover crops has led to a series of conclusions. First of all, such systems are technically sound and do maintain crop yields at substantially higher levels than traditional cropping systems. However, their adoption by farmers is relatively low or absent because (i) the appropriate niches for such systems were not properly identified (e.g., alley cropping must be targeted to high population density areas where firewood is needed and fertilizer is not easily available) and (ii) resource poor farmers require immediate benefits besides improved soil fertility.

As a result of above developments and maybe due to the existence of crop improvement and resource management programs in the same institute, dual purpose grain and fodder legumes have been developed at IITA which improve the soil fertility status besides providing grains and fodder. Such

legumes usually have a large proportion of N derived from the atmosphere, a low N harvest index and produce a substantial amount of above ground biomass. Residual effects on a cereal crop are often dramatic and fertilizer use to a subsequent cereal can be cut by 50% while still producing similar maize yields as a fully fertilized maize crop. Furthermore it was found that, e.g., soybean and cowpea could be false hosts for *Striga hermonthica*. One dual purpose soybean variety, TGX-1448-2E was specifically appreciated by farmers in Northern Nigeria, who commented that this variety yields more, produces more biomass than their own varieties. In addition, their succeeding maize/sorghum crops gave good yields with less N fertiliser than they would normally apply. The highest net benefits for the two seasons (1450 US$) were obtained with the rotation of TGX 1448-2E followed by the local variety Samsoy 2 (1000 US$). The lowest net benefits (600 US$) were obtained with *lablab* (Sanginga et al. 2001).

**3. Need for a multidisciplinary systems approach to implement an Integrated Soil Fertility Management (ISFM) agenda in the tropics**

From our past achievements, it is clear that BNF can contribute directly to the needs of a growing crop or can be added to the soil so contributing to its fertility. For sustainable agriculture in the tropics, there are two options: inorganic N fertilizers and BNF technologies that are less dependent on external purchased inputs. Approaches relying purely on external inputs are not often feasible, particularly for resource-poor farmers of the smallholder systems. In Africa, where the price of inorganic fertilizers is several times higher than world price, alternatives to inorganic fertilizers are especially important. A consensus has emerged that systems of ISFM are the only way forward, and it is in this context that we must consider the inputs from BNF (Figure 2).

Decision by farmers to adopt ISFM is influenced by (and influences) a range of factors which can be grouped in 4 main dimensions, biophysical, economical, social, and policy (Kaaria and Ashby, 2001). The biophysical dimension influence on farmers include the basic characteristics of the BNF technologies as well as the overall quality of the resource base. The main economic factor that influences whether farmers practice ISFM is whether the economic benefits outweigh the costs, especially in the short run. ISFM/BNF technologies are often labor intensive and if labor costs are too high—or come at the wrong time of the year when farmers are busy with other activities-- then farmers can not profitably adopt the technologies. Often labor-intensive practices like ISFM are only profitable when used with high value commercial crops. Social dimension also influence adoption and impact of ISFM. Where crop production responsibilities (and rights) are gender specific, ISFM technologies need to be consistent with these, e.g., appropriate for women work schedules or don't add additional labor for women when men get the benefits. Legumes can have important human health benefits, although care must be taken to assure that foods are properly prepared (e.g., mucuna) and culturally appropriate (if people won't eat them then may be can use as animal feed). Finally, a supportive policy environment is key to achieving widespread adoption. Fertilizer prices should be rational (not subsidized or taxed) and reflect real costs. This is the best way to ensure that farmers use the right combinations of organic and inorganic soil fertility management practices in their technologies. In addition, property tenure security is important to realize benefits of long-term investments, land ownership or long-term rental/use arrangements are important. Infrastructure investments such as roads and communications that open up marketing opportunities can help make adoption of ISFM profitable.

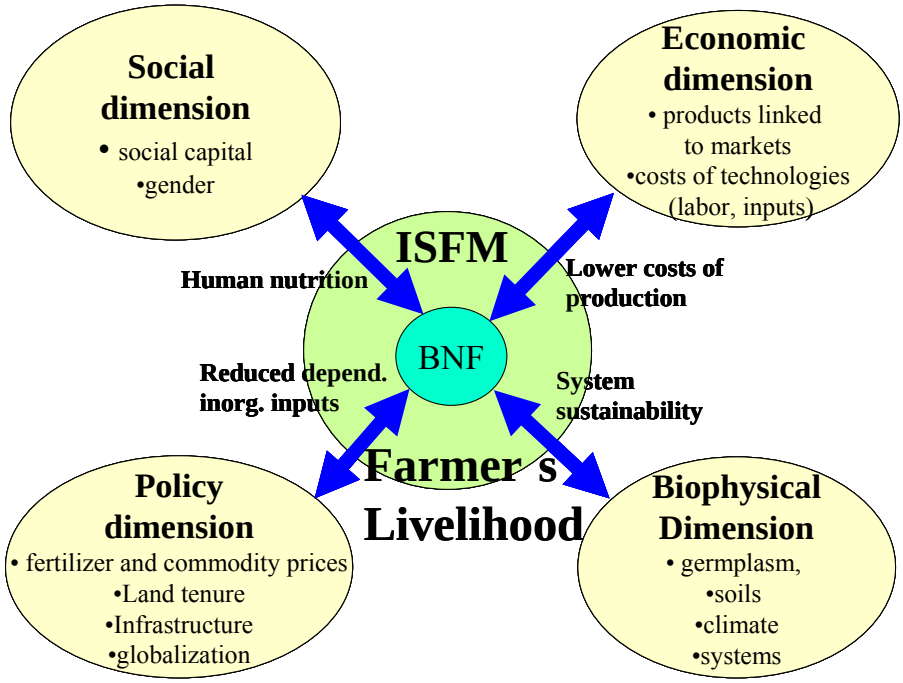


*Figure 2.* The key role of legume-BNF in the overall integrated soil fertility management (ISFM) strategy.

Legume BNF can be a key input to ISFM. When legume BNF technologies are appropriately designed taking into consideration the incentives provided by each of these four dimensions, they could have positive impacts in each dimension as well. Legume-BNF technolologies can improve the sustainability of crop-livestock systems (biophysical), improve profitability, contribute to improved nutrition and gender equity (social). At the marco level, increased use of legume-BNF technologies could reduce use of costly imported inorganic fertilizers (policy).

Most tropical soils have low inherent fertility and exhibit a variety of edaphic and climatic constraints including water stress, nutrient deficiency, low organic matter, and high erodibility. Inadequate soil and crop management has exacerbated these problems to an alarming extent. As a result of insufficient levels of nutrient replacement for that taken in harvest and other losses, high negative nutrient balances are commonly reported, particularly in sub-Saharan Africa.

Intensification of agricultural production on smallholdings is required to meet the food and income needs of the poor, and this cannot occur without investment in soil fertility. Investing in soil fertility management is necessary to help households mitigate many of the characteristics of poverty, for example by improving the quantity and quality of food, income, and resilience of soil productive capacity. The effects of soil fertility degradation are not confined to the impact on agricultural production. The living system of the soil also provides a range of ecosystem services that are essential to the well-being of farmers and society as a whole.

BNF-related research should proceed along the process-component-systems continuum and lead to demand-driven, on-farm problem-solving. Given the diversity of $N_2$-fixing organisms, symbioses and habitats in which these organisms operate and the wide application and demand for fixed-nitrogen, BNF studies are by definition multi-disciplinary. Under the first paradigm for BNF research, microbiologists, plant physiologists and agronomists recognized the need for collaboration to respond to challenges posed by better management of nitrogen fixation, and now is the time to recognize the additional strengths derived from expanding this collaboration into wider interdisciplinarity as a means of better translating

research findings into social benefits. Systems approach includes the involvement of stakeholders to fine-tune problem definition, the research itself, and the implementation of results. Stakeholders are farmers and citizens on farm and community levels, and policy makers and planners at higher level of aggregation. A comprehensive systems approach could be a necessary condition for the development of innovative, BNF-efficient, legume-based sustainable systems of the future. A programme of work must build on and use methods that have already proved successful and also develop and borrow others where significant gaps in understanding or application occur.

## 4. ISFM challenges in relation to BNF-CP

The implementation of ISFM strategies on farms is likely to make the biggest contribution to agricultural sustainability in the tropics during the coming decade. When combined with robust, highly productive crop varieties, it is not uncommon for such systems to double yields in farmers' fields. The use of improved varieties is an integral part of the ISFM approach; ISFM is a specific strategy under the overall INRM research framework that aims at lifting the borders between crop improvement and natural resource management. A vital aspect of these strategies is the incorporation of farmers' indigenous knowledge at an early stage of systems development to enhance the adoption of ensuing technology.

Considerable evidence exists that farmers have accumulated knowledge relevant for agronomic management (Carter and Murwira, 1995; Murage et al., 2000). Encouraging as this is, increasing land degradation, including often substantial soil fertility decline, suggests that locally devised methods, on their own, are no longer effective enough to cope with rapidly changing pressures on farmers (Johannes and Lewis, 1993; Pinstrup-Andersen and Pandya-Lorch, 1994; Murdoch and Clark, 1994).

Farmers generally possess a vast body of knowledge about environmental resources in their farms but this knowledge is largely based on observable features (Talawar and Rhoades, 1998) rather than generalized knowledge. There is a general lack of process-based knowledge about agro-ecosystem function which is needed to cope with change, especially since much of it is unprecedented (i.e. climate change). This is in particular true for colonist farmers (Muchagata and Brown, 2000). In essence, lack of knowledge creates uncertainty that obstructs sound decision-making under conditions of change. This uncertainty about agro-ecosystem function prevents farmers from taking decisions that are too risky, and may have contributed to their reputation of being risk-averse. However, recent research points out that scientific knowledge can reduce farmers' decision-making uncertainty by enhancing local knowledge (Fujisaka, 1996). Some examples already exist that show how this can have positive synergistic effects for agro-ecosystem management (Steiner, 1998; Norton et al., 1998; Robertson et al., 2000).

### 4.1 Research needs

A holistic systems approach of ISFM is needed to address the smallholder to medium scale farming sector throughout the diverse agroecological zones of the tropics. This systems approach does not exclude process and molecular studies, but rather suggests that these tools be focused upon recognized constraints within farming systems. Research efforts on legume-BNF related aspects thereby become tools toward larger purpose, particularly in achieving food security and improving the diets of poor people in the tropics.

#### *4.1.1. Evaluating genetic diversity to overcome environmental constraints*

Environmental factors affect BNF via growth and development of the host plant, the bacteria and also the process of interaction between the symbionts from the time of infection through the development of the nodules to the production and transport of products. The identification of the processes that are most sensitive to environmental constraints promises the greatest success in breeding programs or in an improvement of agronomic practices (Rao, 2001). The major environmental factors affecting BNF in the tropics are drought, soil acidity, soil nutrient deficiency and soil salinity. As substantial genetic variability in tolerance to most environmental constraints exists in both host legumes and rhizobial strains (Hungria and Vargas, 2000), there is potential for breeding and selection for improved genetic adaptation.

Significant gains in impact can be achieved in the short to medium term by taking advantage of the huge legume and *Rhizobium* gene banks in participatory field evaluation and identification of stress-adapted legumes to specific ecological niches.

*Drought:* It was recognized that drought affects BNF in legumes significantly. Decrease in soil moisture causes a rapid decline in the numbers of rhozobia in soil. However, *Bradyrhizobium* strains are more tolerant of desiccation than strains of *Rhizobium* over short periods (Bushby and Marshall, 1977). Rates of $N_2$-fixation by legumes are more sensitive to reductions in soil moisture content than other processes such as photosynthesis, transpiration, leaf growth rates or nitrate assimilation (Serraj et al., 1999). Ureide-exporting legumes with determinate nodules appear to be more sensitive to drought than amide-exporting legumes (Serraj et al., 1999).

Given the expansion of drought at an alarming state, especially in sub-Saharan Africa, and the need for incorporation of legumes into systems to improve soil fertility, there is a real need to improve the drought resistance of nitrogen fixing legumes. Although challenging, there is an opportunity to improve drought resistance using the existing genetic diversity and available tools in genetic engineering. CIAT has been working on development of drought resistant bean varieties, and identified resistant materials like BAT 477, to be used as genetic sources. A drought protocol was also recently developed for improvement of the genetic adaptation of beans in Africa (Amede et al., 2002). A possible strategy in the short-term could be improving water-holding capacity of tropical soils by increasing soil organic matter content and rate of water infiltration while reducing run-off and soil erosion. As most grain legumes in the tropics are grown as intercrops or relay crops, selecting best companion crops and adjusting the planting dates could minimize water stress effects on BNF.

*Soil acidity:* Soil acidity is expanding in the humid and sub-humid tropics, mainly caused by improper land use and high rainfall intensity that encourage leaching of cations. Effects of soil acidity and the associated Al (aluminum) toxicity and P deficiency on BNF could be minimized through increasing the rhizosphere pH. One immediate option is liming but this is beyond the reach of resource-poor farmers, particularly in Africa. There is a consensus that continuous cultivation of legumes over longer time could lead to soil acidification. Therefore, crop rotation or intercropping legumes with cereals (maize-bean or sorghum-cow pea) is one sustainable strategy to improve BNF. Moreover, there are some tropical legumes that produce root exudates (mucilages & organic acids) that could minimize the effects of soil acidification through complexing Al ions. Other potential strategy is to identify legumes less sensitive to Al toxicity. Bean researchers at CIAT are breeding for improved Al resistance. ECABREN bean network in Africa has identified bean materials that are less sensitive to Al toxicity when grown under acidic soils of Democratic Republic of Congo. CIAT researchers in collaboration with NARS partners have selected a number of tropical forage legumes with very high adaptation to acid soils of the tropics (Rao, 2001).

*Soil nutrient deficiency:* As mentioned earlier, the most limiting nutrient for BNF is known to be P, which becomes limiting in most tropical soils not only for legumes but also for all other crops. The P deficit in soils of the tropics is the result of combined effect of low inherent P content, very high P fixation, and limited application of soluble P (Rao et al., 1999). Some legumes (e.g. pigeonpea, chickpea) are much more efficient in utilizing P in P-fixing soils, mainly through release of organic acids that increase its availability. Moreover, ECABREN of CIAT identified bean materials that are performing well under low N, low P and low pH soils of Eastern & Central Africa, indicating genetic difference in nutrient use efficiency. Other institutes are working with P efficient cowpea and soybean (Sanginga et al., 2001).

Soil salinity: Legumes that are grown in the drought-prone environments of sub-Saharan Africa, with saline or sodic soils, are commonly exposed to salt stress. Soil salinity could affect BNF through induction of water stress, pH effect, direct effect of Na ions or a combined effect. However, the rhizobia were found to be more tolerant than the host plant. Since the initial effect of slat stress is commonly expressed as water stress, improving the soil water availability would improve salt resistance of both grain and multipurpose legumes. Another strategy is integration of well-adapted N-fixing perennial legumes to reduce soil pH through acidification.

*4.1.2 Breeding/selection for improved BNF efficiency using conventional and molecular approaches*

As indicated before (section 2.1) one of the bred lines of beans, BAT 477, is not only BNF-efficient but also well-adapted to major abiotic stress factors such as water stress and low P availability in soil. What is the probability that independent genes control tolerance of BNF to different stresses; that still other genes control BNF in stress-free environments; and these have come together in one genotype without any conscious selection? This is unlikely. Rather, the same genes probably confer high BNF under all these conditions. In this case, what mechanism could explain the tolerance of these genes to at least two stress factors? The genes of BAT 477 may be regulatory genes that are less sensitive to an internal stimulus that results in down-regulation and are thus less active in regulating BNF. Thus they confer high BNF under a wide range of conditions. It is significant that some QTL, which were tagged in BAT 477 under low P stress, also contributed to better BNF in the high P supply, suggesting that the corresponding alleles in DOR 364 (less adapted to low P supply) may not be expressed fully, even in optimal environments. Could gene regulation therefore limit BNF under optimal conditions? This hypothesis represents a different perspective on what restricts BNF in common bean. There is a need to investigate to what extent the poor BNF of common bean in fact reflects internal limitations of gene regulation.

*4.1.3. Identification of niches within cropping systems*

Legumes do occupy space and time in cropping systems and consequently, suitable temporal and spatial niches need to be identified within farming systems for widespread adoption by the farmer community. Temporal niches are defined by sequential or simultaneous occurrence of legumes while spatial niches are defined by the optimum location to plant legumes, based on farmers' production objectives. The latter often include under-utilized spaces on farm such as field boundaries, contour strips, or degraded fields. Snapp et al. (1998) identified six temporal niches for legumes. Spatial niches are also related to the existence of within-farm soil fertility gradients, created by inherent soil properties but more often by deliberate land management by the farmer. Such gradients are very often linked to farmers' wealth, and the overall socio-economic environment (e.g., access to input and output markets, credit schemes for intputs, etc.).

*4.1.4. Proper legume management*

Even nutrient use efficient and promiscuous legume germplasm requires proper crop management for optimal contributions of BNF. To alleviate P constraints to BNF, the simplest option is to apply soluble P fertilizer. In absence of such resource, another possible strategy is through application of rock phosphate. Preliminary evidence shows that certain legumes can immediately access P from unreactive rock phosphates where cereals do not have that ability (Vanlauwe et al., 2000a). Proper targeting of P in legume-cereal rotations has also been shown to significantly enhance the growth of maize after application of rock phosphate to herbaceous legumes (Vanlauwe et al., 2000b). A last alternative to alleviate P stress would be through application of farmyard manure which often contains considerable amounts of available P.

Even for N, except for the most efficient $N_2$ fixing legumes, there is often a need to supply a starter N especially for those legumes growing in low fertility soils. In multiple cropping systems of the tropics, it is possibly only the homestead, the most fertile corner of the farm that may not require external P inputs and/or starter N because of continual application of farmyard manure and household residues.

*4.1.5. Approporiate INM strategies*

The efficient use of fixed N incorporated in the legume biomass is the net result of the dynamics of N in the system and is affected both by intrinsic characteristics of N sources (legume residues, N fertilizers) and N sinks (crop uptake, soil N pools), and by environmental factors (temperature, soil moisture, rainfall intensity and distribution, etc.) that govern process rates. The decomposition and N release rates of crop residues and green manures depend on their composition (ratio of C:N and content of lignin and polyphenols as well as soil temperature and moisture and the interaction of residues with soil (affected by management) (Palm et al., 2001). N derived from organic sources which is not taken up by

the crops or incorporated in the soil organic matter pool may be lost from the system through volatilisation, denitrification, and leaching. Improving synchrony of crop demand with the rate of legume residue decomposition is therefore of fundamental importance for the efficient use of N from leguminous green manures, covers and residues.

Within the INM framework, it is now recognized that both organic and mineral inputs are necessary to enhance crop yields without deteriorating the soil resource base. This recognition has a practical dimension because either of the two inputs are hardly ever available in sufficient quantities to the small scale farmer, but it also has an important resource management dimension as there is potential for added benefits created by positive interactions between both inputs when applied in combination. Such interactions can lead to improved use efficiency of the nutrients applied in organic or mineral form or both (Vanlauwe et al., 2001). Two sets of hypotheses can be formulated, based on whether interactions between fertilizer and OM are direct or indirect. For N fertilizer, the *Direct Hypothesis* may be formulated as: *Temporary immobilization of applied fertilizer N may improve the synchrony between the supply of and demand for N and reduce losses to the environment*. Obviously, residue quality aspects will strongly determine the validity of this hypothesis. The *Indirect Hypothesis* may be formulated for a certain plant nutrient X supplied as fertilizer as: *Any organic matter-related improvement in soil conditions affecting plant growth (except the nutrient X) may lead to better plant growth and consequently enhanced efficiency of the applied nutrient X*.

Due to the complexity involved, the efficient use of participatory approaches in the early pre-adaptive stages of BNF research will ensure that BNF technologies are client-oriented and respond to the needs of farmers and other end-users. Farmer participatory research (FPR) is increasingly receiving considerable recognition in both international and national agricultural research and development organizations as an important strategic research issue, vital to achieving impacts that benefit poor people in marginal, diverse and complex environments. There is now a large body of literature that demonstrates considerable advantages and potentials of involving farmers in the research process. FPR can significantly improve the functional efficiency of formal research (better technologies, more widely adopted, more quickly and wide impacts), empower marginalized people and groups to strengthen their own decision making and research capacity to make effective demands on research and extension services and thus have payoffs both for farmers and for scientists.

#### *4.1.6. Exploiting multiple benefits of legumes*

Legumes very often provide other benefits besides fixed N to the cropping system of which they are part. Although rotational effects of legumes on subsequent cereals have often been translated into N fertilizer replacement values, rotational benefits can not always be explained in terms of N addition to the system. Besides improving the soil physical structure, deep-rooting perennial species may recover nutrients from the subsoil and reverse top-soil degradation (e.g., reverse soil acidification caused by fertilizer use, Vanlauwe et al., 2001). Legumes have also been shown to alter pest and disease spectra and to reduce the Striga seedbank. All the above processes are alleviating a constraint to crop growth and may consequently lead to improved use efficiency of applied N fertilizer, following the indirect hypothesis (section 4.1.5.)

### 4.2 Development needs

Innovations can be considered as demand-driven or as supply-driven. It is fair to say that in the eyes of farmers BNF options may belong to the second category, or at best, are a mixture of both. Furthermore soil fertility decline as an ISFM issue is complex, difficult to prevent given farmers' situation, and easily to detect only when yields drop sharply. This infers that many ISFM innovations will be most effective as conservative or preventative innovations; adopting means often to sacrifice short-term profits for reducing a decline in returns in the future. These innovations have often slow rates of adoption. Simultaneously, farmers vary in their risk preferences of an innovation, and perceptions are affected by information introducing further heterogeneity due different sources of and exposure to information. Often farmers do not face the problem targeted by the innovation or the innovation simply does not work. In

addition, farmers will not commit to adoption of an innovation without successfully trialling it. If small-scale trials are not possible or not enlightening for some reason, as frequently the case in heterogeneous and fragile environments that are target regions for BNF, the chances of widespread adoption are greatly diminished. Conducting a trial incurs costs of time, energy, finance and land that could be used productively for other purposes. Furthermore the fact that economic and environmental conditions are rapidly changing today makes the adaptation of present land use systems and the process of including BNF in ISFM largely a process of managing the uncertain.

By taking a pro-poor approach, international agricultural research has developed the means to achieve large-scale impacts, responding to the demands of small-scale farmers for improved agricultural production and ecosystem services. Many ISFM options are locally profitable, even under intensely cultivated, land-scarce conditions. The knowledge-intensity and complexity of the ISFM approach, however, makes it difficult to translate local successes from one area to another, unless the factors favouring and constraining adoption are better understood. Increasing our understanding of where ISFM options are working, why, and for whom, will address the constraints limiting their wider use. The cost of not engaging in this research is likely to be enormous, in terms of greater poverty, stagnant and declining production, degraded ecosystem services, and the loss of intellectual property rights related to the local genetic resources of the soil.

Facilitating widespread use and impact of ISFM to solve soil fertility problems in the tropics will thus require a tighter linkage and feedback between strategic and adaptive research activities. The iterative process of learning and problem solving builds on indigenous knowledge, improves imperfect technologies, and empowers farmers and institutions. Addressing farmers' problems in a systems context generates management options better suited to their local needs. It also produces policy options that are suited to local institutional realities.

*4.2.1 Involving stakeholders in the technology development process*

The paradigm of involving farmers in research is based on strong evidence (Pretty and Hine 2001) that enhancing farmers technical skills and research capabilities, and involving them as decision-makers in the technology development process results in innovations that are more responsive to their priorities, needs and constraints. It is now widely recognized that these farmer participatory research (FPR) approaches may have wider applications for improving rural livelihoods in complex and diverse low potential areas where a "systems" approach is critical for the analysis and improvement of the production systems (Okali et al. 1994).

The active involvement of producers in the design of the ISFM system enables researchers and stakeholders to examine and understand the local farming systems and the larger context within which they exist, to incorporate local knowledge into technology innovation, and to develop locally appropriate solutions. A hallmark of FPR approaches is the link it establishes between the formal and local research systems (Ashby et al., 2000). This link enables farmers to express their technology needs and to help shape the technology developed through formal research. Participatory research decentralises control over the research agenda and permits much broader set of stakeholders to become involved in research, thereby addressing the differential needs of men and women for technical innovation.

Finally, farmer participatory experimentation and learning approaches represent an investment in the human and social capital available to poor farming families that can be harnessed to provide a systematic feedback process on farmers demands and priorities to research providers. These approaches build farmers' capacity to learn about knowledge intensive processes, biological and ecological complexities (Pretty and Hine, 2001) and can create a sustained, collective capacity for innovation focused on improving livelihoods and the management of natural resources.

*4.2.2 Identification of uncertainty within a cropping systems approach*

Scientific and local knowledge can be analyzed in relation to prevailing uncertainties about the innovation using an approach to uncertainty suggested by Rowe (1994). Rowe explains how uncertainty extends through many parts of the decision problem by distinguishing temporal, metrical, structural and

translational uncertainty. Temporal uncertainty is associated with fluctuations of processes over time. Metrical uncertainty is introduced by errors associated with the estimation of parameters in a spatially varying resource base. Structural uncertainty is related to the imperfection of the decision model itself. Translational uncertainty arises from contrasts between the perspectives of individuals involved in the decision process.

For example: In deciding how to apply fertilizer, metrical uncertainty could be reduced by more precise definition of the relationship between inputs and response. Unlike farmers in highly intensive cropping systems, small-scale farmers in tropical systems do not have ready access to modern monitoring techniques. But they do possess long time series understanding of relations at on one location that has been generated through repeated observations. These accumulated observations can be related to relevant scientific soil parameters presented above, or their local counterparts, providing opportunities for the development of spatially explicit indicators.

Temporal uncertainty could be reduced by specifying the phase of crop development for which such a relationship is valid. Farmers have already assembled plenty of experience doing this when deciding, for example, when to enter a fallowed plot into the productive system. Scientists can help to render farmers' experiences made in traditional systems transferable to new cropping circumstances by relating them to underlying processes. On this basis, for example, indicator plants can specifically be selected and grown in new cropping systems. Simple monitoring devices such as leaf colour meters provide more opportunities.

Structural uncertainty could be reduced by defining more of the interactions of fertilizer applications with other variables, such as pest and weed infestation or rainfall, and translational uncertainty could be reduced by formulating the actions suggested to reduce the other types of uncertainty in terms which are relevant to the hillside farmers. Reducing structural and translational uncertainty is probably least amenable to formal scientific investigation. Structural uncertainty because of huge complexity of the interactions and the variation in the natural resource base in hillside environments, and translational uncertainty because of the little attention given by scientists to what matters for farmers. To reduce the former, scientists need to understand whether variation matters to farmers, and if so how much of it farmers are willing and able to manage. Relevant and informative trials are essential.

*4.2.3 Identification of niches within a cropping systems approach*

If farmers had complete information innovations identified as being relevant would be implemented without delay. Information about complex farming systems and their externalities is however not complete. A pragmatic choice of whether or not to implement an innovation at farm level has to be made about whether or not it is sensible to manage variation more closely, which is based on the interrelated questions of whether as-yet unmanaged variation is significant, whether it is controllable and predictable? All three conditions of significance, control and predictability must be satisfied before improvement can occur.

*Significance*: this is largely a question to be decided by individual farmers. But research has demonstrated that farmers are well aware of problems, and their natural tendency to experiment demonstrates their willingness to change.

*Control and prediction*: in most farms there is uncontrolled variation that is usually of no benefit to farmers. Farmers have the capacity for field-by-field control, and some in-field control. However the capacity to control is limited by farmers' experiences based on long-term observations that usually do relate to traditional cropping systems and control by these means cannot directly be used for new innovations. Second, for control to be effective, the relationship between variation of the controllable inputs and output must also be known to some degree.

The key to reducing uncertainty is on-farm trialling, preferably on the farmer's own property. For these reasons, rapid adoption of ISFM management options, involving combinations of unfamiliar and complex innovations that are difficult to trial, are unlikely to occur until they are considered relevant and essential by farmers. Furthermore, even if they are considered relevant and essential, appropriate designs of trialling have to be defined that overcome obstacles including:

- Treatments often must be implemented in combinations which make it difficult to determine from field observations alone the individual impacts of each element of the combination. For a trial to be worthwhile, the results of the trial must be observable.
- The effectiveness of some innovations may be very sensitive to temporal changes (e.g. weather conditions) or the quality of implementation. As a result trials give highly variable results from time to time.
- Economic comparisons based on typical agronomic small-scale research trials can be very misleading. However, the larger the trial is, the less likely the farmer is to make the investment in trialling.

#### *4.2.4 Improving adoption and impacts of ISFM approaches*

Principles of ISFM could influence diverse stakeholders in the tropics to alter the ways they address soils and their management, at a variety of scales. Promotion of ISFM approaches will require increasing participation of national and international research and development organizations, networks, NGO's, and extension agencies working in the tropics. Significant adoption of a range of ISFM technologies has been documented across a number of countries in sub-Saharan Africa. These include (a) integrated nutrient management, (b) micro-dose use of fertilisers, (c) improved manure management practices, (d) inter-cropping systems, (e) integration of multipurpose legumes, (f) improved fallows, and (g) biomass transfer of high quality organic inputs. However, much of these adoption studies have focused on conventional factors influencing adoption of agricultural technologies. The complexity of ISFM technologies and processes require the identification farmers' decision-making processes, constraints and opportunities for the adoption of ISFM technologies, and the identification of farmers' criteria for acceptability of BNF technologies. This will require improving understanding of the complex linkages between livelihood assets and strategies and ISFM adoption, and the impacts of ISFM technologies on rural livelihoods. Measuring the impacts of ISFM is a complex task. We need to develop innovative methods that enable to track changes in the systems through the use of participatory monitoring and evaluation systems to learn from successes and failures.

#### *4.2.5 Building capacity at different scales*

The capacity for ISFM research in the tropics is insufficient both in terms of the numbers of professional personnel and the essential laboratory facilities. ISFM is a knowledge intensive approach to soil management. Professional staff and students alike suffer from isolation and lack of access to up-to-date educational opportunities. Networks run by SROs and CGIAR Centres, such as the TSBF African Network for Soil Biology and Fertility (AfNet) and MIS (Integrated Management of Soils) consortium in Central America provide a vehicle of opportunity to correct this situation. A substantial number of short term, degree-related, and on-the-job training activities, across the tropics could help spread ISFM approaches at all national levels, including university curricula.

Some of the groundwork for scaling up and out has been laid through an emphasis on the synthesis of results and dissemination of information on the technologies and on developing partnerships between research, extension services and NGOs. TSBF-CIAT researchers have experience in developing and applying decision guides to assist extension staff and farmers in selecting among soil fertility options for different situations (Palm et al., 2001). The use of accessible, user-friendly GIS tools and geo-spatial datasets for the region can be used in the scaling process, by identifying recommendation areas for BNF technologies.

Scaling up requires sustained capacity building to build the requisite skills among the NARS to ensure that the work is involving and reaching the intended beneficiaries. It also requires building local capacities and empowering rural communities to improve their technical skills and decision-making on soil fertility, in support of scaling up and sustaining impacts of ISFM technologies. Efforts to engage with policy makers and private sector input suppliers and dealers should also be strengthened.

## 5. Summary and Conclusions

In this brief position paper we have argued that BNF is a key input to ISFM strategy to combat soil fertility degradation and for sustainable intensified agriculture in the tropics. The reasons for lack of success in solving the soil fertility problem lie substantially in the failure to deal with the issue in a sufficiently holistic way. Soil fertility decline is not a simple problem. In ecological parlance it is a 'slow variable', which interacts pervasively over time with a wide range of other biological and socio-economic constraints to sustainable agroecosystem management. It is not just a problem of nutrient deficiency but also of inappropriate germplasm and cropping system design, of interactions with pests and diseases, of the linkage between poverty and land degradation, of often perverse national and global policies with respect to incentives, and of institutional failures. Tackling soil fertility issues thus requires a long-term perspective and holistic multidisciplinary systems approach of integrated soil fertility management.

Developing adoptable legume-BNF technologies to combat soil fertility degradation remains to be a major challenge. Research and development efforts are needed to integrate BNF efficient and stress adapted grain and multipurpose legume germplasm into production systems to intensify food and feed systems of the tropics. Several key interventions are needed to achieve greater impact of legume-BNF technologies to improve livelihoods of rural poor. These include (a) integration of stress-adapted and BNF efficient legume cultivars in rotational and mixed cropping systems, (b) strategic application of inorganic fertilizers and organic residues to facilitate efficient nutrient cycling and appropriate replenishment of soil organic matter, (c) adoptable strategies of soil and water conservation, (d) integrated pest/disease/weed management through the use of biotic stress resistant germplasm with minimum pesticide/herbicide applications, (e) marketing strategies that are economically efficient, and (f) development of an appropriate policy and institutional environment that provides incentives to farmers to adopt legume-based BNF technologies.

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# Implications of local soil knowledge for integrated soil fertility management in Latin America

E.Barrios[1] and M.T. Trejo[2]
[1]Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia
[2]Centro Internacional de Agricultura Tropical (CIAT), Tegucigalpa, Honduras

## Abstract

The increasing attention paid to local soil knowledge in recent years is the result of a greater recognition that the knowledge of people who have been interacting with their soils for long time can offer many insights about the sustainable management of tropical soils. This paper describes two approaches in the process of eliciting local information. Case studies show that there is a consistent rational basis to the use of local indicators of soil quality and their relation to improved soil management. The participatory process used is shown to have considerable potential in facilitating farmer consensus about which soil related constraints should be tackled first. Consensus building is presented as an important step prior to collective action by farming communities in integrated soil management at the landscape scale. Taking advantage of the complementary nature of local and scientific knowledge is highlighted as an overall strategy for sustainable soil management.

**Keywords:** Collective action, Colombia, Honduras, landscape, natural resource management, participatory methodologies, Venezuela

## Introduction

Local knowledge related to agriculture can be defined as the indigenous skills, knowledge and technology accumulated by local people derived from their direct interaction with the environment (Altieri 1990). It is the result of an intuitive integration of local agroecosystem responses to climate and land use change through time (Barrios et al. 1994). Transfer of information from generation to generation undergoes successive refinement leading to a system of understanding of natural resources and relevant ecological processes (Pawluk et al. 1992). WinklerPrins (1999) has provided a recent review of the scope and nature of the existing literature about local soil knowledge and the emerging science of ethnopedology.

There is increasing consensus about the need for enhanced understanding of local knowledge in planning and implementing development activities (CIRAN 1993). The slow rate of assimilation of new technology and new cropping systems has been often attributed to local inertia rather than the failures to take into account the local experience and needs (Warren 1991). According to Walker et al. (1995), increased application of indigenous knowledge to rural research and development can be attributed to the need to improve the targeting of research to address client needs and thus increase adoption of technological recommendations derived from research. Besides, ethical considerations related to participation and empowerment of local communities have gained considerable importance (Chambers 1983).

The complementary role that indigenous knowledge plays to scientific knowledge in agriculture has been increasingly acknowledged (Sandor and Furbee 1996). Experimental research is an important way to improve the information upon which farmers make decisions. It is questionable, however, if relying on experimental scientific methodology alone is the most efficient way to fill gaps in current understanding about the sustainable management of agroecosystems. There has been limited success of imported concepts and scientific interpretation of tropical soils in bringing desired changes in tropical agriculture. This has led an increasing recognition that the knowledge of people who have been

interacting with their soils for long time can offer many insights about managing tropical soils in a sustainable way (Hecht 1990).

Nevertheless, although benefits of local knowledge include high local relevance and potential sensitivity to complex environmental interactions, without scientific input local definitions can sometimes be inaccurate and unable to cope with environmental change. It is thus argued that a joint local/scientific approach, capitalizing on complementarities and synergies, would permit overcoming the limitations of site specificity and empirical nature and allow knowledge extrapolation through space and time as suggested by Cook et al. (1998).

The science of ethnopedology encompasses many aspects, including indigenous perceptions and explanations of soil properties and soil processes, soil classifications, soil management, and knowledge of soil-plant inter-relationships (Talawar 1996). This paper examines three case studies on local soil knowledge and management and the implications of these results on future research on integrated soil management in Latin America. Results from case studies to elicit local information using key-informants are reported for small farmers from Orinoco floodplains in Venezuela and from the Cabuyal river watershed in Cauca, Colombia. A participatory approach was used with farmers from the Tascalapa river watershed in Yoro/Sulaco, Honduras, in order to identify and classify local indicators of soil quality related to permanent and modifiable soil properties. Finally, the potential of the latter approach as a mechanism to facilitate collective action leading to integrated soil management is discussed.

## Case studies

### Orinoco floodplain farmers from Venezuela

The local knowledge about soils and their management by Orinoco floodplain farmers was studied by Barrios et al. (1994). A case study approach with key-informants was used to highlight practices that lead floodplain farmers to high yields and economic success while improving or maintaining soil fertility (Anderson and Ingram, 1989, Brown et al., 1994). In this highly unpredictable environment, the basic assumption is that farmer's indigenous knowledge is the result of an intuitive integration of their perception of changes in the agroecosystem as a result of climatic changes, the major driving force for decision making. The systematic assessment of local knowledge about soils and their management focused on criteria used for selection of new agricultural sites in this typically slash and burn agriculture, for soil classification and soil texture "management" and for managing inherent soil variability.

In the Orinoco floodplains, when farmers are looking for new cropping land they make a first selection based on the type of vegetation growing on the soil. Therefore, traditional farmers use associations of native plants as indicators of soil quality. In order of importance, trees such as 'caujaro' (*Cordia sp*.), 'taparo' (*Crescentia sp*.) and 'yagrumo' (*Cecropia sp*.) and herbaceous species like 'gamelote' (*Paspalum fasciculatum*), 'paja de agua'(*Paspalum repens*), 'tarraya'(Glinus sp.) and 'borrajón' (*Heliotropium indicum*) were used as indicators of "good soils" (Table 1). Conversely, they also use native plants as indicators of where not to establish a cropping field. For instance, trees such as 'melero' (*Combretum frangulaefolium*) and 'toco' (*Crataeva gynandra*) as well as herbaceous species like 'yerbabuena' (*Phyla betulaefolia*) and the grasses 'pata colorada' and 'bochocha' were plants indicating "bad soils". It is not surprising that farmers use vegetation in their first evaluation of potential cropping sites since these integrate complex and often diffuse soil attributes.

Once the agricultural plot has been selected a more detailed examination of the soil allows farmers to plan crop and soil management activities. While darker colored soils are generally recognized as better soils, local farmers identified soil texture as the most important measure on which to select crop and soil management practices. Farmers recognized the importance of fine texture sediment in floodplain soil fertility. Given the great uncertainty of sediment quality every year as influenced by flooding regimes, a traditional system to manage the quality of the incoming sediments was developed by floodplain farmers (Barrios et al., 1994). Vegetation barriers are allowed to grow or are planted by farmers around their agricultural plots in order to "filter" the coarse sediment and only allowing the finer sediment into the

plots. Vegetation barriers are typically composed of trees like 'Jariso'(*Ruprectia sp.*), 'guayabo rebalsero' (*Psidium ovatifolium*) and grasses like 'gamelote'(*P. fasciculatum*) (Fig.1).

Table.1 Most important plant species used as local indicators of soil quality by Orinoco floodplain farmers (modified from Barrios et al., 1994)

| Common name | Scientific name | Botanical family | Plant type** | Soil type |
|---|---|---|---|---|
| Gamelote | Paspalum fasciculatum | Gramineae | H | Fertile |
| Paja de agua | Paspalum repens | Gramineae | H | |
| Tarraya | Glinus sp | Aizoae | H | |
| Borrajón | *Heliotropium sp.* | Boraginaceae | H | |
| Caujaro | *Cordia sp..* | Boraginaceae | T | |
| Pira | *Amaranthus dubius* | Amaranthaceae | H | |
| Taparo | *Crecentia cujete* | Bignoniaceae | T | |
| Yagrumo | *Cecropia sp* | Moraceae | T | |
| Artemisa | *Ambrosia cumanensis* | Asteraceae | H | |
| Granadilla | *Polycarpea sp.* | Caryophylaceae | H | |
| Melero | *Combretum frangulaefolium* | Combretaceae | T | Poor |
| Toco | *Crataeva gynandra* | Capparidaceae | T | |
| Yerbabuena | *Phyla betulaefolia* | Verbenaceae | H | |
| Pata colorada | *s.n.n.i.** | Gramineae | H | |
| Bochocha | *s.n.n.i.** | Gramineae | H | |

* s.n.n.i. = scientific name not identified
** Plant type: H = herbaceous, T = tree.

Soil heterogeneity is very conspicuous because of the uneven distribution of sediment throughout the floodplain. The use of different crops in areas with different soil texture by traditional farmers shows an optimization of soil resource use. This could be seen as a traditional basis for modern site-specific management. Local wisdom indicates that while certain crops only grow well in specific soil textures, e.g., watermelon in sandy soil, beans in clay soil and cotton in mixed soil, other crops such as maize and cowpea are ubiquitous and are found in all soil textures (Barrios 1997).

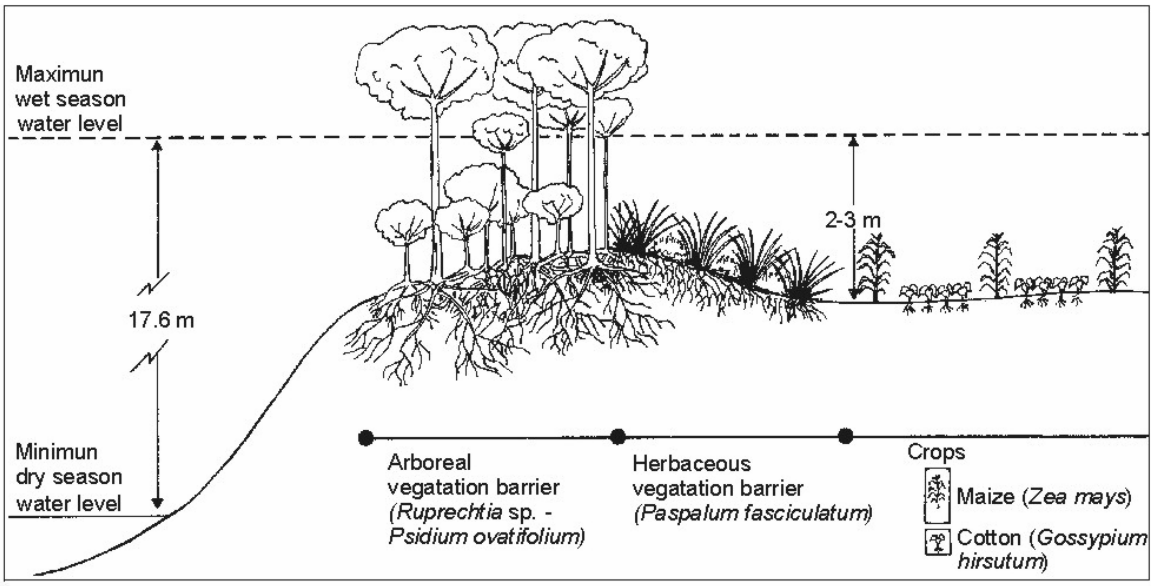


Figure 1. Schematic diagram of vegetation barriers used by Orinoco floodplain farmers to manage the quality (particle size) of the incoming sediment into their agricultural plots (modified from Barrios et al., 1994).

Andean hillside farmers from Colombia

Studies on local knowledge about soils and their management were conducted within the Cabuyal watershed, Cauca department – Colombia using case study approaches with semi-structured questionnaires, participatory farm mappings of soil qualities and identification of local indicators used to discriminate among different soils (Trejo *et al.* 1999). Previous studies in the area by CIAT (Centro Internacional de Agricultura Tropical) during the last 15 years facilitated the identification of key informants from each village. Key informants were selected from eight villages in three altitudinal zones in the watershed (Salamanca 2000). High elevation villages (1700-2200 m.a.s.l.) included: El Cidral, La Esperanza, La Primavera and El Rosario, middle elevation villages (1450-1700 m.a.s.l.) La Campiña and El Porvenir, and low elevation villages (1175-1450 m.a.s.l.) included La Llanada and La Isla. In the predominantly young volcanic-ash soils, Oxic Dystropepts in the USDA soil classification system, 100% of farmers interviewed use soil color for classification and assessment of soil quality. Black colored soils are considered good for cropping and yellow and red soils are considered marginal. Black soils are often found in soils under forest, fallow or pastures. Increasing use of tillage has lead to increased rates of soil loss and thus the usually darker topsoil has given way to the red sub-soil where cultivation is now taking place in many agricultural plots.

Native plants constitute another means by which Andean hillside farmers classify the soils in their farms (Barrios and Escobar, 1998). In Table 2 we find native plants used as indicators of soil quality by farmers in the Cabuyal river watershed. Fertile soils are characterized by trees like 'nacedero' (*Trichanthera gigantea*) and 'guamo' (*Inga sp*.) and herbaceous plants like 'papunga' (*Bidens pilosa*) and 'mariposo'(Clibadium surinamensis) while plants predominating in poor soils invariably include 'helecho marranero' (*Pteridium arachnoideum*) and 'paja garrapatera' (*Andropogon bicornis*). Farmers also identify ubiquitous species such as 'yaraguá' (*Mellinis minutiflora*) and 'caracola' (*Koheleria lanata*) which are then characterized by their vigor and leaf color. Darker green colored leaves are associated with more fertile soils while yellowish colors are indicative of poor soils.

Table. 2 Most important plant species used as local indicators of soil quality by Cabuyal watershed hillside farmers, Colombia (modified from Barrios and Escobar 1998).

| Common name | Scientific name | Botanical family | Plant type** | Soil type |
|---|---|---|---|---|
| Papunga | *Bidens pilosa* | Asteraceae | H | Fertile |
| Mariposo | *Clibadium surinamensis* | Asteraceae | H | |
| Margarita | *Chaptalia nutans* | Asteraceae | H | |
| Mortiño | *Clidemia hirta* | Meliaceae | H | |
| Altusara | *Phytolacca americana* | Phytolaccaceae | H | |
| Siempre Viva | *Commelina difusa* | Commelinaceae | H | |
| Hierba de chivo | *Ageratum conyzoides* | Asteraceae | H | |
| Nacedero | *Trichantera gigantea* | Acanthaceae | T | |
| Cachimbo | *Erythrina sp* | Leguminosae | T | |
| Guamo | *Inga sp* | Leguminosae | T | |
| Helecho marranero | *Pteridium arachnoideum* | Pteridiaceae | H | Poor |
| Paja garrapatera | *Andropogon bicornis* | Poaceae | H | |
| Paja blanca | *Andropogon leuchostachys* | Poaceae | H | |
| Helechillo | *Dichranopteris flexosa* | Pteridaceae | H | |
| Yaraguá | *Mellinis minutiflora* | Poaceae | H | Any soil |
| Caracola | *Koheleria lanata* | Gesneriaceae | H | |

** Plant type: H = herbaceous, T = tree.

Soils are also classified by their structure into 'polvoso' or "powdery", that is, with no macroaggregates indicating degraded soils on the one hand, and 'granoso' or "grain-like" which indicates some level of aggregation associated with better soils. This is an important characteristic used by farmers to assess soil recuperation after degraded soils have been left uncultivated to "rest" or fallow. In these hillside soils, topographic position also plays an important role in local soil classification. Hill tops or 'cimas'are identified as containing poorer soils, while the quality of hillsides or 'lomas' depends on how steep is the slope is. The more fertile soils are concentrated in the flat areas or 'planadas', hollowed areas or 'huecadas' because of the accumulation of eroded soils lost from up the hill as well as riverine floodplains by deposition of nutrient rich sediments (Cerón 2000). Inherently infertile soils are named 'tierra brava' or "angry soils" which should be distinguished from 'tierra cansada' or "tired soils" which are soils degraded by inappropriate management. Farmers consider that while the former are likely to respond to fertilizer applications (i.e. chicken manure) the latter invariably needs a period of fallow phase to recover lost attributes.

Central American hillside farmers from Honduras

A participatory approach was used in Honduras to identify and classify local indicators of soil quality and details can be found in Trejo et al. (1999). In short, six communities were selected from the Tascalapa watershed, namely Santa Cruz, Mina Honda (higher zone), San Antonio, Jalapa and Luquigue (middle zone) and Pueblito (lower zone) to identify and classify local indicators of soil quality at a landscape scale. Brainstorming sessions with farmer groups from the six communities respectively were

followed by a prioritization phase where farmers from each community were split in smaller groups in order to rank local soil quality indicators identified according to their relative importance using paper cards. The final list of local indicators, in order of importance, was then integrated with their corresponding technical indicator in plenary sessions and organized into indicators of permanent (Tables 3) and modifiable (Table 4) soil properties.

Although some local indicators can be rather general like fertility, slope, productivity and age under fallow, other local indicators are more specific. For instance, plant species growing in fallows, soil depth, color, water holding capacity and predominant soil particle sizes provide indicators that can be easily integrated with technical indicators of soil quality.

The classification of local indicators into permanent and modifiable factors provides a useful division that helps to focus on those where improved management could have the greatest impact. This strategy is particularly sound when there is considerable need to produce tangible results in a relatively short time in order to maintain farmer interest as well as to develop the credibility and trust needed for wider adoption of improved soil management practices.

Key permanent soil properties captured by local indicators that are commonly perceived as important by farming communities included slope, soil depth, soil color, soil texture and soil structure. The importance of slope in this hillside environment is obvious as there is a maximum inclination under which agriculture can be practiced. Because of their topography, hillside soils are prone to erosive processes even under natural vegetation or appropriate management. These soils tend to be relatively shallow compared to valley soils and therefore local farmers identify a minimum soil depth required for crop root growth and development (i.e. 12 inches, half a cutlass). Soil color provides a good measure of inherent soil fertility where black soils are seen as good soils and other red and yellowish colors as bad soils. Nevertheless, despite being classified as a permanent property, local farmers recognize that management practices involving crop residue additions could darken light colored soils indicating improvement in their quality. Soil texture is considered important by local farmers because it affects soil water holding capacity as well as the resistance to tillage. Soil workability is also related to soil structure, as good soils are perceived as those that do not compact, and where soil aggregates can be broken by tillage.

Modifiable soil properties of importance were perceived as those related to the lack or presence of burning, the type of native vegetation and the soil biological activity indicated by the presence of soil organisms (i.e. earthworms). The earliest farmers have used fire as an agricultural management tool to recover nutrients held in the native vegetation biomass for the crops, to control pests and to dispose of perceived “excess” plant biomass in the fields (Sanchez, 1976). Despite the realization of the harm done by annual fires on the soil, the lack of farmer consensus that could lead to a concerted action appears to be an important limitation. The participatory methodologies presented here have the potential to facilitate consensus amongst the local farmer community on high priority problems and opportunities. In this capacity, their linkage to concrete plans of action, as explained by Thomas et al. (2000), suggests this approach as a way to promote collective action at a landscape scale. A similar rationale has been successfully used in Africa to stimulate the participatory learning and action research process by Defoer and Budelman (2000).

It is important to note that the type of native vegetation present in a soil is a local indicator of soil quality (Table 5) that not only cuts across the communities studied in Honduras but also across the other two case studies reported in this article. This observation suggests that there may be an underlying fundamental ecological principle behind farmer observations in the three locations. It is proposed here that one such ecological principle is that of natural succession as suggested by Paniagua et al. (1999). Natural and agricultural ecosystems respond similarly to degradation or regenerative processes through natural succession.

Table 3. Integration of local and technical indicators of soil quality related to permanent soil properties identified and ranked according to their importance by Honduran hillside farmers from different villages (adapted from Turcios et al., 1998).

| | Knowledge Integration | | | | | |
|---|---|---|---|---|---|---|
| Ranking | Santa Cruz | Mina Honda | Jalapa | San Antonio | Luquigue | Pueblito |
| 1 | High water retention/ low water retention. (Texture/ water holding capacity) | Spongy, "espolvoreado", not sticky/"Arenisca", hard, sticky. (Texture) | Thick soil layer/thin soil layer. (Soil depth) | Deep or thick soil/ thin soil. (Soil depth) | Soil thickness of at least 12 inches, 2 palms, half a cutlass/thin soil less than 4 inches. (Soil depth) | Flatlands/ "Tierras quebradas" broken lands. (Slope) |
| 2 | Thick top soil/thin top soil. (Soil depth) | Soil with a thick fertile layer/ "frierra", when fertile layer is very thin or absent. (Soil depth) | Soils with gentle slopes, uniform/soils with high slopes. (Slope) | Black color/Light color, yellowish, reddish. (Color) | Good holding of water, soil that absorbs water/ low water retention. (Texture/water holding capacity) | Thick soil layer/thin soil layer, "delgadita". (Soil depth) |
| 3 | Blackish/light colors. (Color) | "Tierra tendida", "poca falda", little slope/"Guindo", "abismo", steep slopes. (Slope) | Soil keeps water for longer time/soil does not keep water. (Texture/water holding capacity) | Good plow penetration/limited plow penetration. (Physical barriers) | Easy to plow/difficult, needs skill to plow. (Physical barriers) | "Harinita", flour like, "huestesita"/ clay soil, sandy soil. (Texture) |
| 4 | Flatter lands/"Tierras quebradas", broken lands. (Slope) | Black color/"colorada", reddish, "amarilla", yellowish. (Color) | Black/various soil colors. (Color) | Few stones/plenty of large stones or "lajas". (Stoniness) | Black color/Yellow color, "moreno", tan, "colorada", reddish. (Color) | Black soils/Reddish soils, "medias coloradas". (Color) |
| 5 | Many stones/few stones. (Stoniness) | "Suelos francos", loamy soils/ "barriales",clay, mud, "arenoso", sandy. (Texture) | Fast water absorption/ slow water absorption, (Texture/infiltration) | Little slope/steep slope or "falda". (Slope) | Loose rocks on topsoil, not many stones/know-ledge of rocks below topsoil by inserting machete. (Stoniness) | Could have small stones/have big stones. (Stoniness) |
| 6 | | Small stones and few/ Many stones. (Stoniness) | Loamy soils, little clay/ "Brarrialosa"or muddy, sandy. (Texture/particle size) | Loams "francos"/ "Barrialosa", muddy, much sand. (Texture) | "Suelos francos", loamy soils/"areniscas", sandy soils, "barrilosas"or clay soils. (Texture) | "No se ende", not a cracking soil/"Se ende", cracking soil. (Clay type) |
| 7 | | | Easy tillage/difficult tillage, "Tronconosa". (Physical barriers) | "No se ende", non-cracking soils/"Se ende", cracking soils. (Clay type) | "No se ende", non-cracking soils/"Se ende", cracking soils. (Clay type) | |
| 8 | | | No stones present/ "Balastrosa", stony, gravely. (Stoniness) | | | |

Table 4. Integration of local and technical indicators of soil quality related to modifiable soil properties identified and ranked according to their importance by Honduran hillside farmers from different villages (adapted from Turcios et al. 1998).

| | Knowledge Integration | | | | | |
|---|---|---|---|---|---|---|
| Ranking | Santa Cruz | Mina Honda | Jalapa | San Antonio | Luquigue | Pueblito |
| 1 | Fertile soil / Non-fertile soil. (Fertility) | "Revenideros", washed land, "tierra lavada"/ "Tierra no lavada", unwashed land. (Erosion) | "Opulento", no need of chemical fertilizer/ needs fertilization. (Soil fertility) | "Opulento", high fertility / low fertility. (Soil fertility) | Good plants, good crop, lush and thick plants / Bad plants, bad crops. (Vegetation type / Yield) | Soil is not poddled, "no se aguachina"/soil is poddled, "se aguachina" (Drainage) |
| 2 | Organic residue incorporation of organic residues. (Soil organic residues) | Good yields given/Bad yields given. (Yield) | Presence of earthworms/lack of earthworms. (Biological activity) | "Verdolaga", "quilete", "chichiguaste", "chango", "Pica pica", "guama" / "tatascán", "Pino". (Indicator plants) | Land with "chichiguaste" and malva/land with "zacate" or native pasture. (Indicator plants) | Soil incorporated/ washed soil. (Erosion) |
| 3 | "Tierra blanda", soft soil, "suelta", loose/ "Tierra amarrada", tied soil. (Structure) | "Buenos guamiles", good fallows, / "Rastrojito", "bajillales", small fallows (Vegetation type) | Soil macroaggregates can be broken into pieces, "suelo suelto", loose soil/Macroaggregates can not be broken, "suelo amarrado", tied soil. (Structure) | High yields/low yields. (Yields) | "Porosita", "despolvorienta", loose soil, "se desparrama", non-compacted / No se desparrama, compacted. (Structure) | "Tierra se espolvorea", soil is not compacted/ soil compacts as balls, "se amarra", it is tied up. (Structure) |
| 4 | Good weed growth/ poor weed growth. (Type of vegetation) | "Terronosa", aggregated, "suelta", loose/"Masiva", compacted. (Structure) | No burnings have occurred in the last 5 years/Lands have been burned in the last 5 years. (Soil burning) | Without "manto" or incorporating decomposing residues/ with "manto". (Soil organic matter) | New land use<10 yrs, from pasture to crop-land, land from ancestors was good/ old land, greater than 10 years of use. (Length of current land use) | Does not occupy fertilizer/needs fertilizer. (Fertility) |
| 5 | No burning/burning. (Soil burning) | Soil with a black layer/ Soil with litter or without black layer. (Soil organic matter) | "Zaléa", "Chichiguaste"/ "Chichiguaste" does not grow, weeds do not develop, "zacate de gallina" (Indicator plants) | "Suelta", loose, "suave", soft, "terronosa", large aggregates/"Tablones", laminar structure. (Structure) | No burning/burning (Soil burning) | No burning/burning (Soil burning) |
| 6 | | No burning/burning. (Soil burning) | Greater yields/Lower yields, more work to produce. (Yield) | No burning/burning. (Soil burning) | "Manto", organic residues incorporated into the soil/ "Manto" not incorporated. (Soil organic matter) | |

Table 4. Contd..

| | Knowledge Integration | | | | | |
|---|---|---|---|---|---|---|
| Ranking | Santa Cruz | Mina Honda | Jalapa | San Antonio | Luquigue | Pueblito |
| 7 | | | Soil does not flood, no "aguachina"/ "aguachina", "sweaty" soil. (Drainage) | "No se aguachina", does not flood/"Se aguachina" gets muddy, water does not filter through. (Drainage) | Soil does not fill with water, "No se empapa"/soil fills with water, "Se empapa", "pichera". (Drainage) | |
| 8 | | | Non washed soils/ washed soils (Erosion) | | Crops grow with little or no fertilizer/only growth with fertilizer. (Fertility) | |
| 9 | | | | | Un-washed land/ washed land. (Erosion) | |

The most adapted plants and organisms in the soil gradually replace less adapted ones as continued selective pressures are exerted (i.e. during regeneration of soil fertility or soil degradation). Native plants and "weeds", as biological indicators, have the potential to capture subtle changes in soil quality because of their integrative nature. They reflect simultaneous changes in physical, chemical and biological characteristics of the soil. There is considerable scope, therefore, to further explore the use of local knowledge about native plants as indicators of soil quality and as a tool guiding soil management decisions.

Table. 5 Most important plant species used as local indicators of soil quality by Tascalapa watershed hillside farmers, Honduras (modified from Turcios et al. 1998)

| Common name | Scientific name | Botanical family | Plant type** | Soil type |
|---|---|---|---|---|
| Chichiguaste | Eletheanthera ruderalis | Asteraceae | H | Fertile |
| Verdolaga | *Portulaca oleraceae* | Portulacaceae | H | |
| Malva | *Anoda cristata* | Malvaceae | H | |
| Zalea | *Calea urticifolia* | Asteraceae | H | |
| Guama | *Inga sp.* | Fabaceae | T | |
| Quilete | *Phytolaca icosandra* | Phytolaccaceae | H | |
| Pica pica | *Mucuna pruriens* | Fabaceae | H | |
| Zacate de gallina | *Cynodon dactylon* | Gramineae | H | Poor |
| Tatascán | *Perymenium nicaraguense* | Asteraceae | H | |
| Pino | *Pinus caribeae* | Pinaceae | T | |

** Plant type: H = herbaceous, T = tree

**Implications for integrated soil management across the landscape**

Farmers are often more enthusiastic to empirical approaches (i.e. local knowledge, on-farm experiments) than prescriptive approaches (i.e. scientific knowledge, recipes for soil management) (Cook *et al*., 1998). Figure 2 illustrates that while scientific information can be very precise its relevance can be relatively low. On the other hand, while local information can be relatively imprecise, yet, it can be very relevant. Although information should ideally be certain in both meaning and context, in reality this is not the case. Research efforts should further explore a suitable balance between precision and relevance as seen in the figure.

The methodological approach proposed by Trejo et al. (1999) goes beyond the identification and classification of local indicators of soil quality. It rests on the hypothesis that in order for sustainable management of the soil resource to take place, it has to be a result of improved capacities of the local communities to better understand agroecosystem functioning. Improved capacities by technical officers (extension agents, NGO's, researchers) to understand the importance of local knowledge is also part of the methodology. Therefore, after identifying if there is poor or a lack of adequate communication between the technical officers and the local farm community as a major constraint to capacity building, the methodology proposed deals with ways of jointly generating a common knowledge that is well understood by both interest groups. The structure of the guide is shown in Fig.3 shows the different sections of the methodological guide.

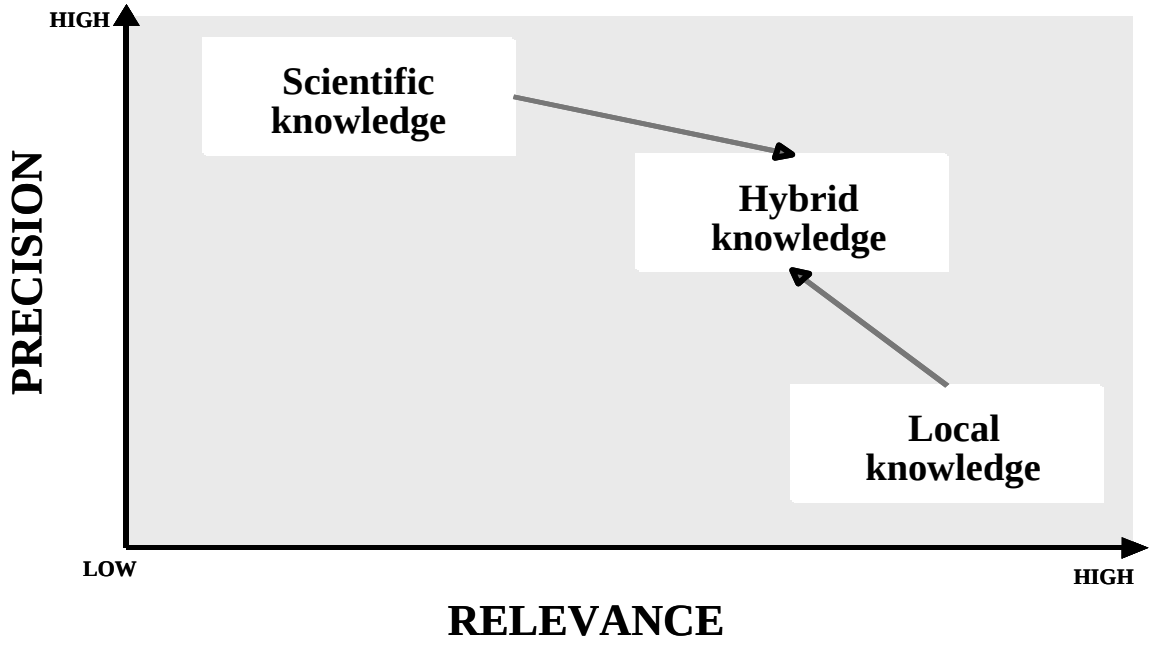


Figure 2. Schematic representation of the comparison between scientific and local knowledge systems

Section 1, which provides a general overview of soil formation factors and processes, based on Jenny's seminal work (Jenny, 1941, 1980), is presented in order to bring the trainees (e.g. technical officers) to a common starting point. Section 2 deals with participatory techniques that help gather, organize and classify local indicators of soil quality through consensus building. Section 3 attempts to find correspondence between local indicators and technical indicators. This is carried out in a plenary session exercise of integration where the most important local indicators of soil quality are analyzed in the context of technical knowledge and are classified into indicators of permanent or modifiable soil properties. The idea is to provide a guideline to focus efforts on soil properties where management can have an impact. An important part of this section is the Soils Fair for farmers that is organized by the trainees. The Fair aims to help farmers develop skills to characterize relevant physical, chemical and biological properties of their soils through simple methods that can then be related to their local knowledge about soil management.

The result of this two-way exchange process has a positive impact on the technical knowledge by nurturing it with local perceptions and demands. The number of successful experiences in natural resource management in agroecosystems will likely increase because of the solid basis provided by local relevance. On the other hand, local knowledge will also be enriched because of greater possibilities for its wider comprehension, appreciation and use. Local communities will be empowered by the joint ownership of the technical-local soil knowledge base constructed during this process.

The two-way improvement of communication channels will likely improve the communication of farmer's perceptions to extension agents and researchers as well as make recommendations by extension agents and NGOs better understood by the farmer community. Better communication opens opportunities for established and/or emerging local organizations to use the methodological approach for consensus building that precedes any collective actions for improved natural resource management through integrated soil management.

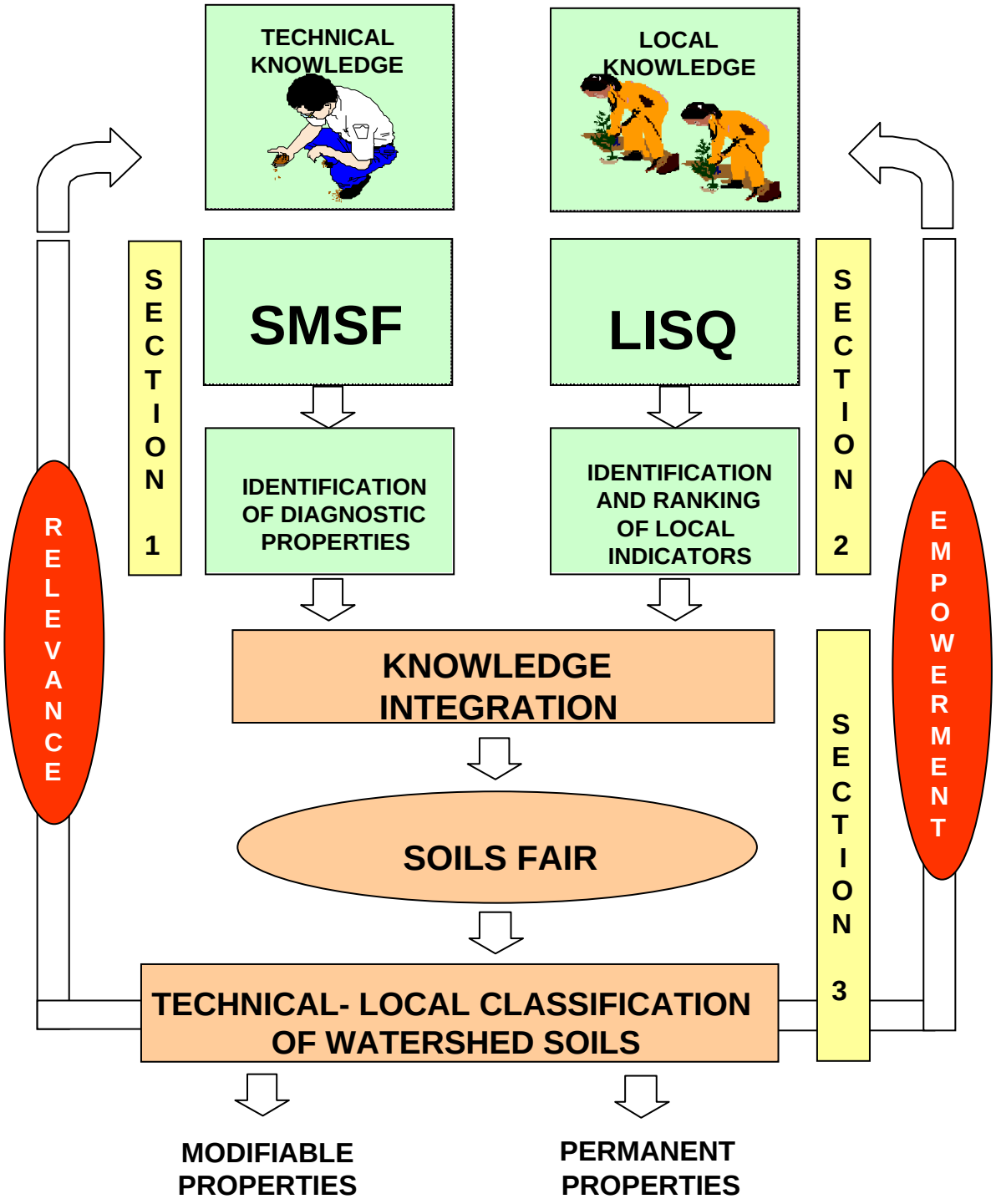


Figure 3. Structure of the methodological guide for the participatory identification and classification of local indicators of soil quality (Adapted from Trejo et al. 1999).

## Conclusions

The considerable importance of local knowledge in guiding future research and development efforts towards a sustainable management of natural resources is highlighted in this study. The case studies presented showed that there is a consistent rational basis to the use of local indicators of soil quality. The use of key-informants was an effective method to elicit local information about soils and their management. In addition, participatory approaches involving group dynamics and consensus building are likely to be key to improve soil management beyond the farm-plot scale to the landscape scale through the required collective action process.

Native plants as local indicators of soil quality were important local indicators of soil quality in all three case studies associated with modifiable soil properties. The use of indicator plants, belonging to the local knowledge base, when related to management actions could ease adoption of improved technologies. This approach would allow the use of plants as indicators of soil quality to which local farmers can relate more closely than to common agronomic measures such as phosphorus availability, organic matter content or pH value. Additional research could also include further integration of scientific spatial analysis (i.e. GIS, topographic modeling) with the spatial perception of natural resources by farmers aiming at improved implementation of site-specific management.

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Special thanks to the farmer communities from Mapire (Venezuela), Cabuyal watershed (Colombia) and Tascalapa watershed (Honduras) for sharing their ample knowledge about soils and their management. The authors are also thankful to R.J. Thomas, S.E. Cook and T. Oberthur for their valuable comments in earlier versions of this manuscript. Financial support was provided by Unesco-MAB for the studies in Venezuela and by the CGIAR systemwide program on Soils, Water and Nutrient Management for the studies in Colombia and Honduras.

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**Decomposition and nutrient release by green manures in** a **tropical hillside agroecosystem**

J. G. Cobo[1,2], E. Barrios[2], D. C. L. Kass[1] & R. J. Thomas[2]
[1] Centro Agronómico Tropical de Investigación y Enseñanza ( CATIE ), Turrialba, 7170, Costa Rica.
[2] Centro Internacional de Agricultura Tropical (CIAT), AA 67 13, Cali, Colombia.

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## Abstract

The decomposition and nutrient release of 12 plant materials were assessed in a 20-week litterbag field study in hillsides from Cauca, Colombia. Leaves of *Tithonia diversifolia* (TTH) and *lndigofera constricta* (IND) decomposed quickly (k=0.035±0.002 $d^{-1}$ ), while those of *Cratylia argentea* (CRA) and the stems evaluated decomposed slowly (k=0.007±0.002$d^{-1}$ ). Potassium presented the highest release rates (k>0.085 $d^{-1}$ ). Rates of N and P release were high for all leaf materials evaluated (k>0.028 $d^{-1}$) with the exception of CRA (N and P), TTH and IND (P). While Mg release rates ranged from 0.013 to 0.122 $d^{-1}$, Ca release was generally slower (k=0.008-0.041 $d^{-1}$). Initial quality parameters that best correlated with decomposition (P<0.001) were neutral detergent fibre, NDF (r=-0.96) and *in vitro* dry matter digestibility, IVDMD (r=0.87). It is argued that NDF or IVDMD could be useful lab-based tests during screening of plant materials as green manures. Significant correlations (P<0.05) were also found for initial quality parameters and nutrient release, being most important the lignin/N ratio (r=-0.71) and (lignin+polyphenol)/N ratios (r=-0.70) for N release, the C/N (r=-0.70) and N/P ratios (r=-0.66) for P release, the hemicellulose content (r=-0.75) for K release, the Ca content (r=0.82) for Ca release, and the C/P ratio (r=0.65) for Mg release. After 20 weeks, the leaves of *Mucuna deerengianum* released the highest amounts of N and P (144.5 and 11.4 kg $ha^{-1}$, respectively), while TTH released the highest amounts of K, Ca and Mg (129.3,112.6 and 25.9 kg $ha^{-1}$, respectively). These results show the potential of some plant materials studied as sources of nutrients in tropical hillside agroecosystems.

### Introduction

Hillsides of tropical America cover about 96 million hectares (Jones, 1993) and have important roles as reserves of biodiversity and source of water for areas downslope (Whitmore, 1997). A high proportion of the Colombian Andean soils (i.e. 83% ) suffer from erosion problems (Amezquita et al., 1998). These soils, particularly the volcanic-ash soils, usually contain high levels of soil organic matter (SOM) but low availability of nutrients due to SOM protection by mineral particles which limits decomposition (Phiri et al., 2001). According to Shoji et al. (1993) plant growth in volcanic-ash soils is limited by the low availability of N and P together with low base saturation and deficiency of some micronutrients (Cu, Zn and Co).

Use of green manures could reduce soil exposure to erosive processes, promote a greater nutrient cycling and improve the synchrony of nutrient release with crop demand. However, the potential benefit of green manures as a source of nutrients to crops can only be achieved if their decomposition and nutrient release patterns are known so that the synchrony of nutrient release with crop nutrient demand can be improved (Myers et al., 1994). Management options include the selection of plant materials with different chemical composition (quality) and by controlling the timing, quantity and form of application to the soil (Anderson and Ingram, 1993; Palm, 1995; Palm et al., 2001). Besides, the single or combined applications

of plant parts used as green manures (i.e. leaves, stems) are likely to influence the decomposition and nutrient release rates to the soil (Lehmann et al., 1995; Handayanto et al., 1997).

Several methods have been used to determine decomposition and nutrient release of plant materials in the field, and the litterbag technique is probably the most widely used because of its simplicity, replicability, and ability to selectively exclude classes of soil fauna (Vanlauwe et al., 1997a). However, while this method may underestimate dry matter and nutrient losses it is considered a great tool for treatment comparisons (Vanlauwe et al., 1997a and b). For this technique, standard quantities of litter are enclosed in nylon-mesh bags; litterbags are then incubated in the field, and weight and nutrient loss are monitored during several weeks by partial retrieval of litterbags.

The quality of plant materials has been considered one of the most important factors that affect decomposition and nutrient release (Heal et al., 1997; Swift et al., 1979). High nutrient contents in plant materials have generally been correlated with high decomposition rates (Gupta and Singh, 1981). Other researchers have found that low lignin/N ratio (L/N) also leads to faster decomposition (Melillo et al., 1982). According to Palm and Sanchez (1990), polyphenol (PP) concentrations can influence decomposition and nutrient release rates in legume materials to a greater extent than lignin (L) or N content. Furthermore, Thomas and Asakawa (1993) reported that the C/N, L/N, PP/N and (L+PP)/N ratios were all inversely correlated with N release rates from herbaceous materials; while weight loss only correlated with the L/N and (L+PP)/N ratios. More recent studies also showed similar correlations between the (L+PP)/N ratio and decomposition and N release for several agroforestry species (Barrios et al., 1997; Lehmann et al., 1995; Mafongoya et al., 1998; Vanlauwe et al., 1997b). Tian et al. (1996), on the other hand, showed that decomposability of plant residues placing nylon-mesh bags inside the rumen of fistulated animals significantly correlated with that using litterbags in the field. Using a similar principle, another promising plant quality index is the in vitro dry matter digestibility (IVDMD) lab test used for animal feed (Harris, 1970). Although the decomposition processes in the rumen and the soil differ, they are sufficiently similar to be thought of as a potential method for comparative plant tissue studies (Chesson, 1997).

In this study we determined the decomposition and release of N, P, K, Ca and Mg by 12 plant materials used by farmers in our study areas. These plant materials were surface applied to a soil in a tropical hillside agroecosystem, and we assessed the relationship of some common plant quality indices and IVDMD for such materials to their respective decomposition and nutrient release rates.

## Materials and methods

### *Site description*

The study was carried out at 'San Isidro' experimental farm located in Pescador, Cauca department, Colombia, at 2° 48' N, 76° 33' W and 1.500 masl. The area has a mean temperature of 19.3 $^{o}$C and a mean annual rainfall of 1900 mm (bimodal). The experiment was conducted from April to August during the first cropping season of 1998 (Figure 1).

The experimental plot had a slope of approximately 30%. The soils, derived from volcanic ashes, have been classified as Oxic Dystropepts (Inceptisols) in the USDA soil classification system (USDA, 1998). Soil characteristics include: pH ($H_20$): 5.1,50 9 kg$^{-l}$ C, 3 9 kg$^{-l}$ N, 4.6 mg kg$^{-1}$ soil of Bray-II P, and 1.1, 0.6, 2.5 and 0.9 cmol kg$^{-1}$ soil of Al, K, Ca and Mg, respectively. Soil bulk density was 0.8 g cm$^{-3}$ and allophane content ranged from 52 to 70 g kg$^{-l}$ (Phiri et al., 2001).

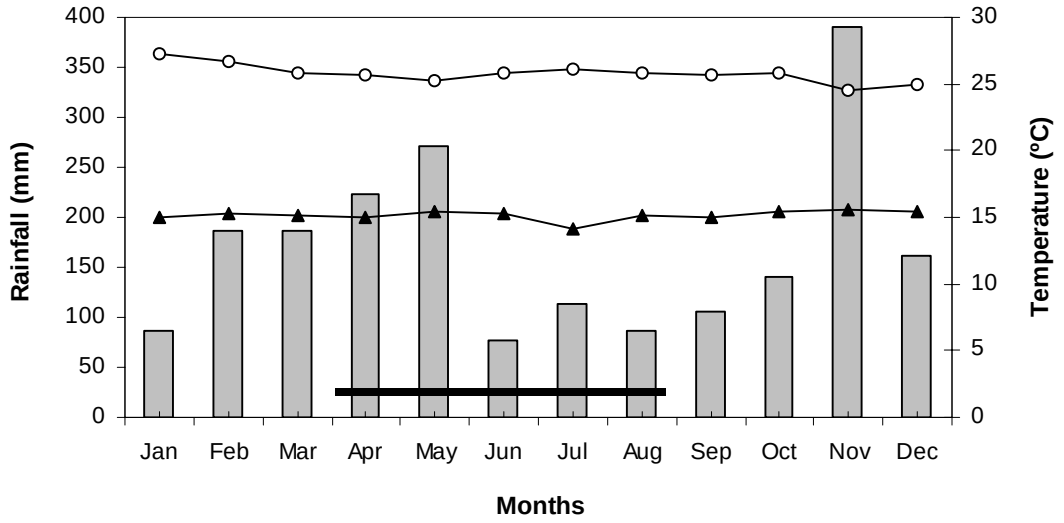


Figure 1. Monthly rainfall (bars) and maximum ( o ) and minimum ( ▲ ) air temperature (°C) at San Isidro Farm, Pescador, Cauca (Colombia), during 1998. The horizontal bar indicates the experimental period.

*Selected plant materials*

Plant materials were selected from plants with known adaptation to the hillside environment and also with contrasting quality. Since two species and three varieties of Mucuna are utilized by farmers in our study areas and they show differences in agronomic behaviour it was considered important to evaluate their decomposition and nutrient release rates. Plant materials included: leaves, with petioles, of *Canavalia brasiliensis* Mart. ex Benth. (CAN), *Cratylia argentea* Benth. (CRA), *lndigofera constricta* Rydb. (IND), *Mucuna deerengianum* (Bort.) Merr. (MDEE), *Mucuna pruriens* (Stick.) DC. var. IITA-Benin (MPIT), *Mucuna pruriens* (Stick.) DC. var. Tlaltizapan (MPTL), *Mucuna pruriens* (Stick.) DC. var. Brunin (MPBR) and *Tithonia diversifolia* (Hems.) Gray (TTH); stems ( <1 cm width) of *Mucuna pruriens* var. IITA-Benin (MPITs) and *lndigofera constricta* (INDs); and a mixture of stems and leaves of *Mucuna pruriens* var. IITA-Benin (MPITm) and *Indigofera constricta* (INDm), in the proportion found at the time of pruning and collection. Stems and the mixture of leaves and stems were studied to relate to common farmer practice of mixed application. It also contributed to expand the quality spectrum of materials evaluated and to compare them with the leaves alone. Pruned materials were collected from herbaceous plants (*Canavalia* and 'Mucunas') and *Tithonia* at flowering, while materials from trees (*Cratylia* and *Indigofera*) were pruned 6 months after the last pruning. Harvest time for herbaceous materials followed farmer practices and for tree materials was associated with optimal pruning regime identified in previous unpublished studies.

*Experimental design*

After collection, each plant material was air and oven dried (60 °C), thoroughly mixed and composited, and a sample was taken for chemical analyses. Then, 15 g of each plant material were placed inside litterbags (20x20 cm nylon bags, mesh size 1.5 mm), corresponding to an application rate of 3.75 Mg dry matter $ha^{-1}$. Litterbags were placed on the soil surface between maize rows in a randomized complete block design with four replications. The maize crop did not receive any additional treatments besides residue quality. At 2, 4, 8, 12 and 20 weeks, one litterbag of each repetition and treatment was collected, manually cleaned, and washed with distilled water to remove soil particles. Remaining plant material was air and oven dried (60 °C) to constant weight before determining dry weight and nutrient contents.

*Chemical characterization of plant materials*

Subsamples of plant materials used in litter bags were analyzed for their in vitro dry matter digestibility (IVDMD), total carbon (C), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and contents of acid detergent fibre (ADF), neutral detergent fibre (NDF), hemicellulose (HEM), lignin (L), polyphenols (PP) and N fixed to ADF (N-ADF). In addition, the amount of plant material retrieved from litterbags at each sampling time was analyzed for total N, P, K, Ca, Mg and ash content.

All plant material was ground and passed through a 1-mm mesh before analysis. C, N and P were determined colorimetrically with an autoanalyzer (Skalar Sun Plus, Breda, The Netherlands), and K, Ca and Mg with an atomic absorption spectrophotometer (Unicam 969, Reading, U.K.). ADF, NDF and lignin were determined using modified techniques of Van Soest and Vine (Harris, 1970) and total polyphenols with a modified Anderson and Ingram (1993) method that uses 70% methanol, 0.5% formic acid and 0.05% ascorbic acid as extractant (Telek, 1989), the Folin-Ciocalteu reagent and tannic acid as standard. HEM was calculated by substracting ADF from NDF. IVDMD was determined by the modified methodology of Tilley and Terry, that includes a 48-h incubation of plant materials with rumen microorganisms followed by acid/pepsine digestion (Harris, 1970). Ash contents were determined by heating at 550 °C for 2 h and these data were used to correct the weight of the plant material remaining for contamination with soil.

*Calculations and statistical analysis*

Decomposition of plant materials and their N, P, K, Ca and Mg release were evaluated through assessment of dry weight and nutrient losses from the materials. The percent of dry weight remaining (DWR), and nutrients remaining (NR, PR, KR, CaR and MgR), for each experimental unit, was calculated as shown:

$$XR(\%) = (Xt/Xo) \times 100,$$

where XR is the percent weight or nutrient remaining, Xt the weight or nutrient content at each sampling time and Xo the starting weight or nutrient values. Dry weight and nutrients remaining were subjected to analysis of variance (ANOVA) at each sampling time. Standard errors of the difference in means (SED ) were calculated from the ANOVA and reported with the data. Whenever necessary, variables were log-transformed to normalize data.

In order to describe treatment trends, treatment means of dry weight and nutrients remaining were regressed over time using a single exponential decay model (Wieder and Lang, 1982). This model is described by the following equation:

$$XRt = 100. \exp^{-kt},$$

where XRt is the dry weight or nutrient remaining at time t and the slope k, the decomposition or nutrient release constant. This model has been recently used by Palm et al. (2001) in their Organic Resource Data-base (ORD) to allow comparisons of the derived rate constants, over similar evaluation times, for different species and experiments. Root square errors were used to assess fit of the model used.

Correlation and linear regression analyses were carried out between chemical parameters of the plant materials used in litterbags and their decomposition and nutrient release rates. The amount of nutrients released by plant materials to the soil was calculated by substracting the nutrients remaining in the residues at the end of the field incubation from the total amount of nutrients initially applied. SAS (SAS Institute, 1989) was used for the statistical analysis.

Table 1. Initial chemical characteristics of the 12 plant materials evaluated.

| Treatment | C | N | P | K | Ca | Mg | C/N | C/P | N/P |
|---|---|---|---|---|---|---|---|---|---|
| . | % | % | % | % | % | % | . | . | . |
| CAN | 44.5 | 3.7 | 0.27 | 1.79 | 1.04 | 0.35 | 12.0 | 165.0 | 13.7 |
| CRA | 44.3 | 3.3 | 0.15 | 1.69 | 1.63 | 0.41 | 13.5 | 295.3 | 21.9 |
| IND | 44.8 | 3.9 | 0.19 | 1.72 | 1.77 | 0.43 | 11.6 | 235.9 | 20.4 |
| MDEE | 45.5 | 4.6 | 0.36 | 1.77 | 1.02 | 0.36 | 9.8 | 126.5 | 12.9 |
| MPBR | 45.6 | 4.1 | 0.29 | 1.42 | 1.06 | 0.53 | 11.0 | 157.1 | 14.3 |
| MPIT | 45.0 | 3.7 | 0.26 | 1.39 | 1.12 | 0.61 | 12.3 | 173.1 | 14.0 |
| MPTL | 45.1 | 3.8 | 0.26 | 1.52 | 1.24 | 0.44 | 11.9 | 173.5 | 14.6 |
| TTH | 38.8 | 3.9 | 0.25 | 3.47 | 3.49 | 0.74 | 9.9 | 155.1 | 15.7 |
| INDm | 44.5 | 2.9 | 0.16 | 1.56 | 1.37 | 0.40 | 15.3 | 281.7 | 18.4 |
| INDs | 44.0 | 1.5 | 0.11 | 1.33 | 0.76 | 0.36 | 29.7 | 400.2 | 13.5 |
| MPITm | 44.4 | 2.9 | 0.23 | 1.53 | 0.90 | 0.54 | 15.1 | 194.6 | 12.9 |
| MPITs | 43.1 | 1.4 | 0.16 | 1.84 | 0.43 | 0.39 | 30.8 | 269.4 | 8.8 |

| Treatment | ADF | NDF | N-ADF | *HEM* | L | PP | IVDMD | L/N | PP/N | (L+PP)/N |
|---|---|---|---|---|---|---|---|---|---|---|
| . | % | % | % | % | % | % | % | . | . | . |
| CAN | 33.5 | 44.1 | 0.70 | 10.6 | 6.5 | 8.4 | 69.6 | 1.8 | 2.3 | 4.0 |
| CRA | 42.6 | 64.2 | 1.53 | 21.6 | 17.7 | 4.8 | 46.5 | 5.4 | 1.5 | 6.9 |
| IND | 28.1 | 36.8 | 0.76 | 8.7 | 6.9 | 8.6 | 72.4 | 1.8 | 2.2 | 4.0 |
| MDEE | 24.0 | 46.6 | 0.73 | 22.6 | 6.9 | 9.3 | 70.4 | 1.5 | 2.0 | 3.5 |
| MPBR | 25.6 | 46.2 | 0.48 | 20.6 | 5.5 | 8.3 | 70.0 | 1.3 | 2.0 | 3.3 |
| MPIT | 27.8 | 43.1 | 0.43 | 15.3 | 6.1 | 8.9 | 71.5 | 1.7 | 2.4 | 4.1 |
| MPTL | 28.9 | 45.6 | 0.56 | 16.6 | 6.3 | 8.9 | 69.1 | 1.7 | 2.3 | 4.0 |
| TTH | 25.2 | 26.6 | 1.41 | 1.4 | 4.6 | 8.7 | 77.4 | 1.2 | 2.2 | 3.4 |
| INDm | 38.5 | 49.1 | 0.59 | 10.7 | 8.1 | 7.8 | 62.6 | 2.8 | 2.7 | 5.5 |
| INDs | 54.0 | 67.6 | 0.33 | 13.7 | 10.0 | 6.6 | 50.9 | 6.8 | 4.4 | 11.2 |
| MPITm | 35.1 | 49.2 | 0.39 | 14.0 | 7.9 | 8.8 | 63.3 | 2.7 | 3.0 | 5.7 |
| MPITs | 50.8 | 62.2 | 0.29 | 11.4 | 11.6 | 8.6 | 55.5 | 8.3 | 6.1 | 14.4 |

CAN=*Canavalia brasiliensis* (leaves), CRA=*Cratylia argentea* (leaves), IND=*lndigofera constricta* (leaves), MDEE=*Mucuna deerengianum* (leaves), MPIT=*Mucuna pruriens* Var. IITA-Benin (leaves), MPTL=*M. pruriens* Var. Tlaltizapan (leaves), MPBR=*M. pruriens* Var. Brunin (leaves), TTH=*Tithonia diversifolia* (leaves), INDm=*I. constricta* (stems+leaves), INDs=*I. constricta* (stems), MPITm=*M. pruriens* Var. IITA-Benin (stems+leaves), MPITs=*M. pruriens* Var. IITA-Benin (stems). C=carbon, N=nitrogen, P=phosphorus, K=potassium, Ca=calcium, Mg=magnesium. ADF=acid detergent fibre, NDF=neutral detergent fibre, N-ADF=nitrogen bound to ADF, HEM=hemicellulose, L=lignin, PP=polyphenols, IVDMD=*in vitro* dry matter digestibility.

**Results**

*Quality of plant materials*

TTH showed the lowest C, NDF, HEM and lignin contents, and the highest IVDMD, K, Ca and Mg values. Conversely, INDs and MPITs had the lowest N and N-ADF contents, but the highest C/N, PP/N and (L+PP)/N ratios (Table I). These materials, along with CRA, were also characterized by having

high ADF and NDF, low IVDMD and high L/N ratio. In addition, CRA had the highest lignin content and N/P ratio, but lowest PP, IVDMD and PP/N ratio, while MDEE had the highest N, P, HEM and PP contents, and the lowest ADF value and C/P ratio (Table 1).

*Decomposition and nutrient release rates*

Large dry weight losses occurred in the first 2 weeks of the experiment but subsequently slowed down and remained relatively stable after week 12 (Figure 2a). A similar pattern was observed for nutrient release (Figures 2b-f), with the exception of Ca release in three of the treatments studied (Figure 2e). Significant differences ($p<0.05$) were found among treatments as shown by SED bars in Figure 2.

Using the single exponential model to fit data was possible to find that the best fits were found for K release, while the worst fit was found for decomposition, as shown by the lowest and highest root square errors, respectively (Table 2). Decomposition rates showed that weight losses were highest in TTH and IND ($k_D$ = 0.037 and 0.034, respectively), moderate in MPBR, MPTL, CAN, MPIT, MDEE, MPITm and INDm ($k_D$ = 0.015 -0.022), and low in CRA, MPITs and INDs ($k_D$ = 0.005 -0.009). Faster N release rates ($k_N$) were found in IND, INDm and MDEE ($k_N$ = 0.048 -0.061) and lower in MPITs, CRA and MPITm ($k_N$ = 0.011 -0.028). Faster P release rates ($k_P$) were found in INDs, MDEE and MPITs ($k_P$ = 0.044-0.063), while CRA presented the lowest rate ($k_P$ = 0.015).

Table 2. Decomposition ($k_D$, $d^{-1}$ ), N ($k_N$, $d^{-1}$ ), p ($k_P$, $d^{-1}$ ), K ($k_K$, $d^{-1}$ ), Ca ($k_{Ca}$, $d^{-1}$) and Mg ($k_{Mg}$, $d^{-1}$) release rates and root square errors (Syx) obtained when fitting the treatment mean values of dry weight and nutrient remaining against time using the single exponential model (Wieder and Lang, 1982)

| Treatment | $k_D$ | $S_{yx}$ | $k_N$ | $S_{yx}$ | $k_P$ | $S_{yx}$ | $k_K$ | $S_{yx}$ | $k_{Ca}$ | $S_{yx}$ | $k_{Mg}$ | $S_{yx}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CAN | 0.019 | 18.7 | 0.045 | 15.4 | 0.033 | 15.2 | 0.097 | 2.1 | 0.008 | 4.7 | 0.022 | 11.0 |
| CRA | 0.009 | 16.9 | 0.026 | 18.4 | 0.015 | 18.6 | 0.101 | 3.5 | nd | nd | 0.013 | 8.5 |
| IND | 0.034 | 17.2 | 0.061 | 12.1 | 0.024 | 14.0 | 0.184 | 1.8 | 0.031 | 10.2 | 0.053 | 9.0 |
| MDEE | 0.019 | 18.3 | 0.048 | 15.7 | 0.044 | 14.3 | 0.116 | 3.2 | nd | nd | 0.019 | 10.4 |
| MPBR | 0.022 | 17.4 | 0.045 | 13.6 | 0.032 | 12.6 | 0.090 | 2.4 | 0.011 | 6.8 | 0.026 | 9.5 |
| MPIT | 0.020 | 18.9 | 0.039 | 15.5 | 0.029 | 14.7 | 0.099 | 3.4 | 0.012 | 9.7 | 0.028 | 10.8 |
| MPTL | 0.021 | 17.0 | 0.042 | 14.8 | 0.030 | 13.6 | 0.086 | 2.3 | 0.013 | 11.2 | 0.032 | 11.4 |
| TTH | 0.037 | 16.7 | 0.044 | 14.7 | 0.022 | 13.1 | 0.231 | 0.8 | 0.041 | 14.2 | 0.066 | 8.9 |
| INDm | 0.015 | 18.8 | 0.054 | 15.0 | 0.028 | 16.3 | 0.207 | 2.5 | 0.030 | 15.0 | 0.074 | 9.5 |
| INDs | 0.005 | 10.3 | 0.040 | 18.0 | 0.063 | 17.4 | 0.181 | 3.6 | 0.019 | 21.7 | 0.122 | 10.1 |
| MPITm | 0.017 | 18.8 | 0.028 | 18.4 | 0.032 | 17.0 | 0.129 | 2.8 | 0.009 | 7.9 | 0.027 | 11.6 |
| MPITs | 0.008 | 16.3 | 0.011 | 20.3 | 0.044 | 18.2 | 0.201 | 2.6 | nd | nd | 0.026 | 12.5 |

nd. not detennined. Treatment abbreviations are as shown in Table

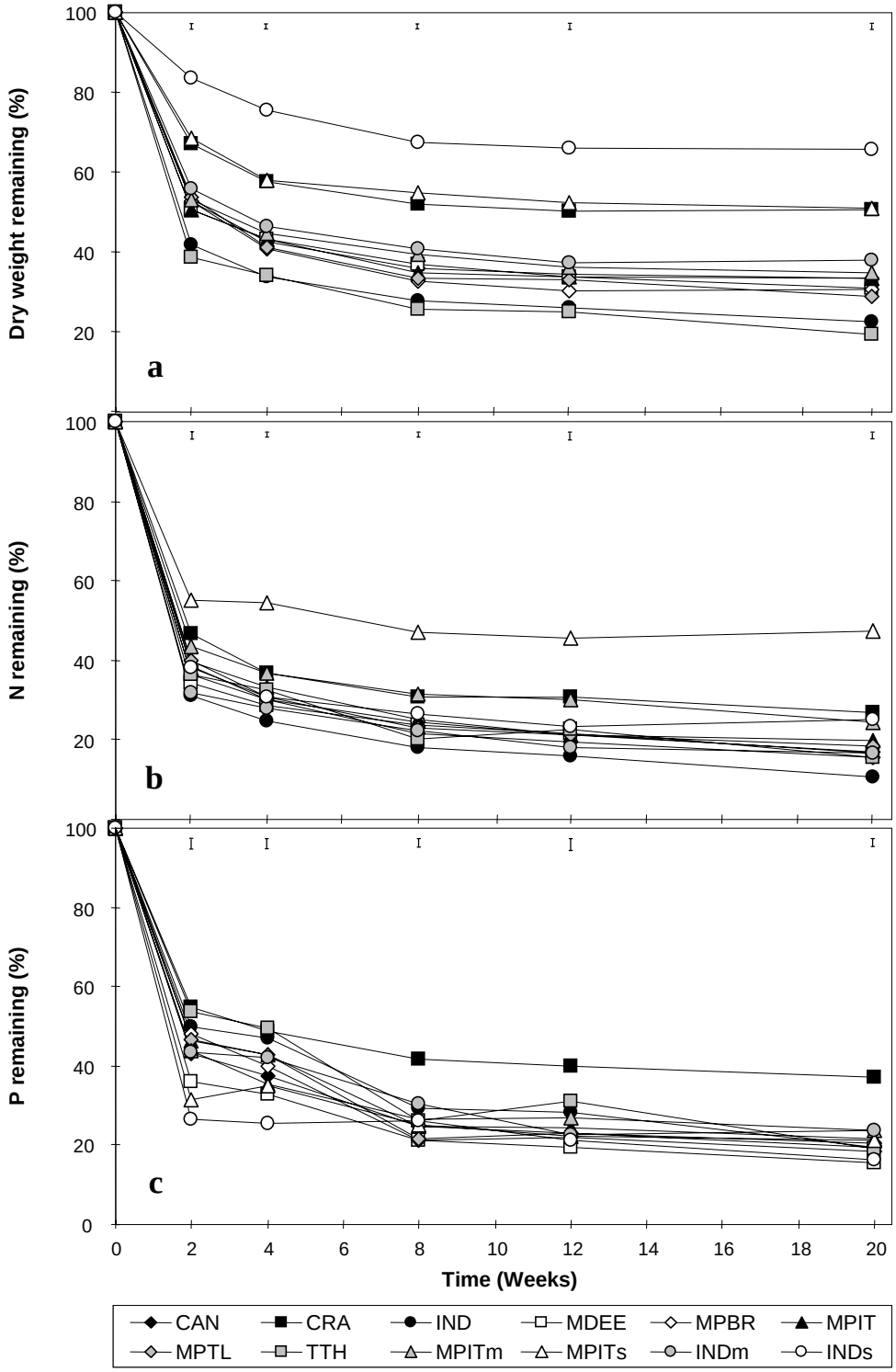


Figure 2. Dry weight loss (a), and N (b) and P (c) release patterns by 12 plant materials during 20 weeks evaluation. Vertical bars refer to standard error of the difference in means (SED) (n=4). Treatment abbreviations as shown in Table 1.

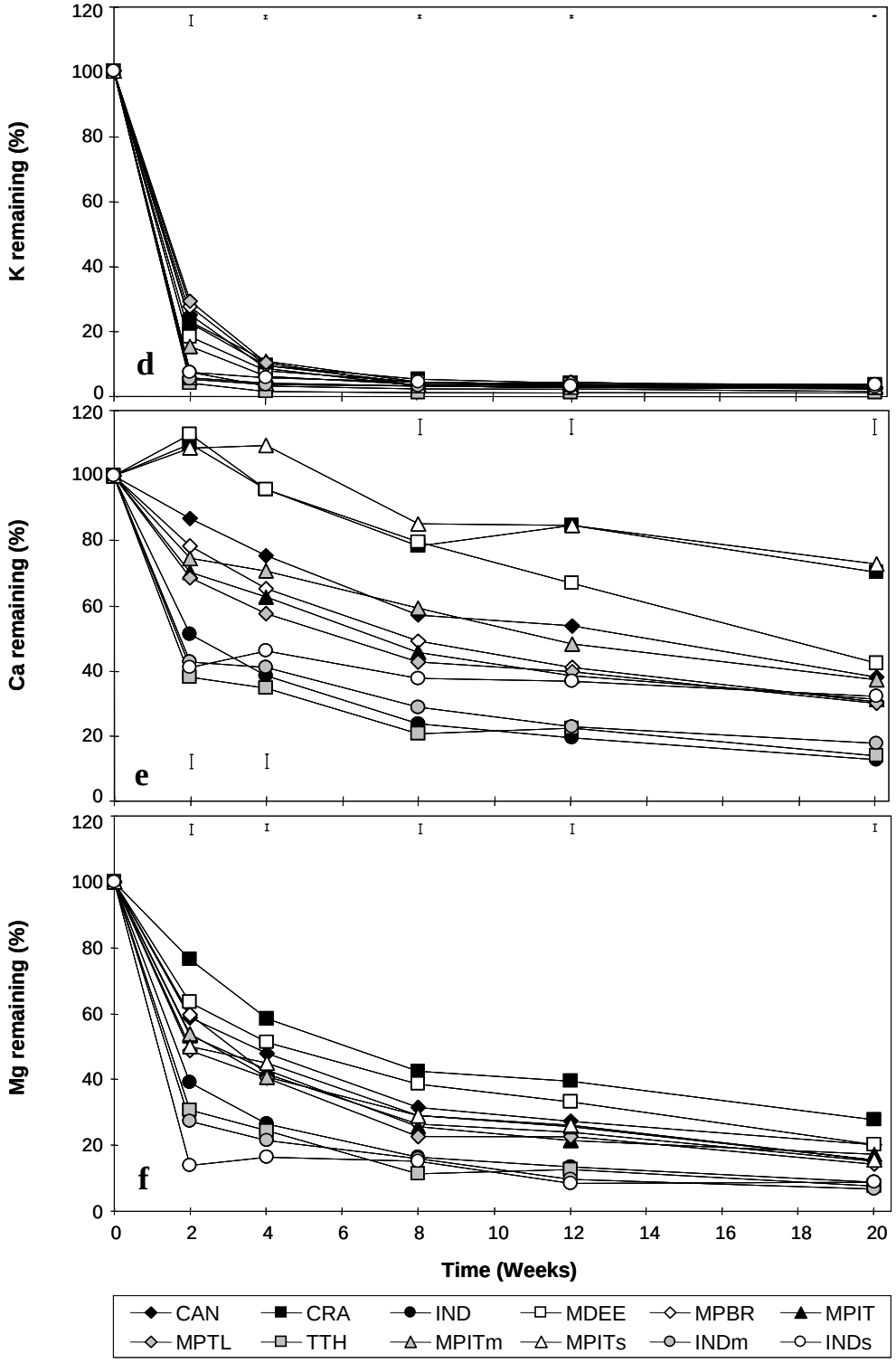


Figure 2. Contd'. K(d), Ca(e) and Mg(f) release patterns by 12 plant materials during 20 weeks evaluation. Vertical bars refer to standard error of the difference in means (SED) (n=4). Treatment abbreviations as shown in Table 1.

For K, high release rates were obtained in all treatments ($k_K \geq 0.086$). Higher K release rates were found in TTH ($k_K = 0.231$), lndigofera materials ($k_K$=0.181-0.207) and MPITs ($k_K$=0.201); while lower K release rates were found for MPTL and MPBR ($k_K$=0.086 and 0.090, respectively). Since CRA, MDEE and MPITs presented initial accumulation of Ca in their tissues, instead of net release, these treatments were not fitted with the model. IND, INDm and TTH, on the other hand, showed high rates of Ca release ($k_{Ca}$=0.030-0.041), while the rest of treatments presented relatively low rates ($k_{Ca}$=0.008- 0.019). The highest Mg release rate was found in INDs ($k_{Mg}$=0.122). IND, INDm and TTH showed intermediate rates ($k_{Mg}$=0.053-0.074), and CRA and MDEE showed the lowest rates ($k_{Mg}$=0.013 and 0.018, respectively).

*Relationships between the quality of plant materials and their decomposition and nutrient release rates*

A significant positive correlation (P<0.05) was found between decomposition rates and N, K, Ca and Mg content, and IVDMD; while a negative correlation was found for ADF, NDF, lignin and the C/N, C/P, L/N and (L+PP)/N ratios (Table 3). The quality parameters showing the stronger relationships were NDF (r = -0.959, P<0.001) and IVDMD (r = 0.871, P<0.001). These relationships could be represented by linear regressions between these quality parameters and decomposition rates (Figure 3), where $k_D$=0.057-0.0008*NDF ($R^2$=0.92) or $k_D$=-0.0381 +0.0009*IVDMD ($R^2$=0.76).

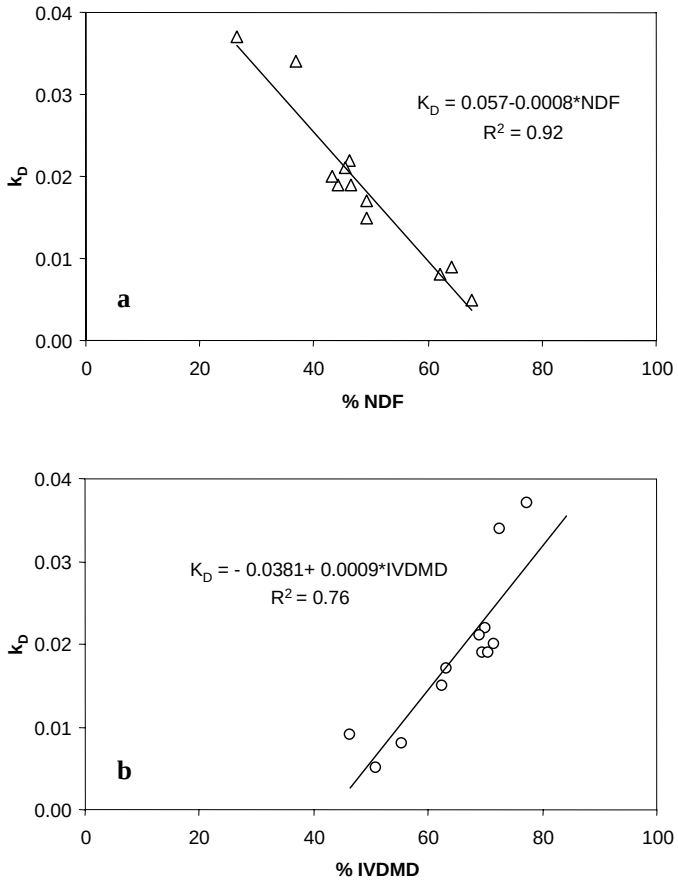


Figure 3. Linear regression between (a) neutral detergent fibre. NDF (Δ) and (b) *in vitro* dry matter digestibility, IVDMD (o) of plant materials evaluated and their respective rates of decomposition ($K_D$) (n=12).

Some quality parameters of plant materials were also significantly correlated to nutrient release rates (Table 3). While N content and IVDMD showed a positive correlation with N release rates, ADF, NDF and lignin contents and the C/N, L/N and (L+PP)/N ratios were negatively correlated. The best indicators of this process were the L/N and (L+PP)/N ratios and IVDMD as indicated by their greater correlation coefficients. For P release, significant correlations were found for Ca and N-ADF contents and the C/N, N/P and PP/N ratios. While K release rates were only correlated with C and HEM contents, Ca release rates correlated with C, K, Ca, N-ADF and HEM contents and the N/P ratio. Mg release rates only correlated with C/P ratios

Table 3. Pearson correlation coefficients (r) between chemical characteristics of organic materials and their decomposition ($k_D$), and N ($k_N$), P ($k_P$ ), K ($k_K$), Ca ($k_{Ca}$) and Mg ($k_{Mg}$) release rates

| | $k_D$ | $k_N$ | $k_P$ | $k_K$ | $k_{Ca}$ | $k_{Mg}$ |
|---|---|---|---|---|---|---|
| C | -0.365 | 0.166 | 0.161 | -0.678 * | -0.704 * | -0.312 |
| N | 0.695 * | 0.591 * | -0.539 | -0.449 | 0.041 | -0.472 |
| K | 0.596 * | 0.038 | -0.326 | 0.535 | 0.698 * | 0.083 |
| Ca | 0.738 ** | 0.355 | -0.582 * | 0.399 | 0.823 ** | 0.171 |
| Mg | 0.613 * | 0.014 | -0.438 | 0.163 | 0.330 | -0.013 |
| ADF | -0.811 ** | -0.573 * | 0.500 | 0.325 | -0.090 | 0.413 |
| NDF | -0.959 *** | -0.587 * | 0.499 | -0.108 | -0.474 | 0.121 |
| N-ADF | 0.357 | 0.098 | -0.654 * | 0.085 | 0.743 * | -0.147 |
| HEM | -0.491 | -0.172 | 0.125 | -0.753 ** | -0.801 ** | -0.459 |
| L | -0.684 * | -0.584 * | -0.051 | -0.024 | -0.153 | -0.104 |
| IVDMD | 0.871 *** | 0.592 * | -0.282 | -0.034 | 0.254 | -0.166 |
| C/N | -0.700 * | -0.574 * | 0.700 * | 0.412 | -0.084 | 0.451 |
| C/P | -0.632 * | -0.225 | 0.388 | 0.406 | 0.186 | 0.648 * |
| N/P | 0.270 | 0.470 | -0.663 * | 0.021 | 0.705 * | 0.081 |
| L/N | -0.771 ** | -0.706 ** | 0.469 | 0.321 | -0.049 | 0.247 |
| PP/N | -0.514 | -0.583 * | 0.662 * | 0.471 | -0.079 | 0.318 |
| (L+PP)/N | -0.717 ** | -0.697 * | 0.565 | 0.393 | -0.058 | 0.287 |

Quality parameters abbreviations are as shown in Table 1. *, **, ***=probabilities associated to pearson correlation coefficients at $p<0.05$, $p<0.01$ and $p<0.001$, respectively. Note: Number of data for analyses=12, except $k_{Ca}$ where n=9.

*Nutrient release by plant materials*

Total release of nutrients, from plant materials after 20 weeks (Table 4), showed that higher amounts of N were released by MDEE, MPBR, IND and TTH (124-144 kg $ha^{-1}$), while MPITs and INDs showed the lowest N release (27.6 and 41.5 kg $ha^{-1}$, respectively). The largest amount of P was released by MDEE and MPBR (11.4 and 8.9 kg $ha^{-1}$, respectively), and the lowest by CRA and INDs (3.5 kg $ha^{-1}$). TTH, on the other hand, presented the highest release of K, Ca and Mg amounts among all treatments evaluated (129.3, 112.6 and 25.9 kg $ha^{-1}$, respectively); while the lowest release of these nutrients was 48.3 kg $ha^{-1}$ K in INDs, 4.4 kg $ha^{-1}$ Ca in MPITs and 10.6 kg $ha^{-1}$ Mg in CAN.

Table 4. Estimated nutrient release (kg $ha^{-1}$) for each plant material evaluated after 20 weeks

| | Total nutrient release (kg $ha^{-1}$) | | | | |
|---|---|---|---|---|---|
| | N | P | K | Ca | Mg |
| CAN | 115.7 | 8.0 | 65.7 | 24.1 | 10.6 |
| CRA | 89.9 | 3.5 | 61.2 | 18.1 | 11.2 |
| IND | 129.8 | 5.7 | 63.6 | 57.8 | 14.8 |
| MDEE | 144.5 | 11.4 | 65.0 | 22.0 | 10.8 |
| MPBR | 130.9 | 8.9 | 51.9 | 27.7 | 17.0 |
| MPIT | 109.7 | 7.7 | 50.6 | 28.8 | 19.1 |
| MPTL | 115.9 | 7.9 | 55.7 | 32.4 | 14.3 |
| TTH | 124.4 | 7.6 | 129.3 | 112.6 | 25.9 |
| INDm | 91.1 | 4.5 | 57.1 | 42.1 | 14.2 |
| INDs | 41.5 | 3.5 | 48.3 | 19.3 | 12.4 |
| MPITm | 83.3 | 6.5 | 56.0 | 21.1 | 17.3 |
| MPITs | 27.6 | 4.7 | 67.2 | 4.4 | 12.5 |
| SED | 1.3 | 0.4 | 0.3 | 1.4 | 0.5 |

Treatment abbreviations are as shown in Table 1. SED: Standard error of the difference in means. n=4.

**Discussion**

Decomposition and nutrient release of plant materials generally followed an exponential trend. Differences among plant materials were related to tissue quality even among closely related species (i.e. *Mucuna*). Significant relationships were detected between the quality of plant materials and their respective decomposition and nutrient release rates (Table 3). NDF and IVDMD were the quality parameters most related to decomposition rates in this study (Table 3; Figure 3). Our results for NDF are consistent with results by Gupta and Singh (1981) showing that plant cell wall content is an important predictor of decomposition rates. On the other hand, although Tian et al. (1996) estimated the decomposability of plant residues by an 'in vivo' ruminant nylon-mesh bag assay, the use of IVDMD as an index related to decomposition in the field has not been reported elsewhere. The highly significant ($P<0.00l$) correlations obtained in this study between NDF and IVDMD, and plant decomposition suggests that lab-based NDF or IVDMD tests could be used as surrogates for decomposition of plant tissue. This finding could be of practical importance for screening of plant materials for different farm uses. Such tests can save time and reduce variability associated with decomposition studies in the field. Other indices studied which have already shown potential in the literature include N and lignin content, and the C/N, L/N and (L+PP)/N ratios because of their correlation with decomposition rates (see Mafongoya et al., 1998).

The rates of nutrient release were also related to the chemical composition of the plant materials studied as shown in Table 3. Higher correlations were found for N release and the L/N and (L+PP)/N ratios, for P release and the C/N and N/P ratios, for K release and the C and HEM contents, for Ca release and Ca and HEM content, and for Mg release and the CIP ratio. Previous studies have shown that lower N release rates from plant materials were related to high L/N ratios (Singh et al., 1999; Thomas and Asakawa, 1993) and (L+PP)/N (Barrios et al., 1997; Handayanto et al., 1994; Lehmann et al., 1995; Thomas and Asakawa, 1993; Vanlauwe et al., 1997b) for several species. P mineralization rates from decomposing plant materials have been correlated to N/P ratios (Palm and Sanchez, 1990) and L/N and C/N ratios (Singh et al., 1999) and this may be related to different decomposer communities developing on plant materials of different quality. Ca release, on the other hand, has been related to cell wall

constituents (Attiwill, 1976; Luna- Orea et al., 1996) and polyphenols (Lehmann et al., 1995). Mg release, also, has been related to cell wall constituents (Luna-Orea et al., 1996) and to initial Mg content in the tissues (Lehmann et al., 1995). Nevertheless, the high potential for K leaching from plant tissues is probably responsible for the limited reports in the literature of significant relationships between plant quality indices and K release as suggested by Tian et al. (1992).

High initial nutrient contents in plant materials can be responsible for high decomposition and net nutrient release because of enhanced microbial growth and activity; however, considerable contents of structural polysaccharides like HEM and lignin, can reduce the effect of initial nutrient content because of physical protection of other cell constituents from microbial attack (Chesson, 1997; Mafongoya et al., 1998). Polyphenols in plant tissues can also reduce decomposition and nutrient release by binding of cell wall constituents and proteins (i.e. Vanlauwe et al., 1997b). The type of polyphenols and their relative content in plant tissues is also important to consider when studying N mineralization from plant materials because different polyphenols have different chemical activities. Earlier studies indicate that the method of drying of legume plant materials has an effect on type and concentration of polyphenols. It has been shown that ovendrying can reduce soluble polyphenol concentrations compared to airdrying (Mafongoya et al., 1997).

Our total polyphenol values are generally higher than those reported for other tropical plant materials as reviewed by Mafongoya et al. (1998). Higher values may be a result of methodological differences. While higher tissue: solvent ratios may not extract all polyphenols (Constantinides and Fownes, 1994) our modified extraction method using a greater proportion of methanol (70% ) compared to the Anderson and Ingram (1993) standard methodology (50%), as well as the addition of formic and ascorbic acids as antioxidants may have led to higher total polyphenol values. In addition, plants growing in soils with poor N availability, as in the case of volcanic-ash soils, can result in higher concentrations of polyphenols than those growing in more fertile soils (Palm et al., 2001).

Decomposition and nutrient release trends for each treatment (Table 2; Figure 2) suggest that these processes are related. Significant correlations ($P<0.05$) were found between decomposition and N release ($r = 0.596$), K and Ca release ($r = 0.912$) and K and Mg release ($r = 0.636$) (data not shown). Significant correlations were also found by Singh et al. (1999) between dry weight loss and N release rates. Lehmann et al. (1995), on the other hand, found significant correlations among dry matter, N and Ca losses, but no connection between Mg or K with N and dry matter losses.

Although decomposition and nutrient release rates found in this study were sometimes higher than those reported by other researchers using similar methodology they fall within the range observed for tropical zones (Handayanto et al., 1994; Mafongoya et al., 1998; Mwiinga et al., 1994; Palm and Sanchez, 1990; Thomas and Asakawa, 1993; Tian et al., 1992). The high rates found in this study could be linked to the intrinsic characteristics of the materials used (species, age, quality, etc.) but also to the climatic conditions (i.e. high moisture and favourable temperature) during the first weeks of the experiment (Figure 1). It is well known that temperature and precipitation can influence the pattern and rate of decomposition of plant materials (Gupta and Singh, 1981).

Nitrogen release rates in this study were higher than those of dry weight loss (Table 2), and this is consistent with previous studies by Mwiinga et al. (1994), Palm and Sanchez (1990), Schroth et al. (1992) and Tian et al. (1992). Phosphorus release rates were usually higher than decomposition rates with the exception of TTH and IND. This could be interpreted as potential for a more gradual P release to the soil from these plant materials. Although K and Mg release rates were higher than decomposition rates, Ca release rates were lower for CRA, MDEE and MPITs as they presented initial immobilisation. Ca immobilisation has been previosuly reported by other authors (Lehmann et al., 1995; Palm and Sanchez, 1990; Schroth et al., 1992) and generally explained by the accumulation of Ca by funghi on decomposing residues.

Plant parts of the same species often show different patterns and rates of decomposition and nutrient release. In our study, plant leaves showed faster decomposition and N release rates than mixtures of leaves and stems, and these mixtures were faster than stems evaluated. In contrast, P release showed the opposite trend (Table 2). For K, Ca and Mg release, however, no consistent trends were found. These

findings suggest that potential nutrient contributions by green manures would be overestimated when rates are based on leaves while their application in the field is generally as a mixture of leaves and stems. Interactions among plant parts could affect expected patterns of decomposition and nutrient release. According to Mafongoya et al. (1998), if decomposition and nutrient release patterns from a mixture of plant materials reflect the weighted averages of the individual components no interactions occurred; if this is not the case, interactions may have taken place. Interactions between stems and leaves have been reported before and explained as a result of high soluble C in the stems, which caused immobilization of N from leaf tissues (Quemada and Cabrera, 1995).

Knowledge of decomposition patterns and rates for different plant materials available on-farm is important for decision making about their optimal use. However, the total amount of nutrients contained in plant materials is critical (Palm, 1995). Results in Table 4 show that the application of dry leaf materials from all species (except CRA) at a rate of 3.75 Mg $ha^{-1}$ can release more than 109 kg $ha^{-1}$ of N and 5 kg $ha^{-1}$ of P, and more than 50, 22 and 10 kg $ha^{-1}$ of K, Ca and Mg, respectively, after 20 weeks of surface application to the soil. Provided that an annual crop like maize can extract close to 80 kg $ha^{-1}$ of N, 18 kg $ha^{-1}$ of P, 66 kg $ha^{-1}$ of K and 15 kg $ha^{-1}$ of Ca and 10 kg $ha^{-1}$ of Mg from the soil (Palm, 1995) we could argue that these leaf materials can potentially supply a considerable proportion of nutrient demand by maize plants. Nevertheless, not all these nutrients would be available to the crop due to potential nutrient losses (denitrification, leaching, etc.), nutrient immobilization by the microbial biomass or simply by incorporation into recalcitrant soil organic matter pools (Vanlauwe et al., 1997a). Our results can be used as indicators of the potential amount and rate of nutrient supply by available options tested in order to improve the nutrient management efficiency of green manure systems in farmer fields. There is great interest in improving synchrony between nutrient release from plant materials and demand by the crop in order to minimize potential nutrient losses and increase nutrient recovery by the crop (Myers et al., 1994).

## Conclusions

The chemical characteristics of plant materials used as green manures play a fundamental role in the decomposition and nutrient release processes. The judicious management of organic nutrient resources as green manures is dependent on using the right amount and quality of plant material, at the right time. Results from this study are useful to tropical hillside farmers for management of on-farm organic resources based on the potential size of the nutrient additions provided by plant materials as well as timing of nutrient additions to meet crop demand. In order to avoid false expectations about the nutrient supplying capacity of plant materials these should closely represent farmer options. The usefulness of different plant quality indices was assessed as they related to decomposition (i.e. NDF, IVDMD) or nutrient release (i.e. (L+PP)/N for N release). Their utility for screening of potential green manure germoplasm was also discussed.

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# Nitrogen mineralization and crop uptake from surface-applied leaves of green manure species on a tropical volcanic-ash soil

Juan Guillermo Cobo[1,2], Edmundo Barrios[1], Donald C. L. Kass[2] and Richard Thomas[1]
[1] Centro Agronómico Tropical de Investigación y Enseñanza ( CATIE ), Turrialba, 7 170, Costa Rica.
[2] Centro Internacional de Agricultura Tropical (CIAT), AA 67 13, Cali, Colombia.

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## Abstract

Leaves of nine green manure (GM) species were surface applied to a tropical volcanic-ash soil at a rate of 100 kg N $ha^{-1}$ in order to evaluate their N-fertilizer value in a glasshouse experiment. GM treatments were compared to urea at two rates, 50 kg N $ha^{-1}$ (FN50) and 100 kg N $ha^{-1}$ (FN100), and to a control with no fertilizer application (FN0). Two weeks after treatment application, upland rice seedlings were sown in order to conduct N uptake studies. Soil volumetric moisture content was maintained close to 50%. In general, soil showed an initial increase in inorganic N followed by a rapid decline with time. After 2 weeks of evaluation FN100, FN50 and leaves of *Mucuna pruriens* var. Tlaltizapan and *Indigofera constricta* presented higher values of inorganic N (157-109 mg N $kg^{-1}$ soil); while, FN0 and leaves of *Mucuna deerengianum, Cratylia argentea* and *Calliandra calothyrsus* presented lower values (75-89 mg N $kg^{-1}$ soil). N recovery by rice, at 20 weeks after planting, was highest for FN100 (59.9%) followed by *Canavalia brasiliensis* (54.6%), *Calliandra calothyrsus* (47.4%) and *M. pruriens* var. IITA-Benin (32.4%); while, *M. pruriens* var. Tlaltizapan, FN50, *Tithonia diversifolia* and *I. constricta* presented lower N uptake (13-20%). Significant relationships were found between some quality parameters of GM evaluated (i.e. total N, fibers, lignin and polyphenol content), soil N availability and rice N uptake. These results suggest that GM that decomposed and released N slowly resulted in high N uptake when they were used at pre-sowing in a tropical volcanic-ash soil.

**Keywords:** Mineralization - Nitrogen - Organic fertilizers - Plant nutrition - Plant tissue quality

## Introduction

N is usually the most limiting nutrient in tropical soils and considerable efforts have been made to develop alternative or complementary cost-effective practices to N fertilization (Sánchez 1981). Green manures (GM) are considered among these alternative management practices since they can lead to increased soil N availability (Giller and Wilson 1991). A predictive knowledge of GM mineralization patterns, however, is needed for improved nutrient use efficiency in agroecosystems (Constantinides and Fownes 1994; Kass et al. 1997; Giller and Cadisch 1997). While very fast N mineralization rates can be responsible for considerable N losses through leaching, denitrification or volatilization, when N mineralization is very slow little N availability can lead to limitations in crop growth (Myers et al. 1994).

The best way to synchronize soil N availability to crop demand is by managing the quantity, quality, timing and placement of plant materials added to the soil (Palm 1995; Mafongoya et al. 1998). The chemical composition of plant materials used (or quality) is one of the most important factors that affect N mineralization rates (Swift et al. 1979; Heal et al. 1997). Plant materials poor in N have limited use in the short term (Constantinides and Fownes 1994) since low N content limits the growth of microorganisms involved in decomposition. The C/N ratio is a useful guide to predict N mineralization patterns. According to Frankenberger and Abdelmagid (1985) C/N ratios greater or equal to 19 limit N availability. Nevertheless, the detection of N mineralization in plant materials with C/N ratios >100 suggest that C compounds such as lignin (L), or polyphenols (PP) can be largely regulating this process

(Thomas and Asakawa 1993). According to Palm and Sánchez (1991), the PP content in tropical legumes can play a greater role in N mineralization than N content or the L/N ratio. This is consistent with Tian et al. (1992), who showed that plant materials with low contents of N, L and PP decomposed and mineralized N rapidly. Furthermore, Handayanto et al. (1994, 1995) and Barrios et al. (1997) also found that the (L+PP)/N ratio significantly correlated with N mineralization.

This study had the following objectives: (1) to evaluate the effect of foliage from nine GM on soil N availability in a tropical volcanic-ash soil, (2) to determine N uptake by an indicator crop (upland rice), and (3) to relate the quality of plant materials evaluated to both their N supplying capacity and the N uptake by the indicator crop.

## Materials and methods

*Site description*

A glasshouse study was carried out at the Centro Internacional de Agricultura Tropical (CIAT) located at 3°30'N 76°21'W and 965 masl. Glasshouse mean temperature (21°C) and relative humidity (67%) were maintained constant during the whole period of study.

*Description of GM species and soil*

GM were selected on the basis of their adaptation to the tropical hillside environment and to volcanic-ash soils, and their differences in plant chemical composition (plant tissue quality). These species included: *Calliandra calothyrsus* Meissn. (CAL), *Canavalia brasiliensis* Mart. ex Benth. (CAN), *Cratylia argentea* Benth. (CRA), *Indigofera constricta* Rydb. (IND), *Mucuna deerengianum* (Bort.) Merr. (MDEE), *Mucuna pruriens* (Stick.) DC. var. IITA-Benin (MPIT), *M. pruriens* (Stick.) DC. var. Tlaltizapan (MPTL), *M. pruriens* (Stick.) DC. var. Brunin (MPBR) and *Tithonia diversifolia* (Hems.) Gray (TTH). Foliage of herbaceous plants (CAN and Mucunas) and TTH was harvested at flowering, while foliage of trees (CAL, CRA and IND) was harvested 6 months after the last pruning.

N concentrations in GM leaves ranged from 2.65% in CAL to 4.63% in MDEE (Table 1). CAL had the highest concentrations of C, acid detergent fiber (ADF) and PP, and highest C/N, L/N, PP/N and (L+PP)/N ratios; while TTH had the lowest contents of C, neutral detergent fiber (NDF), hemicellulose (HEM) and L, as well as the lowest C/N, L/N and (L+PP)/N ratios. IND also had low NDF and HEM contents. CRA had the highest NDF and L contents, and the lowest PP value and PP/N ratio.

The volcanic-ash soil used in the experimental pots was collected from the top 20 cm of an Oxic Dystropept (USDA 1998) located in the San Isidro farm (Pescador, Cauca, Colombia) and later passed through a 2-mm mesh. Soil characteristics included: pH ($H_20$) 5.1, 50 g C $kg^{-1}$, 3 g N $kg^{-1}$, 12 mg $NH_4^+$-N $kg^{-1}$, 42 mg $NO_3^-$-N $kg^{-1}$, and 1.1 and 2.5 cmol $kg^{-1}$ for Al and Ca, respectively. Soil bulk density was 0.8 g $cm^{-3}$ and P availability was low (4.6 mg Bray-P $kg^{-1}$) as a result of a high allophane content (52-70 g $kg^{-1}$) and high P sorbing capacity (Gijsman and Sanz 1998). Triple super phosphate was added to the soil at an equivalent rate of 50 kg $P_2O_5$ $ha^{-1}$ before establishing the experiment.

The experiment was a randomized complete block design with four replicates. The leaves harvested from selected GM were thoroughly mixed and air and oven dried (55±5°C). Dry plant materials were then fragmented into small pieces (<1.5 cm long) and surface applied to 1.5 kg volcanic-ash soil contained in plastic pots at a rate of 100 kg N $ha^{-1}$. Three additional treatments were established: urea applications of 50 and 100 kg N $ha^{-1}$ (FN50 and FN100, respectively) and an unfertilized treatment (FN0) as a control.

Soils were capillary-wetted by placing pots on water-filled plastic saucers (Handayanto et al. 1994) so that volumetric moisture content was maintained close to 50%, while leaching was prevented. Fifteen days after plant materials were added five upland rice seeds (*Oryza sativa* L. var. Oryzica savana 10) were sown in each pot at 1 cm depth. Two weeks after germination rice plants were thinned to two plants per pot.

Table 1. Quality parameters for initial plant materials added to soil. ADF Acid detergent fiber, NDF neutral detergent fiber, HEM hemicellulose, L lignin, PP polyphenols. CAL *Calliandra calothyrsus*, CAN *Canavalia brasiliensis*, CRA *Cratylia argentea*, IND *Indigofera constricta*, MDEE *Mucuna deerengianum*, MPBR *Mucuna pruriens* var. Brunin, MPIT *Mucuna pruriens* var. IITA-Benin, MPTL *Mucuna pruriens* var. Tlaltizapan, TTH *Tithonia diversifolia*

| | C | N | ADF | NDF | HEM | L | PP | C / N | L / N | PP / N | (L+PP) / N |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Treatment | ---------- % ---------- | | | | | | | | | | |
| CAL | 49.4 | 2.65 | 43.7 | 63.2 | 19.4 | 14.50 | 18.44 | 18.6 | 5.47 | 6.96 | 12.43 |
| CAN | 44.5 | 3.71 | 33.5 | 44.1 | 10.6 | 6.52 | 8.42 | 12.0 | 1.76 | 2.27 | 4.03 |
| CRA | 44.3 | 3.28 | 42.6 | 64.2 | 21.6 | 17.72 | 4.78 | 13.5 | 5.40 | 1.46 | 6.86 |
| IND | 44.8 | 3.87 | 28.1 | 36.8 | 8.7 | 6.88 | 8.59 | 11.6 | 1.78 | 2.22 | 4.00 |
| MDEE | 45.5 | 4.63 | 24.0 | 46.6 | 22.6 | 6.86 | 9.28 | 9.8 | 1.48 | 2.00 | 3.49 |
| MPBR | 45.6 | 4.14 | 25.6 | 46.2 | 20.6 | 5.54 | 8.28 | 11.0 | 1.34 | 2.00 | 3.34 |
| MPIT | 45.0 | 3.65 | 27.8 | 43.1 | 15.3 | 6.10 | 8.92 | 12.3 | 1.67 | 2.44 | 4.12 |
| MPTL | 45.1 | 3.79 | 28.9 | 45.6 | 16.6 | 6.26 | 8.89 | 11.9 | 1.65 | 2.35 | 4.00 |
| TTH | 38.8 | 3.93 | 25.2 | 26.6 | 1.4 | 4.56 | 8.65 | 9.9 | 1.16 | 2.20 | 3.36 |

*Sampling and chemical analyses*

All treatments were evaluated at 2, 4, 8, 12 and 20 weeks after initiating the experiment by carefully removing the remaining decomposing material and sampling the whole soil from the pots. Two samples (20 g) were taken for moisture determination (105°C until constant weight) and the extraction of inorganic N. Soil inorganic N was extracted by shaking the 20 g of soil in 100 ml of 2 M KCl on an end-to-end shaker at 150 r.p.m. for 1 h, and filtering through Whatman no.1 filter paper, previously washed with deionized water and 2 M KCl. The resulting soil extracts were then analyzed colorimetrically with an autoanalyzer (Skalar Sun Plus) to determine $NH_4^+$-N and $NO_3^-$-N contents, and expressed on a dry soil basis (CIAT 1993).

At 20 weeks, the fresh weight of aboveground biomass (leaves+stems and panicles) and roots was determined and they were later air and oven dried (55±5°C) for dry weight determination and chemical analysis. Subsamples of each plant material evaluated were analyzed chemically for C, N, ADF, NDF, HEM, L and PP content. In addition, rice plant components sampled at 20 weeks (leaves+stems, panicles and roots) were analyzed for their N content. Dry plant tissues were ground and sieved (1 mm) before analysis. C and N were determined by colorimetry using an autoanalyzer (Skalar Sun Plus). ADF, NDF and L were determined using modified techniques of Van Soest and Vine (Harris 1970) and PP with a modified Anderson and Ingram (1993) method that uses 70% methanol, 0.5% formic acid and 0.05% ascorbic acid as extractant (Telek 1989), the Folin-Ciocalteu reagent and tannic acid as standard. Hemicellulose was calculated by the difference between NDF and ADF.

*Calculations and statistical analysis*

Plant N uptake (milligrams) was calculated by multiplying tissue N contents by tissue dry weights. In order to assess N use efficiency as a function of GM and fertilizer treatments, plant N uptake was expressed as a percent of initial N applied (N recovery) using the following calculation:

$$\text{N recovery (\%)} = \frac{\text{Plant N uptake in treatment} - \text{Plant N uptake in control}}{\textit{Initial N added}} \times 100$$

All variables evaluated in soil and rice were subjected to ANOVA. Whenever necessary, variables were root square-transformed to normalize data and homogenize variance. SEs of the difference in means (SED) were calculated from the ANOVA and reported with the data. Correlation analyses were conducted

to assess the relationships between quality parameters of GM and soil available N and rice N uptake. SAS (SAS Institute 1989) was used for all statistical analysis.

**Results and discussion**

*Soil N availability*

Although fertilized controls (FN100 and FN50) generally produced the highest values of soil available N, considerable quantities of inorganic N were also recovered from soil, after GM application (Fig. 1), suggesting the potential of these plant materials as biofertilizers, as discussed by Palm (1995), Kass et al. (1997), Mafongoya et al. (1998) and Aulakh et al. (2000). GM, however, differed in their impact on soil N availability. Plant materials like MPTL and IND showed high initial soil inorganic N, while MDEE, CRA and CAL had a reduced initial impact on soil N availability, presumably as a result of their higher rates of decomposition and N release (Table 2). A "priming effect" on soil organic matter (SOM) mineralization, as a result of N additions (as mineral or organic fertilizers), could also be occurring (Lovell and Hatch 1998). Nevertheless, SOM mineralization in volcanic-ash soils is lower than expected due to the protection of SOM particles in these soils (Gijsman and Sanz 1998).

Table 2. Estimated decomposition and N release rates ($d^{-1}$) for initial plant materials added to soil. Data for rate calculations obtained from a 20 weeks litterbag field experiment conducted in Pescador (Cauca). A single exponential model was used to fit the data. (Cobo et al., 2002). ND Not determined; for other abbreviations see Table 1.

| Treatment | Decomposition rate | N release rate |
|---|---|---|
| CAL | ND | ND |
| CAN | 0.019 | 0.045 |
| CRA | 0.009 | 0.026 |
| IND | 0.034 | 0.061 |
| MDEE | 0.019 | 0.048 |
| MPBR | 0.022 | 0.045 |
| MPIT | 0.020 | 0.039 |
| MPTL | 0.021 | 0.042 |
| TTH | 0.037 | 0.044 |

Soil $NH_4^+$ levels significantly increased ($P<0.01$) at week 2, especially in FN100 (111.5 mg N $kg^{-1}$ soil) and FN50 (81 mg N $kg^{-1}$ soil), and diminished to almost zero by week 12. Among GM treatments, IND showed the highest value of soil $NH_4^+$ (76.2 mg N $kg^{-1}$ soil) and CAL the lowest (47.7 mg N $kg^{-1}$ soil). Conversely, soil $NO_3^-$ values after 2 weeks were lower than starting values (i.e. 42 mg N $kg^{-1}$ soil), except for FN100, but subsequently, at week 4, there was an overall increase in soil $NO_3^-$, especially in TTH (87.5 mg N $kg^{-1}$ soil), so that by week 8 soil $NO_3^-$ values had surpassed those of $NH_4^+$. Following this peak, soil $NO_3^-$ values also decreased to values close to zero.

Total inorganic N [$(NH_4^+ + NO_3^-)$-N)] increased in all treatments during the first 2 weeks of the experiment (Fig. 1). This effect was significantly higher ($P<0.01$) in FN100 (157.1 mg N $kg^{-1}$ soil) and FN50 (116 mg N $kg^{-1}$ soil), while in FN0 we found the lowest value (75 mg N $kg^{-1}$ soil). Soil inorganic N then followed a declining trend with some treatments showing slightly lower values than FN0 during certain periods (i.e. CAL, CRA and IND at week 4, and MDEE at 8 weeks). This reduction of inorganic N after 4 weeks probably could be the result of rice N uptake and soil N losses, as discussed by Aulakh et al. (2000). Potential soil N losses could be mainly attributed to denitrification since free drainage was prevented by the irrigation system used, and N volatilization is expected to be low in acid soils

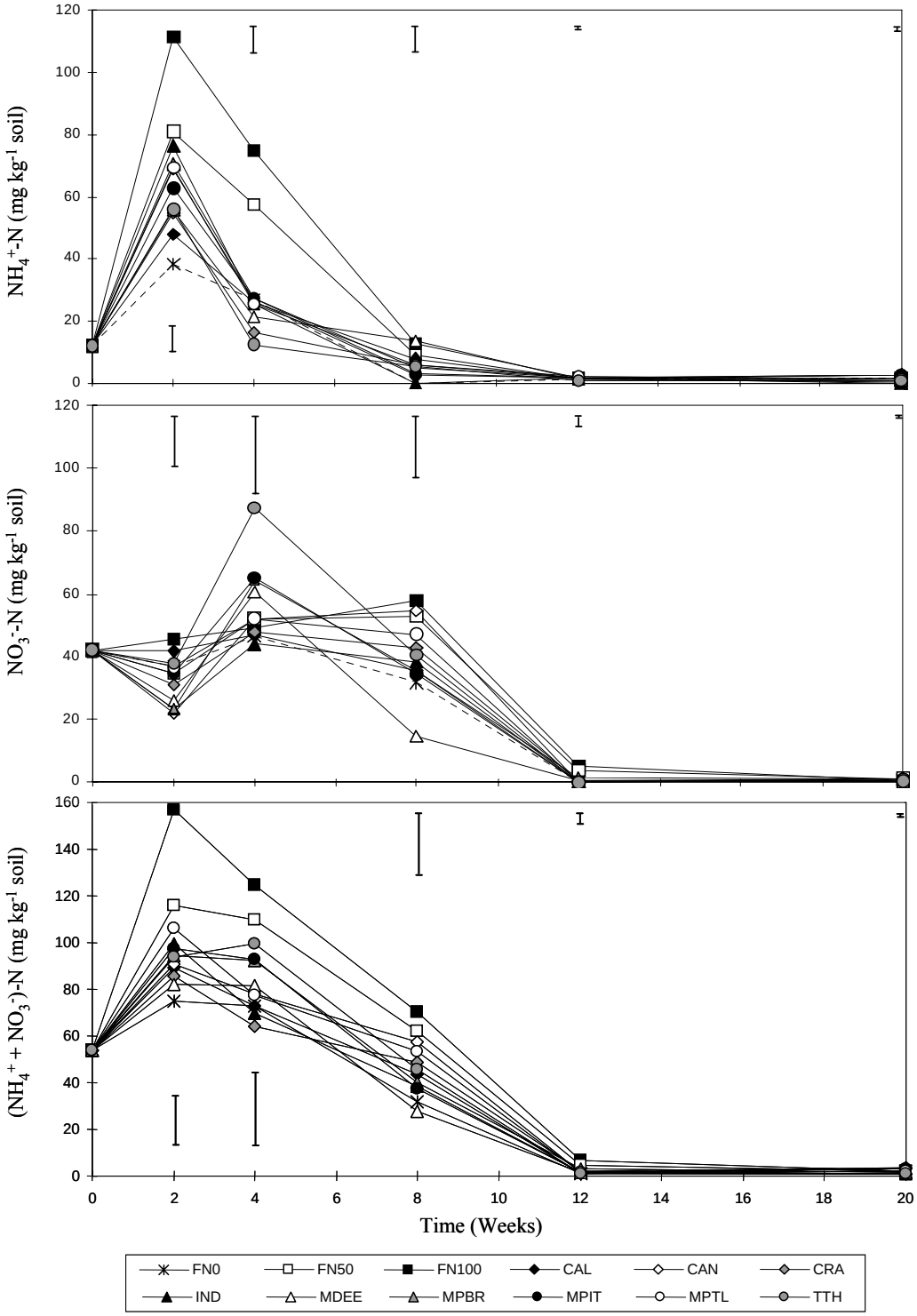


Fig. 1. Soil $NH_4^+$, soil $NO_3^-$ and total soil inorganic N during 20 weeks of evaluation. Data are the mean of four repetitions. Vertical bars indicate SE of the difference in means (SED). FN0 Control with no fertilizer application, FN50 urea application 50 kg N ha$^{-1}$, FN100 urea application 100 kg N ha$^{-1}$, CAL *Calliandra calothyrsus*, CAN *Canavalia brasiliensis*, CRA *Cratylia argentea*, IND *Indigofera constricta*, MDEE *Mucuna deerengianum*, MPBR *Mucuna pruriens* var. Brunin, MPIT *Mucuna pruriens* var. IITA-Benin, MPTL *Mucuna pruriens* var. Tlaltizapan, TTH *Tithonia diversifolia*

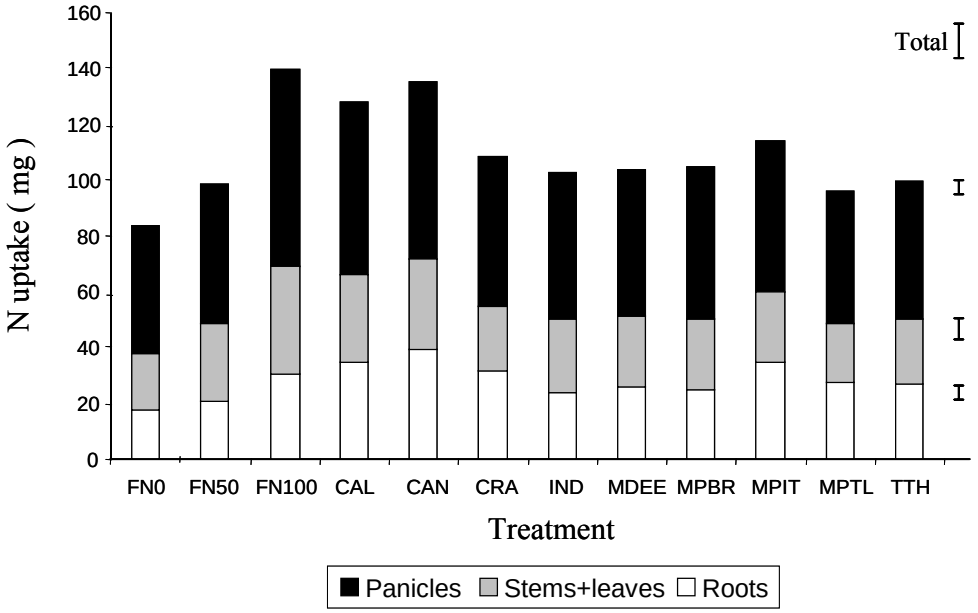


Fig. 2. Rice N uptake at 20 weeks as affected by green manure and fertilizer treatments. Data are the mean of four repetitions. Vertical bars indicate SED for each plant component. For abbreviations, see Fig. 1

(Fassbender and Bornemiza 1987). Denitrification may have occurred at microsites because of experimental soil moisture content (50%). On the other hand, the observation that some treatments had lower inorganic N values than FN0 at certain sampling dates suggests N immobilization by soil microorganisms. However, these events were transient and probably due to chemical changes of plant materials to critical levels over time (i.e. higher C/N and L/N ratios).

*Rice N uptake*

At 20 weeks, plants in FN100, CAL, CAN, MPIT and CRA showed significantly ($P<0.01$) higher N content than FN0 (83 mg) (Fig. 2). N uptake by rice was highest in FN100 (140 mg), but it was not significantly different from that in CAL (128 mg), CAN (135 mg) and MPIT (114 mg). This observation indicates that these GM could have considerable potential as a source of N to crops in tropical volcanic-ash soils. N uptake in the other treatments was statistically similar to N uptake in FN50 (98 mg).

A more detailed analysis showed significantly higher ($P<0.05$) leaves+stems and panicle N content in FN100, CAL and CAN than rice plants in FN0. FN100, CAL, CAN, MPIT and CRA also showed significantly higher ($P<0.05$) root N content than the control. A similar trend was found for plant dry weight. Both plant weight and N uptake were strongly correlated (data not shown).

Expressing N uptake as a percent of initial N applied we observed that N recovery by rice plants ranged from 13.1% in MPTL up to about 60% in FN100. N recovery in IND was 20.1% while in CAL it was 47.4%. Plants in FN50 only recovered 15.6% of the N initially applied (Table 3). Likewise, Fox et al. (1990) report a range of 11.2% (*Cassia rotundifolia*) to 85.1% (Fertilized control) for N recovery by sorghum receiving different legume residues. Aulakh et al. (2000), in a field study using *Vigna unguiculata* and *Sesbania aculeata* as GM, reported N recoveries of 60-79% by rice, but 11-16% by wheat. Additionally, our values for *C. calothyrsus* (47.4%) were higher than those reported by Handayanto et al. (1995) in maize which ranged between 4.2% and 23.1%. The differences in N recovery

values among studies are probably due to differences in the methodology used (i.e. soil and climate conditions, indicator crop, GM type, form and rate of application, N recovery procedures and evaluation period).

Table 3. N recovery by rice from different green manures (GM) and fertilizer treatments after 20 weeks of evaluation. Data are the means of four repetitions. SED SE of the difference in means, FN50 urea application 50 kg N ha-1, FN100 urea application 100 kg N ha-1; for other abbreviations see Table 1

| | Treatment | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| N Recovery | FN50 | FN100 | CAL | CAN | CRA | IND | MDEE | MPBR | MPIT | MPTL | TTH |
| (%) | 15.6 | 59.9 | 47.4 | 54.6 | 26.0 | 20.1 | 21.4 | 22.6 | 32.4 | 13.1 | 17.0 |
| SED | 13.4 | | | | | | | | | | |

Relationships among plant tissue quality, soil N availability, and rice N uptake

Significant relationships were found between plant quality parameters, soil N availability and rice N uptake (Table 4). Fiber and L content, and C/N, L/N and (L+PP)/N ratios showed a negative relationship with soil $NH_4^+$-N and total inorganic N [($NH_4^+$+$NO_3^-$)-N)] at 2 and 8 weeks respectively. On the other hand, N and ADF content, and C/N, PP/N and (L+PP)/N ratios correlated to rice N uptake at 20 weeks (Table 4). These results are in agreement with those found by Palm and Sánchez (1991) who observed that 1 and 8 weeks after application of legume leaves to soil, soil inorganic N was significantly correlated with the PP content and the PP/N ratio of the plant material, while the L/N ratio only correlated with soil inorganic N at week 8. On the other hand, Constantinides and Fownes (1994) suggested a significant relationship between N, L, PP, L/N, PP/N, (L+PP)/N and N mineralization from a 16-week incubation experiment using legume and non-legume leaves. Handayanto et al. (1995) also found a significant correlation between N mineralization rates of *C. calothyrsus* and *Gliricidia sepium* plant materials with their contents of N, PP, their polyphenol protein binding capacity, and the C/N, PP/N, L/N and (L+PP)/N ratios.

Data for soil N availability, N uptake and GM quality, and relationships found suggest that fast-decomposing, high-quality plant materials (e.g. IND) generated high short-term soil N availability but low rice N uptake; while slow-decomposing, lower quality plant materials (e.g. CAL) had a longer-term impact, which resulted in greater N uptake by rice. Reduced performance of higher quality materials could be attributed to the limited synchrony between N mineralization from GM applied and crop uptake. This may be partly explained by the limited effective root system of rice plants before 4 weeks (Fernández et al. 1985), thus missing part of the observed flush of inorganic N at 2 weeks. Therefore, N losses would be expected in treatments generating short-term soil N availability. Pre-sowing surface application of low-quality plant materials (e.g. CAL) and/or surface application of high-quality plant materials (e.g. IND) during periods of high crop N demand (i.e. flowering) could be seen as alternatives for resource poor farmers cropping tropical volcanic ash soils. These practices would increase the agroecosystem nutrient use efficiency and synchrony by reducing potential nutrient losses and increasing N recovery by the crop.

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Table 4. Pearson correlation coefficients and associated probabilities (in parenthesis), according to linear correlation analysis between quality parameters of GM materials added to soil, soil N availability and rice N uptake (n=36). NS Not significant; for other abbreviations see Table 1

| Quality parameters of GM materials | Soil N availability | | Rice N uptake |
|---|---|---|---|
| | $NH_4^+$-N [a] | ($NH_4^+$ + $NO_3^-$)-N [b] | |
| N | NS | NS | -0.336 ( 0.045 ) |
| ADF | -0.355 ( 0.033 ) | -0.354 ( 0.034 ) | 0.352 ( 0.035 ) |
| NDF | -0.335 ( 0.046 ) | -0.342 ( 0.041 ) | NS |
| L | -0.417 ( 0.011 ) | -0.372 ( 0.026 ) | NS |
| C/N | -0.341 ( 0.042 ) | NS | 0.366 ( 0.028 ) |
| L/N | -0.447 ( 0.006 ) | -0.344 ( 0.040 ) | NS |
| PP/N | - 0.363 ( 0.029 ) | NS | 0.323 ( 0.050 ) |
| (L+PP)/N | -0.462 ( 0.005 ) | NS | 0.320 ( 0.050 ) |

[a]$NH_4^+$-N extracted from soil after 2 weeks of evaluation
[b]Inorganic N [($NH_4^+$+$NO_3^-$)-N)] extracted from soil after 8 weeks of evaluation

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**Plant growth, mycorrhizal association, nutrient uptake and phosphorus dynamics in a volcanic-ash soil in Colombia as affected by the establishment of *Tithonia diversifolia***

S. Phiri[1,2], I.M. Rao[2], E. Barrios[2], and B.R. Singh[1]

[1]*Agricultural University of Norway, P.O. Box 5028, NLH, N-1432 Aas, Norway*
[2]*Centro Internacional de Agricultura Tropical (CIAT), Apartado Aéreo 6713, Cali, Colombia*

**Abstract**

*Tithonia diversifolia* has the ability to sequester nutrients from soil in its tissues, including P, and has been shown to be useful for cycling nutrients via biomass transfer and improved fallow. We investigated the effects of its establishment from bare root seedlings (plantlets) and vegetative stem cuttings (stakes) on shoot and root growth characteristics, arbuscular-mycorrhizae (AM) associations, nutrient acquisition and utilisation, and P dynamics in a fine-textured volcanic-ash soil (Oxic Dystropept) of a mid-altitude hillside in southwestern Colombia. One year after establishment, the following determinations were made: leaf area index; shoot and root N, P, K, Ca and Mg acquisition; AM root infection; AM fungal spores per 100 g soil; soil chemical characteristics; and P fractionation into inorganic ($P_i$) and organic ($P_o$) pools. AM root infection in both coarse and fine roots was significantly greater in plants established from plantlets than those established from stakes with differences of 21 and 31 %, respectively. Nutrient uptake efficiency (μg of shoot nutrient uptake per m of root length) and use efficiency (g of shoot biomass produced per g of shoot nutrient uptake) for N, P, K, Ca and Mg were also greater with plants established from plantlets than those established from stakes.(is it right). Improved nutrient acquisition could be attributed to relief from P stress and possibly uptake of some essential micronutrients resulting from AM association. High soil variability masked the effect of the establishment method on phosphorus pools, and neither the biologically available P ($H_2O$-$P_o$, resin-$P_i$, and $NaHCO_3$-$P_i$ and -$P_o$) nor the moderately resistant P (NaOH-extractable P) was significantly affected, although plantlets had higher values. This study has shown that on this soil when *Tithonia* is to be used as a fallow species, the use of plantlets as compared to the stake method of establishment is better for nutrient acquisition and recycling.

**Keywords:** Mycorrhizae, nutrient uptake, plant growth attributes, phosphorus dynamics, *Tithonia*, volcanic ash soil

## Introduction

In recent years, soil fertility has declined in large areas of the Colombian Andes due to intensive land use. Long-term fallows (6-12 years), needed for soil fertility replenishment, have also virtually disappeared due to increasing population and competing land-use demands. As land use pressures mount, there is a progressive shortening of the fallow period. Hence, the development of technologies that could enhance and accelerate fallow functions and provide a similar level of ecological benefits over a shorter time compared to the natural fallow are urgently needed (Phiri et al., 2001). Such technologies are most likely to be accomplished through the introduction of improved fallow species with fast growing, superior soil conserving and fertility-regenerating properties, and with the ability to control weeds. A useful fallow species must have the ability to sequester nutrients, including P, from soils that have high inherent P reserves but low P availability. *Tithonia* (*Tithonia diversifolia* (Hemsfey) A. Gray) is one such species that has been shown to be useful for cycling nutrients via biomass transfer (Nziguheba et al., 1998).

*Tithonia* is a robust succulent non-$N_2$-fixing perennial shrub of the family Asteraceae (compositae), which grows 1 to 3 m in height and bears several bright yellow flowers similar to those of the well-known sunflower plant (*Helianthus annuus),* but the flowers are smaller (about 3 cm in diameter).

*Tithonia* is a native component of natural vegetation in the tropics and subtropics. It grows as a subclimax species that naturally occurs with disturbed soil conditions. *Tithonia* originated from Mexico, but is now widely distributed throughout the humid and sub-humid tropics in Central and South America, Asia and Africa (Sonke, 1997). It frequently grows wild in hedges, along roadsides, on wastelands and riverbanks, and is common in indigenous fallow systems in Southeast Asia (Jama et al., 2000). It produces large quantities of leaf biomass, and its hedges rapidly grow back after cutting and tolerate repeated pruning. Recently, there has been increasing awareness of the use of *Tithonia diversifolia* as an indigenous fallow species to improve soil fertility (Niang et al., 1996). Evidence indicates that this species has an ability to accumulate labile soil nutrients, which might otherwise be lost to runoff and leaching, and store them in its rapidly accumulating shoot biomass, which can then be used as a source of plant nutrients or biofertilizers (Nagarajah and Nizar, 1982; Gachengo, 1996; Niang et al., 1996; Jiri and Waddington, 1998; Phiri et al., 2001).

Research done by institutions such as Kenya Agricultural Research Institute (KARI), Tropical Soil Biology and Fertility Programme (TSBF) and International Centre for Research in Agroforestry (ICRAF) in the highlands of western Kenya has dramatically raised awareness and expectations of *Tithonia* green biomass for soil fertility replenishment (Niang et al., 1996). There is also growing interest in the apparent ability of *T. diversifolia*, probably in association with arbuscular-mycorrhizae (AM), to mobilize and accumulate soil P. Release of P from Tithonia green biomass is rapid, and Tithonia supplies plant available P at least as effectively as an equivalent amount of P from soluble fertilizer (Nziguheba et al., 1998).

*Tithonia* green biomass (green tender stems + green leaves),is relatively high in nutrients when compared to green biomass of other shrubs and trees (Jama et al., 2000). Nagarajah and Nizar (1982) reported nutrient concentration of Tithonia biomass in the ranges of 3.2 to 5.5 % N, 0.2 to 0.5 % P and 2.3 to 5.5 % K based on the analysis of 100 dry samples of green biomass in Sri Lanka. The mean values of nutrient concentration of green leaves of *Tithonia* collected in East Africa are 3.5 % N, 0.37 % P and 4.1 % K on a dry-weight basis (Jama et al., 2000). The concentration of N in *Tithonia* green biomass is comparable to that found in $N_2$-fixing leguminous shrubs and trees, whereas the P and K concentrations are higher than those typically found in shrubs and trees (Jama et al., 2000; Phiri et al., 2001). *Tithonia* biomass is also high in nutrients other than N, P and K. Gachengo et al. (1999), for example, found 1.8 % Ca and 0.4 % Mg per unit dry weight of the green Tithonia biomass.

*Tithonia diversifolia* is deliberately being introduced into mid-altitude hillside agriculture system in Colombia to enhance soil fertility (in a chemical, physical and/or biological sense) and to some extent to suppress weeds (Phiri et al., 2001). Compared with natural fallow, *Tithonia* markedly improved the availability of several essential nutrients, particularly P and K (Phiri et al., 2001). Jama et al. (2000) reported that the biomass production of *Tithonia* is influenced by establishment methods, frequency of cuttings, stand density and site conditions. To facilitate rapid establishment of *Tithonia* on a large scale, there is a need to investigate the effect of its establishment method on soil properties and plant growth attributes. *Tithonia* propagates from seeds that frequently germinate naturally under its canopy. Seedlings can be dug up and transplanted elsewhere. However, when Tithonia is established from seeds in the field, germination can be poor, especially if the seeds are sown deep or covered with a clayey soil (Jama et al., 2000). Under field conditions, Tithonia is more easily established from stem cuttings than from seeds (King'ara, 1998). The main objective of the present study was to determine the effect of method of establishment (vegetative stem cuttings versus bare-root seedlings—here called plantlets) of *Tithonia diversifolia* on shoot and root growth characteristics, AM association, nutrient acquisition and utilization, and P dynamics in soil.

## Materials and methods

### *Site description and experimental design*

This study was carried out at CIAT's "San Isidro" experimental farm in Pescador located in the Andean hillsides of the Cauca Department of southwestern Colombia (2º 48′ N, 76º 33′ W) at 1505 m.a.s.l. The area has a mean temperature of 19.3 °C and a mean annual rainfall of 1900 mm (bimodal).

The plots had a slope of approximately 30 %. The soils, derived from volcanic ashes, have been classified as Oxic Dystropepts (Soil Survey Staff, 1998), having the following characteristics: pH ($H_2O$) 5.1; 50 mg $g^{-1}$ C; 3 mg $g^{-1}$ N; 4.6 mg $kg^{-1}$ soil of Bray-P; and 1.1 and 2.5 cmol $kg^{-1}$ soil for Al and Ca, respectively (Cobo et al., 2000). The soil has a medium to fine texture (45 % sand, 27 % silt and 38 % clay) (IGAC, 1979) of high fragility and low cohesion with shallow humic layers. Low soil P availability is presumably the result of high allophane content (52-70 g $kg^{-1}$), which increases its P sorbing capacity (Gijsman and Sanz, 1998).

The two treatments used were one-year-old *Tithonia diversifolia* (Hems.) Gray (1) bare root seedlings (plantlets) and (2) vegetative stem cuttings (stakes). *Tithonia* stakes, 20-40 cm long with 4 or 5 nodes, were cut from mature plants, planted at a slanting angle of 45-60 degrees with 1 or 2 nodes below the ground level to leave 2 or more nodes above the ground. The two propagating materials were planted at the same plant density (40 000 plants/ha at a staggered spacing of 50 cm x 50 cm) in 20 x 20 m plots. Three one cubic meter monoliths, each including one *Tithonia* plant, were randomly collected within each treatment plot. The experiment was laid down as a randomized complete block (RCB) design with establishment method as treatment.

*Sampling and measurements of plant growth attributes*

After one year of plant growth, a sample area of 1 $m^2$ was randomly selected within each plot and all the above ground biomass in this area was harvested. The biomass from the rest of the plot was harvested for the total biomass determination. The biomass from the sample area was separated into leaves, stems and the reproductive structures (flowers and seeds). The leaves were used for determination of leaf area index, and the leaves, stems and reproductive structures were analysed for N, P, K, Ca and Mg. An area of 0.5 x 0.5 m was selected within the sampling area, and all the soil from the 0-5, 5-10, 10-20, 20-40, 40-60 cm soil depths was collected for root and AM determinations. These samples were air-dried and visible plant roots were removed and then gently crushed to pass through a 2-mm sieve. The <2-mm fraction was used for subsequent chemical analysis.

The leaf area ($cm^2$) was determined by measuring fresh leaves with an LI 3000 Area Meter (LI-Cor Inc., Lincoln, NE). The leaf area index (LAI, $m^2$ of leaf area per $m^2$ of ground area) and the specific leaf area (SLA, $m^2$ of leaf area per kg of dried leaves) were calculated. Measurements of photosynthetic efficiency of intact leaves were made with a portable Plant Efficiency Analyzer (Hansatech, King's Lynn, UK). Leaves were dark adapted for 20 min using leaf clips before a 5-s light pulse (1500 μmol $m^{-2}$ $s^{-1}$) was supplied by an array of red light-emitting diodes The rapid turn-on of the light-emitting diodes allowed the accurate determination of Fo (minimal fluorescence intensity with all photosystem II reaction centers open while the photosynthetic membrane is in the non-energized state in the dark) and, hence, Fv (maximum variable fluorescence in the state when all non-photochemical processes are at a minimum, i.e., Fm-Fo) (Kooten and Snel, 1990; Sundby et al., 1993). The ratio of variable to maximal fluorescence (Fv/Fm = (Fm-Fo)/Fm) (Fm = fluorescence intensity with all photosystem II reaction centers closed) is a measure of the maximal photochemical efficiency of photosystem II.

Root distribution was determined using soil coring method (Rao, 1998). For each replication, a total of 12 soil cores at different soil depths (0-10; 10-20; 20-40; and 40-80 cm) were collected 10 cm from the base of the plant across the row. After washing out the roots on a 1 mm sieve, the "live" roots were hand separated from organic material. Root length was measured with the Comair Root Length Scanner (Commonwealth Aircraft Corporation, Melbourne, Australia) and expressed in km of root length per $m^2$ of ground area. Root biomass was determined after drying the samples in an oven at 70 °C for 2 days. The specific root length was calculated in m of root length per g of dried roots. A number of other plant attributes were determined including nutrient status of plant parts, shoot nutrient uptake, nutrient uptake efficiency (μg of uptake in shoot biomass per m of root length), and nutrient use efficiency (g of shoot biomass production per g of total nutrient uptake) (Salinas and Saif, 1990; Rao et al., 1997).

*AM determinations*

Mycorrhizal association was assessed by the number of spores per 100 g soil and AM root infection percentage in coarse and fine roots according to the method of Sieverding (1991). To separate spores from the soil, a 50 g sample of well-mixed soil, was suspended in water for 1 min (for sedimentation of coarse sand), and then the suspension was decanted over a series of soil sieves (a sieve with 0.350 over one with 0.125 over one with 0.045-mm mesh size). Suspending and decanting were repeated three times. Root material in the top sieve was carefully washed with water and then transferred with a little water to a petri dish. The contents of the medium sieve and of the finest sieve were separately transferred to 100-ml centrifuge tubes. In the tubes, the sievings were brought into suspension in 30 ml water and 30-40 ml of a sugar solution (70 g sugar dissolved in 100 ml water) was injected into the bottom of the tube with the aid of a 50-ml syringe so that a gradient was established in the centrifuge tube. The sample was centrifuged (with a centrifuge with swinging bucket and horizontal head) at 1000 revolutions per min. for 10 min. During this process soil particles settle on the bottom and spores remain on the surface of the sugar gradient. Spores were extracted with syringe from the gradient and placed in a clean sieve with 0.045-mm mesh opening; then the spores were washed with water for 2-3 min. before being transferred in water to a petri dish. Spores in the root fraction and the centrifuged samples were observed and counted under a stereomicroscope at 40x magnification.

To determine AM fungal root infection, the soil was immersed in a tub of water and gently agitated to separate the roots from the soil. The roots were separated into coarse (> 2mm diameter) and fine roots. The roots were then washed with water using a hose over a 1-2 mm screen (to catch roots). The roots were then transferred to a flask and heated in 5% KOH at 90 °C for 15 min. The KOH was then rinsed off the roots with water on a fine sieve. Roots were stained in acidic glycerol/trypan blue for 15 min at 90 ºC and then destained and stored in 50 % acidic glycerol and subsequently used for determination of AM root infection using the modified grid intersect method (Newman, 1966).

*Phosphorus fractionation and analysis*

A sequential P fractionation as per the method of Tiessen and Moir (1993) was carried out on 0.5-g sieved (<2-mm) soil samples. In brief, a sequence of extractants with increasing strength was applied to subdivide the total soil-P into inorganic ($P_i$) and organic ($P_o$) fractions. The following fractions were included: (1) resin $P_i$ extracted with anion exchange resin membranes (used in bicarbonate form) was used to extract freely exchangeable $P_i$. The remaining $P_o$ in the extraction from of the resin extraction step ($H_2O$-$P_o$) was digested with potassium persulfate ($K_2S_2O_8$) (Oberson et al., 1999). (2) Sodium bicarbonate (0.5 *M* $NaHCO_3$, pH = 8.5) was then used to remove labile $P_i$ and $P_o$ sorbed to the soil surface, plus a small amount of microbial P (Bowman and Cole, 1978). (3) Sodium hydroxide (0.1 *M* NaOH) was used next to remove $P_i$ more strongly bound to Fe and Al compounds (Williams and Walker, 1969) and associated with humic compounds (Bowman and Cole, 1978). (4) HCl $P_i$ was obtained by extraction with 1.0 *M* HCl; (5) HCl hc-P and -$P_o$ were extracted with hot and concentrated HCl; and (6) residual P was obtained by digestion with perchloric acid ($HClO_4$). To determine total P in the $NaHCO_3$ and NaOH extracts, an aliquot of the extracts was digested with $K_2S_2O_8$ in $H_2SO_4$ at >150 °C to oxidize organic matter (Bowman, 1989). Organic P was calculated as the difference between total P and $P_i$ in the $NaHCO_3$ and NaOH extracts, respectively. Inorganic P concentrations in all the digests and extracts were measured colorimetrically by the molybdate-ascorbic acid method (Murphy and Riley, 1962). All laboratory analyses were conducted in duplicate and all the data are expressed on an oven-dry weight basis.

*Statistical analysis and data presentation*

Analyses of variances were conducted (SAS/STAT, 1990) to determine the significance of the effects of method of *Tithonia* establishment on soil properties and plant growth attributes. Planned F ratio was calculated as TMS/EMS, where TMS is the treatment mean square and EMS is the error mean square (Mead et al., 1993). Where significant differences occurred, least-significant-difference (LSD) analysis was performed to permit separation of means. Unless otherwise stated, mention of statistical significance refers to $\alpha = 0.05$.

**Results and Discussion**

*AM association*

Establishment of *Tithonia* by plantlets resulted in significantly greater mycorrhizal root infection (P=0.05) in both coarse and fine roots, as compaewd to Tithonia established by stakes and the differences were of 21 and 31%, respectively (Table 1). The corresponding difference in the number of spores per 100 g of soil was 30% but the difference between the two methods was not statistically significant (P=0.05). The higher AM infection of plants established with plantlets could have contributed to the greater acquisition of nutrients (Table 2) observed under this treatment. Increased mycorrhizal uptake of simple forms of organic P ($P_o$) (Jayachandran et al., 1992) and increased net release of P from organic matter due to uptake by mycorrhizal hyphae (Joner and Jakobsen, 1994) have been demonstrated. Although the source of soil P is envisaged to be the soil solution and to be the same for both roots and hyphae, the transfer across the symbiotic interface results in increased nutrient acquisition by the plant (Smith and Read, 1997). This is because mycorrhizal hyphae, due to their small size and spatial distribution compared to roots, are able to penetrate soil pores inaccessible to roots resulting in exploitation of a larger soil volume for nutrient acquisition, particularly of non-mobile nutrients such as P, Zn and Cu (Smith and Read, 1997). Rhodes and Gerdemann (1975) demonstrated the ability of the hyphae of mycorrhizal fungi to absorb $^{32}P$ from a distance as much as 7 cm away from the roots. The kinetics of P uptake into hyphae may differ from that of roots. The fungal membrane transport system seems to have a higher affinity for phosphorus (lower $K_m$ value) than roots (Cress et al., 1979), leading to more effective absorption from low concentrations in the soil solution and possibly lower threshold values below which uptake ceases (Smith and Read, 1997).

Table 1. Effect of method of establishment (stake or plantlet) on mycorrhizal (AM) association and nutrient uptake efficiency of *Tithonia diversifolia*. LSD values are at 0.05 probability level (n = 3).

| Plant attributes | | Method of establishment | | |
|---|---|---|---|---|
| | | Stake | Plantlet | $LSD_{(P=0.05)}$ |
| AM infection in fine roots | (%) | 49 | 79 | 11 |
| AM infection in coarse roots | ″ | 48 | 69 | 12 |
| Number of spores in 100 g of soil | | 418 | 509 | ns |
| P uptake efficiency | (µg/m) | 30 | 48 | 12 |
| N uptake efficiency | ″ | 167 | 331 | 128 |
| K uptake efficiency | ″ | 379 | 662 | 130 |
| Ca uptake efficiency | ″ | 116 | 184 | 56 |
| Mg uptake efficiency | ″ | 37 | 61 | 19 |

ns = not significant.

The work with cassava by Yost and Fox (1979) illustrates this point. This species appears to have a very high P requirement, coupled with a very inefficient P uptake system in the absence of mycorrhizal colonization. Despite this, cassava is well known for its growth on soils of low fertility and its efficiency of uptake is markedly increased when roots are colonized by mycorrhizal fungi (Smith and Read, 1997). The increased efficiency of the plantlet to associate with mycorrhizae may be related to the initial physiological competence of the plantlet compared to the vegetative stem cutting (stake). Plantlets have all the basic components of a mature plant and are able to start photosynthesis shortly after transplanting.

Plantlets are also likely to associate with AM faster than cuttings because they already have roots and produce photoassimilates that are an essential component for an effective plant-mycorrhizal symbiosis. This symbiosis is likely to proliferate rapidly once established. Meanwhile, the stakes have to initiate root and shoot growth before they can associate with AM resulting in a time lag for symbiosis to be established. How long this lag period lasts is unknown.

Table 2. Effect of method of establishment (Stake or Plantlet) on shoot and root attributes and nutrient uptake and use efficiency by *Tithonia diversifolia*. LSD values are at 0.05 probability level (n = 3).

| Plant Attributes | | Method of establishment | | |
|---|---|---|---|---|
| | | stake | plantlet | $LSD_{(P=0.05)}$ |
| Photosynthetic efficiency | (Fv/Fm) | 0.82 | 0.82 | - |
| Leaf area index | ($m^2/m^2$) | 1.12 | 2.30 | 0.37 |
| Leaf biomass | (kg/ha) | 814 | 1387 | 209 |
| Stem Biomass | ″ | 5568 | 13880 | 1807 |
| Reproductive structures | ″ | 630 | 1279 | 320 |
| Total shoot biomass | ″ | 7012 | 16546 | 2296 |
| Total root biomass | ″ | 839 | 989 | ns |
| Total root length | ($km/m^2$) | 3.5 | 5.2 | ns |
| Specific root length | (m/g) | 42 | 53 | ns |
| Root length/leaf area | ($m/cm^2$) | 0.37 | 0.23 | 0.15 |
| Shoot N uptake | (kg/ha) | 67 | 148 | 43 |
| Shoot P uptake | ″ | 12 | 21 | 3 |
| Shoot K uptake | ″ | 153 | 296 | 26 |
| Shoot Ca uptake | ″ | 47 | 82 | 17 |
| Shoot Mg uptake | ″ | 15 | 27 | 6 |
| N use efficiency | (g/g) | 88 | 104 | 15 |
| P use efficiency | ″ | 529 | 741 | 119 |
| K use efficiency | ″ | 45 | 56 | 7 |
| Ca use efficiency | ″ | 132 | 187 | 16 |
| Mg use efficiency | ″ | 442 | 581 | 96 |

ns = not significant.

*Growth attributes*

*Tithonia* established by plantlets had a total shoot biomass of 16.5 t/ha, which was significantly higher ($P<0.05$) than the 7 t/ha under vegetative stem cutting (stake) establishment (Table 2). The total root length and root biomass were not significantly affected by the method of establishment, although, on average, plants established by plantlets had greater root biomass, root length and specific root length indicating that *Tithonia* under this method of establishment had developed a finer root system. It is generally observed that thicker roots may be more favorable for mycorrhizal association (St John, 1980). It appears that in the case of *Tithonia* both thick and fine roots were colonized by mycorrhizae. *Tithonia* plant established by using plantlets had significantly higher shoot uptake and use efficiency of N, P, K, Ca and Mg (Table 2). The higher values of these attributes in plants established using plantlets could be attributed to greater mycorrhizal (AM) colonization under this establishment method, which might have increased the effective volume for nutrient uptake. There is evidence that nitrogen (N) is taken up by AM hyphae from inorganic sources of ammonium (Ames et al., 1983). Any direct effect of AM on $NO_3^-$

uptake is not known (Sieverding, 1991). Potassium (K) and Mg are often found in higher concentrations in mycorrhizal than non-mycorrhizal plants, although a direct transport of K and Mg in AM is not confirmed (Sieverding, 1991). Some experimental work suggests that in K-deficient soils the improved K uptake is related to the AM fungal species and that K may be transported by AM fungal hyphae (Sieverding and Toro, 1988). Calcium (Ca) transport in AM hyphae is not clearly confirmed; the Ca uptake is apparently affected by interaction with other elemental nutrients. However, it should also be noted that this improvement in nutrient acquisition could be as a result of relief from P stress and possibly from the uptake of some essential micronutrients. These processes will result in general improvement in growth, thus indirectly affecting the uptake of other nutrients. The differences between mycorrhizal and non-mycorrhizal plants usually disappear if the latter are supplied with a readily available P source (Bethlenfalvay and Newton, 1991; Azcón-Aguilar and Barea, 1992, Barea et al., 1992; Bethlenfalvay, 1992).

Available P (Bray-II) in the 0-5 and 5-10 cm soil depth was significantly greater in plots where *Tithonia* was established by plantlets (Table 3). The plantlet method resulted in significantly higher Ca and Mg in the profile up to 20-cm soil depth (Table 3), and a lower content of exchangeable Al (results not shown for brevity). These differences may be related to the differences in mycorrhizal associations between the plantlet and stake establishment methods. Bowen (1980) and Jehne (1980) reported that AM might play an important role as transport paths for nutrient cycling processes. AM-root external mycelia presumably can efficiently and intensively extract nutrients from a greater soil volume and thus reduce the amount of solubilized or mineralized nutrients that are chemically fixed or leached. This function of AM fungi was concentrated in the 0-20 cm depth of the soil profile where most root growth occurred.

Table 3. Effect of establishment method on root distribution, mycorrhizal association and nutrient availability down the soil profile.

| *Soil depth* (cm) | ***Method*** | AM infection (%) | | Spores per/100 g soil | pH ($H_20$) | Ca | Mg | P - Bray II | SOM (%) | Root length | *Root biomass* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Fine roots | Coarse roots | | | (meq/100 g soil) | | (ppm) | | (km /m²) | (kg/ha ) |
| 0-5 | Plantlet | 81 | 67 | 647 | 5.4 | 3.76 | 0.93 | 10.2 | 11.4 | 1.3 | 121 |
| | Stake | 67 | 61 | 543 | 5.1 | 2.18 | 0.51 | 5.63 | 11.3 | 0.9 | 269 |
| | | (12)† | | | | | (0.17) | (0.9) | | (0.2) | (121) |
| 5-10 | Plantlet | 65 | 76 | 481 | 5.0 | 1.42 | 0.31 | 10.1 | 10.1 | 1.0 | 277 |
| | Stake | 36 | 62 | 497 | 4.9 | 0.81 | 0.21 | 3.8 | 9.6 | 0.7 | 151 |
| | | (10) | (11) | | | (0.29) | (0.04) | (2.31) | | (0.2) | (65) |
| 10-20 | Plantlet | 72 | 83 | 590 | 5.2 | 2.91 | 0.56 | 7.97 | 11.0 | 1.3 | 377 |
| | Stake | 59 | 54 | 587 | 5.0 | 1.39 | 0.30 | 3.94 | 11.7 | 1.0 | 237 |
| | | | (21) | | | (0.68) | (0.16) | (2.31) | | | |
| 20-40 | Plantlet | 75 | 81 | 198 | 5.1 | 0.86 | 0.22 | 4.82 | 7.0 | 0.8 | 148 |
| | Stake | 29 | 38 | 283 | 5.0 | 0.89 | 0.28 | 4.62 | 5.4 | 0.6 | 141 |
| | | (16) | (13) | (38) | | | | | | | |
| 40-60 | Plantlet | 67 | 86 | 167 | 5.3 | 0.85 | 0.18 | 3.77 | 3.2 | 0.8 | 66 |
| | Stake | 33 | 16 | 106 | 5.0 | 0.67 | 0.16 | 3.54 | 3.2 | 0.3 | 41 |
| | | (18) | (9) | (38) | | | | | | (0.3) | |

† Where treatment effects are significant, the LSD values at 0.05 probability level are presented in parentheses (n = 3).

***P fractionation***

*Biologically available P* ($H_2O$-$P_o$, resin-$P_i$, and $NaHCO_3$-$P_i$ and -$P_o$): The biologically available P consists of labile P and represents soil solution P, soluble phosphates originating from calcium phosphates, and weakly adsorbed $P_i$ on the surfaces of sesquioxides or carbonates (Mattingly, 1975). The resin $P_i$ and the $NaHCO_3$-$P_i$ are considered readily available for plant uptake. At soil layers of 0-5, 5-10 and 10-20 cm, the resin $P_i$ was significantly higher under the plantlet establishment method (Table 4). The

resin P decreased sharply with increasing soil depth and accounted for 0.4 % and 0.07 % of the total soil P at the 0-5 and 40-60 cm soil layers, respectively. The $NaHCO_3$- $P_i$ was higher under the plantlet establishment method; however, the differences were not significant except at 10-20 cm soil depth. Similar to the resin P, the $NaHCO_3$-$P_i$ decreased sharply with increasing soil depth and accounted for 4.5% and 0.4% of the total soil P at the 0-5 and 40-60 cm soil layers, respectively. The organic fractions of the bioavailable P include the $H_2O$-$P_o$ and $NaHCO_3$-$P_o$, which is considered "readily mineralizable" and contributes to plant-available P (Fixen and Grove, 1990). This $P_o$ fraction includes nucleic acid-P, sugar-P, lipid-P, phytins, and other high-molecular-weight P compounds (Bowman and Cole, 1978). The $H_2O$-$P_o$ contribution to the total soil P was very small and decreased steadily with depth. The plantlet establishment method had a higher $H_2O$-$P_o$ at the 0-5 and 5-20 cm soil depths. The $NaHCO_3$-$P_o$ was on average 4% of the soil total P. The method of establishment of *Tithonia* did not affect this fraction. The absence of an effect of the establishment method on $NaHCO_3$-$P_o$ is consistent with results by Tiessen et al. (1992), who found that $NaHCO_3$-$P_o$ was relatively constant in shifting cultivation systems on an Oxisol. The sum of all the fractions making up the bioavailable P ($H_2O$-$P_o$ + resin-$P_i$ + Total $NaHCO_3$ P) was less variable and was about the same under the two establishment methods. It decreased with increasing soil depth and ranged from 56.4 (0-5 cm) to 18.0 µg/g (40-60 cm), which was between 4 to 9% of total P (Table 4; Fig. 1).

Table 4. Distribution of P (µg/g) in various fractions at different soil depths as affected by the *Tithonia* establishment method.

| Depth | Method | $H_2O$ | Resin | Bicarbonate | | NaOH | | HCl 1*M* | HCl hc† | | Residue | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Po | Pi | Pi | Po | Pi | Po | Pi | Pi | Po | Pt | P |
| | | (µg /g) | | | | | | | | | | |
| 0-5 cm | Plantlet | 3.35 | 4.36 | 21.4 | 35.5 | 183 | 146 | 15.8 | 80.6 | 21.7 | 375 | 880 |
| | Stake | 2.35 | 2.55 | 17.3 | 32.6 | 176 | 252 | 15.4 | 37.1 | 15.0 | 301 | 828 |
| | | (0.54) ‡ | (1.46) | | | | (51) | | (7.0) | | (53) | (46) |
| 5-10 cm | Plantlet | 2.67 | 3.26 | 19.1 | 29.6 | 146 | 172 | 14.8 | 67.8 | 21.6 | 361 | 784 |
| | Stake | 1.71 | 1.66 | 12.8 | 29.1 | 155 | 130 | 10.0 | 45.7 | 10.9 | 319 | 717 |
| | | (0.53) | (0.92) | | (5.2) | | | (1.8) | (14.6) | (5.8) | | |
| 10-20 cm | Plantlet | 2.12 | 2.73 | 12.2 | 26.2 | 160 | 94.2 | 11.6 | 63.0 | 15.7 | 315 | 660 |
| | Stake | 1.54 | 1.34 | 7.6 | 25.5 | 130 | 88.3 | 7.6 | 53.4 | 17.3 | 238 | 603 |
| | | | (0.5) | (2.3) | | | | (2.6) | (8.3) | | | |
| 20-40 cm | Plantlet | 1.37 | 0.44 | 2.7 | 14.5 | 82.6 | 72 | 6.1 | 30.7 | 12.2 | 238 | 420 |
| | Stake | 1.36 | 0.41 | 2.3 | 13.1 | 58.7 | 130 | 3.2 | 29.2 | 14.0 | 160 | 457 |
| 40-60 cm | Plantlet | 1.66 | 0.30 | 1.1 | 15.2 | 52.5 | 73 | 3.2 | 25.5 | 16.5 | 160 | 336 |
| | Stake | 0.83 | 0.23 | 2.0 | 16.2 | 52.4 | 72 | 4.1 | 26.2 | 8.9 | 154 | 329 |

† HCl hc =Hot and concentrated HCl.

‡ Where treatment effects are significant the LSD values at 0.05 probability level are presented in parentheses (n = 3).

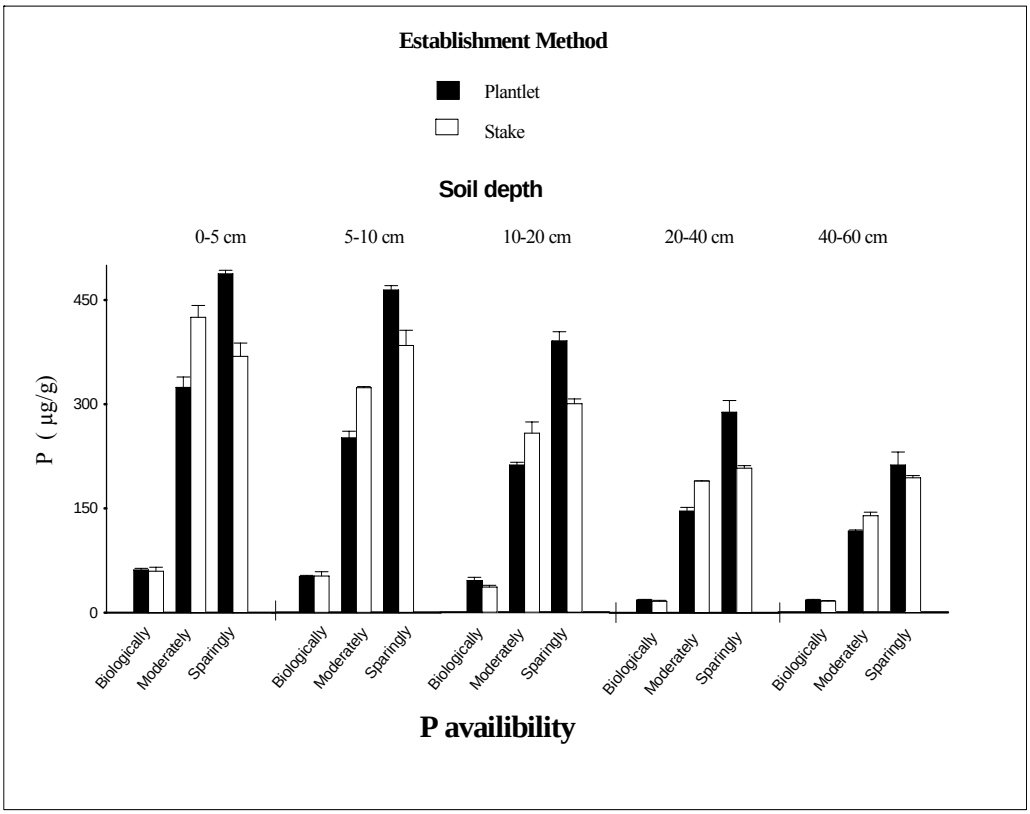


Figure 1. Distribution of three soil P fractions (ready, reversibly and sparingly available P) through 0 to 60 cm soil depth. This grouping of the fractions has been calculated from Table 4. Standard error values are shown for each mean value.

*Moderately resistant P (NaOH-extractable P):* This fraction is thought to be associated with humic compounds, and amorphous and some crystalline Al and Fe phosphates (Bowman and Cole, 1978). The NaOH (0.1 *M*, pH = 8.5) used completely solubilize the synthetic iron, aluminum phosphate and any labile-$P_o$ (Anderson, 1964). A large proportion of P was recovered in this fraction, where the total NaOH ($P_t$) represented between 37 % and 18 % of the total soil P at the 0-5 and 40-60 soil layers, respectively (Fig 1). The plantlet establishment method resulted in high NaOH-$P_i$, however, the results were not significant (Table 4). The effect of the establishment method was variable on the NaOH-$P_o$ fraction and did not follow any particular trend with increase in soil depth.

The *sparingly available P* includes the 1*M* HCl, the hot-and-concentrated HCl ($P_i$ and $P_o$) and the Hedley et al. (1982) residual-P. The dilute HCl (1*M*) acid extractant is used to dissolve acid-soluble P, which consists of relatively insoluble Ca-phosphate minerals such as apatite (Williams et al., 1980). This fraction is clearly defined as Ca-associated P, since the Fe- or Al-associated P that might remain unextracted after the NaOH extraction is insoluble in acid. There was rarely any $P_o$ in this extract. On average the dilute HCl-Pi represent about 1 % of the total soil P and was only significantly affected by the establishment method at 5-10 and 10-20 cm soil layers. It increased sharply with increasing soil depth from the 5-10 to 40-60 cm soil layers. The hot concentrated HCl is useful for distinguishing $P_i$ and $P_o$ in very stable residue pools. The $P_o$ extracted at this step may also simply come from particulate organic matter that is not alkaline extractable, but it may be easily bioavailable. The plantlet establishment method

resulted in a significantly higher HCl hc-$P_i$ at the 0-5, 5-10 and 10-20 cm soil layers (Table 4). The HCl hc-$P_o$ showed a tendency to be greater under the plantlet establishment method, but was only significantly different from the stake establishment method at 5-10 cm soil layer. The residual P is thought not to be available on a short time scale such as one or two crop cycles, but a small fraction of this pool may become available during long-term soil P transformations. The residual P represented a high proportion of the total P and was significantly affected by the establishment method at the 0-5 cm soil layer. This fraction decreased steadily with increasing soil depth.

**Conclusions**

This study has shown that the better method of establishing *Tithonia* as a fallow species in volcanic-ash soil is the use of bare root seedlings (plantlets) in comparison to vegetative stem cuttings (stakes). Establishment by bare root seedling resulted in increased plant growth and nutrient acquisition, which are desirable plant attributes for fallow systems because of enhanced nutrient cycling.

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# Characterization of the phenomenon of soil crusting and sealing in the Andean Hillsides of Colombia: Physical and Chemical constraints

*C. Thierfelder[1], E. Amézquita[2], R.J. Thomas[3] and K. Stahr[1]*

[1] *University of Hohenheim, Germany*
[2] *Centro Internacional de Agricultura Tropical (CIAT), Apartado Aéreo 6713, Cali, Colombia*
[3] *ICARDA, P.O. Box 5466, Aleppo, Syria (formerly CIAT, Colombia)*

## Abstract

Soil degradation is increasing around the globe, bringing challenges that demand an investigation of influencing factors. This study investigates the new degradation phenomenon of soil crusting and sealing on volcanic Inceptisols in Andean hillsides. Crusting and sealing are commonly accepted soil deterioration factors that create unstable surface conditions and soil erosion. On an Inceptisol in Santander de Quilichao in Colombia, field trials were conducted on existing erosion run-off plots using Cassava as the main crop. During the investigation, field samplings and analyses were taken of: penetration, shear strength, infiltration and cassava yield. Results from penetration and shear strength measurements clearly showed chicken manure's significant influence on soil structure. Chicken manure generally led to structural constraints. In addition, chicken manure plots displayed a reduction of infiltration. This strengthens the hypothesis that inappropriate fertilizer management is one of the key factors of structural deterioration on Inceptisols in the Andean environment. Further research is necessary to find out sustainable soil treatments in Andean hillside farming.

**Keywords***:* soil crusting, soil sealing, soil erosion, chicken manure, Inceptisols, tillage system

## Introduction

Soil erosion is a major problem worldwide. Climatic impacts aside, the main reasons for soil erosion are both, inappropriate land-use and improper fertilizer management, (Lal and Stewart, 1990; Oldeman, 1990; El-Swaify, 1991) as well as socio-economic constraints (Steiner, 1994, Mueller-Saemann, 1998 *et al*.). In the process of acquiring a basic knowledge of soil degradation, efforts have focused on structural changes at the soil surface (Sumner and Miller, 1992; Sumner and Stewart, 1992; Bresson, 1995; Valentin and Bresson, 1998)). Recent observations indicate that the physical and chemical degradations of soils in the Andean zone are related to the phenomena of soil crusting and sealing.

Soil crusts are thin layers of hardened soil on the surface, occurring on dry soils (Roth, 1992; Bresson, 1995). The term "soil sealing" is used to describe superficial impermeabilities mainly occurring in wet circumstances. Soil sealing occurs if dissolved aggregates infiltrate in the soil pores leading to compact soil horizons and thus reducing infiltration (Scheffer-Schachtschabel, 1998). Both phenomena negatively impact water infiltration, and reduce air permeability and seedlings' emergence (USDA, 1996, Bajracharya *et al*., 1996, Le Bissonnais, 1990). Due to the reduction of water infiltration, the surface run-off increases; resulting in enhanced soil erosion and reduced harvest yield.

The soil crust development of Andean soils of volcanic origin is not yet well understood. Therefore, the aim of this work is to characterize the phenomenon of soil crusting on Andean Inceptisols. This project is supported by special project funds from the DAAD/Germany, the Eiselen Foundation/Germany, the BMZ/Germany and the University of Hohenheim/Germany.

## Materials and Methods

*Location*

Field research was conducted at the Santander de Quilichao Research Station, Dep. Cauca of Colombia (3°6'N, 76° 31' W, 990 m.a.s.l). Trials had been installed on an amorphous, isohyperthermic oxic Dystropept (Inceptisol), developed from fluvially translocated partly weathered volcanic ashes. The field site has a bimodal rain distribution with two maximas in April-May and October-November, with a mean annual rainfall of 1799 mm, a rain intensity up to 330 mm/h and a mean annual temperature of 23.8°C. The measurements of soil crusting have been made on 27 Standard Erosion Experimental Plots. These plots, originally designed by the soil conservation team from the University of Hohenheim as completely randomized blocks in three repetitions, have been used since 1986 (Table 1). They were sampled at 0 to 5cm depth.

Table 1. The history of treatments in Santander de Quilichao

| Treat | 93/94 | 94/95 | 95/96 | 96/97 | 97/98 | 98/99 | 99/00 | 00/01 |
|---|---|---|---|---|---|---|---|---|
| 1 | Bare fallow | Bare fallow | Bare fallow | Bare fallow | Bare fallow | Bare fallow | Bare fallow | Bare fallow |
| 2 | Cowpea, mF[1] | Cassava oF4[2] | Maize oF4 | Cassava oF4 | Cowpea oF4 | Maize oF4 | Cassava oF4 | Cassava oF4 |
| 3 | Cassava | Cassava | Cassava | Cassava | Cowpea | Cassava | Cassava | Cassava |
| 4 | Bush fallow | Cassava mF | Maize mF | Cassava mF | Cowpea mF | Cassava mF | Cassava mF | Cassava mF |
| 5 | Br[4] P[5] | Cassava mF | Maize mF | Cassava mF | Cowpea mF | Maize mF | Cassava oF8[3] | Cassava oF8 |
| 6 | Co mF(V)[9] | Cassava | Maize | Cassava | Cowpea | Maize | Cassava | Cassava |
| 7 | Cassava Ca[6] | Cassava Ca | Maize Ch[8] | Cassava Co | Cowpea mF | Maize Ch | Cassava Ch | Cassava Ch |
| 8 | Br P | Br P | Maize mF | Br Cm[7] | Br Cm | Maize Cm | Cassava mF | Br Cm |
| 9 | Bush fallow | Bush fallow | Bush fallow | Bush fallow | Bare fallow | Bare fallow | Cassava mF | Cassava mF |

[1]mF = mineral Fertilizer.
[2]oF4 = organic Fertilizer. (Chicken manure 4 t ha$^{-1}$)
[3]oF8 = organic Fertilizer. (Chicken manure 8 t ha$^{-1}$)
[4]Br= *Brachiaria decumbens*
[5]P = *Pueraria phaseoloides*
[6]Ca = *Centrosema acutifolium*
[7]Cm = *Centrosema macrocarpum*
[8]Ch = *Chamaecrista rotundifolia*
[9](V) = Vetiver

## Treatments

The treatments from December 1999 are described in Table 2. Before planting, the experimental plots have been limed with dolomitic lime (500 kg/ha) and plots with mineral fertilizer have been fertilized with 300 kg/ha mineral fertilizer (10N-30P-10K). Chicken manure from a local poultry farm had the following nutrient content (N: 3.43%, P: 1.82%, K: 2.73%, Ca: 3.32%, Mg: 0.64%, Fe: 1364 ppm).

To quantify and describe soil crusting and sealing, different measurement tools have been used in the field.

After planting Cassava in December 1999, field measurements with a Pocket Penetrometer (Model DIK-5560) were carried out.

Besides pentrometer measurement, a Hand Vane Tester (Model EL26-3345) was used to measure shear strength at the soil surface. Both tools were used weekly, each Penetrometer measurement 24 times and Torvane measurement 6 times per plot.

To describe direct effects of soil crusting and sealing on infiltration, a mini-rainsimulator was used in the field. Infiltration was measured by irrigating a defined soil area (32,5cm x 40cm) with a special amount of rain (90mm/h). The construction of this mini-rainsimulator enabled to subsample run-off periodically (every 5 min). The difference between irrigated amount of rain water and run-off data is defined as infiltration.

Cassava root yield in December 2000 was measured after harvest to determine the impact of soil compaction process.

Table 2. Treatments of 27 Experimental Plots in Santander de Quilichao from 1999-2001.

| Treatment | Plots | | | Cultivation in 1999-2001 |
|---|---|---|---|---|
| (1) Bare fallow | 25 | 26 | 27 | Raking at the beginning |
| (2.) Cassava + 4t/ha chicken manure (trad.) | 2 | 13 | 19 | Rototiller, 4 t/ha chicken manure |
| (3) Cassava monoculture | 3 | 11 | 24 | Rototiller, no fertilizer |
| (4) Cassava minimum tillage | 4 | 17 | 22 | No tillage, mineral fertilizer, Mulch |
| (5) Cassava + 8t/ha chicken manure | 5 | 9 | 21 | Rototiller, 8t/ha chicken manure |
| (6) Cassava+ 4t/ha chicken manure (Vetiver) | 6 | 10 | 16 | Rototiller, 4t/ha chicken manure |
| (7) Cassava + *Chamaecrista rotundifolia* | 7 | 12 | 20 | Rototiller, mineral fertilizer, |
| (8) Cassava rotation (*Brachiaria decumbens* | 8 | 14 | 18 | Rototiller, mineral fertilizer |
| (9) Cassava intensive tillage | 28 | 29 | 30 | Intensive Rototiller, mineral fertilizer |

**Results and Discussion**

*Penetrometer and Torvane*

Results of Penetrometer and Torvane measurement are presented in Figures 1. During the wet season, penetration resistance was similar in all treatments. At the beginning of the dry season in May/June, differences between treatments were noted. Notably, the Cassava + 8 t/ha chicken manure became a hard soil (penetration resistance 25,4 kPa, shear strength 67 kg/cm²). Over time the minimum tillage plot generally became harder than other plots, but the well-developed and stable aggregate structure prevented negative impact on water infiltration (see below). The high amount of chicken manure caused a dispersion of clays in the wet season and results in uniform clods after drying. It was noticed that the Cassava monoculture and Cassava intensive tillage tended to be extremely soft, thus building up a single-grain structure also called pseudo-sand. Torvane measurement data tended to be similar to penetrometer measurement. Figure 1 indicates the increase in shear strength in the dry season especially within treatments of Cassava + 8 t/ha chicken manure**.**

In general, all treatments except the Cassava intensive tillage treatment had a high shear strength from June-July and turned from 13 – 22 kg/cm$^2$ in the wet season up to 43 – 76 kg/cm$^2$ in the dry season.

*Infiltration*

Results are presented in Figure 2. Cassava + 8t/ha Chicken manure had the lowest infiltration after 55 minutes with a final infiltration capacity of 36 mm/h.

It has to be emphasized that Cassava min. tillage as well as Cassava rotation treatment had both an excellent infiltration capacity. Minimum tillage influenced the soil structure positively in the way that aggregation over a long time period is supported. This helped to build up a soil structure, as also the mulch at the surface led to a better infiltration.

*Yield*

Results of harvest data are presented in Table 3. Overall, the best root yields were found in Cassava 4t/ha chicken manure and Cassava rotation. High Cassava root yields in these treatments are due to improved soil conditions such as moderate soil hardening, sufficient fertilization, enhanced soil aggregation and high water infiltration. In contrast, the lowest yields were found with Cassava monoculture and Cassava intensive tillage treatments. The Cassava monoculture treatment is characterized by a low nutrient content in the soil through insufficient fertilization over a long period of time.

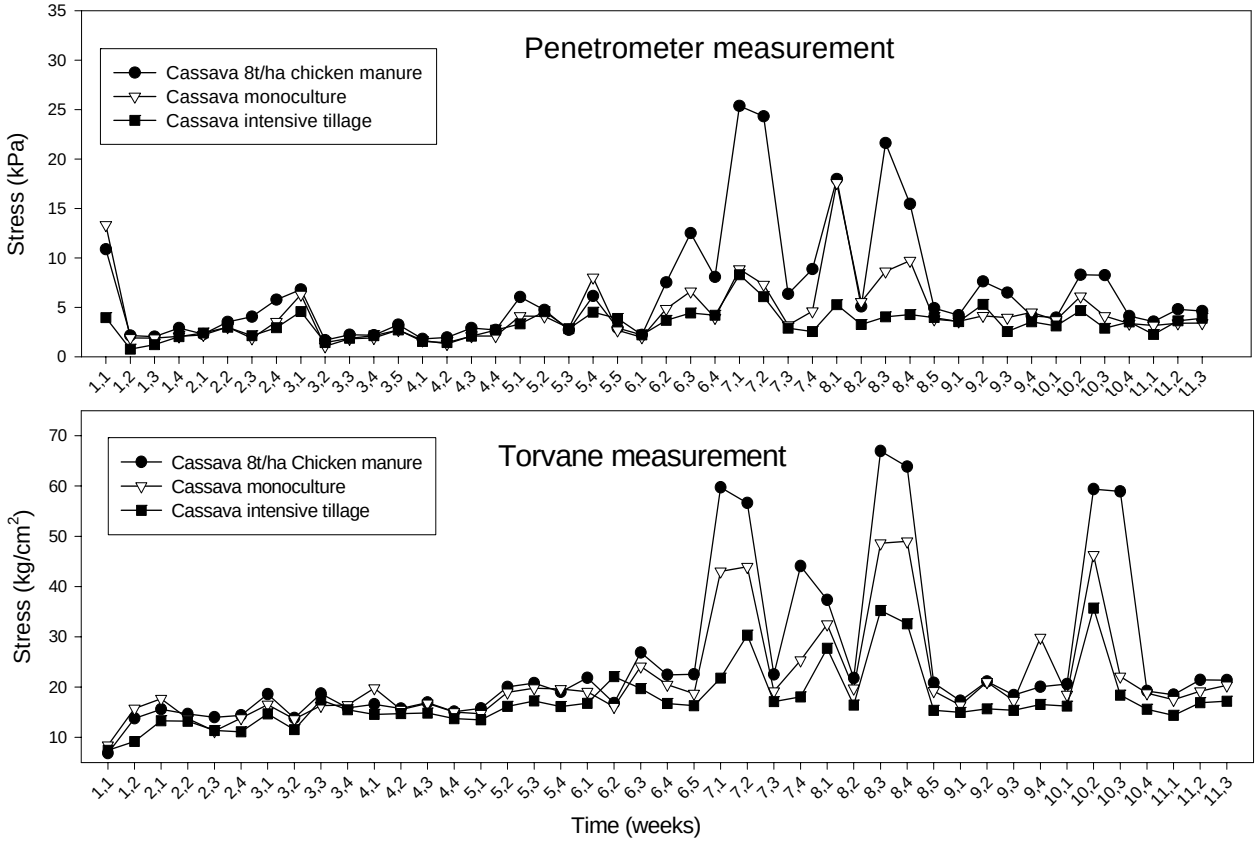


Figure 1: Influence of soil treatment and crop management on penetration resistance and shear strength, Santander de Quilichao, Jan-Nov 2000

The single grain structure and low infiltration capacity contributed to low root yield. The Cassava intensive tillage treatment is characterized by a breakdown of the pore system. Thus, leading to a lack of infiltration and reduced yields. In both treatments, roots were very small and economically worthless. Cassava 8 t/ha chicken manure had high amounts of plant biomass but hard soil structure, preventing optimal development of Cassava roots. In Cassava minimum tillage treatment, root growth was limited to the area loosened before planting. Therefore yields in both treatments were lower than in Cassava rotation and Cassava 4 t/ha chicken manure

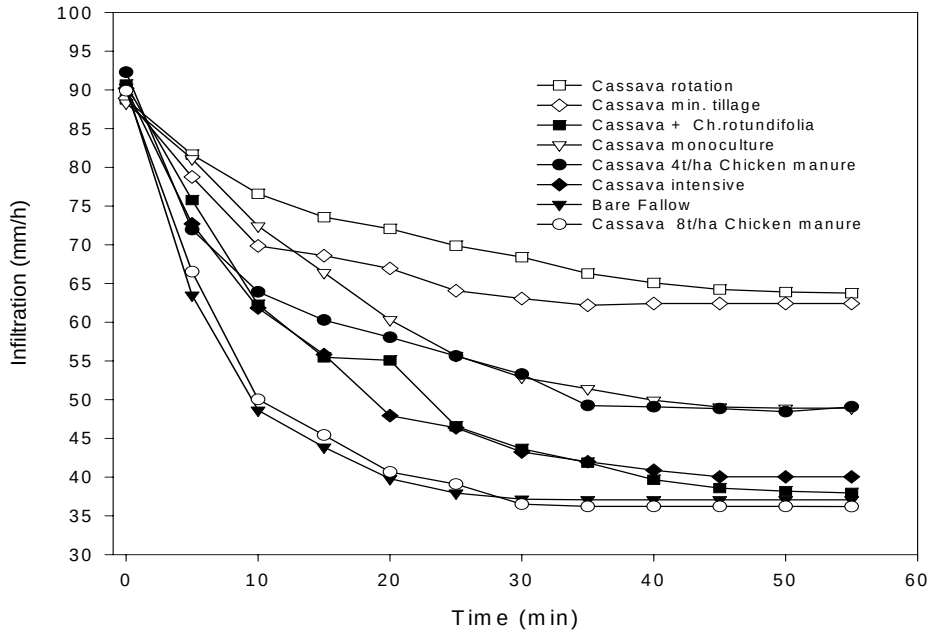


Figure 2. Effect of treatment on infiltration measured by rainsimulation, March 2000. Location: Santander de Quilichao**.**

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Table 3. Cassava root yields, Santander de Quilichao, 2000.

| Treatment | Yield (t/ha) |
|---|---|
| Cassava monoculture | 4.33 a |
| Cassava int. tillage | 11.98 b |
| Cassava + *Chamaechrista rotundifolia* | 21.05 c |
| Cassava (V) 4t/ha chicken manure | 21.90 c |
| Cassava 8 t/ha chicken manure | 23.17 cd |
| Cassava minimum tillage | 27.01 cd |
| Cassava rotation (*Brachiaria decumbens* + *Centrosema macrocarpum*) | 30.59 e |
| Cassava 4 t\ha chicken manure | 30.92 e |

Means followed by different letters within the column are significant at 0.05 probability level (Duncan test).

**Discussion**

In summary, penetration resistance and shear strength showed no risk of structural damage in the wet season. This worsened in the dry season when Chicken manure treatment turned into hard and impermeable soils. Although, the minimum tillage treatment had high penetration resistance and high shear strength values, this caused no deterioration because of a good aggregation status. This can clearly be seen in the results of infiltration measurement. Monoculture and intensive tillage had neither high penetration resistance nor high shear strength. In contrast, these treatments easily built up the so-called pseudo-sand that lead to high proportions of small aggregates, and thus to high amounts of soil erosion. The more modern techniques of Minimum tillage and Cassava rotation had the best and most sustainable status. Those treatments had a good aggregation, showed adequate infiltration rates and did not suffer from human induced fertilizer damage, e.g. soil hardening due to chicken manure or deterioration of soil matrix through intensive tillage. Chicken manure, especially 8 t/ha, had a severe impact on soil surface.

Further research is needed to specify the reasons why chicken manure has such an influence on aggregates. It is unclear which dispersion agent might be that leads to aggregate dispersion. Furthermore, structural changes through intensive tillage or minimum tillage have to be looked at more closely in order to ascertain how severely aggregate breakdown affects plant growth on Inceptisols.

**Conclusion**

Results from penetration and shear strength measurement showed the marked influence of chicken manure on soil structure. Chicken manure generally resulted in a deterioration of soil's structural status. A reduction of infiltration, especially in chicken manure plots, substantiates the hypothesis that inappropriate fertilizer management is one of the key factors in structural deterioration on Inceptisols. Dispersion of clays, generally cited as the main reason for soil sealing, is influenced by the impact of chicken manure. Further research will need to focus on the impact of fertilizers on the soil surface in order to design sustainable land-use systems for Andean hillside farming.

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*Report for IDRC 'Folk Ecology' Project*

**Increasing understanding of local ecological knowledge and strengthening interactions with formal science strengthened.**

J.J. Ramisch and M. Misiko
TSBF-CIAT, PO Box 30677, Nairobi, Kenya

**Rationale:** The project is testing a community-based interactive learning approach, which aims to improve and sustain agricultural productivity by facilitating a common understanding between scientists, farmers and other stakeholders about how agro-ecosystems operate and how best to manage them.

The major goal of the project is to develop innovative and interactive learning tools to facilitate the exchange of knowledge and skills between farmers, scientists and other agricultural knowledge brokers. The specific focus of the project is to broaden farmers' soil fertility management strategies by incorporating scientific insights of soil biology and fertility into their repertoire of folk knowledge and practical skills.

A parallel goal is to strengthen the understanding of indigenous agro-ecological knowledge among scientists, extensionists and other stakeholders and to elucidate the local realities and complexities that determine farmers' decision making. This interactive and multidirectional communication process provides opportunities for both farmers and scientists to question and validate their knowledge. It also presents a mechanism for disseminating and sharing useful local knowledge between different groups of agricultural stakeholders.

**Progress:** The major activities of the first year were largely exploratory in nature, covering three main areas: 1) community studies and learning activities (this Activity section), and 2) development of methodologies for the research and for farmers to share information with each other and with researchers, and 3) monitoring and documentation (for both, see Activity 2.2 "Community-based learning and dissemination strategy developed"). The coming year will see much more emphasis on communication strategies, building on existing knowledge, and broadening the scope of farmer-to-farmer exchanges.

Community studies and learning activities: The four study sites all have some previous exposure to either TSBF or local NGO's that had worked on soil fertility management. They cover a range of agro-ecological conditions and ethnicities, and thereby present an interesting and representative diversity of communities in Western Kenya (Box 1).

**Box 1. Overview of study sites**

| Site name | District | Ethnicity | Pop. Density (people / $km^2$) | Annual Precip. (mm) |
|---|---|---|---|---|
| **Ebusiloli** | Vihiga | Luyia | 1100 | 1800-2000 |
| **Bukhalalire** | Busia | | 384 | 1270-1790 |
| **Muyafwa** | Busia | | 365 | 1270-1790 |
| **Aludeka** | Teso | Teso | 436 | 760-1015 |

The project began with introductory, community discussions, which led into exploratory group work to assess the types and extent of knowledge and assumptions held locally about soil fertility and soil ecological processes. Once this baseline study of 'folk ecological' knowledge was completed, there were

various follow-up activities concentrating on key informants and specialist groups.

*Community and key informant interviews and seminars*
The introduction of the project centred on community interviews held in the four sites. These events, facilitated by a multi-disciplinary team had as their objectives:

- Determining the local "vocabulary" used for discussing soil fertility
- Identifying concepts locally related to soil fertility knowledge (classification, process, relationships)
- Identifying the elements of locally understood "common sense" related to soil fertility
- Identifying the individuals or groups who possess specialised knowledge of soil fertility and its management
- Identifying the assumptions or "rules" of local soil fertility knowledge.

Following the initial meetings, farmers and researchers alike were eager that findings be returned to initial groups for discussion and validation. The collective findings of the community interviews were synthesised and presented back to the communities in open seminar events, which led to follow up activities on locally important themes. In particular, transect walks and other ground-truthing activities helped both broaden the involvement of community members beyond the participants of the initial meetings and to build rapport with potential key informants with specialist knowledge.

Key findings from the baseline study activities include:

- Local soil types were readily identifiable. Local descriptions distinguished more soil types than were recognised as distinct soils by scientists. Soil maps are based on 'expert opinion' but do not reflect the high familiarity and local knowledge of farmers in daily contact with their land. Individual farmers also adapt common local names to the soils found on their own land.
- Soil names reflected features of the surface layer: colour, texture, depth, fertility, erosion, first user or settler (i.e. history). Soil was understood holistically, as "mother", "ourselves", "life", or "wealth", and not just as a physical surface on which life is found. The soil was more commonly acknowledged as the source of life and wealth rather than alive or a type of wealth in its own right.
- Farmers identified a diversity of directly observable, constituent parts of soil (living and non-living), including minerals, sand, silt, decaying things, worms, insects, moisture, and temperature. The presence of invisible or microscopic aspects of the soil was observed indirectly, through the growth of specific wild plants, or through crop performance.
- No single local terminology exists to describe soils' fertility status, and there was no significant gender difference in the use vocabulary or concepts. A linguistic difference was that the Teso word "*aboseteit*" referred to soil fertility and things that enhance it, while Luyia used a more general word "*obunulu*" to denote both a fertile soil and rich, fatty meat.
- Multiple analogies were used when describing soil fertility, including paired opposites like "healthy / sick or hungry", "strong / weak or tired", "young / old", "moist / dry". The aspects considered important in describing fertility were texture (light, loose soils were preferred to heavier ones, which would stick on implements), colour (darker soils were considered more fertile), health or energy (as seen in crop performance, "weak", "old", or "tired" soils need to rest or to be fed).
- Many locally known plants indicate high or low soil fertility. These indicator species, however, are not universal and their interpretation may vary. The presence of certain uncommon species may be enough to imply "high" fertility, while the relative performance of widespread species is often compared to give an indication of fertility. Generally, indicator species appear to reflect "inherent" soil properties more than trends of improvement or decline. Knowledge of plant indicators is both widely accepted and highly debated, and will be investigated further. In

particular, the distribution and use of this knowledge is being more intensively studied by the Master's student Nelson Otwoma (see "Training" below).

- Respondents assumed that without inputs soils become "poor" or "worthless". It was also widely believed that using inorganic fertilisers encourages crops to overexploit the soil's energy and can quickly "exhaust" or "bleach" the soil. Because organic inputs have longer residual effects than inorganic ones, respondents felt that both must be used in combination, or one will disrupt a desired balance of elements in the soil.
- Applying "farmyard manure" and constructing terraces were the most common soil management interventions. There was extreme individual variation between farmers in terms of what materials were included in "manure" and the manner in which they were managed while decomposing or applied to cropland. Manure management will be a major topic for further investigation. Only farmers in Aludeka did not commonly use manure, since land is relatively abundant and trypanosomiasis limits cattle keeping.

Major changes in managing soil fertility over the last fifty years include the introduction of inorganic fertiliser, construction of terraces, systematic use of livestock manure, fallow trees and compost. Traditional farming encompassed fallowing, shifting cultivation and slash-and-burn as major practices. Practices that were introduced by the government and had been or were being abandoned include crop rotation on an annual basis, since land is too limiting. The follow-up activities with key informants have particularly emphasised participant observation of management practices, which are notoriously difficult to discuss in the abstract and are more meaningfully observed on the ground.

*Issues relating to dissemination and learning*

Traditionally, information was disseminated communally and government did not have a role in provision of services like agricultural extension. Farmers learned mainly through observation, apprenticeship and experience, resources were abundant and knowledge on the environment was extensive. Today, farmers have more knowledge on intensive agriculture but use of this knowledge is constrained by limited access to key resources, including land, biomass and livestock. Many farmers reported that reduced landholdings and the difficulty of acquiring new land limit their ability to fully exploit their traditional knowledge of soils and their management. As a result of land scarcity, there was little correspondence between soil type and crops grown, even when farmers stated that a given soil was not well suited to the crop being grown. Resource constraints will almost certainly limit the relevance and amount of traditional knowledge being passed on to later generations.

Usually, information about meetings and other research events is given out to relatively few farmers. This information later reaches their friends and also neighbours and relatives. In addition, most of such events are held in the open where most passers-by see. Nevertheless, some farmers did not feel encouraged to attend these events. As an example, a woman who lives adjacent to a TSBF research plot in Emuhaya said: "I would like to attend research events, …but I have no one to 'follow' (i.e. orientate her to them)". She was aware that research on soil fertility had been continuing for long in her village. She also knew it would be beneficial but had never regarded herself to be part of the process.

Specifically relating to dissemination of knowledge on soil fertility, there was a common feeling amongst participants in the four sites was that there was inadequate awareness creation on soil fertility research. Many farmers did not understand how they would participate or even directly gain. It is as a result of this that many farmers still expect money or other handouts from researchers. Farmers suggested some steps that could be useful in enhancing the spread of knowledge on soil fertility:

- Experimental and demonstration plots should be soil-based; located in different soil types found in the study areas, which would assist farmers to relate the practices to their situation easily. Participants observed that some trial plots may have performed better than others due to differences in soils and that some preferred practises would be inapplicable in certain soils. At present, TSBF hires trial plots depending on their availability, adequacy of size and shape of trial

plot, willingness of farmers to rent their plots out and to co-operate, security, accessibility, absence of such barriers as rocks and termite mounts, representativeness of agro-ecological zones.

- Plots should bear well-labelled posters showing procedures on experiments and stating that it is pure "trial" and not something automatically beneficial or "interesting" to farmers. One farmer suggested that trial plots that are managed by the researcher should be hidden from busy roads so that they are not seen by passers-by especially when they perform poorly (as was the case with some plots in 2000).
- Technologies should be better adapted to farmer conditions. Participants in focus group discussions suggested that green manure species that mature within a shorter period and which can be inter-planted with crops and/or eaten would be preferred. Such technologies should be developed so that they can be broadcast in the farm, without necessarily having to be planted carefully in lines or rows. The main concern was that new technologies should not require rigorous skill and experience.
- Group-based approaches, including collectively identified and run plots can be effective venues and tools for passing new technologies to farmers. In Emuhaya, several 'Farmer Field Schools' have emerged spontaneously to broaden community participation beyond the original, rather exclusive 'Adaptive Research Farmer Groups'. Local level meetings where farmers could exchange ideas have been tried in the past in other sites, but have not been sustained. It is necessary to involve many people in activities of dissemination. Awareness can be done through field days, demonstrations, visits or exposure tours to other areas.
- It is widely felt that individualistic behaviour and the absence of 'traditional' practices that once united communities (beer brewing, labour sharing, etc.) undermine collective endeavours today. It is certainly true that few activities promote positive competition amongst farmers. Household differences and clan rivalries are also major sources of division, although most key informants felt that they could be overcome with good leadership.
- Low interest in research work was partly attributed to poor leadership. Researchers, like local leaders were said to "stand before farmers and address them". The two were therefore similar. Just as local leaders never delivered on their promises, research was initially seen to be unproductive. For instance, a bean variety that is suitable for N Eastern Kenya was planted on one of the key informant's plot in Emuhaya. As with the poorly performing trial plots in 2000, this inadvertently created the impression that "if a specialist's work failed, what is the point in learning how to copy it?"
- Farmers have 'tools' of measuring researchers. Those with meaningful intentions and hardworking are known and easily draw farmers' attention. Farmers should be consulted when deciding on ways of teaching.
- Farmer research groups have limited participation of non-members through charging of subscriptions. Most farmers perceive subscription as extortion and expressed their objection that "information from research bodies should not be passed through such groups".

**Training and capacity building:** To investigate the dynamics of how agro-ecological knowledge is generated and shared within a community, two master's level research activities are being conducted. The first project takes a more anthropological approach to understanding the role of local indicators of soil fertility change (particularly plant species and plant growth traits) and the degree to which different groups or individuals have come to recognise given indicators, or value the information that those indicators impart. The second study (still in preparation) will take a more ethnobotanical approach to understanding the distribution and relevance of indicator species, and will likely be situated in a contrasting environment.

***Student Thesis (submission by end 2003)***

**"The role of indigenous knowledge in the management of soil fertility among smallholder farmers of Emuhaya division, Vihiga district."**

Nelson Juma Otwoma
University of Nairobi

**Justification:** This study will add to the search for information on soil fertility management being pursued by many researchers and planners. Besides, there is a growing appreciation and recognition of the importance of local or indigenous knowledge in the sustainable use of natural resources. But the lack of information stands in the way of good understanding of these methods. By taking time and effort to document the systems, they become accessible to change agents and client groups (Brokensha et al. 1999: xv).

The study does not, however, pretend that local knowledge and practices has the quick solution to the many problems facing farmers in the area of soil fertility management. Far from that, it recognizes the importance of integrated knowledge systems (modern and indigenous) and while focusing on the latter the study will pay attention to the former.

The Folk Ecology Project (that provides a background for this study) needs specific information that can facilitate the integration of two knowledge systems (modern and indigenous), which eventually will enable scientific information to become a component of the larger pool of local knowledge to be more efficiently applied by the local people themselves particularly in the area of soil management.

The Emuhaya division study site lies within a region, which has poor subsistence economy due to unreliable rainfall and highly fragile soils. Smallholder farmers in this region face the double tragedy of environmental degradation and increasing demand for food. While the extension workers and other agencies could be willing to assist, their efforts could be hampered by the prevailing low socio-economic status, especially among the small farmers. This, therefore, calls for the need to carry out a study, which could inform the donor community or, more importantly, the policy makers and communities themselves to enable them formulate a broad strategy within which resources can be more effectively focused.

The findings of this study could, therefore, enable governments, policy-making bodies, non-governmental organizations and donors to formulate and design strategies that can alleviate suffering emanating from soil nutrient depletion among smallholder farmers. Agricultural research institutions can also base on the findings to institute the intervention programmes that could improve the conditions of smallholder farmers so that they are not left vulnerable to adverse environmental effects. Extension workers can also use the report to enable them understand the indigenous knowledge perspective of soil fertility management practices.

In addition, the findings are also potentially replicable. Brokensha *et al* (1999) argue that it is quite apparent that indigenous innovations, which are found to be effective in one part of the globe, can be equally effective when made available to populations in similar ecological conditions in other parts of the world. The documentation of the vast amount of unrecorded; often rapidly disappearing indigenous knowledge could provide the basis for many effective development interventions, if this knowledge could be shared.

The general objective of the study is to describe indigenous knowledge of soils and how it relates to the management of soil fertility in the study area. Specific objectives include:

i) To identity the local diagnostic criteria for differentiating soil types among smallholder farmers within the study area.
ii) To identify local indicators for discerning soil nutrient depletion or loss among the study population.
iii) To investigate the soil fertility management practices used by smallholder farmers in the study area.

**Methods:** The field research phase of this study covered the long rains growing season of 2002, allowing the student to follow the on-farm activities and decision-making processes of key informants responding to various indicators of crop performance and soil fertility change. As such, it was expected to provide a useful window on an important aspect of local ecological knowledge and the extent to which it can (or does) inform local practice.

Many of the older key informants, for example, have stressed that much of the knowledge they have acquired about changing agricultural conditions is no longer particularly relevant to their livelihoods for the simple reason that their land base is now so constrained that there are fewer opportunities to match crops to given micro-sites on farm. The adapted knowledge of younger farmers, however, indicates that local soil variability can still be profitably exploited with different management strategies, at least by some classes of motivated individuals.

***Student Thesis (submission by 2004)***

**Identification of local plants as indicators of soil quality in the Eastern African region**

Somoni Franklin Mairura
Kenyatta University, Kenya

**Rationale:** Local plants as indicators of soil quality, like other biological indicators of soil quality, simultaneously reflect changes in the physical, chemical and biological characteristics of the soil. Because of their integrative nature they are often better early warning indicators than other conventional methods to detect changes in soil quality.

Natural and agricultural systems respond in a similar way to degradation and regeneration processes through the ecological principle of succession. During succession, plants and soil organisms that are best adapted, gradually substitute those least adapted, because of the selection exerted by changes in soil characteristics (i.e. some plants can tolerate more degraded soils than others, etc.). If we are able to identify local plants used by farmers to characterize their soils across a region we may be able to organize this information and identify trends which can provide insights about their potential use in making decisions about land management.

CIAT's work in Latin America has shown the important role played by local plants as indicators of soil quality (Barrios and Escobar, 1998). This document proposes a collaborative activity among CIAT, SWNM and AHI scientists to identify local plants used as indicators of soil quality in the Eastern Africa region using the AHI sites as a representative sample (i.e. Kenya, Tanzania, Uganda).

This collaborative work will lead to the preparation of a table with local plants used as indicators of soil quality to be included as a contribution of AHI to Guide #1 "Identifying and Classifying Local Indicators of Soil Quality (LISQ), Eastern Africa Edition (2001)". Within this context, work will clearly identify the localities where the observations are being conducted, and will select key informants and elder representatives of the different farmer communities in the study area for group analysis (brainstorming) sessions. The following questions will guide the discussion for identifying and prioritizing local plants as indicators of soil quality from the local knowledge base:

i) Are there any local plants (weeds, shrubs, trees) that only grow in fertile soils?
ii) Are there any local plants (weeds, shrubs, trees) that only grow in poor soils?
iii) Are there any local plants (weeds, shrubs, trees) that grow in all soils but that according to their growth, vigor and color can be used as indicator of the soil condition?
iv) If you were buying a new plot which plants would you use to characterize the quality of such plot for agricultural purposes?
v) After several seasons of cropping, you decide to leave your plot fallow by allowing natural regeneration of the native vegetation to take place. At what stage in that regeneration do you go back to cultivation? Are there any plants that indicate that your plot is ready for cultivation again?

Information gathered will be organized and prioritized using pair-wise ranking in order to provide a list of most important to least important of all the plants used as indicators of soil quality.

*Report to BMZ, 2002*

**Evaluation of current ISFM options by participatory and formal economic methods**

JJ Ramisch and I Ekise
TSBF-CIAT, PO Box 30677, Nairobi, Kenya

**Rationale:** Declining soil fertility problem is the single greatest threat to food security and livelihoods in Western Kenya. Findings of most soil fertility research work in the region indicate that the soils of this region are generally deficient in Nitrogen and Phosphorus nutrients. This problem has been caused by high population density and poor farming methods. For instance in Emuhaya area, farmers continuously crop their fields with minimal use of inorganic or organic fertilizers. This type of farming can not be sustained in the long run and if not checked could lead to deterioration in the farming environment. Some of the indicators of a deteriorating environment are; sharp decline of crop harvests, high incidences of crop and animal pests and diseases, frequent famine, deteriorating farm incomes among others.

**Progress:** A baseline survey of soil fertility management practices and socio-economic conditions was completed and analysed for 314 farmers in the West Kenya site. The methodology was shared with the Ugandan and Tanzanian sites. These data are being compiled and analysed along with comparable studies conducted at the other BMZ project sites in West Africa (Togo and Benin) to produce a scientific paper relating soil fertility management practices to the contrasting socio-economic and agro-ecological conditions of the sites.

Farmers, extension, and KARI-Kakamega field staff were trained in participatory monitoring and evaluation methods. Several forms of farmer recording keeping were introduced in 2001 to monitor and evaluate progress with the soil fertility management technologies. However, lack of funds has limited follow-up, which has lead to widely varying levels of farmer interest and disparate standards of data collection.

A good number of partners have since initiated trials in the region whose main goal was to enable farmers to produce agricultural products while reversing nutrient depletion on their soils. The purpose of this was to increase the farmer's capacity to develop, adapt and use integrated nutrient management strategies. The integrated soil fertility management options tried include; biomass transfer using Tithonia diversifolia, use of improved fallow plants (Mucuna, Crotolaria grahamiana, C. ochroleuca, C. paulina, Canavalia, Sesbania sesban etc), use of high quality compost, integration of inorganics and organics. The partners in this research include; the African Highlands Initiative (AHI), Tropical Soil Biology & Fertility Programme (TSBF), International Centre for Research in Agroforestry (ICRAF), Kenya Forestry Research Institute (KEFRI), Kenya Agricultural Research Institute (KARI), Ministry of Agriculture Extension service and Farmer research groups. The research work was implemented through the framework of participatory technology development and transfer.

The initial target number of farms was 60 located in 5 villages of Ebusiloli sub-location of Bunyore East location in Emuhaya division of Vihiga district. The work was implemented through the farmer research group framework, which focused the village as the unit of research work. Each village was organized into a research group with elected officials managing their respective groups.

The specific objectives of this study are:

i) To quantify the costs and benefits of the practiced ISFM technologies in order to show the profitability of each technology.
ii) To conduct participatory ranking of the ISFM options based on farmers criteria and perceptions.
iii) To identify the constraints facing the ISFM practitioners and possible solutions to overcome them in order to improve the adoption of technologies being practiced.
iv) To build the capacity of the farmer field schools to innovate and share the results for collective action.

The FFS Framework: The farmer field schools work together to implement the study. Suitable farms were identified and the owner contracted using the procedures of TSBF and ICRAF being currently used to implement other trials. The decision support systems (DSS) layout for the trial (see section 2.3) in Emuhaya was adopted. There is concern from the farmers that treatment plot sizes need to be increased for more visibility. They propose to have 10 m x 10 m plots. The farmer field schools propose to include the local (indigenous) plants and test them as well. The treatments will be randomly selected and established.

**Formal economic analysis of current ISFM options**

**Rationale:** In sub-Saharan African countries like Kenya, small-scale farmers account for about 70% of the over all production and produce more than 75% of the total food crops. Soil erosion, depletion of ground cover due to overgrazing and nutrient depletion due to continuous cropping has lead to low living standards among the majority of the rural households. The depletion of the natural resources (land and forests) as a result of population pressure and continuous cropping in the study area does not augur well for the future generations who are expected to live on and derive their subsistence from such lands.

To reverse the trend of rapid decline in the quality of soil and the physical environment, large investment in soil fertility technologies and soil conservation works is needed. This study seeks to justify and warrant such investment by providing quantitative and empirical evidence of the importance, appropriateness and economic competitiveness of agroforestry-based and other integrated soil fertility management (ISFM) technologies as strategies that are potentially capable of solving and alleviating productivity problems. The findings will be useful in terms of postulating suggestions to policy makers pertaining the incentives and institutions that can be put in place by the government and other stake holders to enhance the promotion and expansion of the emerging technologies of addressing soil nutrient depletion.

**Training and capacity building:** Two master's level research projects are currently on-going. The first uses the policy analysis matrix (PAM) technique to evaluate the private and public benefits and costs of different ISFM options. This approach is particularly useful for examining the role of transaction costs and market failures in influencing profitability of new technologies. The second study determines whether the soil fertility management and livelihood enhancement needs of different classes of farmers are being met with the ISFM options currently available to them, by contrasting the profitability of different options (using gross margin analysis).

***Student Thesis (submission in early 2003)***

**The Competitiveness of Agroforestry-based and other Soil Fertility Enhancement Technologies for Smallholder Food Production in Western Kenya.**

Julius Mumo Maithya
University of Nairobi, Kenya

**Abstract**: Most countries in sub-Saharan Africa have been faced with persistent food insecurity accompanied by low and declining agricultural production and productivity. Although in Kenya population growth has been on the decline, increased settlement on arable land has exerted pressure and heavy demands on natural resources especially land. As a consequence, continuous cropping has been very common among majority of the smallholder farmers leading to soil nutrient depletion. Many studies in Kenya have shown that soil fertility depletion among smallholder farms is responsible for the persistent food insecurity and declining per-capita food production.

In order to address the soil fertility problem, researchers in International Centre for Research in Agroforestry (ICRAF) and Tropical Soil Biology and Fertility programme (TSBF) have been able to develop and promote agroforestry-based technologies. They include biomass transfer and improved fallows.

Although these agro forestry based technologies together with *Minjingu* rock phosphate are being used by farmers in western Kenya, little is known about their economic competitiveness in terms of how efficient resources are being used to produce food under these soil fertility enhancement technologies. The proposed study is an attempt to bridge the above-mentioned gap in knowledge by providing a quantitative evidence of farm level profitability (both private and social) of food production under the above mentioned soil fertility replenishment technologies. The study will be carried out in Siaya and Vihiga districts, western Kenya.

The Policy analysis methodology (PAM) will be used to analyse both primary and secondary data. A multi stage stratified sampling method will be used to select a total of one hundred and twenty farmers, sixty from each of the two districts. The selected farmers will be interviewed using structured questionnaires.

A reconnaissance survey will be conducted in the area of study to identify the farmers to be interviewed. A questionnaire pre-test will be done on farmers in the area but the sample of the pre-test farmers will be outside the sampling frame.

The over-all objective of the study will be to determine the competitiveness of both agro- forestry based soil enhancement technologies and use of Minjingu Rock Phosphates for smallholder food production. The specific objectives will include:

i) To determine the financial profitability of food production under agroforestry-based technologies (improved fallows and biomass transfer) and *Minjingu* rock phosphate as alternative soil nutrient replenishment technologies.
ii) To determine the social profitability of food production under agroforestry-based technologies and *Minjingu* rock phosphates as strategies of the soil fertility enhancement.
iii) To compare the competitiveness of both inorganic fertilizers and agroforestry-based technologies for food production.
iv) To compare the profitability of maize and horticultural production using agroforestry based technologies.

*Student Thesis (submission by 2004)*

**Assessment of adoption potential of soil fertility improvement technologies in Chuka Division, Meru South, Kenya**

Ruth Kangai Adiel
Kenyatta University, Kenya

**Abstract:** Declining soil fertility is a key problem faced by farmers in Eastern Kenya. The problem has been worsened by increased population growth and at the same time, high demand for agricultural produce. To solve the problem land users are being encouraged to adopt soil fertility improvement technologies, which use locally available resources. In on-going demonstration trials at Kirege primary school (Chuka division), a number of such technologies are being demonstrated for which farmers are being encouraged to voluntarily select the technologies that they would wish to adopt on their farms. This study will therefore set out to evaluate the extent of the technology adoption as well as how the farmers modify such technologies, and the gender issues in dissemination and adoption of the technologies. To do this, a farmer follow-up study will be carried out in Chuka division over a period of two cropping seasons. Data will be collected using farm surveys, which include both formal and informal surveys, on-farm trials and visual records. Gross margin analysis will be used to determine the most profitable treatments / technologies. Lastly, logistic regression analysis will be used to determine important variables in the adoption of a new technology.

The overall objective of the study is to increase food production by better understanding the adoption of technologies capable of improving soil fertility status in the smallholder cropping systems of central and eastern Kenya. The specific objectives are:

i) How do different socio-economic classes of farmers in Chuka, eastern Kenya differ in their soil fertility improvement needs?
ii) Which soil fertility management technologies have been most adopted by different classes of farmers?
iii) How profitable, agronomically beneficial, and labour demanding are the soil fertility management technologies being used by farmers in Chuka?
iv) How are the farmers of different genders or socio-economic classes modifying the soil fertility management technologies?
v) How are the farmers of different genders or socio-economic classes disseminating the soil fertility management technologies?

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# Integrated soil fertility management: evidence on adoption and impact in African smallholder agriculture

Frank Place[1], Christopher B. Barrett[2], H. Ade Freeman[3], Joshua J. Ramisch[4] and Bernard Vanlauwe[4]
[1]ICRAF, Nairobi, Kenya
[2]Cornell University, USA
[3]ICRISAT, Kenya
[4]TSBF, Nairobi, Kenya

**Abstract:** This paper reviews current organic nutrient management practices and their integration with mineral fertilizers in Sub-Saharan Africa with a view to understanding the potential impacts on a range of input markets. A number of different organic nutrient management practices have been found to be technically and financially beneficial, but they differ considerably as to their effectiveness and resource requirements. Review of African smallholder experiences with integrated soil fertility management practices finds growing use, both indigenously and through participation in agricultural projects. Patterns of use vary considerably across heterogeneous agroecological conditions, communities and households. The potential for integrated soil fertility management to expand markets for organic inputs, labor, credit, and fertilizer is explored. We hypothesize that markets for organic markets are hampered by inherent constraints such as bulkiness and effects on fertilizer markets are conceivably important, although no good empirical evidence yet exists on these important points.

## 1. Introduction

There has been renewed attention on soil fertility replenishment in Sub-Saharan Africa as critical to the process of poverty alleviation, as symbolized clearly by the award of the 2002 World Food Prize to Pedro Sanchez, a pioneer in the field. Soil fertility is crucial because in Africa poverty is mainly a rural phenomenon. With 70% of the population in the rural areas and 60% of those living below the poverty line, a whopping 85% of the poor are found in rural areas (Mwabu and Thorbecke, 2001). Since over 95% of the rural population is engaged in agriculture to some degree, any short to medium term poverty reduction strategy that ignores agriculture is doomed to fail.

In many places, the rural poor cannot expand land holdings. Per capita arable land in Sub-Saharan Africa has shrunk dramatically from .53 to .35 hectares between 1970 and 2000 (FAOSTAT, 2002). Accelerated and sustainable agricultural intensification is required. Returns per unit land must increase in order to provide sufficient food for the (rural and urban) poor and output per worker must rise in order to lift the incomes of the poor. This has clearly not taken place as evidenced by the stagnant crop yields and per capita indices for agricultural and food production. For example, per capita agriculture, food, cereal, and livestock production indices are all below levels from 1990. While the first steps to reverse this trend are hotly debated, it is certain that increased agricultural productivity and improved rural livelihoods cannot occur without investment in soil fertility.

There is no shortage of evidence showing the dismal state of Africa's soils. African soils exhibit a variety of constraints, among them: physical soil loss from erosion, nutrient deficiency, low organic matter, aluminum and iron toxicity, acidity, crusting, and moisture stress. Some of these constraints occur naturally in some tropical soils, but they are exacerbated by severe degradation processes. Degradation of some form is pervasive on the continent, with less than 20% of soils said to be unaffected by degradation (FAOSTAT, 2002) and about two-thirds of agricultural land to be degraded (Oldeman et al., 1991). About 85% of degradation is attributed to water and wind erosion, with the rest being mainly *in situ* chemical degradation (Oldeman et al., 1991).

The lack of nutrient inputs among smallholder African farmers exacerbates the nutrient deficiency of soils. Fertilizer use was never high in Africa. Exchange rate devaluations and the termination of government fertilizer subsidy programs throughout the continent over the past fifteen years

have sharply increased the real price of mineral fertilizers, putting them beyond the reach of most small farmers in Africa, at least at anything approaching recommended application levels. As a result, while the rest of the world averages 97 kilograms of fertilizer per hectare, in Africa, only 9 kilograms are applied to the average hectare of land (Gruhn et al, 2000). The rate is lowest in central Africa (2 kg per ha) and in the Sahel (5 kg per ha). Even when fertilizer is combined with other organic sources, studies throughout the continent have found high negative nutrient balances to occur in nearly all countries (Henao and Baanante, 2001). The estimated losses, due to erosion, leaching, and crop harvests are sometimes staggering, at over 60 – 100 kg of N, P, and K per hectare each year in Western and Eastern Africa (e.g. Stoorvogel and Smaling, 1990; de Jager et al. 1998).

Integrated soil fertility management (ISFM), developed more fully in section 3, is being widely studied and is rapidly becoming more accepted by development and extension programs in Sub-Saharan Africa, as well as, most importantly, by smallholder farmers in Sub-Saharan Africa. This paper begins with a brief setting of the context, demonstrating the key variations in agro-ecology, market opportunities, and farming systems in Africa and how these will condition the incentives for ISFM. The following section synthesizes evidence to date on the biological and financial impacts of organic nutrient practices and ISFM. Section 4 synthesizes available evidence on markets for organic nutrients, including supporting markets for seed, labor and credit. Section 5 provides a comprehensive summary of evidence on farmer investment in and management of organic nutrients and ISFM. Lastly, we conclude the paper with implications for research priorities, design and dissemination of ISFM, and policy reform.

## 2. Potential for mineral and organic inputs in SSA

Sub-Saharan Africa is very heterogeneous in terms of soils, climate, agricultural potential, market access, and population density. These differences influence the types of organic nutrients that are technically feasible to produce, the types of crops that will benefit from such application, opportunity costs of land and labor, and cost of acquiring mineral fertilizers. In short, the incentives for producing and using specific types of nutrient inputs are highly variable across the continent.

The physical and agroclimatic conditions in Sub-Saharan Africa are extremely diverse. Broad agro-ecological zones range from the semi-arid tropics, with around 400-800mm of rain per year, to humid highland regions that may average over 1,800mm of rain supporting two growing seasons. Soils are also quite distinct in texture, inherent soil physical, chemical, and biological health, potential for erosion and other forms of degradation. For example, crusting is a major problem in the semi-arid zone, aluminum toxicity in the humid lowlands, and erosion in the hilly highlands. In the more favorable zones, a wider range of organic based systems will be feasible, but they will also need to compete against a wider range of agricultural enterprises for land and labor. In the drier zones where growing plants becomes riskier and costlier, livestock assumes a more important role in the provision of organic nutrients.

Soils are also highly varied within small geographic areas. They maybe affected by physical features such as topography or historical land use and vegetation cover. Thus, it is quite common to find relatively fertile soils where deposition has taken place due to erosion. Soil variation may also occur across or within farms due to management patterns. For example, greater soil fertility status has been found among wealthier than poorer households in western Kenya (Shepherd and Soule, 1998) and in plots near homesteads (Prudencio, 1993).

Population densities vary noticeably within each of these zones, but generally, population pressure is highest in the more favorable agricultural zones. They are relatively lower in the semi-arid lands and minor portions of the humid lowlands (e.g. in forest margin areas) and subhumid zone (e.g. Zambia). They are highest in the highlands of East Africa, with densities of over 600/km$^2$ being very common. Densities of 250/km$^2$ or more are also found in some humid lowlands and sub-humid areas in West (e.g. Nigeria) and Southern Africa (e.g. Malawi). Such densities imply that average farmsizes among smallholder farmers will be 2 hectares or lower. Small farm sizes limit farmers' ability to find niches for the production of intermediate inputs for green manure or feed for livestock. Despite high population densities, the agricultural labor supply is not always plentiful in such areas, especially where

school enrollment rates among children are high and non-farm income-earning opportunities are strong. Moreover, many very poor rural households are relatively labor scarce, exhibiting high shadow wage rates (Barrett and Clay forthcoming), limiting uptake of labor-using technologies, even among the poor in high population density areas.

Market infrastructure development is similarly varied across the zones, but is not fully functional or efficient in any of the zones. There are low densities of main trunk roads with feeder roads that are of low quality and often seasonally impassible. The more densely populated areas enjoy somewhat better transportation opportunities, piggy-backing on public transport vehicles and greater densities of market centers. Despite a general tendency towards liberalization of both input and output markets throughout the continent, in some cases government parastatals still play an important role (e.g. coffee in Kenya, maize in Malawi). Further, liberalization has yielded spatially heterogeneous and generally mixed price and market access incentive effects due to changing risk characteristics, limited inter-seasonal credit availability, and meager private storage or transport capacity (Yanggen et al. 1998, Barrett and Carter 1999, Reardon et al. 1999).

## 3. Organic nutrient management, integrated soil fertility management, and crop yields in SSA

The Integrated Soil Fertility Management (ISFM) paradigm acknowledges the need for both organic and mineral inputs to sustain crop production without compromising on environmental issues (Buresh et al., 1997; Vanlauwe et al., 2002). The paradigm further acknowledges that plants also require a conducive physical, biological, and chemical environment, apart from nutrients, to grow optimally. Besides these organic and mineral inputs, the soil organic matter pool, which reflects past soil management strategies, is another substantial source of nutrients. Each of these sources contributes to crop production and the provision of environmental services individually, but more interestingly, these resources can be hypothesized to interact with each other and generate added benefits in terms of extra crop yield, improved soil fertility status, and/or reduced losses of nutrients to the environment.

The earlier work on soil fertility management in SSA focused on the use of mineral inputs to sustain crop production. Numerous studies that have looked at crop responses to applied fertilizer report substantial increases in crop yield and financial returns (e.g. Yanggen et al., 1998; Snapp et al., 1999). National fertilizer recommendations exist for most countries, but actual application rates are nearly always much lower due to constraints of a socio-economic rather than a technical nature (see section 5). On the technical side, however, mineral inputs were further discredited due to the observed environmental degradation resulting from massive applications of fertilizers and pesticides in Asia and Latin America between the mid-1980's and early-1990's as a spin-off of the Green Revolution (Theng, 1991). As a result, soil fertility management strategies were refocused towards the use of organic amendments and considerable enthusiasm emerged around so-called "agro-ecological" approaches to agricultural development in the tropics (Uphoff 2001).

Among the most commonly used or promising organically based soil nutrient practices are: animal manure, compost, incorporation of crop residues, natural fallowing, improved fallows, relay or intercropping, and biomass transfer. These are briefly described in table 1 below. While we focus on soil nutrient management practices, there are a host of other management practices that are vitally important to overall soil fertility, including soil conservation techniques, weed management practices, and cropping strategies themselves.

Initially, organic resources were merely seen as sources of nutrients, mainly nitrogen (N), and a substantial amount of research was done on quantifying the availability N from organic resources as influenced by their resource quality and the physical environment (see Palm et al., 2001, for example). Various classes of organic resources were identified based on their short-term N supply, which in turn depends on nutrient acquisition methods, concentrations of nutrients in biomass, total biomass production, and decomposition characteristics (Vanlauwe and Sanginga, 1995; Vanlauwe et al., 1998). More recently, other contributions of organics have been emphasized in research, such as the provision of other macro and micro-nutrients, reduction of phosphorus sorption capacity, carbon/organic matter, reduction of soil borne pest and disease spectra in rotations, and improvement of soil moisture status. There are

some key differences in the way that the organic systems contribute to soil fertility. Those systems that use nitrogen-fixing species are able to add nitrogen without withdrawing it from soils (either *in situ* or *ex situ*). Some can produce over 150 kg of nitrogen per hectare (e.g. a single season crotalaria fallow). Plant systems that are based on trees may further recycle deep nutrients (through roots) that would otherwise have been unavailable to annual crops. The different systems are not necessarily equally effective in providing nutrients. Organic sources will differ in terms of nutrient content, mineralization processes (in which the nutrients in the organic compounds can become available to the crop), and the provision of other soil fertility benefits (e.g. weed reduction). Aside from the organic source itself, management aspects can also affect the effectiveness of organics in increasing soil fertility. A key management distinction is the growing of legumes *in situ* (as opposed to transferring biomass from outside the plot) which can provide other benefits to crops through rotation affects (e.g. reducing the incidence of weed) and through water infiltration effects (from the root systems).

Despite these positive aspects, organic nutrient systems are not able to sufficiently replenish soils by themselves. First, concentrations of phosphorus and potassium are very low in organic manures. Second, the efficiency with which N and other nutrients can be used by crops can be low. Other problems related to the sole use of organic inputs are low and/or imbalanced nutrient content, unfavorable biomass quality, limited land for production of organic material, or high labor demand for transporting bulky materials (Palm et al., 1997).

It has been recently acknowledged that organic and mineral inputs cannot be substituted by one another and are both required for sustainable crop production (Buresh et al., 1997; Vanlauwe et al., 2002). This is due to (1) practical reasons – the amount of either fertilizer or organic resources alone would not be sufficient or organic resources were found unsuitable to alleviate certain constraints to crop growth, e.g., the lack of P in Nitisols with strong P sorption characteristics (Sanchez and Jama, 2002) and (2) the potential for added benefits created through positive interactions between organic and mineral inputs. Several attempts to quantify the size of added benefits and the mechanisms creating those have been made. Vanlauwe et al. (2002) reported that integration of maize stover increased the recovery of urea-N, most likely due to its temporary immobilization of urea-N. In a multilocational trial in West Africa, Vanlauwe et al. (2002) demonstrated added benefits from combined organic and mineral treatments through reduced moisture stress at critical growth phases of the crop. In a set of trials in sandy soils of Zimbabwe with various mixtures of cattle manure and ammonium nitrate, Nhamo (2001) observed added benefits ranging between 663 and 1188 kg maize grains per hectare. This synergy was attributed to the supply of cations contained in the manure.

Although the above list of observed positive interactions between organic and mineral inputs is not exhaustive, very often these inputs are also demonstrated to have only additive effects. But because of declining marginal increases from one single type of input, the additive effects are often superior in terms of overall yields and net returns, as shown by Bationo et al. (1998) for millet in Niger and Rommelse (2000) on maize in Kenya. Fortunately, negative interactions are hardly ever observed, indicating that even without clearly under standing the mechanisms underlying positive interactions, applying organic resources in combination with mineral inputs has negligible downside risk and considerable upside potential, thereby constituting an appropriate fertility management principle.

The ISFM paradigm has further broadened the scope for potential interventions in a number of ways. First, interactions between various crop growth factors were widened beyond nutrients. In Sahelian conditions, e.g., Zaongo et al., (1997) observed striking increases in water use efficiency for sorghum after application of fertilizer. Secondly, recognizing that soil fertility varies widely within a farm due to site-specific management by the farmer with drastic effects on crop yields, attempts are on-going to target resources, both of organic and mineral origin, to this within-farm variability in soil fertility status, rather than developing blanket recommendations. Bationo et al. (Unpublished data) showed a considerable improvement in P use efficiency from 47 to 79% when applying the P on a non-degraded homestead field rather than a degraded bush field. Vanlauwe et al. (Unpublished data) showed that N fertilizer use efficiency decreased from 45 to 30% when topsoil carbon contents increased from 0.3 to 0.8%. Thirdly, ISFM also highlights the need for improved germplasm. Improved crop germplasm does not only have a

major role to play in improving nutrient acquisition but also in providing more organic inputs. Efforts have recently been made by various research centers to develop dual or multipurpose grain legume varieties (e.g. Sanginga et al., 2001).

In summary, there is considerable evidence demonstrating the important contributions of organic matter to agricultural crop yields. There is more limited, but still significant evidence attesting to the positive impacts of integrating organic and mineral nutrient sources in the short and long term. One interesting caveat is that nearly all research on ISFM has taken place on cereal crops. Yet, as we shall see in section 5, much fertilizer use by smallholders in Africa is steered towards more high value crops. The effects of organics and ISFM on non-cereals remain under-researched.

## 4. Actual nutrient management practices of African farmers

There are likewise several socio-economic sources of complementarity between organic and mineral inputs in soil fertility maintenance. Mineral fertilizer must be brought to the farm while organics can be home-grown, saving on transport costs and reducing uncertainties of market acquisition. The two approaches to soil fertility management require investment using different household resources, with fertilizer requiring financial capital and organics requiring labor and land (initial investment in livestock will require capital). The capital-intensive nature of fertilizer use is exacerbated by inflexible packaging arrangements creating a minimum $20 - $30 expenditure for a single bag. Several development projects and retailers sell fertilizer in smaller amounts, but farmers' lack of trust in shopkeepers seems to inhibit the growth of decentralized repackaging. Finally, in terms of quantities available, imported mineral fertilizers are in theory plentiful if the demand is there. On the other hand, production of organics is limited by available land and therefore supplying sufficient amounts for one's farm, let alone for sale in the market, can prove challenging.

Macro or meso level factors may impinge on the ability of communities to access certain types of nutrients. For example, fertilizer has been absent from retailers in Uganda until recently and is more readily available in peri-urban areas than in remote areas, very few cattle keepers are found in Malawi, and many types of green manures cannot grow effectively in drier zones. But it is the heterogeneity among households more than variation between agroecological zones that explains most of the observed differentiation in the use of different soil fertility practices. Significant uptake of integrated organic and mineral practices for improving soil fertility has occurred throughout SSA, in the highlands of East Africa (Murithi, 1998; Gebremedhin and Swinton, 2002; Place et al., 2002a; Clay et al., 2002), the humid lowland zone (Tarawali et al., 2002), the sub-humid zone (Mekuria and Waddington, 2002; Kristjanson et al., 2002; Peters, 2002), and the semi-arid areas (Freeman and Coe, 2002; Shapiro and Sanders, 2002; Kelly et al., 2002). Studies also show significant payoffs from the integration of mineral and organic sources of nutrients across different ecozones (Place et al., 2002a; Kelly et al., 2002; Shapiro and Sanders, 2002; Freeman and Coe, 2002; Peters, 2002; Mekuria and Waddington, 2002).

Several interrelated micro-level factors are at play in farmer input use patterns, including commercialization and access to land, labor, and capital. It is quite well documented that fertilizer use is strongly linked to commercialized production of cash crops (Kelly et al., 2002), ranging from parastatal run input-output supply programs to informal and opportunistic networks of peri-urban agriculture. There is some evidence to suggest in cash cropping systems organic inputs replace fertilizer when fertilizer supply becomes problematic (Bosma, *et al.*, 1996; Mortimore, 1998) or that the availability of mineral fertilizers for use on cash crops facilitates a broadened use of organic materials on food crops (Raynaut, 1997).

The relationship between commercialization and organic systems is also in general positive (Murithi, 1998; Kelly et al., 2002; Freeman and Coe, 2002), but there are obvious exceptions. Use of manure on cereal food crops is an old practice in the Sahel and southern Africa and continues today (Enyong et al, 1999; Williams, 1999; Ndlovu and Mugabe, 2002). Experimentation with new, plant-based, organic inputs often begins with their application on cereal crops, following traditional practices such as heaping or burning of familiar plant residues (Snapp et al., 1999). But animal manure is also commonly used on higher value commodities such as potato, coffee, and vegetables (Freeman and Coe,

2002; Shapiro and Sanders, 2002). And, as with manure, farmers have shifted promising innovations using new green organics systems (or integrations of organic and mineral fertilizers) onto higher value commodities such as vegetables (Place et al., 2002a). Furthermore, small farmers appear to consistently favor organics that serve as more than just a soil fertility amendment, offering food or animal feed that can be consumed or marketed as well, as with dual purpose legumes such as pigeon pea.

This pattern underscores that the positive yield returns described in the previous section can make the use of organics remunerative even in semi-subsistence systems, including places where purchased fertilizers remain unattractive. This difference, the propensity for using organics to increase production in high-value systems and farmers' preference for dual-purpose varieties over those that serve as fertility-enhancing inputs only, highlight the value of cash liquidity in areas plagued by a dearth of inter-seasonal credit. Those who earn cash from crop sales, or can avoid spending cash on input purchases, can often afford to hire labor or to purchase food and thereby dedicate their labor to input production on their own farm instead of having to hire out their labor in order to earn wages. But when the labor demands of the low external input (LEI) technology are substantial, as in many biomass transfer systems or other LEI technologies, the foregone wage earnings can impede adoption among poorer farmers (Reardon et al. 1999, Moser and Barrett 2002).

Land availability commonly constrains use of organic inputs produced on farm, like improved fallows (Place et al., 2002a). On the other hand it is not a major factor in biomass transfer systems, which are often focused on small plots of high value crops. The evidence on the effect of labor availability on adoption of organic inputs is mixed. While additional labor effort is often identified by farmers, they commonly find ways to reduce labor burdens to fit their needs through adaptation of extended technologies. For example, intercropping of pigeon pea with maize in Malawi saves labor (and land) compared to a sequential system (Waddington, 1999). Farmers in Western Kenya are also opting to use local plant species (such as *Tithonia* or *Vernonia*) identified as good nutrient sources as additions to existing composting systems, which use labor in small increments rather than as part of cut-and-carry systems which would demand major labor inputs at the time of crop planting (Misiko and Ramisch, unpublished data).

A key motivation for the promotion of organic nutrient systems is that by requiring little capital, they might reach the poor better than commercially distributed fertilizer. This is critical, because many studies have found that the poor are unable to use mineral fertilizers and the consequences on soil fertility and farm incomes are enormous (Soule and Shepherd, 2000). This largely seems not to be true in the case of animal manure because incomes tend to be highly positively related to livestock ownership. Manure use therefore appears to increase with a household's wealth (Mekuria and Waddington, 2002). But poorer households are using agroforestry-based nutrient systems and compost in Western Kenya at the same proportion as wealthier ones (Place et al., 2002a). Moreover, participatory methods are involving the poor much more in technology design.

Will the use of organics encourage greater use of mineral fertilizers?[1] A recent study of agroforestry improved fallow and biomass transfer systems in Western Kenya found that the systems were being used by 30 – 45 percent of those households who were not using fertilizer or manure (Place et al., 2002c). However, the use of agroforestry has not yet spurred an increase in the use of fertilizer. On the other hand, Abdoulaye and Lowenberg-DeBoer (2000) analyze data from Niger to show that patterns of intensification exhibit a pattern of graduation from manure to mineral fertilizer use. Expansion of options is good for smallholders. However, there remain information gaps as to how much the different options are being perceived as complements or substitutes by farmers.

## 5. Implications of organic nutrient systems on input markets

Markets depend fundamentally on there being positive net returns to moving goods across space or time, through transport and storage, respectively. The development of markets (formal or informal) for organic

[1] This relationship is not at all straightforward because proceeds from better harvests will normally be spent on other items before the time when fertilizer is needed for the next season.

inputs in Africa, as throughout the world, has been shaped and constrained by the extreme variability in the supply of organic resources and their relative 'bulkiness' (low nutrient value per unit mass). These factors conspire to limit trade in organic inputs, leading to extremely localised patterns of use.

The supply of organic resources that are potentially important contributors to agriculture – manure, crop residues, and other plant biomass – is both seasonally and spatially variable. Spatial variability can be observed as gradients of input use at the farm scale, inter-household variability based on differential resource endowments, and variability at the landscape and higher levels due to agro-climatic differences. Seasonal variability affects the abundance of key materials: crop residues are available in vast quantities only at harvest or as thinnings before then, manure is more abundant during rainy seasons than in dry ones but more likely to be dispersed by grazing across the landscape. Temporal variability is also seen in the quality of materials. The nitrogen content, in particular, of manure or harvested organic materials declines rapidly with the passage of time, as does the overall nutrient value of young plant materials like leaves if they are allowed to mature or senesce. Inter-seasonal storage of organic soil nutrient amendments is therefore impractical.

The second factor, bulkiness, is a key constraint on the transport of organic materials over any significant distance for use as inputs. The much observed 'ring management' of many Sahelian farming systems (cf. Prudencio, 1993; Ruthenberg, 1980) results from the concentration of inputs on fields declining with increasing distance from their source (typically the homestead). Comparing yield benefits from manure application against the labor involved in transporting it, Schleich (1986) found that for a community in Côte d'Ivoire, ox carts were profitable up to a distance of 1 km, whereas transport on foot was not profitable at any distance. Since animal powered transport can increase the efficiency of labor-intensive transport activities to the point of profitability, dynamic community-level markets for the exchange of draft power have been reported for transporting manure (Mazzucato and Niemeijer, 2001 in Burkina Faso; Ramisch, 1999 in Mali; Tiffen *et al.*, 1994 in Kenya; Sumberg and Gilbert, 1992 in the Gambia).

Because transportation is an important limit, there is a strong incentive to produce organic inputs *in situ* (such as companion planting of legumes with cereal crops or as improved fallows in rotation with them). An animal based analogue is the corralling of animals on fields in the dry season, which exchanges crop residues for manure. Throughout much of West Africa, the manure of large semi-sedentary and transhumant herds is a key resource for settled farmers (Landais and Lhoste, 1990; Bonnet, 1988; McIntire and Gryseels, 1987; Powell and Coulibaly, 1995), and such manure is often the catalyst for inserting pastoralists into the exchange networks of a settled community (Ramisch, 1999; Guillard, 1993; Dugué, 1987; Lachaux, 1982). Where markets can valorise increased crop production, exchanges of 'surplus' manure or compost between settled farmers are also common, either for cash (Tiffen *et al.*, 1994) or labor for other activities (Ramisch, 1999; Guillard, 1993).

High labor requirements for collection, transportation, and application of organic inputs are an important limiting factor for market participation. Where local labor markets and credit are incomplete, a household's capacity to use organic inputs depends primarily on the availability of household or reciprocal labor (Ahmed et. al, 1997; Barrett et. al., 2002). This has implications for labor allocation decisions that may not be consistent with households' income diversification strategies. The low quality of manure being used by many farmers under traditional management systems results in low concentration of plant nutrients (especially nitrogen and phosphorous) and correspondingly low returns to farm labor (Probert, n.d.). Under these circumstances households may seek to free farm labor to pursue off-farm activities that provide a higher return or are less risky. HIV/AIDS has also reduced labor availability for farm work in many countries in eastern and southern Africa These households are likely to prioritise labor saving technologies even in perceived labor surplus areas. Nonetheless, surprisingly little is known about how returns to integrated soil nutrient management practices compare with alternative investments off-farm.

The problem lies not just in markets for soil amendments themselves, but also in the materials for *in situ* production of organic inputs. Farmer willingness to pay for germplasm for green manure is low because of free distributions by projects, high quantities demanded, and an ability to harvest and reuse

seed for most green manure plants. Where intensification of leguminous grains is linked to market development farmers have shown greater willingness to invest in improved seeds (Jones et. al., 2002). The challenge here lies in identifying the right varieties that have the best potential for fixing nitrogen while at the same time meeting preferred market requirements for the food product beyond soil fertility improvement. The proliferation of markets for *Mucuna* seeds in West Africa, for example, was related to its perceived ability to suppress the noxious grass *Imperata*. Within 2-3 years this weed was controlled and *Mucuna* no longer marketed (Houndekon *et al.*, 1998). Species with multiple benefits, such as dual-purpose soybeans or cowpeas are more likely to be adopted than those purely for soil improvement. Social networks play an important role in facilitating the reallocation of slack resources (Mazzucato and Niemeijer, 2001). The anecdotal evidence that exists for the development of seed distribution markets for legume cover crops suggests that social networks are paramount in spreading both information and the small amounts of seed that become periodically available for members outside the group (Misiko, 2000).

**6. Summary and ways forward to enhance the contribution of integrate soil fertility management**

Integrated soil fertility management practices are thriving in agricultural research and development projects, as the use of organic inputs increases, both on a stand-alone basis and in conjunction with mineral fertilizers. Much of this initiative is due to farmer innovation and adaptation, often in response to macroeconomic and sectoral reforms that have driven up real fertilizer prices throughout the continent. Organic systems have been found to complement fertilizers in many ways, both in a biophysical sense (enhancing soil fertility beyond nutrients alone) and in a socio-economic sense (requiring different types of household resources). Some organic systems are performing well on their own and in integrated systems, as measured by yields and profits. Like mineral fertilizer, there appears to be more interest in, and impact from, the use of organics and integrated systems on higher value crops. Because of their low cash requirements, some organic-based systems are reaching poorer households that otherwise are scarcely using any fertilizer.

But there are limits to the amounts of organics that can be produced on-farm, particularly where labor constraints bind. There remains insufficient evidence as to whether increased use or organic inputs is spurring increased overall use of nutrient inputs. While biophysical research in integrated soil fertility management is progressing rapidly, more research is needed on farmers' practices, including their innovations and integration of individual components. There is also an urgent need to extend both bodies of research to higher value crops and whole farm analyses.

Markets for organic biomass are limited mainly due to the inherent characteristic of relatively low quality of nutrients per weight resulting in bulkiness. Markets have developed for animal manure, especially quasi-contractual arrangements between owners of free grazing cattle and stover owners. Markets for green manure do not exist to any significant degree. Markets for green manure germplasm have developed in response to demand from projects and from farmers when the plant yields feed or food product in addition to soil nutrient replenishment.

In order to ultimately contribute to increased productivity through improved soil fertility management, a few steps can be highlighted. First, there is still need to develop more attractive options, components and integrated strategies for small farmers of which improved germplasm is an integral part. This requires tighter linkage and feedback between strategic and adaptive research activities. Farmers are moving quickly in experimentation and the researcher community must be more active in monitoring this work. This will require more partnerships among farmers, extension, development projects, and researchers to bring wider development efforts into the knowledge base of researcher.

Second, because ISFM practices are knowledge intensive, a major challenge is to identify scaling up processes that are both effective and not too costly in terms of information provision and technical support. It will be especially challenging to overcome the many bottlenecks of information flow across different organizations, from organizations to communities, between communities, and between farmers within communities. There is a need to develop incentive systems that reward improved flows of information. Rewards to communities for their efforts similar to the Landcare system in the Philippines or the Presidential award in Kenya are worth exploring, as are ways of utilizing existing rural collective

action (e.g. community-based organizations) to facilitate information flow.

Third, there must be major efforts to make agricultural commercialization more attractive to small farmers. Low rates of market participation are leading correlates of both poverty and the absence of sustainable agricultural intensification through increased investment in the land (Barrett and Carter 1999, Reardon et al. 1999). Increasing commercialization requires improving access to input markets, including for working capital (e.g., credit, savings) needed to purchase mineral fertilizer, organic inputs and seed and to hire labor, perhaps especially for women, who are key soil fertility managers in much of the continent. This is relatively easier in favorable agricultural zones where investment in market infrastructure can have a big impact. Indeed private, commercial interests sometimes undertake such investment voluntarily in support of lucrative contract farming schemes. Stimulating greater market participation is trickier in drier areas, although research from South Asia suggests that the marginal returns, in terms of both poverty reduction and production value, are highest for road infrastructure investments in low potential rainfed areas (Hazell and Fan 2001). Roads are important, but the organization of marketing and finance demand attention as well, building on local self-help groups to help resolve coordination and contract enforcement problems bedeviling much commerce in rural Africa today.

Rapid growth in experimentation with organic soil inputs has fuelled the emergence of an extremely promising integrated soil fertility management paradigm that is just beginning to be evaluated carefully. A wide variety of studies report widespread experimentation with ISFM across all agroecological zones in Africa, including by many farmers who had not been using mineral fertilizers. Nonetheless, problems of market access, and household-level availability of land, labor and working capital continue to limit the extent of adoption of ISFM among poorer small farmers. One finds pockets of active and effective users surrounded by vast areas of non-use.

Much remains to be done, both in terms of research and development practice, to establish how best to employ the emergent ISFM paradigm to overcome or increase Africa's miniscule rates of mineral fertilizer application and stimulate agricultural productivity growth. The task is made all the more pressing by economic policy reforms that have caused a sharp drop in fertilizer use by small farmers in many areas. The core challenges to scaling up limited successes with ISFM to date appear threefold: improving integration between strategic and adaptive research, accelerating and expanding the flow of information among farmers, and increasing agricultural commercialization through improved market access, especially in lower potential rainfed regions.

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**Table 1: Description of Main Organic Soil Fertility Practices in Sub-Saharan Africa**

| Organic Practice | Description |
|---|---|
| Animal manure | The spread of solid and liquid excrement from animals, mainly cattle. Intensified livestock production systems involve the collection of manure in stalls or pens, while the more extensive systems involve direct deposition of manure by grazing animals. |
| Compost | The collection and distribution of a range of organic compounds that may include soil, animal waste, plant material, food waste, and even doses of mineral fertilizers. Prior to application of compost onto the field, there is a period of incubation to decompose materials. |
| Crop residues | The in situ cutting, chopping, and incorporation of crop residues into the soil. This operation is often done at the time of land preparation for the following season. |
| Natural fallow | Withdrawal of land preparation or cultivation for a period of time to permit natural vegetation to grow on the plot. The breaking of the crop cycle and lead to regeneration and the fallows can also recycle nutrients. |
| Improved fallow | The purposeful planting of a woody or herbaceous plant to grow on a plot for a period of time. In addition to benefits of natural fallows, improved fallows can achieve equal impacts of natural fallows in shorter time periods because of purposeful selection of plants, such as those that fix atmospheric nitrogen. |
| Intercropping systems | Nutrient sources are integrated with crops in both time and space. The organic source may be a permanent feature on the plot such as with alley farming or scattered trees or may also be annual legumes. Intercrops are normally carefully planted, but trees in certain parkland systems (e.g. *Faidherbia albida*) are naturally growing. |
| Relay systems | Relay systems are similar in sharing space with the crop, but the organic source is planted at a different time than the crop. |
| Biomass transfer | The transport and application of green organic material from its ex situ site to the cropping area. The organic source may be purposefully grown or growing naturally. |

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**Finding common ground for social and natural science in an interdisciplinary research organisation – the TSBF experience**

J.J. Ramisch (TSBF-CIAT), M.T. Misiko (TSBF-CIAT), S.E. Carter (IDRC, Canada)

**Abstract:** Continuing dialogue between the natural and social sciences means that the conception of "development", and of integrated natural resource management (INRM) in particular, continues a healthy evolution from largely discipline-based approaches to more integrative, holistic ones. Reflecting a microcosm of this evolution, the Tropical Soil Biology and Fertility (TSBF) Institute of CIAT is today dedicated to integrated soil fertility management and the empowerment of farmers through participatory technology development. Yet its origin in 1984 was as a body devoted to researching the role of soil biology in maintaining soil fertility, to combat declining per capita food production and environmental degradation.

This paper examines the changing theoretical and methodological approaches of integrating social science into TSBF's research activities over the past decade, and identifies strategic lessons relevant to INRM research. The interdisciplinary "experiment" of TSBF has steadily taken shape as a shared language of understanding integrated soil fertility management. While individual disciplines still retain preferred modes of conducting fieldwork (i.e.: participant observation and community-based learning for "social" research, replicated trial plots for the "biological" research) a more "balanced" integration of these modes is evolving around activities of mutual interest and importance, such as those relating to decision support for farmers using organic resources. Since TSBF is working constantly through partnerships with national research and extension services, it has an important role in stimulating the growth of common bodies of knowledge and practice at the interface between research, extension, and farming. To do so requires strong champions for interdisciplinary, collaborative learning from both natural and social science backgrounds, the commitment of time and resources, and patience.

**Rationale:** As part of a CG-wide review, papers were invited which analyze the contribution of social research (sociology, anthropology, geography, political science, psychology) to research process, results, outcomes and development impact of agricultural or natural resource management research. Papers should assess the extent to which social research has influenced the relevance of research outcomes for the poor. Preference will be given to papers that analyze experience over time with social research and its impact in an organization such as a CGIAR Center, National Agricultural Research Institute or NGO, as distinct from a project. Topics to address include:

1. Introduction: brief overview of the history of social research in the institution that identifies main phases and trends over time in number and type of staff and resources involved and their main objectives.
2. What have been the effects of social research done by the institution on research and innovation processes : e.g. on problem identification, research priorities, client or target group identification, methodologies, on-farm approaches, technology design, criteria for successful results, scaling up, evaluation, impact assessment etc. How and why has this changed in relation to the main phases and trends in use of social research over time identified in (1) above ?
3. How has social research done by the institution been incorporated into the organization, its work culture, team composition, policies and procedures. Have synergies been achieved by combining social research with other disciplines? Why or why not?
4. Are there any effects of social research on results achieved by the institution, on adoption and use of its research results by client groups, outcomes of use for clients, and development impact associated with the institution's research. If there is no evidence to enable you to address this question, why is this ?

5. Has social research had any influence on relevance to the poor of the institution's research? Why or why not? If there is no evidence to enable you to address this question, why is this ?
6. Conclusion: summarize the critical success and/or failure factors that have affected the use of social research by the institution and lessons learned.

**1. Introduction**

The Tropical Soil Biology and Fertility (TSBF) Programme (now Institute) was created in 1984 under the patronage of the Man and Biosphere programme of UNESCO and recently incorporated into the Future Harvest system of food and environment research centres as a research Institute of the Centro Internacional de Agricultura Tropical (CIAT). As an international research body, the underlying justification of TSBF's work has been that "the fertility of tropical soils is controlled by biological processes and can be managed by the manipulation of these processes" (Woomer and Swift, 1994).

Being an organisation with an explicitly biological and ecological mandate and origin, TSBF has nonetheless sought social science input into its research program since 1992. It has always been a small team (never more than six internationally recruited scientists) and therefore much of TSBF's considerable output has been generated through collaboration with partner organisations (both national and international), with special focus on sub-Saharan Africa. The decision to develop and maintain a core competency at the interface of social and natural sciences at TSBF since 1992, rather than looking for such competency from partners, is therefore significant. A decade after the creation of the Resource Integration Officer (since renamed Social Science Officer) position, it is worth re-evaluating the effects and effectiveness of this decision.

This paper examines TSBF's historical record as a "laboratory" for developing meaningful interdisciplinary dialogue and collaboration, and asks whether what has emerged has been "social soil science" or merely "soiled social science". To illustrate some of the tensions inherent in interdisciplinary undertakings, examples of theoretical and methodological evolution are drawn from "grey" project literature, personal commentary, and publications. The strategic lessons learned from this particular organisation reflect in microcosm the much broader debates about the potential for "rigorous" science under competing disciplinary approaches to integrated natural resource management (INRM). They also address the assumption that developing a common institutional culture and language within INRM falls more to social scientist "newcomers" than to biological or natural scientists.

**2. Theoretical shifts**

The smallness of TSBF when contrasted with the larger international research centres has obliged an inherent recognition that the organisation cannot do all things in all places. As a result, strategic decisions about which research themes and methods to pursue become all the more important. "Smallness" has also meant that individual personalities and disciplinary backgrounds have had a much more direct impact on the organisational research agenda and that agendas can change with less institutional inertia than would be the case in a larger centre. On the down side, the institution has been very vulnerable to changes in core personnel (especially the gaps that occur when posts are changing hands) and frequently science has taken a back seat to mere matters of survival.

The development of a TSBF research agenda that looked beyond the soil to the people cultivating it has moved from descriptive, characterisations of farming systems to more strategic study of social differentiation, power, and networks as they relate to soil fertility management innovation. An interest in dissemination has broadened into investigation of social dynamics, knowledge, and farm-level decision-making. There has also been a tradition of self-reflection, examining the consistency and coherence of TSBF's stated goals, methods, and actual practice, as well as the extent to which grassroots action conforms to its depiction to outsiders. As such, social science practice has developed quite healthily over the ten years 1992-2002, driven significantly by the following factors:

a) The disciplinary background of the Social Science Officer (and to a lesser extent, that of field staff). Three people have held this position – Simon Carter (1992-1997, Geographer), Patrick Sikana (1998-2000, Anthropologist), Joshua Ramisch (2001-present, Human Ecologist) – and

each has had preferred research topics and interests. In addition, Eve Crowley (1994-1996, Anthropologist) worked with TSBF on a Rockefeller Social Sciences Fellowship; a position shared half time with ICRAF.

b) The demand for "socio-economic" understanding of processes being studied by other TSBF staff and collaborators.
c) The natural evolution of projects from inception to later stages. This organic growth has typically moved from characterisation using very descriptive studies to more explanatory work building on existing practices through to development of longer-term interactive learning activities.
d) Evolving social science debates concerning knowledge, power, and participation. The co-supervision of MSc and MA students from local universities has been an especially useful vehicle for maintaining contact with these debates.
e) Responding to donor agendas, including but not limited to perceived needs for research results readily useful to farmers, a clearer understanding of agrarian change and its links to changes in soil fertility, livelihoods analysis, impact assessment, and identifying the most effective ways of "scaling up" organisational successes.

2.1. Demand driven – but by whom?

There has always been a tension between the research agendas demanded from *within* TSBF by social scientists (i.e.: disciplinary interests, evolving projects and debates) and those expected from *outside* (i.e.: from other TSBF staff, partners, donors). This tension results from different research paradigms and differing ideas about the role of research in relation to social change. From the natural science perspective, the key contribution of social science to INRM often appears to be identifying and understanding the social factors that limit "adoption" or the "appropriateness" of given technologies. Other socio-cultural phenomena, such as "policy" might be acknowledged as important to the fate of different innovations, but most teams (even multi-disciplinary ones) lack the capacity to generate relevant policy-related questions, experiments or interventions. In other words, when the organisation is researching natural resource problems, the natural-social science dialogue has most often begun with identifying "black boxes" of external, *social* forces that need illumination, rather than defining truly *interdisciplinary* questions about how research (including technical research) can support positive change in rural societies.

This tension is reflected clearest in the history of the social science position itself, which is discussed at length in the next section. Created in 1992, the post was originally charged with "Resource Integration". This step was perceived as a natural evolution for TSBF, which always held an ecological, systems-oriented approach to thinking. Although TSBF's strength remained at the plot level, the diversity of forces impinging on the plot draws attention naturally towards a hierarchical systemic analysis (Scholes *et al.*, 1994).

The Resource Integration Officer was therefore initially charged with "developing a model for integrating biophysical and socio-economic determinants of soil fertility for small-scale farms" (Swift *et al.*, 1994). Under this rubric, social factors were expected to be integrated into holistic models as additional explanatory variables. Once key, perhaps universal variables were identified, these could then be added to a "minimum set" of characterisation data collected for TSBF sites (cf. Anderson and Ingram, 1993). However, the main contributions to the TSBF programme remained in terms of site selection, selection of themes for process research, and client group selection, with much less emphasis on experimentation, or monitoring and evaluation (Crowley, 1995).

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experimentation, or monitoring and evaluation (cf. Crowley, 1995).

## 2.2. Historical evolution

### *2.2.1. Carter (1992-1997)*

The first incumbent in this post was a geographer, Simon Carter, with a background in both social and natural scientific traditions. Recognising the need to start from where TSBF "was at", but also charged with the task of helping to make the program's research more relevant to farmers, he began to work at the intersection between these two positions, and to generate information about how soil fertility was managed. Everyone in the programme agreed that it was important to know more about resource availability and use, and to begin to think about the relationships between research on soil fertility management and a better understanding of social and environmental change within African farming systems.

Understanding spatial variability in soil management was also a common concern to the programme, with practical implications at two different scales. Understanding the importance of spatial variability at plot and landscape scales, and how farmers dealt with these, had clear practical implications for research on-farm and in communities, such as the questions research should address, involving farmers, and designing experiments. Secondly, given that a high priority for TSBF was the development of its African network (AFNET), identifying key regional differences in soil fertility management strategies could be key to developing AFNET. As a result a range of work was undertaken including development of simple GIS databases for East Africa, a more detailed one for Western Kenya, detailed formal survey work in Western Kenya, participatory characterisation of farmers' recognition and management of farm and landscape-level management of soil variability in Kenya and Zimbabwe.

Carter (from 1994 with support from Eve Crowley) sought to align research at TSBF with on-going debates on agrarian change in order to broaden the conceptual base underpinning many of the assumptions about the potential contributions of ecological research on soil fertility management to rural development in Eastern and Southern Africa. Hypotheses generated from the literature drove much of the data collection efforts undertaken from 1993-1996 (eg. Crowley and Carter, 2000). In addition, efforts were made to expose AFNET members in Kenya and Zimbabwe to a range of on-farm research methodologies and tools and approaches that could, over time, facilitate inter-disciplinary exchange (Carter et al, 1992; Crowley & Carter, 1996). This work culminated in a four-country project funded by the EU from 1995-1998 (Carter & Riley, 1998).

The modus operandi that evolved within TSBF between 1992-1996 had important methodological implications, however, for the research undertaken by the Resource Integration Officer, and later the Social Science Fellow. The pressure was on them to demonstrate, through quantitative means, the validity of social science perspectives and the fallacies underlying some of the assumptions of colleagues, as well as to collect quantitative data that would be of use for biological and economic modelling (little use was made of the additional quantitative survey data that was collected on behalf of other colleagues, who were simply too busy with other projects and priorities to explore the data). With hindsight it was probably a strategic error to agree to conduct an extensive formal survey in Western Kenya. A lot of time and labour was spent generating, collating, cleaning and exploring the data, and insufficient priority was given to interdisciplinary analysis, writing-up and dissemination of the results. Difficulties in collaboration, the departure of the Social Sciences Fellow, and increasing demands from other projects undermined the considerable investment the programme had made in this work, although the long-term worth of the dataset is undoubtedly high. On a more basic note, insufficient priority was given in the early years to simply learning to communicate more effectively across disciplines.

Recognising that the unique contribution of the Resource Integration Officer to TSBF's overall research strategy was its attention to social questions, the position was renamed Social Science Officer in 1997. By this time it was recognised that the contribution of the post had had moved beyond collection of an enlarged "minimum set" and creating a more open "sequence" or menu of methods that would be useful for "defining the resource bases and management strategies of different socio-economic groups" (Carter and Crowley, 1995). Changes in personnel during 1996-7 had opened new opportunities for

collaboration, and work moved into its strongest experimental phase, including researcher-managed experiments in conjunction with ICRAF, researcher-managed work under the EU project, and farmer participatory research begun in 1996. In 1997 a project was developed to support some of this on-farm experimental work. Significantly, it also included support for two masters students to look at how farmers in Western Kenya gained access to and shared knowledge about soil fertility management. This small step paved the way for a significant shift in focus over the next few years.

*2.2.2. Sikana (1998-2000)*

The brief tenure of Patrick Sikana brought the newly renamed Social Science Officer position towards much more autonomy on purely "social" research topics than had previously been the case. As a social anthropologist with farming system research experience in southern Africa, he prioritised deepening TSBF's understanding of farmers' local soil ecological knowledge and the rationales behind their existing soil management practices. This period also initiated critical investigations of how social networks aid and hinder the functioning of integrated soil fertility management (ISFM) research projects and the dissemination of ISFM knowledge.

However, there was a significant lag time of nine months between Carter's departure and Sikana's arrival, which would have implications on the ground (discussed in methodological changes below). Furthermore, Sikana had been in the post slightly over a year, and just begun organising new projects for the Social Science Office when he was killed in the crash of a Kenya Airways flight from Abidjan in January 2000. His death devastated the small organisation at a time when its future was also being shaken by financial uncertainty.

Indeed, the issue of continuity of personnel has had major impacts on developing an interdisciplinary and social science research agenda, at least in the short to medium term. Not only has TSBF seen significant turnover of personnel since 1992, but so has AFNET. The retrenchment of public sector employees, as part of structural adjustment or other "reform" programmes, has gutted national research bodies and extension services. The relatively low numbers of social scientists present in national systems must also been see in the light of the stark fact that they tend to be much more attractive to donors and thus more likely to move on from low paid national positions. Social scientists trained in participatory methods are also much less likely to return to agricultural research jobs when conservation and health present more prominent and well-funded fields. Finally, staff turnover in African organisations has been exacerbated by sudden deaths like Patrick's, attributable to disease, accidents, and general insecurity.

The AfNet membership is still overwhelmingly natural scientists (over 150 soil scientists, biologists, agronomists) with social science represented only by six (socio-) economists. While there is a general appreciation that "social science" is important to the network, there is still great unfamiliarity with what can really be offered or understood. The emphasis remains on economic information about the "profitability" or "adoptability" of known technologies, with no expertise or experience in applying strategic, interdisciplinary research questions at the interface of human-environment interactions to soil fertility management. AFNET could have made it a higher priority to try to attract more social scientists, but soil and agricultural scientists need to be trained to recognise where social science can make their lives easier. This has to happen at university and in special training courses, and (rather like gender mainstreaming) has to have the soil and agricultural scientists in TSBF as its champions, not just the social scientists. Host institutions have also to provide the space for scientists to engage in interdisciplinary research. Unfortunately, while recognised by the various AfNet coordinators, this has tended to be subsumed, and therefore obscured, within the larger problem (true within AFNET as within the CG system more generally) of declining numbers of soil scientists faced with increasing obligations and expectations.

The lack of "champions" for social science research within TSBF can also be seen in the example of Ritu Verma, an IDRC-funded MA student who worked with TSBF in Western Kenya from October 1997 to April 1998. Her research comprehensively examined gender and agricultural practice but without a strong link to the core of TSBF was never meaningfully integrated into other projects. Ironically, her

book “Gender, Land, and Livelihoods in East Africa: Through Farmers’ Eyes” (Verma, 2001) is the most extensive TSBF text produced by social science research but presents its arguments in such detail that it has been difficult to absorb or disseminate, making it a testimony to missed opportunities.

*2.2.3. Ramisch (2001- present)*

One of the main objectives since the arrival of Joshua Ramisch in early 2001 has been enhancing the “institutionalisation” of the social science research agenda. This search for greater continuity within the research agenda has been assisted by the recruitment of two full time research assistants (a socio-economist based in Maseno, and anthropologist based in Nairobi), as well as broadened efforts at building a social science “constituency” within AfNet. Core activities of the office have retained an anthropological focus, including research on indigenous soil ecological knowledge, farmer decision-making, understanding innovation processes, and the role of social differentiation in ISFM practices

Staff turnover in 2001 also gave TSBF a chance at a relatively clean slate. The AFNET coordinator position was filled by Andre Bationo and Bernard Vanlauwe became the ISFM Officer at roughly the same time as Ramisch arrived. While there has been a risk of losing institutional memory through this process, the simultaneous arrival of so many new staff has facilitated team building, new collaborative activities, and presented opportunities for cross-disciplinary learning. Evidence of this interdisciplinary thinking has emerged clearly in presentations and papers written by core TSBF staff (e.g. Bellagio, Centres Week, and INRM presentations 2001, 2002; unpublished), as well as increasing numbers of interdisciplinary activities on the ground in Kenya, Uganda, and Zimbabwe.

The strategic alliance in 2001 with the Centro Internacional de Agricultura Tropical (CIAT) has helped give TSBF greater financial security and a higher profile. It also presents opportunities to link the Institute to a broader interdisciplinary community and to draw on the expertise of CIAT’s long-established social research programmes. While the transaction costs of inter-continental collaboration are high, crosscutting endeavours within TSBF-CIAT have taken place around the Bellagio meeting in 2002, the training of an Argentinean in NUTMON methods in Ethiopia, and joint supervision of an M.Sc. student in Western Kenya.

However, the 8$^{th}$ AFNET meeting held in Arusha in May 2001, also clearly demonstrated that amongst partners TSBF is still perceived essentially as a biology-based organisation with minimal social science input. Active recruiting of social scientists has begun through networking and proposal development, but has been complicated by the rapid expansion of AFNET in the past two years. The massive influx of new members and the expansion of activity into West Africa have simultaneously increased the potential demand for INRM input and diluted the few interdisciplinary voices present within the network. The AFNET mandate of increasing the use of “integrated” approaches frequently takes a back seat to its more “traditional” and familiar mandate of increasing support of biological approaches to partner institutes through curriculum development and networked experiments. The role of social science within AFNET remains an unresolved problem, acknowledged as important (for “integrated” resource management, for greater “adoption”, and ultimately donor approval of soil fertility management topics (Bationo, forthcoming)) but not backed by resources or strong champions within the network.

A final point to note is that all of the social scientists who have worked at TSBF have been relatively young and in the early stages of their careers, whereas the biological scientists have generally been more senior. The onus has been on the social scientists to communicate novel ideas in terms their colleagues could understand or accept; this was relatively easy with concepts such as spatial variability, but much harder with feminist political ecology. Furthermore, in the past, strong personalities or opinions have tended to block communication between individuals and to limit interactions within the team. The new team that came together in early 2001 has begun to overcome some of these historical difficulties, further stimulated by meetings held in conjunction with the union with CIAT and the formation of the strategic Alliance for ISFM between CIAT, TSBF, and ICRAF. However, without a more senior social scientist or generalist present to mentor or to mediate communication, interdisciplinarity will always be a challenge.

## 3. Methodological shifts

The most fundamental evolution has been from largely descriptive, empirical work towards developing more theory-driven, strategic research and the broader use of participatory approaches. At the same time, there has been a search for the optimal degrees of participation relating to the "fieldwork" aspects – which actors, doing which tasks, using which methods. This search has highlighted some of the still extant divides between the rhetoric of research aims and the realities of operational daily practice, as well as tensions that exist between different models of the role of research in stimulating change. Examples are drawn from among the longest-running TSBF projects.

### 3.1. "Research" or "action research"?

The development of social science at TSBF has been implicitly predicated on two very different models of how change is brought about in rural communities and what role outsiders and scientists can play in that process. The more conventional approach suggests that a "good technology sells itself" and that working with communities merely requires that the "best bet options" are made available to the "categories of farmers" who are likely to benefit from them. In this model, which is still widely held by many natural scientists including TSBF partners, a "research" organisation has too few resources and no comparative advantage in doing dissemination, and is better placed to research and evaluate the dissemination and technology promotion activities carried out by partners (local NGO's or national agricultural bodies). The alternate approach argues that understanding local processes of innovation, resource distribution, resource allocation decisions, and information transfer is essential to developing technologies relevant to their users' conditions. Integral to this second approach is the development of meaningful communication and learning across disciplinary boundaries – something that TSBF has attempted to do repeatedly, but which still remains problematic.

As TSBF and its partners became more versed in participatory methods, tension has developed between these models. The desire for more "development" oriented activity has been highlighted in the redesigning of the "Resource Integration" theme of TSBF in 2000 into the new Focus 1, demonstratively titled "Empowering Farmers", into which all the other bio-physical Foci's arrows flow. It may also have been further accentuated by the recruitment in the late 1990s of TSBF field staff for Kenya with NGO backgrounds in action research. The argument has been that without actively engaging in dissemination and community organisation the phenomena of interest to research (knowledge flows, further innovation and adaptation, etc.) will be too scarce to be viable or observable. Indeed, these staff members have found it difficult to define or implement "research" as an independent activity, devoid of extension or development components.

In reality, most partner organisations have lacked the resources (personnel, transport, and operating funds) to carry out such work, and indeed have often turned to TSBF for material or logistical support. The decision to devolve more of the research, experimentation, and dissemination activities to the host communities, therefore, is not so much ideologically driven as pragmatic. The increasing use of farmer-designed and farmer-run experiments, farmer-to-farmer training, and group-based activities has effectively begun to address the desire for more "action" oriented work while providing social processes worthy of investigation. What has emerged in the project areas of Western Kenya (where TSBF and local groups have had a reasonably long, 5-8 year history of contact) are prolonged, one-to-one relationships between scientists and farmers. Interactive, two-way learning, through community-based interactive sessions and farmer-based demonstrations, has been enhanced by researchers, and is widely conducted in local dialects. The ongoing challenge, however, has been finding optimal roles for researcher, extensionist, and farmer participation under these continuing conditions of resource constraint.

### 3.2. Collaboration and "participation"

Under the prevailing orthodoxy of participation, it is difficult to find projects that do not describe themselves as using and embracing "participatory" methods, to the extent that the term invites dismissal or covert cynicism (cf. Cooke and Kothari, 2001). These methods are usually assumed to apply only to relationships between researcher / extensionist and "client", where they are used to "level" the power

relationships between actors. Yet in the TSBF context, where planning and implementation of activities is explicitly done in partnership with national research and extension institutions, participatory methods of collaboration have had to evolve. If cross-disciplinary learning has been difficult within TSBF, it has been even more so between TSBF and its partners, a fact which must be acknowledged before looking at the effectiveness of "participation" in the dealings of "researchers" with farmers.

This point needs to be based on what might be called "realistic expectations" of change. True collaboration must recognise (however reluctantly) that working with the human resources that are on hand within networks means starting from the perceptions and skills of those partners and moving at the best pace possible. It would have been easy to "cook" fancy results about participation if the social scientists had simply gone it alone. Working in partnership through AFNET, however, has forced TSBF to confront the realities of public funded research in Africa, the conservatism and logistical difficulties of which demand considerable patience. It is relatively easy for partners to influence each other's rhetoric, harder to alter each other's conceptualisations of problems, and harder still to make lasting changes in the way each carries out research tasks. "Participation" is not an approach whose benefits are learned or appreciated quickly and the socialisation of knowledge backwards and forwards between scientists and farmers depends fundamentally on the generation of experience.

The progress of AFNET towards "internalising" the rhetoric of farmer participatory research may seem glacially slow for being one of the more advanced scientific networks (cf. review of on-farm research in the EU-funded project, Carter *et al.*, 1998). As mentioned above, the scarcity of AFNET members trained in participatory methods able to act as "champions", and the lack of continuity in many institutions facing financial crisis, hinder the development of a more interdisciplinary research culture.

However, progress is being made in learning new attitudes and unlearning old ones. For example, the Zambian EU team decided to work on *fundikila* mound systems and to clear land on the research station to replicate the farmers' practices on-station, in full view of their peers. The Zimbabwean and Kenyan research teams have come to acknowledge the various micro-niches that farmers recognise and manage and have incorporated these into various research designs. Within the BMZ-funded project, increasingly sophisticated understanding of wealth and gender differences as they relate to soil fertility management have been incorporated into the project design. Finally, previously distinct elements of process and on-farm research have been combined in activities where complex soil-crop scenario modelling has been fed back into negotiation or decision support work conducted with farmers.

### 3.3. The politics of community-based research

It is, of course, never easy to surrender control of research agendas, even where the research is ostensibly for the benefit of the rural poor (i.e.: TSBF's Theme 1 is "Empowerment of Farmers" with new technologies). If TSBF has seemingly embraced what Ashby (1992) calls the "devolution to farmers [or other stakeholders] the major responsibility for adaptive testing and sharing of accountability for quality control over research", what have the political implications of this move been? Examples relating to defining innovation, the use of local youth as enumerators, and the micro-political dynamics of groups demonstrate.

#### *3.3.1. Defining "innovation"*

Farmer participatory research activities at TSBF began in community settings where portions of land were already being hired for research-designed activities, including both "pure" experimental treatments and "demonstration" plots to showcase the presence of nutrient deficiencies or the efficacy of various technologies. These activities tend to cloud the local understanding of what "research" actually is or can be, creating a sense that research generates information that "important" (the payments for land are known locally) but which comes in forms not readily accessible or understandable to "ordinary people". Even when experimentation has been ostensibly "turned over" to farmers, it is common to hear the new technologies being referred to as "belonging to the researchers".

Beyond a basic unfamiliarity with the intentions and operationalisation of collaborative research with scientists, there is the problem that many of the "experimentation" activities undertaken do not

provide ideal venues for farmers to innovate in ways familiar to them. TSBF has a goal of providing farmers with a "basket of options" for ISFM (Swift *et al.*, 1994), including legume cover crops, improved fallows, biomass transfer (cut-and-carry) systems, improved compost manure, and various combinations of organic and inorganic fertilisers. In the EU and BMZ-funded projects, after initial PRA's in the communities, farmers were given the chance to select technologies from this "basket" to try on their own land. Selection of otherwise completed technologies, however, is not the same as participating in the technology design process.

The "over-designing" of technologies before involving farmers in their development is a natural consequence of scientists failing to a) trust in the innovative capacity of farmers or b) know how to apply farmers' knowledge and innovation as contributions to "formal" scientific activity. It limits farmers' role to relatively passive activities, such as selecting niches or adapting application rates to local circumstances, which ultimately discourages any sense of ownership of the technology development process. However, to recognise certain behaviour as an "innovation" requires channels of communication and trust to exist between farmer and scientist, and a willingness to see all modifications of practice (including abandonment and complete reversals) as potentially useful.

Observations of innovative farmer practice can feed into researchable topics, such as the use of Tithonia as a nutrient-rich mulch (now a staple "technology" promoted by TSBF and others in East and Southern Africa). When translating the Tithonia biomass transfer technology to other farms, a commonly heard comment is that the cut-and-carry system is "labour intensive". Harvesting biomass from hedgerows all at once before planting one's crops is indeed a large, and previously non-existent task, even if pruning hedgerows or applying plant material on cropland are familiar activities already in the household calendar. As a result, many farmers have begun harvesting their Tithonia sporadically (as part of normal hedge maintenance) and transferring it to their compost pile (another familiar task). Clearly the decision not to continue with the cut-and-carry operation and instead supplement the compost pile with Tithonia should be seen as an "innovation" or indeed as a logical supplementation of existing practices. However, while Tithonia had been identified as a "best bet" for direct application to fields since it decomposes so rapidly, it may not be the "best" option for materials to be added to compost piles that sit for a time before application. A natural entry point for truly interdisciplinary research is experimentation based on farmers' own practices (many report that Tithonia speeds the "cooking" of compost piles making it ready for use sooner) to validate the use of Tithonia or alternative materials as part of the composting process.

### *3.3.2. Local youths as enumerators*

Among the many tools and approaches used for conducting its social fieldwork in Western Kenya in the early 1990s, TSBF relied on young and literate people, recruited from the local communities as enumerators. They were typically given basic training that would allow them to support "community-level" research activities such as questionnaire administration and the setting up of trial plots. Over time, they began to take on more responsibilities, received further training, and by 1997 were facilitating farmer-led experimentation. However, personnel changes at TSBF, and attitudinal differences between TSBF on the one hand, and the local partner KARI (Kenya Agricultural Research Institute) on the other, had important implications for the role of these enumerators and the work they carried out.

TSBF staff had viewed the capacity development of these youth as part of a community-based learning strategy to build rapport with other farmers. Indeed, the local communities were openly sympathetic to this approach, since it provided immediately tangible benefits to locals employed as enumerators, and also ensured that research was carried out by people who would be familiar to community-members and at home with the local cultural norms and vernacular. However, what was perhaps never explicit was how (if at all) the inclusion of these enumerators in project activities differed from the way that other local people were trained to work on experimental plots as paid labourers.

During the interval between Carter's departure and Sikana's arrival, the enumerators carried on their work, with backstopping where possible from KARI. However, without strong advocacy for participatory methods rather than more top down approaches, KARI staff tended to view the enumerators

who were already "part of the community" as a useful channel for "passing useful scientific skills and knowledge *into* the local community". At the same time, because of their training, regular association with TSBF staff, and the perceived status benefits accruing from their employment, many of the enumerators tended to count themselves more as part of *TSBF* than as part of the "*community"*. In the end, this distancing between enumerator and community (enhanced by youth and the fact that many of the enumerators did not themselves farm) undermined their ability to link farmers and researchers effectively.

Since then, an effort has been made to build individual capacity within KARI and the national extension service for participatory research. Currently, an agricultural extension agent who speaks the local dialects has been hired for facilitating community-based input. This expert works with community groups, farmer field schools (FFS), individual farmers and other local stakeholders. However, as with the enumerators, these activities have demanded considerable backstopping by the Social Science Officer and other disciplines within TSBF.

### *3.3.3. The micro-politics of groups*

As TSBF placed more attention on building capacity in its partners for farmer participatory research, it also shifted to working with local farmers as groups and individuals. In the earlier 1990s, on-farm trials were based on individual's farms. In such arrangements, host farmers were expected to define and explain experiments to other local and visiting farmers. While we do not know the exact accomplishment through this arrangement, there are indications in Kabras and Vihiga that selecting "model" farmers to work with disaffects them from many other farmers.

Down the road, focus shifted to the group approach. Initially, it seemed obvious that involving many farmers would have a multiplier effect. However, it soon became apparent that the *manner* in which TSBF talks to *whom* is more important than mere numbers. Groups are on frequently unstable and many are not especially open to new membership. When researchers request farmers to work with them collectively, "new" groups emerge. But these "new" groups usually comprise members of a previous, defunct group. This means that one has to *deliberately* seek the inclusion of all types of farmers (within and outside groups) in research and dissemination. This role of a local unifier is tricky and can even appear comical before local farmers.

Intervening research on the nature of social capital and the role of local groups and networks in passing agricultural information (Misiko, 2001) has shown that there is still a tendency for some groups or individuals to view their participation in TSBF as "secret knowledge" that is not to be shared with others. Likewise, non-participants are often wary of inquiring about project activities, assuming that they are not welcome or need to be invited by some patron. This attitude has persisted for multiple reasons, and in spite of the considerable efforts of TSBF and other research bodies to present their work as "open to all" by actively seeking to include marginalized groups. Because local politics takes precedence even over the "good intentions" of outsiders, the vast exposure that many farmers have had to project work in Western Kenya does not, therefore, translate into widespread use or understanding of ISFM.

The initial willingness of TSBF to accept "groups" as representatives of community interests has led to numerous problems. After all, groups exist and persist when they have strong roles and identities, histories of their own which often only become known with time. For example, the most vocal members of groups have frequently been people who are either not well respected by others locally, or possessed of agendas that run far beyond ISFM. This later group tends to see the research project as a vehicle for access to new resources and political leverage than as an opportunity for new learning (Sikana, 1995), although it may take project staff a long time to appreciate this reality. Since much of TSBF's on-farm work has been initiated in the context of structural adjustment programmes and the cessation of donor funding for major local development projects, it is natural that farmer concerns about water, health, poor infrastructure, or education would be mapped onto the "research" activities if TSBF was the only "development" agency working in their area. Beyond such explicit "hijacking" of groups, there are frequently tensions between participants over the definitions of goals, membership, and indeed the "success" of the group's activities.

Nevertheless, working through groups provides an opportunity to diffuse risk and broaden responsibility and ownership of activities. Groups should be seen neither as a panacea for community-based management's difficulties, nor as a replacement for effective dissemination strategies. When setting up experiments or demonstrations at the local level, having wider input about where in the landscape, whose land, or which soils are suited to which types of research activity has proven invaluable. With our broadened knowledge of the diversity of local soil types, requests by farmers to have activities replicated on different soils become logical and understandable, when previously they might have been dismissed as unjustified demands for a share of a perceived research "pie". In the end, such replication turns out to be both good science and good politics.

## 4. Strategic lessons: finding common ground

### 4.1. Building on the easiest topics

The challenges that TSBF has tried to address are highly complex in both biophysical and social terms. As such, interdisciplinary collaboration depends on developing a better understanding of what changes are taking place, and of developing a modus operandi that can generate useful knowledge as part of an on-going dialogue between scientists and farmers.

The parallel dialogue that must take place, between social and natural scientists, has been easiest around themes that integrate themselves readily into natural science work, including spatial variability, wealth ranking and ISFM practice, and the importance of understanding the strengths and weaknesses of existing local knowledge. It has been considerably harder to incorporate elements that relate to the political nature of "research", such as using livelihoods analysis or feminist political ecology to find the place of ISFM and research interventions within local practice.

### 4.2. Championing workable models

If AFNET collaborators have been slow to adopt interdisciplinary and participatory approaches, it is due in part to the relative lack of successful, convincing models of how such approaches pay short or long-term benefits to NRM research. Further constraints have been staff turnover (which leads to fragmented agendas and loss of institutional memory), scarcity of time and resources, and a shortage of generalists or social scientists within partner organisations. The rhetoric of interdisciplinarity and participation have rapidly infiltrated research bodies because they are relatively cost free and often there is the perception that donor funding is linked to such language. Simplified versions of interdisciplinary activities, linking ISFM with participatory wealth ranking, or moving from local soil taxonomies to broader understanding of how soil fertility is managed locally, have also begun to take hold within local practice. While some natural scientists are "afraid of having to become social scientists", there is a slowly growing constituency within AFNET that sees advantages for interdisciplinary collaboration. Nevertheless, without relatively senior "champions" for interdisciplinary or socially oriented approaches within TSBF, new methods and approaches are at a disadvantage compared with the more familiar status quo.

### 4.3. Negotiating the role and nature of "research"

Given the variables of donor climate, institutional and personnel changes, and socio-political change on the ground, truly interdisciplinary INRM research will need to develop a common language and common priorities that can form a core identity in dealing with outside forces. This requires an iterative process of negotiating the role of "research" in the development of local communities. If donors, researchers, and extensionists feel the need to "scale up" local successes and achievements to *broader* communities, it must be reconciled with the desires of the initial community members for taking research accomplishments to greater *depth*. If moving towards group-based research methods means shifting the burden of implementation to national partners, a common path for "participation" will need to be negotiated. In particular, the skills and attitudes necessary to support more decentralised forms of research need to be cultivated by the scientists, agents, and farmers involved.

Despite the rhetoric of interdisciplinary collaboration, cross-disciplinary learning and

communication remain complicated by the divergent ideas of what role "research" can and should play in bringing about change in rural communities. Resolving these divergences often falls to social scientists, since their disciplinary orientation predisposes them to thinking about such issues and their colleagues are more likely to see these issues as somehow separate from their daily activities of research. However, building common bodies of knowledge and practice can only happen with the full participation of all disciplines involved in INRM. If we look at how far an organisation like TSBF has come in ten years, from research foci that concentrated on the integration of biological processes to ones which now embrace the livelihoods and knowledge of the farmers who practice integrated soil fertility management, there is room for hope.

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**Modelling nitrogen mineralization from organic sources: representing quality aspects by varying C:N ratios of sub-pools**

M E Probert[a], R J Delve[b], S K Kimani[c] and J P Dimes[d]
[a] CSIRO Sustainable Ecosystems, Long Pocket Laboratory, 120 Meiers Road, Indooroopilly, Queensland 4068
[b] Tropical Soil Biology and Fertility Institute of International Centre for Tropical Agriculture, PO Box 6247, Kampala, Uganda
[c] Kenya Agricultural Research Institute, Muguga, PO Box 30148, Nairobi, Kenya
[d] International Crops Research Institute for Semi-Arid Tropics, PO Box 776, Bulawayo, Zimbabwe.

**Abstract**
The mineralization/immobilization of nitrogen when organic sources are added to soil is represented in many simulation models as the outcome of decomposition of the added material and synthesis of soil organic matter. These models are able to capture the pattern of N release that is attributable to the N concentration of plant materials, or more generally the C:N ratio of the organic input. However the models are unable to simulate the more complex pattern of N release that has been reported for some animal manures, notably materials that exhibit initial immobilization of N even when the C:N of the material suggests it should mineralise N. The APSIM SoilN module was modified so that the three pools that constitute added organic matter could be specified in terms of both the fraction of carbon in each pool and also their C:N ratios (previously it has been assumed that all pools have the same C:N ratio). It is shown that the revised model is better able to simulate the general patterns on N mineralised that has been reported for various organic sources. By associating the model parameters with measured properties (the pool that decomposes most rapidly equates with water-soluble C and N; the pool that decomposes slowest equates with lignin-C) the model performed better than the unmodified model in simulating the N mineralization from a range of feeds and faecal materials measured in an incubation experiment.

*Keywords: decomposition, mineralization, quality factors, simulation, modelling*

## 1. Introduction

The cycling of nutrients through the decomposition of plant residues is important in all ecosystems. However in the soil fertility management of many tropical farming systems, organic sources play a dominant role because of their short-term effects on nutrient supply to crops (Palm et al., 2001). There is now a considerable literature reporting decomposition and nutrient release patterns for a variety of organic materials from tropical agro-ecosystems. This information has been drawn together so that it can be used for improvement of soil fertility through better management of organic inputs (e.g. Giller and Cadisch, 1997; Palm et al., 2001), and understanding has emerged of how resource quality factors influence the release patterns.

In nutrient and capital poor tropical farming systems, effective use of whatever nutrient sources are available will be required to raise and maintain productivity (Giller et al., 1997). If models are to be useful in helping to design farming systems that use various nutrient sources more effectively, it is a first requirement that the models must be able to reliably describe the release of nutrients from the different organic sources. Palm et al. (1997) pointed out that there is little predictive ability for making recommendations on combined use of organic and inorganic nutrient sources. One reason for this is the inability of models to adequately capture the short-term dynamics of the release of nutrients from organic materials.

In this paper we report on how one particular model, APSIM (Agricultural Production Systems Simulation Model, McCown et al., 1996; Keating et al., 2002), represents the decomposition of organic inputs, and how the quality of the inputs influences nitrogen release. The manner in which the dynamics of soil carbon and nitrogen are modelled in APSIM's SoilN module (Probert et al., 1998) is similar to what is found in many other models - see reviews by Ma and Shaffer (2001) and McGechen and Wu

(2001). Models do differ in the pool structure used to describe the decomposition of organic inputs, with the pools differing in their rates of decomposition. However, we are unaware of any model where the pools differ in chemical composition, with the effect that inputs decompose with non-varying composition. We show that the assumption that all pools have the same C:N ratio fails to adequately represent the observed behaviour for release of N from some organic inputs. We present a modification of APSIM SoilN which allows for different C:N ratios in each pool. The modified model was able to better match the mineralization/immobilization of N observed in laboratory incubation studies.

**2. Modelling the decomposition of organic sources**

The development of the APSIM SoilN module (Probert et al., 1998) can be traced back via CERES models (e.g. Jones and Kiniry, 1986; Godwin and Jones, 1991) to PAPRAN (Seligman and van Keulen, 1981). Briefly, crop residues and roots added to the soil, are designated fresh organic matter (FOM) and are considered to comprise three pools (FPOOLs), sometimes referred to as the carbohydrate-like, cellulose-like and lignin-like fractions of the residue. Each FPOOL has its own rate of decomposition, which is modified by factors to allow for effects of soil temperature and soil moisture. For inputs of crop residues/roots it has usually been assumed that the added C in the three FPOOLs is always in the proportions 0.2:0.7:0.1. In this manner the decomposition of added residues ceases to be a simple exponential decay process as would arise if all residues were considered to comprise a single pool.

Although the three fractions have different rates of decomposition, they do not have different compositions in terms of C and N content. Thus whilst an input might be specified in terms of the proportion in each of the FPOOLs, thereby affecting its rate of decomposition, the whole of the input will decompose without change to its C:N ratio. If the analogy can be made with the dissolution of a substance, we might say that the whole of the residues decompose congruently. Alternatively the system can be described as having three soil organic C pools but only one soil organic N pool (Gijsman et al., 2002).

The release of N from the decomposing residue is determined by the mineralization and immobilization processes that are occurring. The C that is decomposed from the residue is either evolved as $CO_2$ or is synthesized into soil organic matter. APSIM SoilN assumes that the pathway for synthesis of stable soil organic matter is predominantly through initial formation of soil microbial biomass (BIOM), though some C is transferred directly to the more stable pool (HUM). The model further assumes that the soil organic matter pools (BIOM and HUM) have C:N ratios that are unchanging through time. The formation of BIOM and HUM thus creates an immobilization demand that has to be met from the N released from the decomposition of the residue and/or by drawing on the mineral N (ammonium- and nitrate-N) in the system. Any release of N during the decomposition process in excess of the immobilization demand results in an increase in the ammonium-N. The model operates on a daily time step, so that decomposition of the residue fractions is happening simultaneously with decomposition of the soil organic matter pools.

If we ignore the dynamic nature of the system, the N mineralization from a substrate can be expressed succinctly as (Whitmore and Handayanto, 1997):

$$N_{mineralized} = C_{decomposed} \{1/Z - E/Y\} \quad \ldots\ldots \text{ equation (1)}$$

where Z is the C:N ratio of the decomposing substrate, E is a microbiological efficiency factor which can be taken to be 0.4 (the value in APSIM SoilN for the fraction of the decomposing carbon that is transformed into soil organic matter), and Y is the C:N ratio of the soil organic matter being formed. Equation (1) implies that there is a C:N ratio of substrate that determines whether decomposition results in net N mineralization or immobilization. Assuming the initial product of decomposition is soil microbial biomass with Y = 8 (the value used in APSIM SoilN), the critical value can be calculated as 20. As shown by Whitmore and Handayanto (1997), this expression accounts for much of the variation found in the data that have examined N mineralized (or immobilized) in relation to the C:N ratio of the added organic matter.

The rate of net N mineralization is dependent on the rate of decomposition. Thus allowing the pool sizes of the three FPOOLs to be an input that characterizes the type of organic input will alter the rate of net N mineralization (as shown by Quemada and Cabrera, 1995; Quemada et al., 1997). However changing the pool sizes alone cannot alter whether a source exhibits initial net N mineralization or immobilization (since this is determined by the C:N ratio of the source).

In studies of the mineralization of N from various manures, Kimani et al. (2001) and Delve et al. (2001) encountered situations where there was an initial immobilization of N, despite the fact that the overall C:N ratio of the material was such that it would be expected to result in net mineralization. This behaviour can not be modelled without assuming that the three FPOOLs also differ in their C:N ratios.

*2.1 Modifications to the model*

Modifications were made to the APSIM SoilN module so that any input of organic material could be specified in terms of both its fractionation into the three FPOOLs, and the C:N ratios of each FPOOL. In the modified model, each FPOOL is assumed to decompose congruently. The rates of decomposition of the three FPOOLs were not changed from the released version of APSIM (0.2, 0.05 and 0.0095 $day^{-1}$ respectively under non-limiting temperature and moisture conditions).

Using this enhanced version of the model, we have explored the effects on simulated N mineralization from hypothetical sources that differ in respect of firstly, their fractional composition (the proportion of C in the 3 FPOOLs), and secondly, the C:N ratios of the FPOOLs.

The effects are illustrated by contrasting four assumptions as to how an organic input decomposes:

1. using the released version of ASPIM SoilN (v 2.0)
2. changing the fractional composition of the FPOOLs but with the C:N ratio being the same in all pools
3. changing the FPOOLs to have different fractional compositions and different C:N ratios, in the first instance with FPOOL1 differing from a common value for FPOOLs 2 and 3
4. with the fractional composition and C:N ratios differing between all 3 FPOOLs.

*2.2 Specification of model inputs*

The enhancements made to the model result in extra information being needed to specify the inputs. Ideally it should be possible to derive the necessary information from known (measured) properties of the organic sources.

The experimental data reported by Delve et al. (2001) have been used to investigate whether the analytical data for a range of feeds and faecal samples can be used to specify the model to simulate the N mineralization measured in a laboratory incubation experiment.

## 3. Materials and Methods

*3.1 Simulation of mineralization from hypothetical sources*

The model was configured to simulate a simple incubation study, involving a single layer of soil under conditions of constant temperature (25$^{o}$C) and at a soil water content that ensured there was no moisture restriction on decomposition. Initial nitrate-N concentration in the soil was 20 mg N $kg^{-1}$. The effect of different organic inputs was investigated by incorporating materials that contained a constant amount of N (100 mg N $kg^{-1}$ soil) but with varying C:N ratio. A control system was also simulated without any added organic input.

The output from the simulations are presented as net mineralization/immobilization expressed as a percentage of the N added:

$$\text{N mineralization (\%)} = 100 \times (\text{Mineral-N}_{input} - \text{Mineral-N}_{control})/\text{N added}$$

where Mineral-$N_{input}$ is the simulated ammonium- + nitrate-N in systems with the added source, and Mineral-$N_{control}$ in the absence of any input.

*3.2 Simulating a laboratory incubation study*

The model was specified to simulate the incubation study of Delve et al. (2001). Using a leaching tube incubation procedure (Stanford and Smith, 1972), they measured net N mineralization for feeds and faecal samples resulting from cattle fed a basal diet of barley straw alone, or supplemented with 15 or 30% of the dry matter as *Calliandra calothyrsus*, *Macrotyloma axillare* or poultry manure. The soil used was a humic nitisol with organic C content of 31 g $kg^{-1}$, C:N ratio of 10 and pH (in water) of 5.9. The incubations were conducted at 27°C.

Data were reported on the chemical composition of the feeds and faecal samples including: total C and N; water soluble C and N; acid detergent fibre (ADF), neutral detergent fibre (NDF) and acid detergent lignin (ADL) (van Soest et al., 1987).

## 4. Results

Experimental data (Kimani et al., 2001), that indicated the need to reconsider how N mineralization from organic inputs is modelled, are illustrated in Figure 1. For a wide range of manures, their results consistently show an initial immobilization or delay in mineralization lasting several weeks, even for materials that have overall C:N ratios of less than 20. This pattern of response is noticeably different to studies of N mineralization from plant materials (e.g. Constantinides and Fownes, 1994); plant materials with low C:N typically exhibit positive net mineralization from the commencement of the incubation period.

Other authors also report initial N immobilization followed by net mineralization in experiments with animal manures having low C:N ratios (Trehan and Wild, 1993; Olesen et al., 1997). The faecal samples studied by Delve et al. (2001), with C:N ratios in the range 20-27, had even more complex patterns of mineralization; some materials showed initial net mineralization before an extended period of immobilization lasting for at least 16 weeks of incubation (see below).

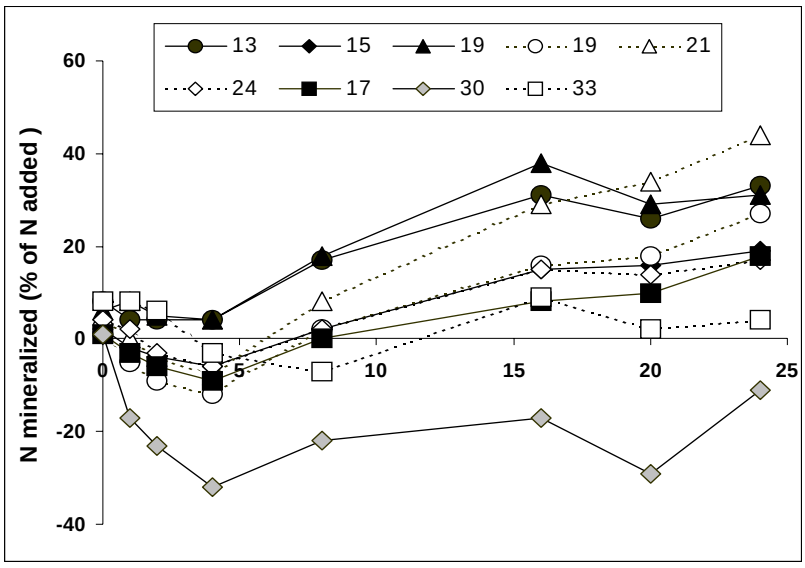


**Figure 1**. Net nitrogen mineralised from different manures in an incubation study lasting 24 weeks. C:N ratios of the manures are shown in the legend. Data of Kimani et al. (2001)

*4.1 Modelling N mineralization from hypothetical sources*

Simulation of mineralization for sources with different C:N ratios using the released version of APSIM SoilN is shown in Figure 2. The results are in general agreement with experimental studies for plant materials where net N mineralization is closely related to the N content and hence C:N ratio (e.g. Constantinides and Fownes, 1994; Tian et al., 1992). For sources with C:N < 20, net mineralization occurs from the outset (as predicted by equation 1). However with C:N > 20, there is initially immobilization of mineral-N and it is only as newly formed soil organic matter is re-mineralized that mineral-N in the system begins to increase.

The lower pane of Figure 2 shows the same data plotted against the C:N ratio for different periods of incubation. Again the pattern of response is familiar from experimental data that have been used to infer the C:N ratio of a substrate, around 20-25, that determines whether net mineralization or immobilization occurs. The simulation results show that the C:N ratio of the substrate that results in zero net mineralization changes with the period of incubation, increasing from approximately 21 at day 10 to 26 at day 100. Such an effect has not generally been recognized when discussing critical C:N ratios with respect to mineralization/immobilization, though its importance was recognized by De Neve and Hofman (1996). Thus incubation period is a factor that will complicate efforts to compare results from different incubation studies. Furthermore other aspects of the incubation conditions can also be expected to have similar effects as the incubation period; in particular higher incubation temperature is likely to have much the same effect as increasing the incubation period.

The effect of changing the pool structure of the input by modifying the fractions in each of the FPOOLs is illustrated in Figure 3. For inputs with low C:N (<20), a greater proportion of material in the FPOOLs with lower rates of decomposition simply slows the release of mineral-N. Where C:N is >20 so that net immobilization occurs, inputs with a greater proportion of material with lower rates of decomposition result in less immobilization during the early stages of decomposition, but it also takes longer before the system exhibits positive net mineralization. It is to be noted that simply changing the proportions of the input between the three pools with unaltered C:N ratio can not cause a switch from causing net mineralization to immobilization, or vice versa.

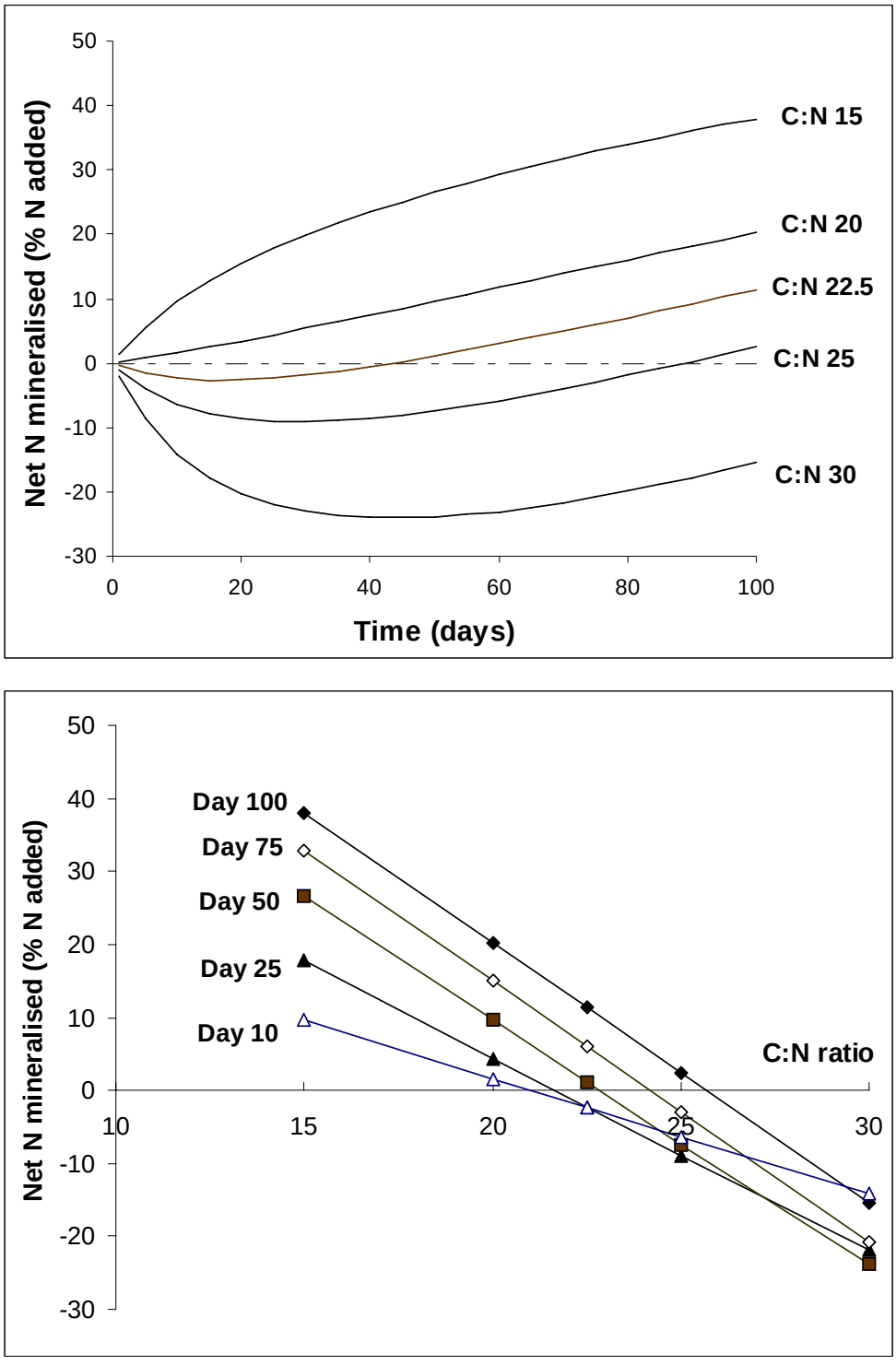


**Figure 2**. Simulation of nitrogen mineralization from organic inputs with different C:N ratios using the released version of APSIM SoilN. The model assumes that all inputs have the same fractional composition in terms of the three FPOOLs (0.2:0.7:0.1), and that, for a given source, all FPOOLs have the same C:N ratio.

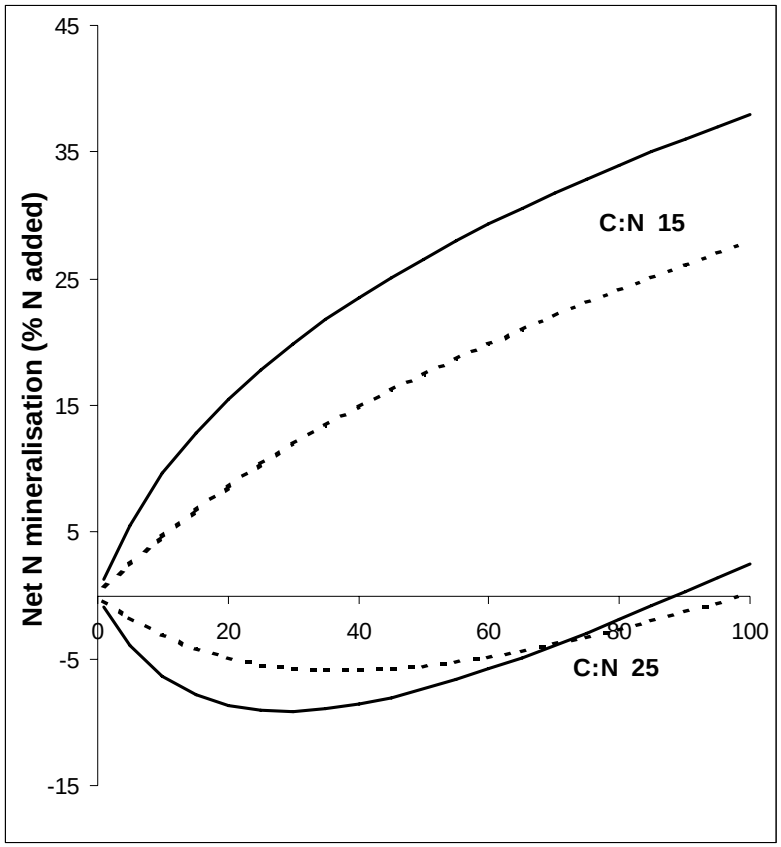


**Figure 3**. Effect of changing the composition of organic inputs by varying the proportions in the three FPOOLs. The continuous lines refer to substrates where FPOOLs comprise 0.2:0.7:0.1 of the total carbon; the dashed lines 0.01:0.49:0.5. The C:N ratios of all FPOOLs (for a given source) are the same.

Effects of changing the composition of the input by modifying the C:N ratios of the different FPOOLs are shown in Figures 4 and 5. In Figure 4, all materials have the same overall C:N ratio, but the C:N ratio of FPOOL1 is now greater than for the material in pools 2 and 3. The result is that the material in FPOOL1 which decomposes most rapidly creates an immobilization demand, and the higher the C:N ratio the greater the initial immobilization. However if C:N of FPOOL1 is higher, there must be compensating decreases in the C:N ratios of the other pools. As incubation time increases, the differences between different materials decrease so that there is little longer-term effect of the C:N ratios of the FPOOLs on net mineralization which is determined largely by the overall C:N ratio.

Figure 5 illustrates variation in the C:N ratio between FPOOLs 2 and 3. Again all materials have the same overall C:N ratio and here the C:N of FPOOL1 is also fixed at 10. With the low C:N in the rapidly decomposing pool, there can be an initial net mineralization, especially when the C:N of FPOOL2 is also relatively low. However, as FPOOL1 is depleted, there can be a switch from net mineralization to net immobilization. Increasing the C:N of FPOOL2 results in increasing immobilization and the immobilization persists to longer times.

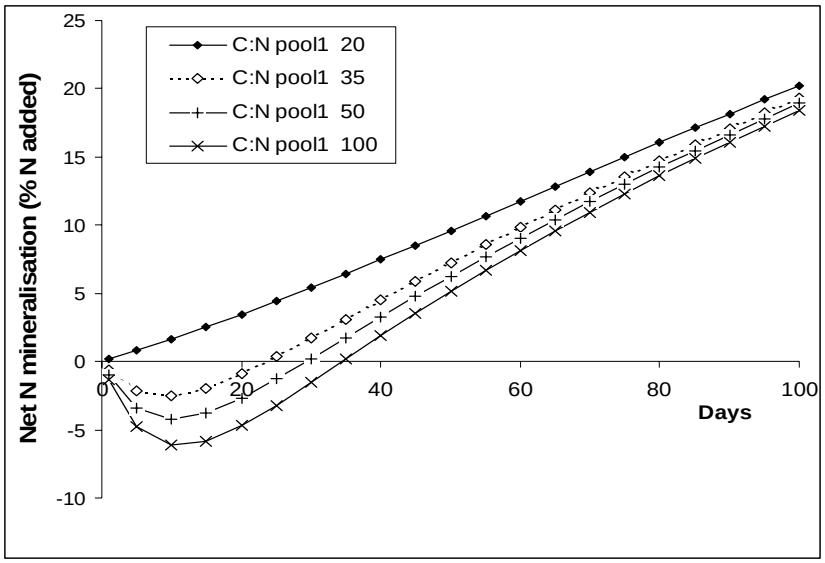


**Figure 4**. Effect of changing the composition of organic inputs by modifying the C:N ratios of the FPOOLs. In this example, the input has fractional composition 0.2:0.7:0.1 and overall C:N ratio of 20, with the C:N ratio of FPOOL1 as shown in the legend (C:N ratios of FPOOLs 2 and 3 are equal)

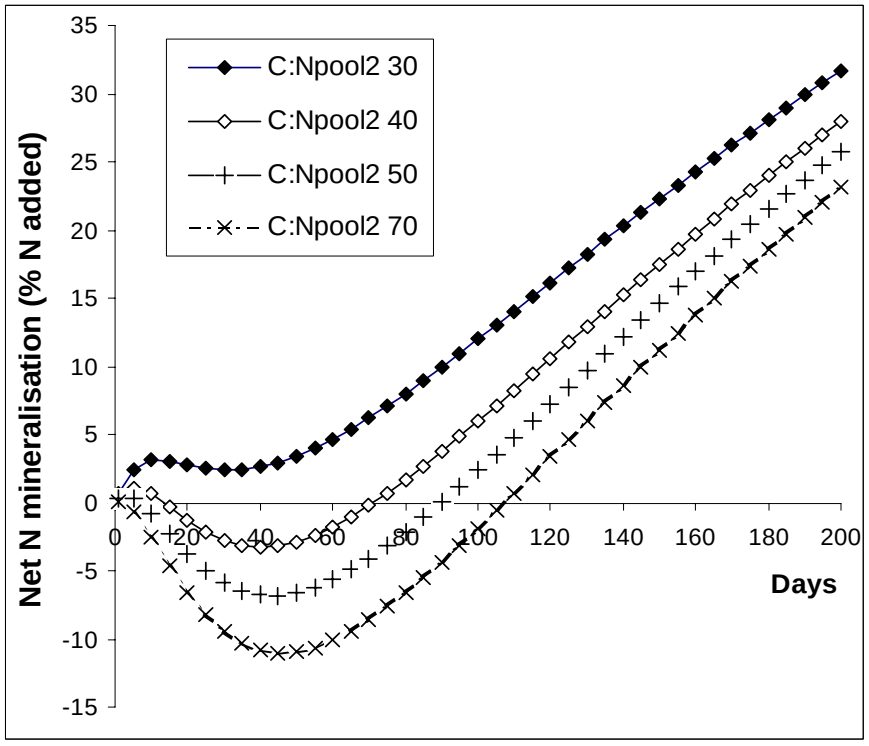


**Figure 5**. Effect of changing the quality of organic inputs by varying the C:N ratios of the FPOOLs. In this example, the input has fractional composition 0.1:0.7:0.2, overall C:N ratio of 20 and C:N ratio of FPOOL1 of 10, with C:N of FPOOL2 as shown in the legend.

*4.2 Modelling the mineralization study of Delve et al. (2001)*

The modelled net mineralization from hypothetical sources display patterns of N release that are similar to published experimental data. Notably the several weeks delay before mineralization became positive, as exhibited by several of the manures studied by Kimani et al. (2001), is consistent with variation in the C:N ratio of FPOOL1 (Figure 4). On the other hand, the longer delay reported by Delve et al. (2001) is more like the pattern shown in Figure 5 associated with variation in FPOOL2 and 3.

We have attempted to use the analytical data reported by Delve et al. (2001) to specify the "quality" aspects of organic inputs represented in the model. We assume the soluble components of C and N equate to FPOOL1; thus the analytical results are sufficient information to determine the proportion of total C in this pool and its C:N ratio. Also we assume that ADL, which measures lignin, equates to FPOOL3 permitting the fraction of C in this pool to be estimated; the fraction of C in FPOOL2 is found by difference. Since the overall C:N ratio (on a total dry matter basis) is also known, the only missing information is the distribution of non-water soluble N between pools 2 and 3. A series of simulations were carried out for each source with the different combinations on C:N in the two pools (constrained by the C:N of the total DM).

Figure 6 shows the simulation of N mineralization for the control treatment. Although there is a slight under-prediction, the general pattern agrees well with the measured data. It is to be noted that in the model the net N mineralization from an organic source is only influenced by the control treatment when there is inadequate mineral N in the system to meet an immobilization demand.

The net N mineralization for the feeds and a selection of the faecal samples studied by Delve et al. (2001) is shown in Figure 7. The outputs from two simulations are compared, these being the outputs from the modified and unmodified versions of the model. The input data used for the modified model are set out in Table 1.

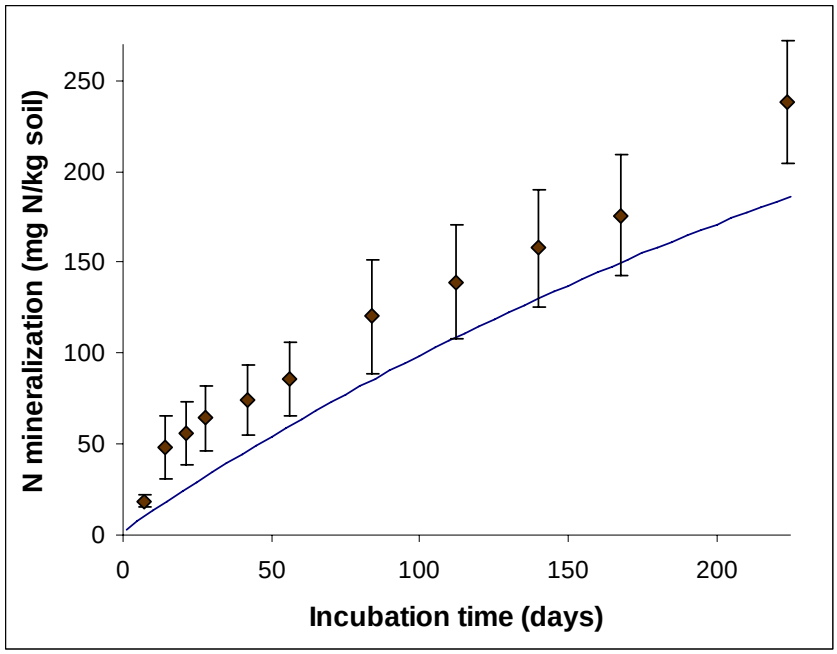


**Figure 6.** Simulation of the control treatment of Delve et al. (2001). The symbols denote measured data with error bars representing ± standard error of the mean of 3 replicates. The continuous line is the output from the model. Overall C:N ratio was measured; FPOOL1 based on measured C and N as water soluble components; proportion of C in FPOOL3 based on measured ADL. C:N of FPOOL2 and 3 selected, subject to constraint that must be consistent with overall C:N, to give reasonable fit between simulated N mineralization and measured data.

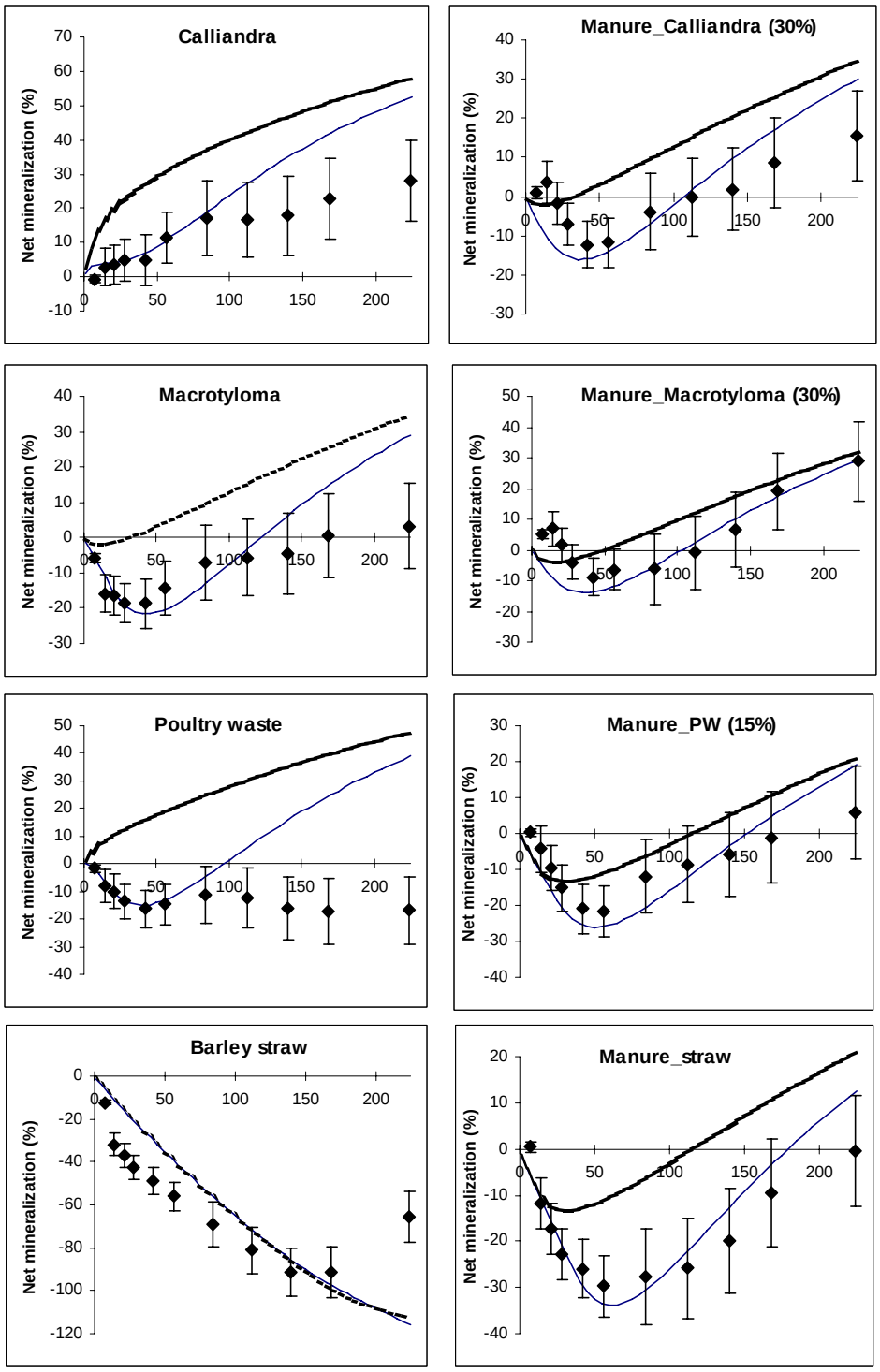


**Figure 7**. Net nitrogen mineralization from feeds and faecal materials (data of Delve et al., 2001). Experimental data shown as symbols with bars representing □ standard errors. The heavy broken line is for the model where all organic material is assumed to decompose with the same C:N ratio; the continuous line is for the model with different C:N ratio in each FPOOL. Parameters used to specify the different sources (proportion of C and C:N in the three FPOOLs) are set out in Table 1.

**Table 1**. Composition of organic materials (feeds and faecal samples) used for simulating the mineralization study of Delve et al. (2001).

| Sample | Overall C:N | Proportion of carbon in FPOOLs (%) | | | C:N of FPOOLs | | |
|---|---|---|---|---|---|---|---|
| | | Pool 1 | Pool 2 | Pool 3 | Pool 1 | Pool 2 | Pool 3 |
| Calliandra | 13 | 12 | 74 | 14 | 9 | 44 | 3 |
| Macrotyloma | 22 | 16 | 74 | 10 | 17 | 67 | 4 |
| Poultry waste | 17 | 5 | 88.5 | 6.5 | 4.5 | 202 | 1.5 |
| Barley straw[1] | 86 | 6 | 84.5 | 9.5 | 24 | 103 | 103 |
| Calliandra_Manure (30%)[2] | 22 | 4 | 74 | 22 | 16 | 40 | 9 |
| Macrotyloma_Manure (30%) | 23 | 5.5 | 73.5 | 21 | 14 | 36 | 11 |
| Poultry waste_Manure (15%) | 27 | 4.5 | 82 | 13.5 | 12 | 41 | 10 |
| Barley straw_Manure | 27 | 9 | 71.5 | 19.5 | 20 | 66 | 9 |

[1] simulated N mineralization was not sensitive to partitioning of N between pools 2 and 3
[2] value in parentheses denotes proportion of supplement in diet

For most of the materials the goodness of fit is substantially better for the modified than for the unmodified model. Using the analytical data to specify the fraction of C in each of the FPOOLs and the C:N ratio of FPOOL1, it was possible to choose values for the C:N ratios of FPOOL2 and FPOOL3 to obtain satisfactory fits with the measured data.

In general the fit is better for the faecal samples than for the feeds, with the poorest fit for the poultry waste. The pattern of net mineralization measured for the poultry waste, which had an overall C:N ratio of 17, is different from the other materials in that the change from immobilization to mineralization that occurred after 50 days was not maintained, and further net immobilization occurred later in the incubation. The simulation for the barley straw (C:N 86) predicts that immobilization continues for at least 200 days. Because all mineral N is immobilized in this treatment, the simulated immobilization is determined by the rate of mineralization of the control treatment and is not sensitive to how N is partitioned between FPOOLs 2 and 3. The under-prediction of N mineralization in the control treatment (Fig. 6) is the cause of the under-prediction of net immobilization by the barley straw.

## 5. Discussion

The essence of equation (1) is built into many dynamic simulation models that describe the decomposition of organic residues and the associated mineralization of N. Such models are capable of capturing the gross effect of C:N ratio (as illustrated in Fig. 2) on mineralization/ immobilization from plant residues. However they are not able to represent the more complex pattern of mineralization/immobilization that has been reported from laboratory incubation studies of N release from manures with low C:N (e.g. Fig. 1). To capture this pattern of N release it is necessary to conceptualize the organic input as comprising discrete fractions that differ not only in their rates of decomposition but also in their chemical (i.e. C and N) composition.

The observed behaviour suggests that the fraction of the substrate that decomposes fastest has a higher C:N ratio than the bulk of the material. If the portion that decomposes fastest can be equated to the water-soluble fraction, this is consistent with the analytical data of Kimani et al. (2001) (Table 2). Their data show that the soluble component, which amounted to some 12% of the total carbon, had a much higher C:N ratio than the materials as a whole.

**Table 2**. Carbon and C:N ratio in manures and their water soluble fraction. Data are means, with standard deviation in parentheses, across 45 diverse manure samples. Data of Kimani et al. (2001)

| | % C | C:N ratio |
|---|---|---|
| Total | 32 (7.0) | 21 (5) |
| Soluble fraction[1] | 3.8 (1.9) | 68 (60) |

[1] soluble C expressed on total DM basis (i.e. average of 12% of total C was measured in the soluble fraction)

In contrast, the mineralization data of Delve et al. (2001) (Fig. 7) and chemical composition of their materials (Table 1) indicate that the measured water-soluble component had a smaller C:N than the bulk materials. To simulate the observed mineralization data it was necessary to assume that the materials had higher C:N in FPOOL2 than in FPOOL3.

To some extent, this difference between in the C:N of the water-soluble components in the two studies can be explained by the nature of the manures. Those in the study of Delve et al. (2001) were fresh faecal material, whereas the manures studied by Kimani et al. (2001) had been collected from farm situations where they would have been exposed to varying degrees of weathering what would have been expected to remove some water-soluble components. However if this is the explanation, we are unable to satisfactorily account for why the analytical data of Kimani et al. (2001) should still indicate considerable amounts of water-soluble C, nor why there should have been preferential loss of N relative to C resulting in increased C:N for the water-soluble components.

By simulation of hypothetical materials, we have shown that the model can be parameterised to simulate the general pattern of N mineralization that is observed for various organic sources. Nonetheless, it remains a challenge to know how appropriate parameters should be selected for a given source and/or how to derive the parameter values from other information that may be available as analytical data for supposed "quality factors". Here we have used data for C and N in the water-soluble components to specify FPOOL1, and the measured ADL to specify the C in FPOOL3. To obtain the goodness of fit shown in Fig. 7 for the manures required C:N in FPOOL2 in the range 36-66, with corresponding C:N in FPOOL3 of 9-10 (Table 1). Attempts to estimate the C:N of FPOOL2 from measured data for N associated with ADF and NDF (Delve et al., 2001) produced values that were considerably higher (range 63-174 for the manure samples) with the corresponding values for pool 3 becoming very narrow (<0.8); the goodness of fit for simulations of N mineralization using these values were substantially worse than those shown in Fig. 7.

For the feed materials (Calliandra, Macrotyloma, poultry waste), the predictions were less good than for the faecal samples. To obtain a reasonable fit in the early stages of the mineralization a high C:N in FPOOL2 is required, but this results in very low values for FPOOL3 and over-prediction as the incubation period progresses beyond 100 days.

The resource quality factors that have been shown to influence N release from organic sources are the C:N ratio (or N concentration in plant materials for which C concentration varies little), lignin and polyphenol concentrations (Palm et al., 2001). These studies suggest that the effect of lignin is consistent with the concepts in the model in as much as higher lignin content can be represented by a greater proportion of the C in the slow decomposing pool. But it is also necessary to hypothesize that the FPOOLs differ in their C:N ratio. The polyphenol concentration in the materials studied by Delve et al. (2001) were low (<1.6%) except for the Calliandra feed. It remains uncertain how the effects of polyphenols on decomposition and N mineralization can be represented by the model.

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# Dynamics of charge bearing soil organic matter fractions in highly weathered soils

Koen Oorts[1], Roel Merckx[1], Bernard Vanlauwe[2], Nteranya Sanginga[3] and Jan Diels[3]
[1]K.U. Leuven, Department of Land Management, Kasteelpark Arenberg 20, 3001 Heverlee
[2]Tropical Soil Biology and Fertility Program, Unesco-Gigiri, PO Box 30597, Nairobi, Kenya
[3]International Institute of Tropical Agriculture, c/o Carolyn House, 26 Dingwall Road, Croydon CR9 3EE, UK

## Abstract

Soil organic matter contributes significantly to cation exchange capacity, especially in highly weathered soils, where it can account for up to 90% of the total CEC of the topsoil. To determine how different amounts and qualities of plant residues affect the development of charge in these soils, we set out to (i) determine the effects of litter quality on the development of charge in soil and in its size separates and to (ii) determine the dynamics of this phenomenon in the field. For (i) we relied on a 20-year old arboretum where we collected soil samples under seven multipurpose tree species: *Afzelia africana, Dactyladenia barteri*, *Gliricidia sepium, Gmelina arborea, Leucaena leucocephala*, *Pterocarpus santalinoides*, and *Treculia africana*. For (ii) we installed decomposition tubes in the field with six treatments (control and *Afzelia, Dactyladenia, Gmelina, Leucaena* and *Treculia* at 15 Mg dry matter $ha^{-1}$) and followed the development of charge in the top 10 cm over a period of two years.

Samples from both experiments were dispersed by ultrasound and then physically fractionated by wet sieving and sedimentation. CEC measurements were made at 6 different pH values between 7.5 and 2.5 with the silver-thiourea method.

In the arboretum samples, carbon contents and CEC at in situ pH ranged between 7.16 and 13.62 g C $kg^{-1}$ soil and between 2.8 and 6.5 $cmol_c$ $kg^{-1}$ soil respectively. The clay and fine silt fractions were responsible for 76 to 90% of the soil CEC at pH 5.8. The contribution of the fine silt fraction to this CEC ranged from 35% to 50%. After 20 years, the fine silt reflected the treatment differences most clearly (Carbon: 34.1 – 65.8 g C $kg^{-1}$ fraction and CEC: 16 - 36 $cmol_c$ $kg^{-1}$ fraction at pH 6). The clay fraction seemed to be unaffected by the different organic inputs as it did not show clear differences in carbon content and CEC between treatments. Carbon content and pH together explained more than 85 % of the variation in CEC for the whole soil and the fractions. Differences in CEC between treatments could, as a consequence, be explained by the differences in carbon content. In total, SOM was responsible for 75 to 85% of the CEC of these soils.

The decomposition tube experiment revealed that after 23 months total soil carbon contents ranged between 3.8 and 5.3 g C $kg^{-1}$ soil while CEC values at pH 5 (=average pH) ranged between 1.9 and 2.5 $cmol_c$ $kg^{-1}$ soil. Fine silt carbon contents ranged between 18.3 and 26.5 g C $kg^{-1}$ fine silt and CEC values at pH 5 varied between 5.3 and 8.9 $cmol_c$ $kg^{-1}$ fine silt. Fine silt fractions again reflected the differences between the treatments most clearly, indicating that the lowest quality residues such as *Treculia* and *Dactyladenia* resulted in the largest CEC values and the largest carbon contents.

While the results from the first experiment confirm a role of low quality residues in the build-up of charge in weathered soils after 20 years, the second experiment indicates that even a single addition of these residues enhances charge characteristics significantly and for a significant length of time.

**Key words**: soil organic matter, charge characteristics, multipurpose trees, CEC, decomposition.

## Introduction

The beneficial effects of soil organic matter management in the tropics have been amply documented as far as they relate to soil functions such as nutrient release (nitrogen and phosphorus in particular) and soil architecture (Vanlauwe et al., 1998; Nziguheba et al., 2000; Feller and Beare, 1997). Much less information is available on the relations between soil organic matter changes and the

associated changes in nutrient retention capacity for neither cations nor anions. Nevertheless, soil organic matter is known to contribute to the total charge of a soil, a charge that is mostly pH-dependent. As a consequence, empirical relations do exist that predict soil cation exchange capacities based on soil organic carbon concentrations (Manrique et al., 1991; Asadu et al., 1997; Krogh et al., 2000). In highly weathered soils, the creation of extra charge, on top of the one derived from soil mineral components, can be an important management goal as CEC values can be increased by factors from values as low as 1 $cmol_c\ kg^{-1}$ soil to 4 - 6 $cmol_c\ kg^{-1}$ soil (Gallez et al., 1976; Oades et al., 1989). Apart from a general idea on soil organic matter dynamics, we do not have a precise idea on how fast we can positively affect charge characteristics and in which size fractions the impact is most strongly seen. In the present paper we present a dual approach. First, we will investigate the changes in charge brought about by a 20-year continuous input of tree litter of known quality in an attempt to relate litter quality with the ensuing changes in soil charge characteristics. Secondly, we will address an important and ensuing management issue in this that it is crucial to determine how fast the changes in charge come about by an input of litter of a given quality and also, how long lived these changes are.

## Materials and methods

*Site description*

For the first part of the experiment, we relied on a 20-year old arboretum established in 1979 on a ferric Lixisol (WRB, 1998) at the International Institute of Tropical Agriculture (IITA) in Ibadan, South Western Nigeria (3°54'E and 7°30'N) where we collected soil samples under seven multi-purpose trees: *Afzelia africana, Dactyladenia barteri, Gliricidia sepium, Gmelina arborea, Leucaena leucocephala, Pterocarpus santalinoides* and *Treculia africana.* For more information on this site we refer to Oorts et al., (2000) and Kang and Akinnifesi (1994). We took soil samples in March 1999 from the surface horizons (0-10 cm) of the corresponding plots by taking 4 cores (10 cm depth, 10 cm dia) from each alley at random throughout the alley. Samples from different alleys were considered as field replicates. Litter was collected from the soil surface before soil sampling and leaves from the respective trees collected. Both litter and leaves were air dried before analysis. For the field incubation experiment, decomposition tubes (10 cm depth, 10.5 cm dia) were filled with topsoil (0-10 cm) of a ferric Lixisol (WRB, 1998) sampled at the I.I.T.A. campus and were installed in an adjacent plot. They were either kept bare or were amended with litter derived from *Afzelia*, *Dactyladenia*, *Gmelina*, *Leucaena* and *Treculia*. In the amended treatments soil was mixed with litter at an addition rate of 15 tons dry matter/ha in the top 10 cm of each core. Destructive sampling took place at 3, 6, 12 and 23 months after application. In both experiments, all soil samples were air-dried, and passed through a 4 mm sieve to remove roots and large stones before fractionation and analyses.

*Fractionation*

The soil organic matter fractions from the arboretum samples and decomposition tubes sampled at 6 and 23 months after application were obtained by size separation after ultrasound dispersion. To this end, soil suspensions (25g soil and 125 ml distilled water) were subject to a 10 minutes sonication treatment at 62.5 W (=1500 J $g^{-1}$ soil) with Misonix Sonicator XL2020. The soil suspension so obtained was then separated into the following size classes: > 2 mm, 0.25-2 mm and 0.053 - 0.25 mm using wet sieving (Fritsch analysette 3, 50 Hz, 1.5 mm amplitude). The fractions on the sieve were collected and further split into mineral and organic components through flotation-decantation on water. Material smaller than 0.053 mm was collected and manually sieved through a 0.020 mm screen. The fine silt fraction (0.002 - 0.20 mm) was separated from a subsample by sedimentation (four cycles) and the clay fraction (< 0.002 mm) collected from the respective supernatants by flocculation with $CaCl_2$ (± 0.02 M). The clay fraction was next washed salt-free by dialysis (Spectra/Por 4, MWCO 12-14.000). All fractions were dried overnight at 60°C and weighed. The above separation scheme resulted in 9 fractions: 2-4 mm mineral (M2000), 2-4 mm organic (O2000), 0.250-2 mineral (M250), 0.250-2 organic (O250), 0.053-

0.250 mineral (M53), 0.053-0.250 organic (O53), 0.020-0.053 (coarse silt), 0.002-0.020 (fine silt) and < 0.002 (clay). Dry weight recoveries over the different samples ranged between 98.1 and 99.6 %.

*Analyses*

Soil pH was always measured in a 0.01 M $CaCl_2$ solution at a 1:5 soil:solution ratio after 1 h shaking. Organic carbon and nitrogen contents of soil and plant samples were determined using a CN analyser- mass spectrometer (ANCA-GSL preparation module and 20-20 Stable Isotope Analyser, Europa Scientific) after ball-milling. Plant material was analysed for lignin and (hemi)-cellulose content by the acid detergent method (Van Soest, 1963; Van Soest and Wine, 1967). Polyphenolics were determined by a revised Folin-Denis method (King and Heath, 1967). To account for the specifics of highly weathered soils, we used a CEC method designed to operate at in situ soil pH and at low ionic strengths. An unbuffered AgTU (silver-thiourea complex) solution (0.01 M $Ag^+$, 0.1 M TU) was used to measure CEC and base saturation at prevailing pH of the whole soil samples from the arboretum (Pleysier and Juo, 1980). Variation of CEC with pH was determined on whole soil samples and the three smallest size separates. In short, (a full description of the method is found in Oorts et al., 2000) subsamples were weighed in centrifuge tubes and pH was increased by shaking for 2 h with 15 ml $10^{-3}$ M NaOH. Next, 15 ml unbuffered AgTU (final concentration: 0.01 M $Ag^+$, 0.1 M TU) was added and after shaking overnight, pH was recorded, samples were centrifuged and a first 1 ml subsample was taken from the clear supernatant for Ag analysis by AAS. Subsequently, the soil was gradually acidified by adding small amounts of 1 M $HNO_3$ and after each equilibration, pH was measured and a subsample taken from the supernatant for Ag analysis. The whole procedure resulted for each sample in 6 CEC measurements between pH 2.5 and 7.5.

**Results and discussion**

*Arboretum*

Soils in the arboretum were predominantly sandy, with an approximate composition of 79% sand, 13% silt and 8% clay. The largest soil organic carbon concentrations were observed in the *Dactyladenia*, *Leucaena* and *Treculia* stands ranging between 10.79 and 13.62 g C $kg^{-1}$ soil (Table 1). The four other soils had comparable and considerably lower carbon concentrations in a range of 7.16 to 7.97 g $kg^{-1}$. CEC values at prevailing soil pH ranged correspondingly between 4.51 and 6.47 $cmol_c$ $kg^{-1}$ for the three top stands and between 2.80 and 3.90 $cmol_c$ $kg^{-1}$ for the four others that were lower in carbon. Most of the variation in CEC could be explained by the differences in carbon content, while an additional part of the CEC variation was explained by the pH.

$CEC = 0.15 + 0.43 * C\ (g\ kg^{-1})$ $\quad n = 28, R^2 = 0.767, P<0.001$ (1)

$CEC = -6.97 + 1.25\ pH + 0.41 * C\ (g\ kg^{-1})$ $\quad n = 28, R^2 = 0.870, P<0.001$ (2)

Also when CEC values were obtained at different pH values, most of the variation could be explained by differences in organic carbon concentration and pH. These two together explained 85% of the variation.

$CEC = -1.79 + 0.50 * pH + 0.36 * C\ (g\ kg^{-1})$ $\quad n = 168, R^2 = 0.849, P<0.001$ (3)

This allows concluding that in these soils the concentration of organic carbon is the main source of variation between the different treatments. The regressions between soil carbon content and CEC allowed calculating values for the CEC of the soil organic matter. From equation (1) it can be seen that values are obtained in the order of 430 ± 50 $cmol_c$ $kg^{-1}$ C, at a pH of 5.8 which is the average in situ pH.

*Fractions*

The CEC of the coarse silt, fine silt and clay fractions increased with decreasing particle size (clay > fine silt > coarse silt), except for *Treculia*, *Dactyladenia* and *Leucaena*, where the fine silt had comparable or higher CEC values than the clay fractions. Clay and fine silt fraction had the highest contribution to the CEC of the whole soil, together they were responsible for 76 to 90% of the CEC of the soil at pH 5.8 (Table 2). The contribution of the fine silt fraction to the CEC at pH 5.8 ranged from 35% to 50%. For the soils under *Treculia* and *Dactyladenia*, this fine silt fraction had the highest contribution. The coarse silt fraction contributed 9 to 15% of the CEC. The recovery of the CEC in the fractions ranged from 95 to 104%. In Table 2, also the changes in organic carbon for the three main size separates are given. In general, the carbon concentrations of both silt fractions followed the same trends as the whole soil samples, with largest values for *Dactyladenia*, *Treculia* and *Leucaena*.

As for carbon, the treatment effects on CEC were clearly present in the silt fractions, while the clay fractions were rather similar (Figure 1). The CEC values for the clay fractions varied between 15 and 20 $cmol_c\ kg^{-1}$ at pH 3 and between 24 and 32 $cmol_c\ kg^{-1}$ at pH 7. The variation in CEC values for the clay fraction could be explained for 83% by pH only, confirming the absence of a treatment effect through the residue application on CEC values of the clay fraction. Contrary to this, the CEC values of the fine silt fraction were highly dependent on the treatment and pH could only explain 24% of the variation. Carbon concentration and pH together explained 95% of the variation in CEC of the fine silt fraction. The same was true for the coarse silt fraction: pH alone explained 18% of the variation and pH together with carbon concentration explained 90%. It confirms that changes in CEC due to residue management are seen in silt fractions rather than in clay fractions, at least at this time scale.

*Decomposition tubes*

Soil in the decomposition tubes had a similar sandy texture as the arboretum soils: 76% sand, 16% silt and 8% clay. The results in Table 3 show that due to the single application of residues, important differences in soil carbon content and CEC were obtained and still obvious after up to 23 months after application. After 6 months, the residue application resulted in an increase in total soil organic carbon content from 4.22 g C $kg^{-1}$ soil in the control to concentrations up to 6.07 g C $kg^{-1}$ soil in the soil amended with *Treculia*, six months after application. The change in organic carbon content was the largest for this species and decreased from *Treculia*>*Dactyladenia*>*Gmelina*>*Leucaena*>*Afzelia*. Correspondingly CEC values decreased from 2.75 $cmol_c\ kg^{-1}$ soil for the *Treculia* amendment to 2.07 $cmol_c\ kg^{-1}$ soil for *Afzelia*, only slightly larger than the 1.92 $cmol_c\ kg^{-1}$ soil for the control. The carbon concentrations in the fine silt fraction, six months after amendment, followed the same trend, while the largest values were obtained for *Dactyladenia* and *Treculia*, and the smallest for *Afzelia*. CEC values of the fine silt fraction could be separated into two groups: on the one hand *Treculia*, *Gmelina* and *Dactyladenia* with values between 10.49 and 10.66 $cmol_c\ kg^{-1}$ fine silt and on the other hand *Leucaena* and *Afzelia* with values of 8.76 and 8.41 $cmol_c\ kg^{-1}$ fine silt respectively. Still, all residue treated soils had larger CEC values in the fine silt fraction than the unamended soil with 7.89 $cmol_c\ kg^{-1}$ fine silt. Also for the clay fraction after six months, the organic matter concentrations seemed larger in the amended soils than in the control (values between 28.48 and 30.67 g C $kg^{-1}$ clay for the amended soils and 25.48 g C $kg^{-1}$ for the control). However, the CEC values were similar for treated and untreated soils in a range of 19.35 to 21.25 $cmol_c\ kg^{-1}$ clay. After 23 months, the effects were still present in some treatments, while a decrease in carbon concentrations was obvious, both in control and amended soils. For the whole soil, the same order as at 6 months was still visible with *Treculia* still displaying the largest carbon content (5.25 g C $kg^{-1}$ soil) and *Afzelia* and *Leucaena* becoming similar as the control soil with carbon concentrations between 3.76 and 3.85 g C $kg^{-1}$ soil. CEC values for the whole soil at 23 months were also still larger than the control for *Treculia* and *Gmelina*, while they were similar as for the control for *Leucaena*, *Afzelia* and *Dactyladenia*. Treatment effects could much more clearly be seen in the fine silt fraction. For *Treculia*, *Dactyladenia*, *Gmelina* and *Leucaena* values were observed between 20.60 and 26.49 g C $kg^{-1}$ fine silt in contrast to the values of 18.57 and 18.26 g C $kg^{-1}$ fine silt for the *Afzelia* and control soils respectively. Trends in CEC values of the fine silt fraction followed the lines set by the organic matter

concentrations: larger values for the silt fractions derived from *Treculia* and *Dactyladenia* than for those obtained from *Gmelina* and *Leucaena*, in turn larger than for *Afzelia* which was no longer discernible from the control value. Not surprisingly, neither carbon concentrations nor CEC values were affected by the treatments in the clay fraction.

In general, the *Treculia* and *Dactyladenia* treatments were still displaying strong effects on soil organic carbon concentrations and ensuing CEC values of the total soil and its fine silt fraction in a time frame of up to 23 months after addition. *Gmelina* also produced similar effects, but definitely to a lesser extent. Referring to the quality of the different residues (Table 4), it becomes clear that the changes brought about in soil carbon and/or CEC are indirectly due to the differences in biochemical quality of the residues. *Dactyladenia* and *Treculia* had the lowest nitrogen contents and consequently the larger C/N ratios, predicting a slower decomposition and hence a larger residual carbon build-up. Both species also displayed the largest polyphenol concentrations, hence the largest polyphenol/N ratios, also pointing to slow decay rates. Lignin concentrations, however, were not in line with these observations.

The magnitude of the changes is significant and important in view of the generally small values obtained for both organic carbon contents and CEC values in this weathered Lixisol. An increase in carbon content and charge at in situ pH in the order of 20%, still observable, 23 months after a single addition of *Treculia* residues is a relevant result that may lead to the inclusion of such amendments in a realistic farming system. The phenomena were - as also indicated in earlier work (Oorts et al., 2000) - restricted to the fine silt fraction. Whether the absence of any effect in the clay fraction was due to a saturation of the clay fraction with organic matter or to the limited time frame (organic matter derived from the residue not yet sequestered in the clay fraction) could not be ascertained. Yet, the former possibility seems unlikely in this soil, strongly weathered and depleted in carbon. More likely seems the latter possibility confirming the slower turnover of organic components, as size of the soil particles with which they are associated becomes smaller.

## Conclusion

Both parts of the experimental program confirm the strong relation between soil organic matter and charge development in highly weathered soils, such as the ferric Lixisol in Ibadan, Nigeria. In the soil derived from the arboretum, after 20 years of continuous input of litters widely ranging in nitrogen, lignin and polyphenol contents, large differences in organic matter resulted with concomitant large differences in CEC. Because differences in CEC could be explained almost completely by the variation in soil organic carbon concentration, the effect of residue inputs was judged indirect. Differences in CEC were due to changes in the silt fractions predominantly, indicating that changes in clay fractions are not readily obtained in a time-span of less than 20 years. The decomposition tube experiment was completely in line with the above findings in this that a low quality residue proved instrumental in enhancing charge in these soils. Yet it also demonstrated that such effects could be obtained already after a single addition of 15 Mg/ha and that they were still obvious almost two years after this addition.

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**Table 1:** Soil characteristics of the surface (0-10 cm) horizons of the selected plots in the Ibadan-arboretum.

| Treatment | C g kg$^{-1}$ | N g kg$^{-1}$ | pH | CEC cmol$_c$ kg$^{-1}$ | Sand† g kg$^{-1}$ | Silt g kg$^{-1}$ | Clay g kg$^{-1}$ |
|---|---|---|---|---|---|---|---|
| ***Afzelia*** | 7.68 ± 0.87‡ | 0.51 ± 0.08 | 6.3 ± 0.2 | 3.79 ± 0.30 | 817 ± 10 | 113 ± 9 | 58 ± 4 |
| *Dactyladenia* | 12.04 ± 2.26 | 0.75 ± 0.15 | 5.5 ± 0.2 | 4.51 ± 0.78 | 779 ± 21 | 127 ± 11 | 78 ± 10 |
| *Gliricidia* | 7.48 ± 0.61 | 0.61 ± 0.08 | 5.5 ± 0.1 | 3.03 ± 0.57 | 811 ± 19 | 112 ± 5 | 68 ± 17 |
| *Gmelina* | 7.97 ± 0.41 | 0.66 ± 0.06 | 6.1 ± 0.2 | 3.90 ± 0.52 | 785 ± 9 | 120 ± 7 | 71 ± 7 |
| *Leucaena* | 13.62 ± 1.92 | 1.26 ± 0.19 | 6.0 ± 0.1 | 6.47 ± 0.87 | 738 ± 29 | 138 ± 9 | 107 ± 22 |
| *Pterocarpus* | 7.16 ± 0.77 | 0.52 ± 0.07 | 5.5 ± 0.2 | 2.80 ± 0.44 | 797 ± 17 | 116 ± 3 | 79 ± 14 |
| *Treculia* | 10.79 ± 1.29 | 0.62 ± 0.07 | 5.8 ± 0.1 | 5.08 ± 0.84 | 798 ± 26 | 122 ± 7 | 68 ± 18 |

† sand: 0.053-2 mm, silt: 0.002-0.053 mm; clay: < 0.002 mm; ‡ average ± standard deviation of 4 replicates.

**Table 2:** Organic carbon content and contribution to the whole soil CEC at pH 5.8 of the particle size fractions of the surface (0-10 cm) horizons from the selected plots in the Ibadan-arboretum.

| | Organic carbon (g C kg$^{-1}$) | | | CEC (cmol$_c$ kg$^{-1}$ whole soil) at pH 5.8 | | |
|---|---|---|---|---|---|---|
| **Treatment** | **Coarse Silt** | **Fine Silt** | **Clay** | **Coarse Silt** | **Fine Silt** | **Clay** |
| *Afzelia* | 23.3 ± 6.9 † | 40.3 ± 5.5 | 37.1 ± 3.1 | 0.44 ± 0.04 | 1.42 ± 0.13 | 1.47 ± 0.04 |
| *Dactyladenia* | 28.1 ± 3.8 | 52.4 ± 6.9 | 36.5 ± 3.7 | 0.46 ± 0.09 | 2.15 ± 0.41 | 1.96 ± 0.29 |
| *Gliricidia* | 27.6 ± 2.2 | 36.2 ± 1.6 | 33.0 ± 2.3 | 0.41 ± 0.01 | 1.26 ± 0.09 | 1.63 ± 0.35 |
| *Gmelina* | 18.8 ± 1.2 | 37.8 ± 1.8 | 35.3 ± 5.3 | 0.38 ± 0.09 | 1.42 ± 0.17 | 2.05 ± 0.19 |
| *Leucaena* | 42.0 ± 8.5 | 56.3 ± 7.3 | 35.7 ± 5.6 | 0.76 ± 0.11 | 2.61 ± 0.23 | 2.95 ± 0.55 |
| *Pterocarpus* | 24.0 ± 4.6 | 34.1 ± 4.7 | 29.4 ± 3.1 | 0.34 ± 0.06 | 1.19 ± 0.17 | 1.82 ± 0.31 |
| *Treculia* | 46.1 ± 5.0 | 65.8 ± 5.2 | 34.7 ± 5.3 | 0.86 ± 0.08 | 2.84 ± 0.26 | 1.83 ± 0.37 |

† average ± standard deviation of 4 replicates.

**Table 3:** Carbon contents and CEC of the whole soil, fine silt and clay fractions of the different treatments after 6 and 23 months decomposition in the field.

| Treatment | Whole soil | | Fine Silt | | Clay | |
|---|---|---|---|---|---|---|
| | C g $kg^{-1}$ | CEC at pH 5 cmol $kg^{-1}$ | C g $kg^{-1}$ | CEC at pH 5 cmol $kg^{-1}$ | C g $kg^{-1}$ | CEC at pH 5 cmol $kg^{-1}$ |
| 6 Months | | | | | | |
| Control | 4.22 | 1.92 | 18.99 | 7.89 | 25.48 | 20.20 |
| Afzelia | 4.74 | 2.07 | 20.95 | 8.41 | 29.67 | 20.37 |
| *Dactyladenia* | 5.71 | 2.61 | 28.84 | 10.64 | 29.02 | 20.51 |
| *Gmelina* | 5.34 | 2.42 | 24.58 | 10.49 | 28.48 | 19.35 |
| *Leucaena* | 5.18 | 2.50 | 23.23 | 8.76 | 30.51 | 20.84 |
| *Treculia* | 6.07 | 2.75 | 27.80 | 10.66 | 30.67 | 21.25 |
| 23 Months | | | | | | |
| Control | 3.85 | 2.17 | 18.26 | 5.79 | 28.45 | 22.64 |
| Afzelia | 3.82 | 1.94 | 18.57 | 5.31 | 27.64 | 21.06 |
| *Dactyladenia* | 4.67 | 2.19 | 24.42 | 8.08 | 27.91 | 21.85 |
| *Gmelina* | 4.63 | 2.30 | 20.60 | 6.46 | 28.64 | 20.55 |
| *Leucaena* | 3.76 | 2.08 | 21.33 | 6.50 | 27.13 | 21.31 |
| *Treculia* | 5.25 | 2.53 | 26.49 | 8.94 | 26.65 | 21.89 |

**Table 4:** Biochemical composition of the leaf material from the different multipurpose trees in the selected plots in the Ibadan-arboretum.

| **Tree species** | **C g $kg^{-1}$** | **N g $kg^{-1}$** | **Polyph † g $kg^{-1}$** | **Polyph/N** | **Lignin g $kg^{-1}$** | **Lignin/N** | **Cellulose g $kg^{-1}$** |
|---|---|---|---|---|---|---|---|
| ***Afzelia*** | 467 ± 5 ‡ | 38.2 ± 0.8 | 6.4 ± 0.6 | 0.17 ± 0.02 | 87 ± 3 | 2.3 ± 0.1 | 287 ± 14 |
| *Dactyladenia* | 457 ± 4 | 15.9 ± 0.3 | 67.0 ± 2.1 | 4.21 ± 0.13 | 195 ± 14 | 12.2 ± 1.1 | 238 ± 9 |
| *Gliricidia* | 453 ± 3 | 46.6 ± 0.7 | 22.8 ± 5.0 | 0.49 ± 0.11 | 53 ± 16 | 1.1 ± 0.4 | 196 ± 18 |
| *Gmelina* | 465 ± 2 | 29.1 ± 0.5 | 17.7 ± 1.8 | 0.61 ± 0.07 | 130 ± 19 | 4.5 ± 0.7 | 264 ± 43 |
| *Leucaena* | 455 ± 1 | 53.0 ± 0.2 | 85.4 ± 11.5 | 1.61 ± 0.21 | 51 ± 12 | 1.0 ± 0.2 | 126 ± 19 |
| *Pterocarpus* | 478 ± 2 | 33.3 ± 0.4 | 15.6 ± 2.5 | 0.47 ± 0.08 | 152 ± 6 | 4.6 ± 0.2 | 248 ± 19 |
| *Treculia* | 467 ± 3 | 21.9 ± 0.3 | 88.2 ± 7.8 | 4.03 ± 0.40 | 91 ± 9 | 4.1 ± 0.4 | 215 ± 15 |

† Polyph = Polyphenolics; ‡ average ± standard deviation of 4 replicates.

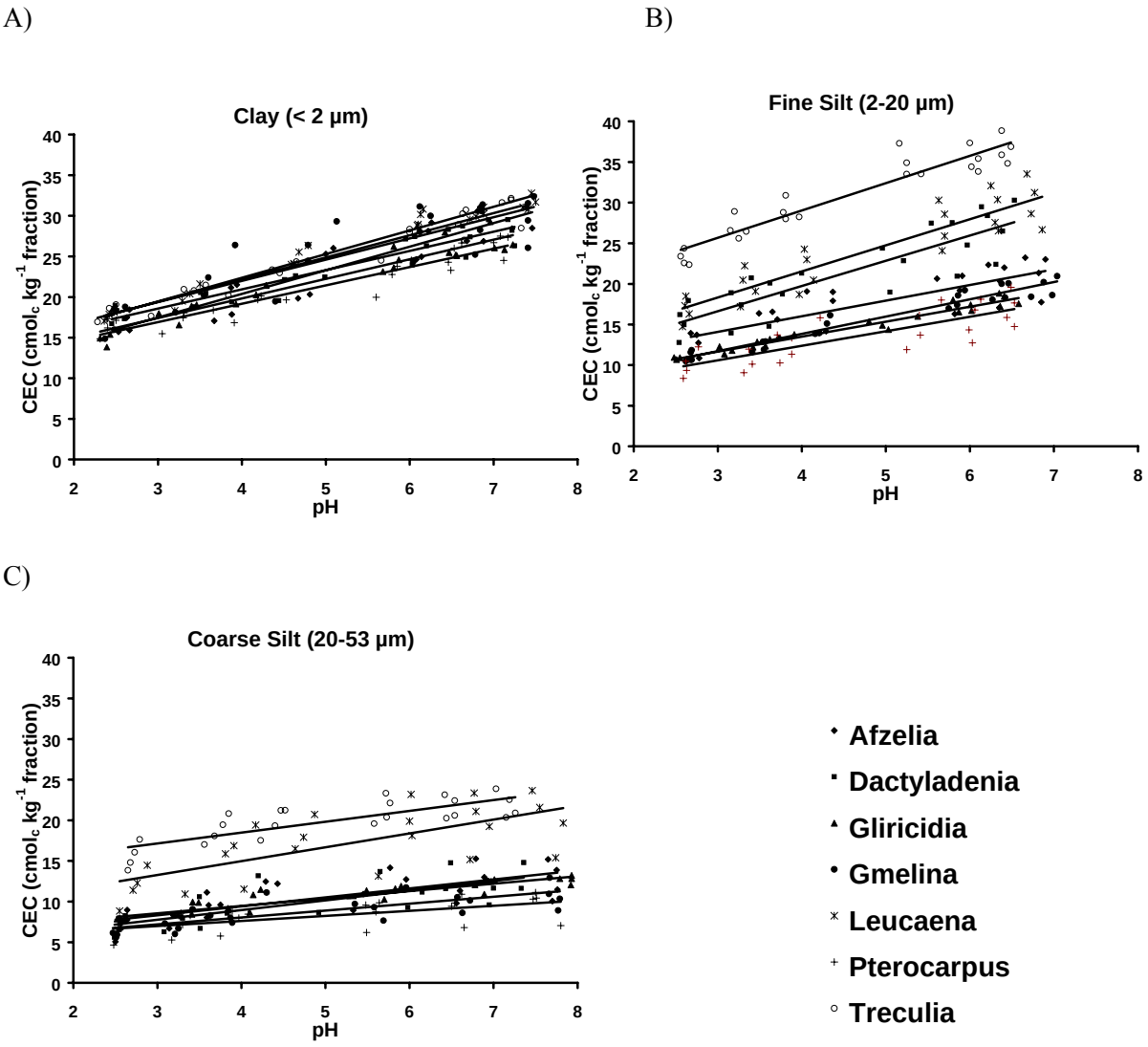


**Figure 1:** CEC versus pH for (A) clay fractions, (B) fine silt fractions and (C) coarse silt fractions derived from the 0-10 cm upper horizon from the selected plots in the Ibadan arboretum.

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# Fertility status of soils of the derived savanna and northern guinea savanna and response to major plant nutrients, as influenced by soil type and land use management

Vanlauwe, B[1], J Diels[1], O Lyasse[2], K Aihou[2], ENO Iwuafor[3], N Sanginga[3], R Merckx[4] and J Deckers[5]
[1]RCMD, IITA, Ibadan, Nigeria, c/o L.W. Lambourn & Co., 26 Dingwall Road, Croydon CR9 3EE, England.
[2]Institut des Recherches Agricoles du Bénin, B. P. 884, Cotonou, Benin Republic.
[3]Institute of Agricultural Research, Zaria, Nigeria.
[4]Laboratory of Soil Fertility and Soil Biology, Faculty of Agricultural and Applied Biological Sciences, K.U.Leuven, Kardinaal Mercierlaan 92, 3001 Heverlee, Belgium.
[5]Institute for Land and Water Management, Faculty of Agricultural and Applied Biological Sciences, Vital Decosterstraat 102, 3000 Leuven, Belgium.

**Keywords**: fertilizer use, maize, missing nutrient trial, Olsen-P, on-farm level, particulate organic matter, pot experiment

## Abstract

Although the fertility status of soils in the West African moist savanna is generally believed to be low, crop yields on farmers' fields vary widely from virtually nil to values near the potential production. The soil fertility status was evaluated for a number of farmers' fields selected at random in 2 villages (Zouzouvou and Eglimé) representative for the derived savanna (DS) benchmark area and in 2 villages (Danayamaka and Kayawa) representative for the Northern Guinea savanna (NGS) benchmark area. The relation between soil fertility status and soil type characteristics and fertilizer use was explored. In an accompanying missing nutrient greenhouse trial, the most limiting nutrients for maize growth were determined. While soils in the DS villages were formed on different geological units, soils in the NGS villages could be differentiated according to their position on the landscape. Generally, soils in the DS contained a smaller amount of silt (104 vs 288 g $kg^{-1}$), a larger amount of sand (785 vs 584 g $kg^{-1}$), C (9.3 vs 6.3 g $kg^{-1}$), N (0.7 vs 0.5 g $kg^{-1}$), Olsen-P (10.7 vs 5.4 mg $kg^{-1}$), and had a higher CEC (7.0 vs 4.8 cmolc $kg^{-1}$) than soils in the NGS villages. The large silt content of the soils in the NGS is a reflection of the aeolian origin of the parent material. Within the benchmark areas, general soil fertility characteristics were similar in the villages in the NGS, except for a larger amount of particulate organic matter in Kayawa than in Danayamaka. This may also have led to a significantly larger amount of ammonium-N content in the 0-20 and 20-40 cm soil layers in Kayawa compared to Danayamaka (42 vs 24 kg N $ha^{-1}$ in the 0-20 cm soil layer). Differences in topsoil soil characteristics between the DS villages were a reflection of differences in clay quality (kaolinitic vs 2:1 clay minerals) of the parent material and past fertilizer use. The Olsen-P and exchangeable K contents were observed to increase with increased fertilizer application rate in both benchmarks, while fertilizer application rate had no significant effect on the organic C or total N content of the soil nor on its ECEC. The response of maize shoot biomass production to applied N was similar for both benchmarks (biomass accumulation in the treatment without N was, on average, 55% of the biomass production in the treatment which received all nutrients), while soils in the NGS responded more strongly to applied P than soils in the DS (37% vs 66% of biomass production in the treatment which received all nutrients). The more favourable P status of soils in Eglimé (DS) was attributed to the more intense use of P fertilizers, as a result of government-supported cotton production schemes. Response to cations, S or micronutrients were neglegible. A significant linear relationship was found between the soil Olsen-P content and the response to applied P up to levels of 12 mg $kg^{-1}$ in the topsoil. Above this level, a plateau was reached.

## Introduction

The fertility status of soils in the West African moist savanna is low. Two major causes are their extensive degree of weathering and the continuous mining of soil nutrients in the absence of sufficiently large amounts of external inputs or sufficiently long soil fertility-regenerating fallow periods (Jones and Wild, 1975; Smaling et al., 1997). In the absence of fertilizer additions, this low soil fertility status usually leads to very low maize grain yields on farmers' fields, e.g., around 0.75 t $ha^{-1}$ in the Southern Benin Republic (Koudokpon et al., 1994), far below the potential yield of 5 – 8 t $ha^{-1}$ (Fisher and Palmer, 1983). As P sorption by West-African savanna soils is low compared to soils of the humid forest zone (Juo and Fox, 1977), the most limiting nutrient for cereal production in the moist savanna is generally believed to be N, followed by P.

Since the early 1990s, research on natural resource management at the International Institute of Tropical Agriculture (IITA) has been following an agro-ecozonal approach. The West African moist savanna zone has been sub-divided into different agro-ecozones, each with their distinctive length of growing periods. Within each agroecozone, benchmark areas have been identified in which most of the IITA resource management research is concentrated (EPHTA, 1996). The benchmark area of the derived savanna (DS), with a growing period of 211-270 days (Jagtap, 1995), is located in Southern Benin Republic while the benchmark area of the northern guinea savanna (NGS), with a growing period of 151-180 days (Jagtap, 1995), is located in Northern Nigeria. As benchmark areas are hypothesized to contain all the biophysical and socio-economic variability found in the entire agro-ecozone, one could in principle extrapolate soil fertility management technologies developed and validated in the benchmark area to all of the agro-ecozone (EPHTA, 1996). A resource management survey implemented in the NGS benchmark led to the identification of 4 resource-use domains: a low (13.8% of survey villages), low to medium (49.2%), medium to high (23.1%), and high (13.8%) resource-use domain (Manyong et al., 1998). Resource use is quantified by an index taking into account variables describing use of external inputs, land use intensity, accessibility to markets, and diversification of the farm enterprise (Manyong et al., 1998).

Besides length of growing period and the socio-economic environment, soils also vary between and within the benchmark areas. In the DS benchmark, 2 main geological units can be distinguished, giving rise to distinct soil associations. In the southern part of the benchmark the predominant soils are deep, red, kaolinitic, freely draining soils developed on coastal sediments often referred to as 'Terre de Bare' and classified as Ferralic Nitisols (FAO, ISRIC and ISSS, 1998). The northern part is underlain by crystalline basement rocks consisting mainly of granite and gneiss, which gave rise to a complex pattern of Acrisols, Lixisols, Luvisols, and Leptosols with inclusions of Vertisols and Cambisols (Faure and Volkoff, 1998). The saprolite is often found within a few meters and the clay fraction contains kaolinite and swelling (2:1) clays in varying proportions according to parent rock and drainage conditions (Volkoff, 1976a; Volkoff, 1976b). A similar resource management survey as in the NGS was implemented in the DS benchmark. This identified a set of resource use domains overlapping with the geological units (IITA, 2000). In the DS benchmark, the production of cotton is supported by a credit scheme for fertilizers and herbicides and a government-regulated market for selling the produce (Bosc and Freud, 1995).

The soils in the NGS benchmark are predominantly developed in a Quaternary loess mantle which covered the Basement Complex granites, gneisses, migmatites and schists (Bennett, 1980; McTainsh, 1984). Processes of clay illuviation, iron segregation, fragmentation and horizontal transport of ironpans, and colluviation led to soil differentiation at the landscape scale. A typical toposequence consists of shallow and/or gravelly soils (Plinthosols or soils with a petroferric phase) on the interfluve crests, deeper soils (Luvisols or Lixisols) on the valley slopes and hydromorphic soils (Gleysols and Fluvisols or soils with gleyic properties) near the valley bottom (Delaure, 1998). As a common characteristic, these soils have a relatively high silt content (20-50%) reflecting the aeolian origin and have a clay fraction with low to medium activity (CEC of clay fraction between 20 and 35 $cmol_c$ $kg^{-1}$ clay).

Agronomically, the most straightforward measure to boost cereal grain yields is the application of fertilizers. Although it is currently believed that both fertilizer and organic matter additions are necessary to sustain agricultural production and preserve the environment (Jones and Wild, 1975; Palm et al., 1997; Vanlauwe et al., 2000b), most farmers in the moist savanna do not apply organic matter except for minimal amounts of farmyard manure and/or household waste in the NGS (Houngnandan, 2000; Manyong et al., 2000). Crop residues are commonly removed from the field either for livestock feed and other purposes in the NGS or through burning in the DS. Although average fertilizer application by farmers in the DS as well as in the NGS is low (Houngnandan, 2000; Manyong et al., 2000), the range of application rates is high. In the NGS villages, the average fertilizer N application rate was 40 kg N $ha^{-1}$ with a large standard deviation of 31 kg N $ha^{-1}$ (Manyong et al., 2000).

The objectives of this paper were: (i) to assess the general soil fertility status of representative farmers' fields in a selected number of villages representative for the DS and NGS benchmarks, (ii) to assess the impact of soil type and fertilizer use on the selected soil characteristics, and (iii) to determine the most limiting nutrients for maize growth in the respective agro-ecozones and their relation with selected soil fertility characteristics.

## Materials and methods

### *Village selection*

As the NGS benchmark area is fairly homogeneous in terms of major soils associations, the 2 villages selected in the NGS were chosen to represent the major resource use domains identified by Manyong et al. (1998). Danayamaka (7°50'E, 11°19'N) belongs to the low to medium resource-use domain and is dominated by the traditional production enterprises of the northern Guinea savanna, such as sorghum, cowpea, and livestock. Kayawa (7°13'E, 11°13'N) belongs to the medium to high resource-use domain. It is characterized by the development of new enterprises such as maize and soybean, and follows a market-oriented strategy in agricultural production (Manyong et al., 1997). The two domains together encompass 72% of the villages surveyed in the NGS benchmark area.

As discussed earlier, in the DS benchmark 2 distinct geological formations are present, together covering 84% of the benchmark area (Volkoff, 1976a; Volkoff, 1976b). As the major soil characteristics were hypothesized to influence the soil fertility status of soils in this benchmark area, one village was selected belonging to each of the 2 soil associations. Zouzouvou (1°41'E, 6°53'N) lies on 'terre de barre' soils, while Eglimé (1°40'E, 7°05'N) is situated in the area underlain by crystalline rocks. The Eglimé soils are rejuvenated and much younger than the more weathered soils of Zouzouvou.

### *Socio-economic survey and farmers' field selection*

A socio-economic survey on general farm characteristics and current use of fertilizer and organic inputs at the field level was implemented in the NGS (Manyong et al., 2000) and DS villages (Houngnandan, 2000). The farmers interviewed were selected following a multi-stage sampling procedure, giving a total number of 200 representative farmers in the NGS villages, and 171 in the DS villages (Houngnandan, 2000; Manyong et al., 2000). Of all fields included in the survey, 12-14 fields were randomly selected in each village to implement researcher-managed on-farm trials. In the NGS, soils near the valley-bottom or fadama soils were excluded from the selection procedure. The farmers using the selected fields were interviewed about past management of these fields. Information was obtained on cropping/fallow history and fertilizer use (type and amount) over the past 10 years.

### *Farmers' fields soil sampling and analysis*

In all farmers' fields, trials were laid out containing 8 plots of 8 m by 8 m. In this paper, only the initial soil characteristics of the trials are considered; the trials themselves are the subject of forthcoming papers. Before implementation of the field trials, soil was sampled from each plot at 0-10 cm depth in April 1998 in the DS villages (one diagonal across the plots, 10 cores per plot) and in May and June 1998 in the NGS villages (both diagonals across the plots, 16 cores per plot). Afterwards, equal amounts of soil

sampled from each of the 8 plots in a field were mixed to form one composite sample per field. All soil samples were air-dried and sieved to pass 4 mm. Part of the soil was ball-milled for organic C (Amato, 1983) and Kjeldahl-N analysis. A second part was analyzed for Olsen-P (Okalebo et al., 1993), effective cation exchange capacity (ECEC) (IITA, 1982), pH-water (soil:water ratio of 2.5), pH-KCl (soil:KCl solution ratio of 2.5), and texture (IITA, 1982). A third part was used to determine particle size classes of soil organic matter (SOM) by wet sieving a previously dispersed soil slurry over a nest of sieves (Vanlauwe et al., 1998). The particulate organic matter (POM) fraction consists of three separately measured SOM fractions: organic material larger than 2 mm (referred to as the 'O2000' fraction), organic material between 2 and 0.250 mm (referred to as the 'O250' fraction), and organic material between 0.250 and 0.053 mm (referred to as the 'O53' fraction).

Immediately after taking the soil samples from the 0-10 cm layer, sufficient soil was taken from the same layer from between the plots to implement a missing nutrient trial, described below. The soil was air-dried and sieved to pass 4 mm before use.

In the NGS villages, soil was sampled for mineral N extraction before planting maize in June 1998 (1 core in the centre of each plot bulked per field) at the following depths: 0-20 cm, 20-40 cm, 40-60 cm, and 60-80 cm. In the DS villages where a cowpea-maize rotation was implemented, soil was sampled at the same depths (2 cores per plot, bulked per field) after the cowpea harvest and before planting maize in August 1998. All samples were kept cool pending analysis. Mineral N was extracted by shaking 30 g fresh soil in 90 ml of a 2N KCl solution and filtering part of the supernatant after centrifugation of the soil slurry. The nitrate-N and ammonium-N content in the soil extract was determined colorimetrically on a continuous flow analyzer system (IITA, 1982).

*Missing nutrient trial*

A missing nutrient trial with soil sampled from all individual fields was established in the greenhouse at IITA, Ibadan, Nigeria. Pots were filled with 2.5 kg of air-dried, sieved soil and the treatments presented in Table 1 were implemented. After applying 75 ml of nutrient solution per pot, an additional 340 ml of distilled water was applied just before planting. Although the nutrient solutions were composed such that only the nutrients under consideration were missing - except for the 'all-N' treatment where $Cl^-$ was added - the final pH (varied between 3.3 and 6.1) and electrical conductivity (varied between 0.9 and 2.4 dS $m^{-1}$) of the solutions were not equal. Preliminary testing, however, showed that after mixing a selected number of soils with the nutrient solutions, final soil pH values were hardly affected due to the buffering capacities of the soils (maximal differences in pH after applying the various nutrient solutions was 0.18 pH units for the selected soils). For the 'minus-N' treatment, a selected number of pots was also included with $CaCO_3$ as the Ca source rather than $CaCl_2$ to assess whether the addition of $Cl^-$ had an effect on plant growth. As both Ca sources gave similar maize growth (data not shown), it was concluded that the addition of $Cl^-$ did not affect maize growth. Although the differences in electrical conductivity of the nutrient solutions are the only factors besides the missing nutrients considered which could influence maize growth, the total salt concentrations were low (varied between 0.2 and 0.4 dS $m^{-1}$ after applying the nutrient solutions to the soil as measured in a 1:2.5 soil:water suspension at 25°C) and as such, this factor was presumed not to influence maize growth.

The pots were arranged in a randomized complete block design with 3 replicates. After application of the nutrient solutions and distilled water, 4 maize seeds (variety Oba Super 2) were planted in each pot and thinned to 2 plants per pot after germination. The pots were watered twice daily thereby avoiding leakage of water through the bottom of the planting pots and avoiding signs of moisture stress on the maize plants. After 7 weeks, the maize plants were cut at the soil surface, oven-dried (65°C), and weighed. The roots were extracted from the soil by sieving over a 0.5 mm sieve, washed, oven-dried, and weighed.

*Mathematical and statistical analyses*

In the pot trial, the relative biomass production in the treatments with one or a range of nutrients removed vs the treatment with complete nutrition was calculated as (equation 1):

$$\frac{\text{Maize shoot or root biomass in the treatment with one or more missing nutrients}}{\text{Maize shoot or root biomass in the treatment with all nutrients applied}} * 100 \quad (1)$$

According to equation (1), a higher relative yield indicates a lower response to the missing nutrient considered.

The land use management, soil, and maize data were analyzed with the MIXED procedure of the SAS system (SAS, 1992) using 'benchmark' and 'village within benchmark' as fixed variables and 'field*village within benchmark' as a random factor. Significantly different means were separated with the PDIFF option of the LSMEANS statement.

To assess the impact of fertilizer use on the observed soil characteristics, the data were also analyzed using 'benchmark' and 'fertilizer class' as fixed variables and 'field*fertilizer class within benchmark' as a random factor. The 'fertilizer class' of a certain field was obtained by rounding the average of the 'N fertilizer class' and the 'P fertilizer class' values for that field. Three 'N fertilizer classes' were defined: I: > 60 kg N $ha^{-1}$ $yr^{-1}$; II: 30-60 kg N $ha^{-1}$ $yr^{-1}$, III: < 30 kg N $ha^{-1}$ $yr^{-1}$ and 3 'P fertilizer classes' I: > 20 kg P $ha^{-1}$ $yr^{-1}$; II: 10-20 kg P $ha^{-1}$ $yr^{-1}$, III: < 10 kg P $ha^{-1}$ $yr^{-1}$ (Fig. 1). As fertilizer class was counfounded within village in the DS villages - nearly all the Zouzouvou soils belong to the class with the lowest fertilizer use, while nearly all Eglimé soils belong to the class with the highest fertilizer use (Fig. 1) – it was not possible to include both 'village' and 'fertilizer class' in the same ANOVA as certain factors were not estimable.

Regression analysis was used to calculate relationships between response to N and P and soil nutrient contents.

## Results

### *Socio-economic characteristics of the villages studied*

Fallows are still quite common in Zouzouvou (2.3 yrs per 10 yr) and virtually non-existent in all other villages (Table 2). In both benchmark areas, cereals are important crops, while more legume crops were grown during the past 10 yr in the DS villages. In the DS, cotton is a common cash crop, and in the NGS pepper and tomato are commonly grown. The type of NPK fertilizer commonly used is different in the two benchmarks. In the DS, cotton fertilizer (14%N, 23%P, 14%K, 5%S, 1%B) is virtually the only compound fertilizer available, and in the NGS several blends can be found, but 15:15:15 and 20:10:10 are the most common ones (Table 2).

While yearly N fertilizer application rates were not significantly different between the 2 benchmark areas, large differences in fertilizer use between the 2 villages in the DS benchmark were observed (Table 2). Farmers in Eglimé used, on average, 88 kg N $ha^{-1}$ $yr^{-1}$ for the past 10 years, and farmers in Zouzouvou used less than 10 kg N $ha^{-1}$ $yr^{-1}$. Differences in fertilizer use between the 2 villages in the NGS were not significant. Farmers in the DS villages used significantly more P fertilizer (27 kg P $ha^{-1}$ $yr^{-1}$) than farmers in the NGS villages (17 kg P $ha^{-1}$ $yr^{-1}$), but again, striking differences in P use were observed between Zouzouvou (8 kg P $ha^{-1}$ $yr^{-1}$) and Eglimé (45 kg P $ha^{-1}$ $yr^{-1}$). In the DS, proportionally more N fertilizer was applied as urea in Eglimé than in Zouzouvou, and the same was true for Danayamaka in the NGS (Table 2).

### *Soil characteristics*

While topsoils in the DS benchmark were generally more sandy and less silty than soils in the NGS benchmark, their organic C, total N, Olsen-P, exchangeable Ca and Mg contents and ECEC were significantly higher (Table 3). Soils in the DS contained more SOM particles with a higher particle size and soils in the NGS contained significantly more of the 'O53' material, leading to similar POM contents in both benchmarks (Table 3).

Although the soil chemical and organic matter characteristics of the 0-10 cm layer appeared to have larger values in Kayawa than in Danayamaka, none of the differences were significant, except for the O53 and POM content (Table 3). This is in sharp contrast with the DS villages, where topsoil in Eglimé contained a significantly larger amount of C, N, Olsen-P, exchangeable Ca, Mg, and K, and had a significantly higher ECEC. Topsoils in Eglimé also had a significantly lower sand and a significantly higher silt content than topsoils in Zouzouvou (Table 3). In the DS villages, nitrate-N and ammonium-N contents were similar for all soil depths, except for the 60-80 cm layers in which fields in Eglimé had significantly more ammonium-N than fields in Zouzouvou (Fig. 2a). The ammonium-N content in the 0-20 cm and 20-40 cm layers was significantly higher in Kayawa than in Danayamaka, while differences in nitrate-N content were similar at all soil depths (Fig. 2b). The soil profile contained more ammonium-N than nitrate-N in all soil layers and villages.

In both the DS and NGS villages, differences in soil organic C and total N content between fertilizer classes were not significant (Table 4). Olsen-P and exchangeable K contents, on the other hand, were significantly higher in class I than in class II or class III soils in both agro-ecozones. In the DS villages, exchangeable Ca and Mg contents were significantly higher in class I than in class III soils (Table 4). No significant differences in mineral N content of the soil profile were found between the different fertilizer classes (data not shown).

***Missing nutrient pot experiment***

The relative biomass yield of maize shoots in absence of N was similar for both benchmarks (Table 5). Soils in the NGS showed a lower relative shoot biomass yield in the absence of P than soils in the DS, indicating a stronger response to applied P (Table 5). In both benchmarks, responses to cations, S, and micronutrients were negligible. In the DS, maize shoot biomass responded more strongly to P in Zouzouvou than in Eglimé, while responses to N were similar in both villages. In the NGS, no differences in responses to N and P between villages were observed (Table 5).

Although a significant linear relationship was observed between shoot biomass response to N and the soil total N content, the relationship explained only 36% of the overall variation (Fig. 3a). This value decreases to 18% (significant at the 1% level) if the data point lying outside the cloud of points is omitted from the regression analysis. The relationships between shoot biomass response to P and Olsen-P contents followed a linear pattern up to about 12 mg Olsen-P $kg^{-1}$, after which responses tended to reach a plateau (Fig. 3b). The linear relationships between shoot biomass response to P and Olsen-P contents below 12 mg Olsen-P $kg^{-1}$ explained between 60% and 74% of the overall variation for Zouzouvou, Danayamaka, and Kayawa. Slopes nor intercepts of the linear relationships were significantly different between these villages. Most of the Eglimé soils contained amounts of Olsen-P exceeding 12 mg P $kg^{-1}$ and responses to P were part of the plateau of the relationship (Fig. 3b).

**Discussion**

The relative maize shoot biomass yield in absence of P was significantly smaller for soils from the NGS (relative yield of 33%) than from soils from the DS (67%), and within the DS, for soils from Zouzouvou (58%) than for soils from Eglimé (75%). The favourable P status in Eglimé soils is certainly caused by the extensive use of P-containing 'cotton' fertilizer, stimulated by the government-supported credit and marketing schemes for cotton production in Benin Republic. This observation is a good example of how agricultural policies may influence soil fertility status. Although the same policies apply to Zouzouvou, the lower fertilizer use in Zouzouvou compared to Eglimé may be explained by the lower occurrence of cotton (*data not shown*) and the lower inherent fertility of the soils caused by more intense weathering. Although 'cotton' fertilizer is usually applied to cotton, P fertilizer is known to have considerable residual effects on soils with low P sorption capacities (Bationo et al., 1986; Buresh et al., 1997), allowing other crops grown in rotation with cotton to benefit from this added P. Although use of P fertilizer is much lower in Zouzouvou than in Eglimé and comparable to P use in the NGS villages, the relative shoot biomass yield in absence of P is higher in Zouzouvou than in the latter villages. This may be related to differences in P sorption capacities of the A and Bt soil horizon between the soil profiles

(Nwoke et al., *unpublished data*). The higher P sorption of the NGS soils is most likely related to the greater amount of fine particles and the composition of these fine particles (Mokwunye et al., 1986). On the other hand, adulteration of locally produced fertilizer blends in the NGS can not be excluded and may have led to lower P application rates as calculated from the information given by the farmers.

The Olsen-P content appears to be a good indicator for P availability of West African moist savanna soils (Fig. 3b), as previously reported by Vanlauwe et al. (2000a). Soils containing Olsen-P values over 12 mg $kg^{-1}$ are less likely to respond to applied P than soils with Olsen-P values below 12 mg $kg^{-1}$. For the latter soils, the response to P increased linearly with decreasing P content. Due to the high fertilizer application rates in Eglimé, little or no response to added P was observed for these soils. As 'cotton' fertilizer is the only commonly available compound fertilizer in Benin, one could wonder whether the composition of this fertilizer is agronomically and economically optimal for application to maize as maize is known to require relatively higher amounts of N than P (Wichmann, 1998).

Notwithstanding significant differences in soil organic C and total N content between benchmarks and, in the DS, between villages, responses to applied N were similar in all villages and benchmarks. Moreover, only a minor fraction of the total variation was explained by a linear relationships between response to N and soil total N content. These observations indicate that total C and N are weak indicators of potential soil N supply. Although inputs of organic matter are expected to be larger in the DS than in the NGS because of the longer growing period, fallow and crop residues are commonly burnt in the DS villages before planting the first season crop. In the NGS, fallow vegetation at the start of the cropping seasons is minimal and crop residues are commonly removed from the field for livestock feed, fencing, or other purposes. As belowground plant components and weeds are the major organic matter inputs, differences between benchmarks may not be as large as would be expected taking into account only the length of growing periods. This is also confirmed by the similar amounts of the easily available POM pool, which was shown to be rather easily influenced by application of fresh organic matter (Vanlauwe et al., 1999). As inputs of organic matter are expected to be in the same order of magnitude in both benchmarks, the larger C contents in the DS soils, and especially in Eglimé, indicate that in the DS, a higher proportion of the C is either physically and/or chemically protected from mineralization. This may be related to the more frequent burning of crop residues and consequent chemical stabilisation of C as charcoal in the DS villages. Physical protection of soil organic C is expected to be higher in the soils of the NGS villages due to their higher silt content and associated C protection capacity (Hassink and Whitmore, 1997). However, commonly used soil tillage practises may hamper the soil C protection mechanisms in contrast with the DS villages, where soils are usually only minimally tilled during weeding activities. Although the input of organic matter as above and belowground crop residues is expected to be larger in Eglimé than in Zouzouvou because of the much higher fertilizer application rates (Table 2), the frequent burning of crop residues and the higher silt content and associated C protection capacity (Hassink and Whitmore, 1997) in the Eglimé soils may mask the potentially higher N supply capacities of these soils. This is also obvious from the similar amounts of mineral N in the soil profile before maize planting. The larger amounts of mineral N in the topsoil in Kayawa compared with Danayamaka are likely the results of a larger amount of easily decomposable POM (Table 3).

The response to missing cations, S, and micronutrients was virtually nil in all fields, indicating that these nutrients are not an immediate source of concern. However, applying higher rates of N and P fertilizer may more rapidly exhaust the soil reserves of these nutrients and lead to other major deficiencies. Especially 'terre de barre' soils, which have an inherently low available K content, as confirmed by the data presented in Table 3, may be susceptible to K deficiency when agricultural production increases (Jones and Wild, 1975). On the other hand, as long as local fertilizer recommendation schemes include application of K fertilizer (Carsky and Iwuafor, 1999) and as farmers usually apply NPK fertilizers, this possibility may turn out to be a rather theoretical one.

Certain differences in soil characteristics between villages within one benchmark area are surely rather the result of inherent soil type characteristics than of management practices. The higher base status and silt content of the Eglimé soils compared with the Zouzouvou soils, e.g., is related to the higher base content of the parent material rather than to the use of external inputs. After all, the Eglimé soils are

rejuvenated and much younger than the more weathered soils of Zouzouvou. The high silt content of the soils in the NGS villages reflects the aeolian origin of the parent material, formed by deposition of loess-like material by Harmattan winds (Bennett, 1980). Through this dust deposition, the soils in the NGS are enriched with bases at an annual rate of 19 kg K $ha^{-1}$, 10 kg Ca $ha^{-1}$, and 4 kg Mg $ha^{-1}$ (McTainsh, 1982). Dust deposition decreases from North to South, and annual enrichment rates in the DS are of the order of 3 kg K $ha^{-1}$, 5 kg Ca $ha^{-1}$, and 2 kg Mg $ha^{-1}$ (Hermann, 1996, cited by Stahr et al., 1996). Other differences in soil characteristics are more likely brought about by differences in soil management and particularly fertilizer use. Although one could argue that in the DS the larger P and K content of soils belonging fertilizer class I compared with soils belonging to fertilizer classes II and III is caused by the fact that fertilizer classes and soil type are confounded (most Eglimé soils belong to class I, while most Zouzouvou soils belong to class III), similar observations were made for fertilizer classes in the NGS, where soil types are similar (Table 4). This clearly shows that application of external sources of P and even K can improve the general P and K status and benefit future crops. This is not true in the case of N fertilizers, as neither the soil total N content nor the mineral N content in the soil profile varied between fertilizer classes (Table 4). One consequence of this observation is that N fertilizers need to be applied yearly to sustain crop growth. While it is often claimed that excessive long-term use of N fertilizers may decrease the soil pH, it is worth noting that topsoil pH values are similar for Zouzouvou and Eglimé (Table 4), while the difference in average yearly N fertilizer application is substantial (Table 2). This indicates that the acidifying activity is not relevant for all fertilizers. (Juo et al., 1995) already found that the acidifying effect of N fertilizer was highest for ammonium sulphate, lower for urea and virtually absent for calcium-ammonium-nitrate.

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**Table 1: Composition of the different nutrient solutions applied in the nutrient omission pot experiment[a].**

| | Solution 1 | Solution 2 | Solution 3 | Solution 4 | Solution 5 |
|---|---|---|---|---|---|
| | complete | minus-N | minus-P | minus-cations/S | minus-micro-nutrients |
| | mmol $l^{-1}$ | | | | |
| Macronutrients | | | | | |
| $NH_4NO_3$ | 100.2 | -- | 111.9 | 146.1 | 100.2 |
| $NH_4H_2PO_4$ | 22.6 | -- | -- | 22.6 | 22.6 |
| $KNO_3$ | 22.7 | -- | 22.7 | -- | 22.7 |
| $Ca(NO_3)_2.4H_2O$ | 35.0 | -- | 35.0 | -- | 35.0 |
| $MgSO_4.7H_2O$ | 21.9 | 21.9 | 21.9 | -- | 21.9 |
| $KH_2PO_4$ | -- | 22.6 | -- | -- | 0 |
| $CaCl_2.2H_2O$ | -- | 35.0 | -- | -- | 0 |
| Micronutrients | | | | | |
| $FeCl_3$ | 0.84 | 0.84 | 0.84 | 0.84 | -- |
| $MnCl_2.4H_2O$ | 0.54 | 0.54 | 0.54 | 0.54 | -- |
| $ZnCl_2$ | 0.72 | 0.72 | 0.72 | 0.72 | -- |
| $CuCl_2.2H_2O$ | 0.58 | 0.58 | 0.58 | 0.58 | -- |
| $Na_2B_4O_7.10H_2O$ | 0.057 | 0.057 | 0.057 | 0.057 | -- |
| $Na_2MoO_4.2H_2O$ | 0.037 | 0.037 | 0.037 | 0.037 | -- |
| $CoCl_2.6H_2O$ | 0.043 | 0.043 | 0.043 | 0.043 | -- |
| Macroelements | | | | | |
| N | 316 | 0 | 316 | 316 | 316 |
| P | 23 | 23 | 0 | 23 | 23 |
| K | 23 | 23 | 23 | 0 | 23 |
| Ca | 35 | 35 | 35 | 0 | 35 |
| Mg | 22 | 22 | 22 | 0 | 22 |
| S | 22 | 22 | 22 | 0 | 22 |

[a] All pots received 75 ml of the respective nutrient solutions and 340 ml of distilled water at planting.

**Table 2: General cropping system and soil fertility management characteristics of the different fields in the derived savanna and the northern guinea savanna benchmark villages[a].**

| | Derived savanna | | | Northern Guinea savanna | | | SE (village) | SE (benchmark) |
|---|---|---|---|---|---|---|---|---|
| | Zouzouvou | Eglimé | Mean | Danayamaka | Kayawa | Mean | (*n*=12) | (*n*=24) |
| Cereals[b] | Maize | | | Maize, sorghum, (rice), (millet), (sugarcane) | | | | |
| Legumes[b] | Cowpea, groundnut, (soybean) | | | Soybean, cowpea, (groundnut) | | | | |
| Other important crops | Cotton | | | Pepper, tomato | | | | |
| Common NPK fertilizer | 'Cotton fertilizer' (14N:23P:14K:5S:1B) | | | 15:15:15, 20:10:10 | | | | |
| Cereal crops in last 10 yrs | 8 | 4 | 6 | 6 | 7 | 7 | 1 | 1 |
| Legume crops in last 10 yrs | 6 | 6 | 6 | 2 | 3 | 2 | 1 | 1 |
| Fallow years in last 10 yrs | 2.3 | 0.3 | 1.3 | 0.3 | 0.0 | 0.1 | 0.5 | 0.3 |
| Yearly N use (kg $ha^{-1}$ $yr^{-1}$) | 8 | 88 | 48 | 54 | 34 | 44 | 8 | 5 |
| Yearly P use (kg $ha^{-1}$ $yr^{-1}$) | 8 | 45 | 27 | 14 | 20 | 17 | 4 | 3 |
| Yearly K use (kg $ha^{-1}$ $yr^{-1}$) | 5 | 28 | 16 | 14 | 19 | 17 | 3 | 2 |
| Proportion of N fertilizer as urea (%) | 22 | 69 | 46 | 56 | 32 | 44 | 6 | 5 |

[a] Derived savanna: Zouzouvou and Eglimé (12 fields each); northern guinea savanna: Danayamaka (14 fields) and Kayawa (13 fields).
[b] Crops in parentheses are less commonly grown

**Table 3: Selected soil (0-10 cm) chemical and physical of the fields in the derived savanna and the northern guinea savanna benchmark villages[a].**

| | Derived savanna | | | Northern Guinea savanna | | | SE (village) | SE (benchmark) |
|---|---|---|---|---|---|---|---|---|
| | Zouzouvou | Eglimé | Mean | Danayamaka | Kayawa | Mean | (*n*=12) | (*n*=24) |
| Chemical characteristics | | | | | | | | |
| Organic C (g $kg^{-1}$) | 7.9 | 10.7 | 9.3 | 5.5 | 7.1 | 6.3 | 0.6 | 0.4 |
| Total N (g $kg^{-1}$) | 0.62 | 0.78 | 0.70 | 0.46 | 0.53 | 0.49 | 0.04 | 0.03 |
| C-to-N ratio | 12.9 | 13.6 | 13.2 | 12.2 | 13.5 | 12.9 | 0.5 | 0.3 |
| Olsen-P (mg $kg^{-1}$) | 8.1 | 13.3 | 10.7 | 5.1 | 5.8 | 5.4 | 1.3 | 0.9 |
| $Ca^{2+}$ content ($cmol_c$ $kg^{-1}$) | 2.80 | 6.78 | 4.79 | 2.24 | 3.52 | 2.88 | 0.64 | 0.45 |
| $Mg^{2+}$ content ($cmol_c$ $kg^{-1}$) | 0.94 | 1.65 | 1.30 | 0.66 | 0.65 | 0.66 | 0.15 | 0.11 |
| $K^{+}$ content ($cmol_c$ $kg^{-1}$) | 0.15 | 0.38 | 0.27 | 0.32 | 0.32 | 0.32 | 0.03 | 0.02 |
| Exch. acidity ($cmol_c$ $kg^{-1}$) | 0.58 | 0.40 | 0.49 | 0.67 | 0.77 | 0.72 | 0.09 | 0.06 |
| ECEC[b] ($cmol_c$ $kg^{-1}$) | 4.61 | 9.38 | 7.00 | 4.10 | 5.48 | 4.79 | 0.81 | 0.57 |
| pH($H_2O$) | 6.7 | 6.7 | 6.7 | 6.1 | 6.0 | 6.0 | 0.1 | 0.1 |
| pH(KCl) | 5.1 | 5.3 | 5.2 | 4.9 | 4.9 | 4.9 | 0.2 | 0.1 |
| Physical characteristics | | | | | | | | |
| Gravel content (g $kg^{-1}$) | 0 | 19 | 10 | 6 | 2 | 4 | 3 | 2 |
| Sand content (g $kg^{-1}$) | 834 | 736 | 785 | 606 | 562 | 584 | 20 | 14 |
| Silt content (g $kg^{-1}$) | 61 | 147 | 104 | 276 | 300 | 288 | 12 | 9 |
| Clay content (g $kg^{-1}$) | 105 | 117 | 111 | 118 | 138 | 128 | 14 | 10 |
| Soil organic matter | | | | | | | | |
| O2000 fraction (g $kg^{-1}$) | 0.12 | 0.07 | 0.09 | 0.04 | 0.04 | 0.04 | 0.01 | 0.01 |
| O250 fraction (g $kg^{-1}$) | 0.20 | 0.19 | 0.19 | 0.16 | 0.19 | 0.17 | 0.02 | 0.01 |
| O53 fraction (g $kg^{-1}$) | 0.25 | 0.29 | 0.27 | 0.31 | 0.44 | 0.38 | 0.04 | 0.03 |
| POM[b] (g $kg^{-1}$) | 0.57 | 0.54 | 0.55 | 0.51 | 0.68 | 0.59 | 0.06 | 0.04 |

[a] Derived savanna: Zouzouvou and Eglimé (12 fields each); northern guinea savanna: Danayamaka (14 fields) and Kayawa (13 fields).
[b] 'ECEC': 'Effective Cation Exchange Capacity'; 'POM': 'Particulate Organic Matter'

**Table 4: Selected soil (0-10 cm) characteristics of the fields in the derived savanna and the northern guinea savanna benchmark villages as affected by fertilizer application[a].**

| | Derived savanna | | | Northern Guinea savanna | | | Minimal SED[c] | Maximal SED[c] |
|---|---|---|---|---|---|---|---|---|
| | Class I | Class II | Class III | Class I | Class II | Class III | | |
| Chemical characteristics | | | | | | | | |
| Organic C (g $kg^{-1}$) | 10.1 | 7.8 | 8.8 | 6.3 | 5.5 | 6.9 | 1.0 | 2.2 |
| Total N (g $kg^{-1}$) | 0.75 | 0.60 | 0.67 | 0.45 | 0.46 | 0.53 | 0.07 | 0.15 |
| C-to-N ratio | 13.5 | 12.9 | 13.0 | 14.9 | 12.2 | 12.9 | 0.7 | 1.6 |
| Olsen-P (mg $kg^{-1}$) | 13.3 | 9.8 | 8.6 | 10.3 | 4.5 | 5.0 | 1.8 | 4.1 |
| $Ca^{2+}$ content ($cmol_c$ $kg^{-1}$) | 6.30 | 4.25 | 3.62 | 2.97 | 2.24 | 3.36 | 1.01 | 2.31 |
| $Mg^{2+}$ content ($cmol_c$ $kg^{-1}$) | 1.56 | 1.30 | 1.08 | 0.77 | 0.65 | 0.65 | 0.23 | 0.52 |
| $K^{+}$ content ($cmol_c$ $kg^{-1}$) | 0.38 | 0.20 | 0.18 | 0.47 | 0.31 | 0.29 | 0.05 | 0.10 |
| Exch. acidity ($cmol_c$ $kg^{-1}$) | 0.42 | 0.30 | 0.58 | 0.70 | 0.61 | 0.82 | 0.12 | 0.28 |
| ECEC[b] ($cmol_c$ $kg^{-1}$) | 8.8 | 6.2 | 5.6 | 5.1 | 4.0 | 5.3 | 1.3 | 2.9 |
| pH($H_2O$) | 6.7 | 7.0 | 6.7 | 6.1 | 6.0 | 6.0 | 0.2 | 0.4 |
| pH(KCl) | 5.3 | 5.5 | 5.1 | 5.0 | 4.9 | 4.9 | 0.2 | 0.5 |
| Soil organic matter | | | | | | | | |
| O2000 fraction (g $kg^{-1}$) | 0.053 | 0.072 | 0.132 | 0.045 | 0.036 | 0.042 | 0.013 | 0.031 |
| O250 fraction (g $kg^{-1}$) | 0.178 | 0.155 | 0.208 | 0.208 | 0.157 | 0.179 | 0.021 | 0.047 |
| O53 fraction (g $kg^{-1}$) | 0.273 | 0.259 | 0.271 | 0.405 | 0.318 | 0.417 | 0.059 | 0.135 |
| POM[b] (g $kg^{-1}$) | 0.503 | 0.465 | 0.611 | 0.658 | 0.509 | 0.637 | 0.083 | 0.189 |

[a] Fertilizer classes for N application are: I: > 60 kg N $ha^{-1}$ $yr^{-1}$; II: 30-60 kg N $ha^{-1}$ $yr^{-1}$, III: < 30 kg N $ha^{-1}$ $yr^{-1}$. Fertilizer classes for P application are: I: > 20 kg P $ha^{-1}$ $yr^{-1}$; II: 10-20 kg P $ha^{-1}$ $yr^{-1}$, III: < 10 kg P $ha^{-1}$ $yr^{-1}$. Overall fertilizer classes, used in the column headings of this table, are the average of the values obtained for N and P fertilizer

[b] 'ECEC': 'Effective Cation Exchange Capacity'; 'POM': 'Particulate Organic Matter'

[c] The minimal and maximal Standard Errors of the Difference (SED) are given because each means comparison has a different number of degrees of freedom.

**Table 5: Response[a] to missing nutrients of the different fields in the derived savanna and the northern guinea savanna benchmark villages[b]. Values nearer to 100% indicate less response to the missing nutrient(s) considered.**

| | Derived savanna | | | Northern Guinea savanna | | | SE (village) | SE (benchmark) |
|---|---|---|---|---|---|---|---|---|
| | Zouzouvou | Eglimé | Mean | Danayamaka | Kayawa | Mean | (*n*=12) | (*n*=24) |
| | % of complete nutrition | | | | | | | |
| Shoot dry matter | | | | | | | | |
| N | 53.6 | 60.2 | 56.9 | 51.9 | 52.2 | 52.0 | 3.1 | 2.2 |
| P | 58.0 | 74.6 | 66.3 | 39.9 | 34.1 | 37.0 | 5.3 | 3.7 |
| Ca, Mg, K, S | 94.4 | 101.1 | 97.8 | 90.8 | 96.0 | 93.4 | 2.9 | 2.1 |
| Micro[c] | 96.0 | 96.9 | 96.5 | 98.1 | 94.5 | 96.3 | 3.2 | 2.3 |
| Root dry matter | | | | | | | | |
| N | 71.3 | 92.1 | 81.7 | 81.3 | 77.7 | 79.5 | 5.5 | 3.9 |
| P | 61.4 | 87.6 | 74.5 | 43.2 | 31.9 | 37.6 | 6.2 | 4.4 |
| Ca, Mg, K, S | 81.4 | 104.5 | 93.0 | 96.0 | 95.1 | 95.5 | 4.8 | 3.4 |
| Micro[a] | 105.6 | 121.3 | 113.4 | 100.9 | 106.4 | 103.6 | 5.0 | 3.6 |

[a] Proportion of shoot and root biomass in the treatment with one or more missing nutrients over shoot and root biomass in the treatment which was given all nutrients.
[b] Derived savanna: Zouzouvou and Eglimé (12 fields each); northern guinea savanna: Danayamaka (14 fields) and Kayawa (13 fields).
[c] 'Micro' indicates missing micronutrients (Fe, Mn, Zn, Cu, B, Mo, Co).

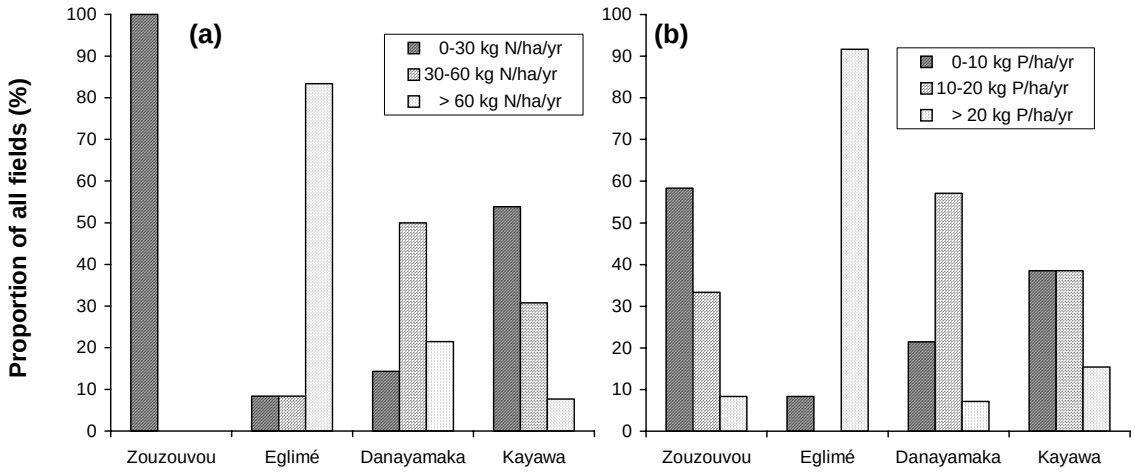


Fig. 1: Proportion of farmers' fields belonging to the various (a) N and (b) P fertilizer classes in the derived savanna benchmark villages (Zouzouvou and Eglimé) and in the northern guinea savanna benchmark villages (Danayamaka and Kayawa).

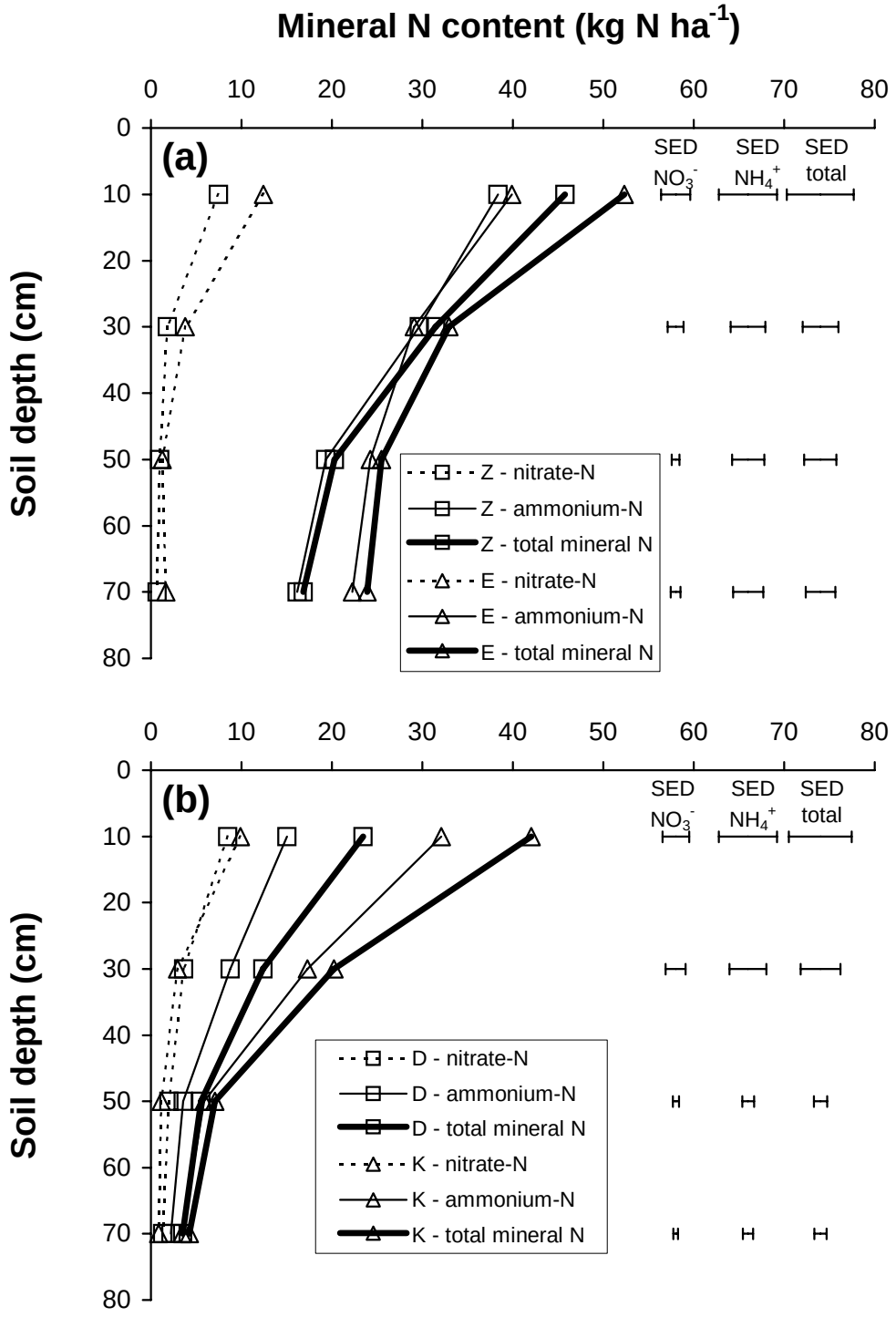


Fig. 2: Nitrate, ammonium, and total mineral N content in the soil profile in (a) the derived savanna benchmark villages ('Z' = Zouzouvou; 'E' = Eglimé) and (b) in the northern guinea savanna benchmark villages ('D' = Danayamaka; 'K' = Kayawa). 'SED' = Standard Error of the Difference.

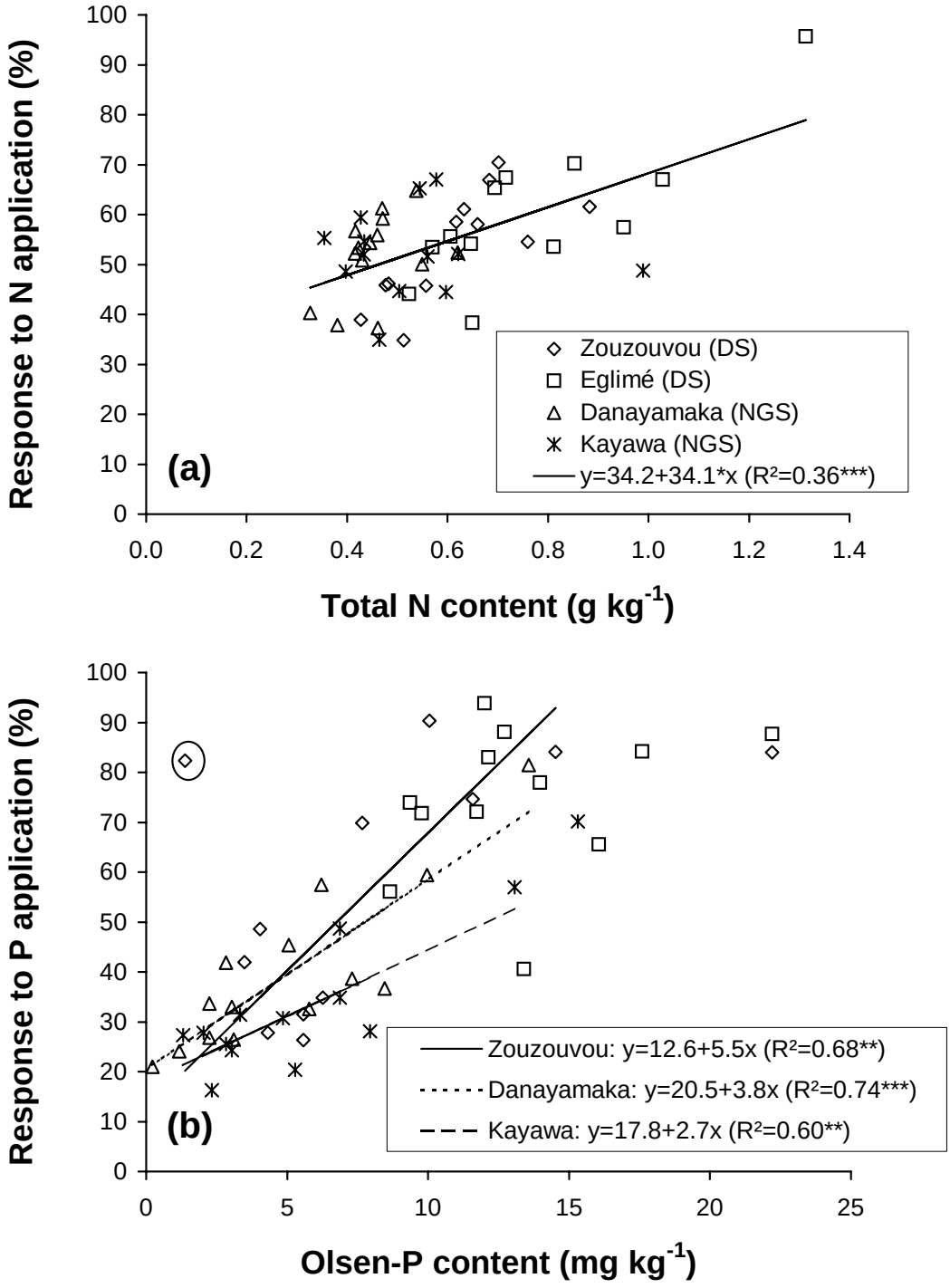


Fig. 3: Relationships between (a) the response to N and the soil total N content and (b) between the response to P and the soil Olsen-P content in a greenhouse pot experiment. The response is expressed as relative shoot biomass yield in the treatments with one or more missing nutrients relative to the treatment receiving all nutrients. As such, values closer to 100% indicate a lower response. 'DS' = derived savanna; 'NGS' = northern guinea savanna. The value encircled in Fig. 3b was excluded from the regression analysis.

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# Root distribution of Senna siamea grown on a series of soils representative for the derived savanna zone in Togo, West Africa

B Vanlauwe, FK Akinnifesi, BK Tossah, O Lyasse, N Sanginga and R Merckx
Soil Microbiology, IITA, Ibadan, Nigeria, c/o L.W. Lambourn & Co., 26 Dingwall Road, Croydon CR9 3EE, UK.
Programma em Agroecologia, Universidade Estadual do Maranhao, Caixa Postal 3004, Sao Luis, 65045-971 MA, Brazil.
Institut Togolais de Recherche Agronomique, BP 1163, Lomé, Togo.
Laboratory of Soil Fertility and Soil Biology, Faculty of Agricultural and Applied Biological Sciences, K.U. Leuven, Kardinaal Mercierlaan 92, 3001 Heverlee, Belgium.

***Keywords:*** *alley cropping, root abundance, root length density, root weight density, tap root*

## Abstract

Although crucial for assessing the functioning of alley cropping systems, quantitative information related to the hedgerow tree root distribution remains scarce. Soil mapping and destructive soil sampling was used to assess the impact of soil profile features on selected root characteristics of Senna siamea hedgerows, growing in alley cropping systems in three sites (Glidji, Amoutchou, and Sarakawa) representative for the derived savanna of Togo, West Africa. While the soil profiles in Glidji and Sarakawa contained a clay accumulation horizon, the Amoutchou profile was sandy up to 1 m. The number of small roots (diameter < 2 mm), quantified on a soil profile wall, decreased with depth in all sites. For most soil depths, the abundance of small roots tended to be higher near the tree base, e.g., ranging from 5.3 $dm^{-2}$ in Amoutchou to 21.4 $dm^{-2}$ in Glidji for the 0-20 cm layer, than in the middle of the alley, e.g., ranging from 3.1 $dm^{-2}$ in Amoutchou to 13.8 $dm^{-2}$ in Glidji for the 0-20 cm layer. Root length density (RLD) of the 0-10 cm and 10-20 cm layers was significantly higher in Glidji than in Amoutchou ($P < 0.05$) and in Sarakawa ($P = 0.08$). Differences in RLD between sites were not significant for layers below 30 cm. For each layer, root weight densities (RWD) were similar in all sites, e.g., ranging from 0.44 mg $cm^{-3}$ in Amoutchou to 0.64 mg $cm^{-3}$ in Glidji in the 0-10 cm layer, indicating that the roots in the Glidji topsoil had a smaller overall diameter than in Amoutchou. In Amoutchou, the relative RLD was lower than in Glidji or Sarakawa for the top 40 cm of soil, while the inverse was observed for the layers between 50 and 100 cm deep and this was related to the sandy soil profile in Amoutchou. Another consequence of the sandy profile was the larger tap root diameter below 50 cm in Amoutchou compared to Sarakawa. For all sites, significant ($P < 0.001$) linear regressions were observed between RLD's, RWD's, and the abundance of small roots, although the variation explained by the regression equations was highest for the relationship between RLD and RWD. The potential of the hedgerows to recover nutrients leached beyond the reach of food crops or the safety-net efficiency was evaluated for the tree sites.

## Introduction

Several of the unresolved questions related to alley cropping in particular and agroforestry systems in general are associated with the root dynamics of the tree component. In alley cropping systems, 'ideal' hedgerows recover soil N and other nutrients only from layers below the rooting depth of the accompanying food crop. By doing so, trees recover nutrients leached beyond the reach of annual food crops and thus improve nutrient use efficiencies. Real-world hedgerows recover a substantial proportion of their nutrients from layers simultaneously exploited by food crop roots and increase competition in favor of the trees. To assess possible belowground competition for water and nutrients between the trees and associated food crops, data on root abundance as a function of soil depth, soil characteristics, and time are needed (Schroth, 1995; Van Noordwijk and Purnomosidhi, 1995).

*Senna siamea* Irwin & Barneby is a non-$N_2$-fixing leguminous tree which is commonly found in natural fallows in the moist savanna zone of West-Africa. *Senna* has been widely used in alley cropping trials (Ruhigwa et al., 1992; Danso and Morgan, 1993; Van der Meersch et al., 1993; Schroth and Lehmann, 1995; Aihou et al., 1999; Tossah et al., 1999; Vanlauwe et al., 2001a) or other agroforestry systems (Leihner et al., 1996) in West-Africa. Tossah et al. (1999) reported annual *Senna* aboveground biomass productions of 9.2, 1.8, and 9.8 ton $ha^{-1}$, in Glidji (Southern Togo) on a Rhodic Ferralsol, in Amoutchou (Central Togo) on a Haplic Arenosol, and in Sarakawa (Northern Togo) on a Ferric Acrisol, respectively. Although *Senna* has been depicted as an aggressive scavenger for nutrients due to its laterally spreading root system (Hauser, 1993), Aihou et al. (1999) and Tossah et al. (1999) concluded that *Senna* trees rely mainly on the subsoil as a source of nutrients. While Vanlauwe et al. (2001a) found only a small recovery of applied $^{15}N$-urea in the *Senna* hedgerow during intercropping with maize on a non-acid Alfisol, Ruhigwa et al. (1992) concluded that *Senna* would compete for nutrients with the associated food crop in alley cropping systems, as most of its fine root biomass was confined to the top 20 cm of an acid Ultisol. Schroth et al. (1995) stated that the lateral development of *Senna* roots was favoured by the shallow soil depth on a Ferric Acrisol in Central Togo. Akinnifesi et al. (1995) found significant decreases in root length densities of *Enterolobium cyclocarpum* and *Leucaena leucocephala* with increases in soil bulk density. Above observations clearly indicate possible interactions between soil chemical and physical conditions on the one hand and the root distribution and competitive character of *Senna* trees on the other hand.

The objectives of this paper were (i) to quantify the root distribution of *Senna* hedgerows, growing in alley cropping systems on a number of sites representative for the derived savanna of Togo, (ii) to evaluate the effect of soil profile characteristics on the observed root distributions, (iii) to assess the potential of *Senna* trees to recover nutrients leached beyond the reach of food crops or the so-called safety-net efficiency, and (iv) to explore relationships between the different methods used to quantify root distributions.

## Materials and methods

*Site and soil characteristics and establishment of the alley cropping trials*

The trials were established on a Rhodic Ferralsol in Glidji (Southern Togo – 6°15'N, 1°36'E), on a Haplic Arenosol in Amoutchou (Central Togo – 7°22'N, 1°10'E), and on a Ferric Acrisol in Sarakawa (Northern Togo – 9°37'N, 1°01'E). The present soil types represent about 57% of the soils in the DS (Jagtap, 1995). All sites are located in the Derived Savanna (DS) zone, which is characterized by a length of growing period between 211 and 270 days (Jagtap, 1995). Total rainfall in Glidji was 950 mm in 1995 and 876 mm in 1996 (bimodal pattern), in Amoutchou 1540 mm in 1995 and 1250 mm in 1996 (unimodal pattern), and in Sarakawa 1357 mm in 1995 and 1289 mm in 1996 (unimodal pattern). The site in Amoutchou had a groundwater table between 0.8 and 1.4 m below the soil surface, while the groundwater table of the others sites is deeper than 10 m.

The trials were established in 1991 in Glidji and in 1992 in Amoutchou and Sarakawa. A randomized complete block design with four replicates was laid out with five treatments consisting of four alley cropping plots and a no-tree control treatment. Plot size was 10 by 12 m and the hedges were planted at 4 m distance, making 3 10-m-long hedges per plot. The *Senna* seeds used in the three sites were collected from a *Senna* fallow near Lomé, Togo. In Glidji, the *Senna* trees were pruned 3 times yearly (before planting around mid-April, about 5 weeks after planting, and about 11 weeks after planting) in 1992 and again in 1994, 1995, and 1996 at 0.25 m above the soil surface while in Amoutchou and Sarakawa, the *Senna* trees were pruned 3 times in 1995 and 1996 (Tossah et al., 1999). During the years in which the trees were pruned, maize was planted at a distance of 80 (between rows) by 30 cm (within rows) and thinned to one plant per pocket. A basal application of 26 kg P $ha^{-1}$ as TSP and 50 kg K $ha^{-1}$ as KCl was applied to the maize at planting follwed by two applications of 22.5 kg N $ha^{-1}$ of urea approximately 3.5 and 7.5 weeks after planting.

*Quantification of selected root characteristics and soil sampling*

In September 1996, a trench was dug in each field in two *Senna* alley cropping plots, perpendicular to the hedgerow, 15 cm away from the tree base, extending 2 m away from the trees, and 2 m deep. After leveling the profile wall, *Senna* root abundance was determined using a 10 by 10 cm grid by counting all living roots within each grid, after removing the top 1 mm of soil, following the method described by Akinnifesi et al. (1999). Dead roots were identified by their brittle structure and dark cortex. Roots > 5 mm, between 2 and 5 mm, and < 2 mm were counted separately.

After determining the root abundance, soil samples were taken from the profile wall with a 10 by 10 cm square auger (5 cm deep), 0.1, 0.5 and 1.5 m away from the tree base, from the following soil layers: 0-10, 10-20, 20-30, 50-60, 80-90, 110-120, and 140-150 cm. In Amoutchou, both root counting and soil sampling was restricted to 100 cm because of the high water table. In Glidji, soil was also destructively sampled at 190-200 cm. Separate soil samples were taken from the same layers for routine soil analysis (organic C (Amato, 1993); Kjeldahl total N; effective cation exchange capacity (IITA, 1982); base saturation; pH($H_20$) (20 g dry soil in 50 ml $H_2O$); texture (IITA, 1982)). The diameter of the taproot was measured at 10 cm depth intervals up to a depth of 2 m, after taking the soils samples for root and soil characterization. Bulk densities were determined on the wall of a nearby soil profile, dug in 1995 to determine the soil type (Tossah et al., 1999).

The roots were removed from the soil collected with the 10 cm by 10 cm square augers by washing over a 0.5 mm sieve after submerging the samples overnight in a hexametaphosphate-Na-carbonate solution (20.94 g Na-hexametaphosphate $L^{-1}$ and 4.45 g $Na_2CO_3$ $L^{-1}$) and stored in a 1% formaldehyde solution. Dead and live roots were separated as described above. The roots < 2 mm were spread evenly on a perspex sheet, scanned with Paintshop Program software, and the root length density (RLD) were measured with the Delta-T-Scan image analysis program (Webb et al., 1993). Preliminary investigations with a limited number of root samples showed a very close relationship between root lengths measured with the image analysis program and the original Tennant-method (Tennant, 1975).

*Statistical methods*

All root data were subjected to ANOVA with the MIXED procedure of the SAS system (Littell et al., 1996). Regression analysis between the various root characteristics was carried out with the REG procedure of the SAS system (SAS, 1985). Tap root diameters, root weight densities, and root length densities were log-transformed before ANOVA (Gomez and Gomez, 1984). Large (> 2mm) and small (< 2mm) root abundances, collected on the profile wall, were combined into 4 distances (0-50, 50-100, 100-150, and 150-200 cm away from the tree) and 6 depths (0-20, 20-40, 40-80, 80-120, 120-160, and 160-200 cm) for ANOVA analysis. Values for root abundance were log($n$+1) transformed before statistical analysis (Gomez and Gomez, 1984). Two extremely large values for root length density measured on one of the two Glidji profiles (see below) were excluded from the statistical analysis. Means were estimated with the LSMEANS statement, while significantly different means were separated with the PDIFF test of the LSMEANS statement (Littell et al., 1996).

## Results

*Soil profile characteristics*

The profile in Amoutchou contained mostly sand down to 1 m depth, while the profiles in Glidji and Sarakawa showed clay accumulation below 50 cm (Table 1). Consequently, the organic C and total N content and ECEC are higher in the subsoil in Glidji and Sarakawa than in Amoutchou. While the bulk density of the topsoil was similar in all sites, the bulk density of the layers below 40 cm was lower in Amoutchou than in both other sites (Table 2).

*Abundance of roots*

For all sites, the abundance of roots < 2 mm diameter in the 0-20 cm, 40-80 cm, and 80-120 cm layers was significantly ($P < 0.05$) higher between 0 and 0.5 m away from the hedgerow (21.4, 5.3, and

5.5 $dm^{-2}$ in the 0-20 cm layer in Glidji, Amoutchou, and Sarakawa, respectively) than between 1.5 and 2 m away from the hedgerow (13.8, 3.1, and 3.7 $dm^{-2}$ in the 0-20 cm layer in Glidji, Amoutchou, and Sarakawa, respectively) (Fig. 1). This was also true for the 20-40 cm layer in Amoutchou, for the 120-160 cm layer in Glidji and Sarakawa, and for the 160-200 cm layer in Sarakawa. Distance to hedgerow had no effect on the number of roots < 2 mm in the 20-40 cm layer in Glidji and Sarakawa (Fig. 1). In Glidji and Sarakawa, more shallow soil layers contained significantly ($P < 0.05$) more roots < 2 mm than deeper soil layers up to 120 cm depth at the 4 considered distances away from the tree base. Below 120 cm, differences between layers were not consistently significant. In Amoutchou, only the top 0-20 cm layer contained more ($P < 0.05$) roots < 2 mm than the deeper soil layers, while below 20 cm differences in root abundance were not consistently significant (Fig. 1).

In Glidji and Sarakawa, the abundance of roots > 2 mm in the 0-20 cm layer was significantly ($P < 0.05$) higher close to the hedgerow (0-0.5 m) (1.8 and 0.8 $dm^{-2}$ in Glidji and Sarakawa, respectively) than furthest away from the hedgerow (1.5-2 m) (0.8 and 0.4 $dm^{-2}$ in Glidji and Sarakawa, respectively) (Figs. 2a and 2c). Below 80 cm no differences in number of roots > 2 mm were observed for the considered lateral distances. In Amoutchou, all soil layers contained more ($P < 0.05$) roots > 2 mm closest to the hedgerow (0-0.5m) (1.1 $dm^{-2}$ in the 0-20 cm layer) than furthest away from the hedgerow (1.5-2 m) (0.3 $dm^{-2}$ in the 0-20 cm layer) except the 20-40 cm layer (Fig. 2b). Generally, in Glidji and Sarakawa, more shallow (0-80 cm) soil layers contained more ($P < 0.05$) roots > 2 mm, while in Amoutchou, only the 0-20 cm layer contained more ($P < 0.05$) large roots than the layers below 20 cm. Below 80 cm, no differences in large root abundance were observed between soil layers.

*Root length densities and root weight densities*

The root length density (RLD) of the 0-10 cm and 10-20 cm layers was significantly ($P < 0.05$) higher in Glidji (1.46 and 1.15 cm $cm^{-3}$ in 0-10 and 10-20 cm layer, respectively) than in Amoutchou (0.50 and 0.22 cm $cm^{-3}$ in 0-10 and 10-20 cm layer, respectively) (Fig. 3a). The 10-20 cm and 20-30 cm layers had a significantly ($P < 0.05$) higher RLD in Sarakawa than in Amoutchou. Differences in RLD between sites were not significant for layers below 30 cm (Fig. 3a). The 0-10 cm layer had a higher ($P = 0.08$) RLD under the tree than 1.5 m away from the tree (Fig. 3b). Deeper layers contained similar root length densities (RLD's) irrespective of the distance to the tree base (Fig. 3b). In Glidji, 2 soil cores (0-10 cm and 10-20 cm, both 0.5m away from the tree) in one of the profile pits contained very high RLD's (22.8 and 24.9 cm $cm^{-3}$, respectively), which were excluded from the statistical analysis, as mentioned previously.

The root weight density (RWD) of the 0-10 cm was similar in all sites (0.64, 0.44, and 0.56 mg $cm^{-3}$ in Glidji, Amoutchou, and Sarakawa, respectively) (Fig. 4a). The 10-20 cm layer had a significantly ($P < 0.05$) higher RWD in Glidji than in Amoutchou. Differences in RWD between sites were not significant for layers below 20 cm (Fig. 4a). The 0-10 cm layer had a higher ($P = 0.09$) RWD under the tree than 1.5 m away from the tree (Fig. 4b). Deeper layers contained similar root length densities (RWD's) irrespective of the distance to the tree base (Fig. 4b).

*Tap root diameter*

At the soil surface, the taproot diameter was significantly ($P < 0.05$) larger in Glidji (215 mm) than in Amoutchou (91 mm) and in Sarakawa (77 mm) (Fig. 5). Between 10 and 50 cm, no significant differences in taproot diameter between sites were observed. Between 60 and 100 cm, the taproot diameter was significantly ($P < 0.05$) larger in Amoutchou than in Sarakawa (Fig. 5). For all sites, the taproot diameter decreased with soil depth, although differences between specific soil layers were not consistently significant (Fig. 5).

*Correlations between selected root characteristics*

For all sites, significant ($P < 0.001$) linear regressions were observed between RLD's, RWD's, and abundances of roots < 2 mm (Fig. 6). While the slopes of the regression lines relating RLD's with numbers of small roots were similar for all sites (Fig. 6a), the slope of the regression line relating RWD's

with numbers of small roots was significantly higher for Amoutchou than for Glidji (Fig. 6b). The regression line relating RLD's with RWD's had a significantly higher slope for the Glidji data than for the data obtained on the other two sites (Fig. 6c).

In Amoutchou, the relative RLD, calculated based upon the regression lines presented in Fig. 6a, appeared to be lower than in Glidji or Sarakawa for the top 40 cm of soil, while the inverse was observed for the layers between 50 and 100 cm deep (Fig. 7).

**Discussion**

The soil profile characteristics influenced root abundance in the different soil layers. Although none of the soil layers in the top 1 m showed severe chemical (Table 1) or physical (Tables 1 and 2) restrictions to root growth, the soil layers below 50 cm contained a relatively higher RLD in Amoutchou than in the two other sites, most likely because of their more sandy texture (Table 1) and lower bulk density (Table 2). The taproot diameter in the layers below 50 cm was also larger in Amoutchou than in Sarakawa. The presence of local accumulations of roots observed in the Glidji topsoil and local increases in root abundances in the subsoil (Fig. 1) indicates that roots are not homogeneously distributed within a certain soil layer, but follow trails with minimal resistance to root growth, such as macropores or soil cracks. Rowe et al. (1999) reported a large variation in recoveries of subsoil $^{15}$N-labeled ammonium sulphate by *Peltophorum dasyrrhachis* and attributed this to large heterogeneity in root distributions.

The larger values for root abundance in the topsoil in Glidji compared to Sarakawa was most likely caused by the more intense pruning regime, as the chemical and physical characteristics of the topsoil varied only little between the two sites (Tables 1 and 2). After all, in Glidji, the trees were pruned the first time already one year after planting and had been pruned 12 times prior to root quantification, while in Amoutchou and Sarakawa, the hedges grew for 4 years before their first pruning and had been pruned only 6 times before root quantification. Van Noordwijk and Purnomosidhi (1995) observed that a lower pruning height led to a larger number of superficial roots of smaller diameter on an Indonesian Ultisol. Schroth (1995) stated that shoot pruning of trees seemed to increase root branching in the topsoil and restrict tree roots to shallower soil depths compared with roots of unpruned trees. Although in Glidji also root length densities in the top 20 cm layer were much higher than in the two other sites, root weight densities were similar in all sites. This could be an indication that a more intensive pruning regime does not only lead to a larger number of superficial roots but also to roots with a smaller diameter. The necessity to prune the hedgerow trees in alley cropping systems during the cropping season results in a tree root system more comparable to the root system of an annual crop and, as such, reduces the potential of hedgerows to fulfill their hypothesized nutrient recovery potential. As regular pruning affects both the distribution of roots in the profile and their size, one could argue that screening of hedgerow trees for root competitiveness should be done on regularly-pruned trees and not on trees that are allowed to grow continuously.

The root safety-net zone is usually equated with that part of the soil profile from where trees recover substantial amounts of nutrients, not accessible to the associated food crop. Cadisch et al. (1997) developed an index for quantifying the nutrient recovery efficiency of the root safety-net - the safety-net efficiency - defined as the ratio [tree N uptake from the safety-net layer]:[tree N uptake from the safety-net layer + N leached beneath the safety-net layer]. A high safety-net efficiency requires a minimal RLD to a certain depth, a minimal level of activity of the roots present in the soil layers considered, and a minimal demand by the tree for the nutrient considered. Assuming that during the major part of the maize growing season few maize roots are found below 60 cm (Vanlauwe et al., 2001b), *Senna* root safety-nets could be identified in Glidji and Sarakawa with a thickness of at least 140 cm and minimal RLD's of 0.2 and 0.1 cm cm$^{-3}$, respectively. In Amoutchou, a *Senna* root safety net could be identified with a thickness reaching the upper boundary of the ground water table and a minimal RLD of 0.1 cm cm$^{-3}$. The safety-net was also observed to cover the complete alley from hedgerow to hedgerow, as the distance to hedgerow had only an impact on RLD's for the 0-10 cm soil layer, maximally 50 cm away from the tree base. The minimal RLD's needed for maximal nutrient uptake depend on the anion, but the safety-net hypothesis is usually linked to the recovery of nitrate-N as this nutrient is very mobile. Van Noordwijk (1989)

estimated the minimal RLD to be 0.1 cm $cm^{-3}$ for nitrate recovery and 1 cm $cm^{-3}$ for K recovery. Although based on the observed RLD's the trees growing in all sites have the potential to recover a substantial amount of mineral N from the subsoil, some important processes and tree management aspects may hamper the optimal functioning of the root safety-net. Firstly, mineral N dissolved in water flowing preferentially through macropores may bypass any recovery mechanisms of mineral N by the trees. Vanlauwe et al. (2001a) observed substantial amounts of urea-derived N in the 120-150 cm soil layer already at 21 days after urea application and attributed this to preferential flow through macropores. Although tree roots may equally prefer to grow through macropores, it is doubtful whether water moving down macropores can be sufficiently fast absorbed by tree roots growing through these macropores. Secondly, the presence of roots in the subsoil does not necessarily mean that they are actively retrieving nutrients from the soil solution, although Schroth (1995) stated that the presence of roots from competitive crops such as maize may restrict the lateral spread of tree roots and force them into the subsoil. Vanlauwe et al. (2001a) also observed a larger recovery of $^{15}N$-labeled ammonium sulphate by the maize than by the *Senna* hedgerow in an alley cropping trial. Evidently, during the dry season, trees will rely mostly on their subsoil roots for nutrient and water uptake. Thirdly, pruning of the tree canopy at the start of the food crop growing season strongly restricts the demand of the hedgerow for nutrients and water at a time where nutrient availability may be high due to the application of prunings and/or fertilizer and due to the presence of relatively large amounts of mineral N after the first rains caused by the so-called 'Birch' effect.

Although most of the soil layers in the Glidji profile contained a larger RLD than in the Sarakawa profile, especially in the top 20 cm, the average yearly pruning biomass productions was similar on both sites (9.2 and 9.7 t $ha^{-1}$ in Glidji and Sarakawa, respectively – Tossah et al., 1999). The impact of a more dense root systems in Glidji is likely to be counteracted by the lower yearly precipitation, a lower top and subsoil fertility status (Table 1), and a higher competition with maize due to a relatively higher proliferation of tree roots in the same soil layers with maximal maize root densities. The very low yearly biomass production in Amoutchou (1.8 t $ha^{-1}$ – Tossah et al., 1999) is likely caused by the very low soil fertility status of the complete profile and the temporarily high groundwater table which restricts nutrient uptake to the top 1 m during the rainy season.

The highly significant relationships between RLD's and RWD's and their relatively high $R^2$ values indicate that both root characteristics are closely related, irrespective of sampling depth or distance to hedgerow tree. For similar RWD's, *Senna* roots in Glidji had a significantly higher RLD, which confirms that they had a smaller diameter in Glidji than in the other two sites, as discussed earlier. Although the linear regressions between RLD's or RWD's and the number of small roots counted on a profile wall were highly significant, these regressions explained less of the variation than regressions between RLD's and RWD's. This may not be surprising as the ratio [RLD in a three-dimensional volume]:[number of roots visible on a two-dimensional plane] depends on the spatial arrangement of the tree roots and varies with sample position, sample depth, and sampling time (Van Noordwijk, 1987). As the relationships between RLD and small root abundance are quite similar for all sites, these could be used to estimate RLD's from root counting data on a profile wall, provided the relationship between the various root characteristics is known for the species of interest.

**Conclusions**

The sandy profile in Amoutchou resulted in a relatively higher proportion of RLD's in the subsoil and a larger tap root diameter compared to the Glidji and Sarakawa, of which the soil profile contained a clay accumulation horizon. The *Senna* roots contained more roots of a smaller diameter in Glidji than in Sarakawa, which was most likely the result of differences in tree management rather than soil profile characteristics.

In Glidji and Sarakawa, root safety-nets with a thickness of at least 140 cm and a minimal RLD of 0.2 and 0.1 cm $cm^{-3}$, respectively, were present. In Amoutchou, the thickness was limited due to the presence of a temporarily high groundwater table. However, the presence of tree roots at a certain depth

does not prove that they are active. Moreover, several processes and tree management practices were identified which may lead to significant bypasses of the safety-net.

Close relationships were found between RLD's and RWD's indicating that RLD's could be estimated by a less tedious quantification of RWD's. Although the linear regressions between RLD's or RWD's and the number of small roots counted on a profile wall were highly significant, these regressions explained less of the variation than regressions between RLD's and RWD's.

**Acknowledgments**

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**Table 1: Selected soil profile characteristics of the sites in Glidji, Amoutchou, and Sarakawa in Togo, West Africa.**

| Site/Soil depth | Organic C | Total N | ECEC[a] | BS[a] | pH ($H_20$) | Sand content | Silt content | Clay content |
|---|---|---|---|---|---|---|---|---|
| cm | % | | $cmol_c$ $kg^{-1}$ | % | | % | | |
| Glidji | | | | | | | | |
| 0- 10 | 0.31 | 0.030 | 2.0 | 100 | 5.28 | 89 | 4 | 6 |
| 10- 20 | 0.16 | 0.019 | 1.9 | 84 | 5.07 | 90 | 4 | 5 |
| 20- 30 | 0.18 | 0.023 | 2.8 | 75 | 5.03 | 83 | 3 | 13 |
| 50- 60 | 0.18 | 0.034 | 4.1 | 86 | 4.93 | 64 | 2 | 33 |
| 80- 90 | 0.16 | 0.031 | 3.8 | 95 | 5.13 | 61 | 3 | 35 |
| 110-120 | 0.12 | 0.029 | 4.1 | 88 | 4.58 | 58 | 3 | 38 |
| 140-150 | 0.10 | 0.025 | 3.6 | 92 | 4.78 | 60 | 3 | 37 |
| 190-200 | 0.11 | 0.025 | 4.4 | 86 | 4.82 | 55 | 3 | 42 |
| Amoutchou[b] | | | | | | | | |
| 0- 10 | 0.29 | 0.022 | 2.9 | 100 | 5.33 | 86 | 9 | 4 |
| 10- 20 | 0.17 | 0.016 | 2.6 | 80 | 5.41 | 87 | 7 | 5 |
| 20- 30 | 0.14 | 0.014 | 3.4 | 81 | 5.48 | 86 | 8 | 5 |
| 50- 60 | 0.10 | 0.011 | 2.0 | 90 | 5.48 | 85 | 7 | 7 |
| 80- 90 | 0.08 | 0.011 | 3.6 | 81 | 5.24 | 78 | 8 | 13 |
| Sarakawa | | | | | | | | |
| 0- 10 | 0.43 | 0.033 | 2.8 | 100 | 5.17 | 85 | 7 | 8 |
| 10- 20 | 0.30 | 0.025 | 2.8 | 84 | 5.18 | 82 | 9 | 9 |
| 20- 30 | 0.23 | 0.020 | 3.9 | 79 | 5.17 | 80 | 10 | 11 |
| 50- 60 | 0.33 | 0.039 | 4.8 | 68 | 4.49 | 47 | 7 | 47 |
| 80- 90 | 0.18 | 0.029 | 4.9 | 71 | 4.75 | 48 | 9 | 44 |
| 110-120 | 0.16 | 0.025 | 5.4 | 68 | 4.67 | 49 | 9 | 43 |
| 140-150 | 0.14 | 0.019 | 4.9 | 79 | 4.55 | 51 | 13 | 37 |
| 190-200 | 0.08 | 0.016 | 4.3 | 82 | 4.90 | 55 | 14 | 32 |

[a] 'ECEC': 'Effective Cation Exchange Capacity'; 'BS': 'Base Saturation'
[b] Samples below 90 cm could not be taken because of water-logging during sampling

**Table 2: Bulk density of the different soil layers at the sites in Glidji, Amoutchou, and Sarakawa in Togo, West Africa.**

| Site | Horizon (cm) | Bulk density (kg $dm^{-3}$) |
|---|---|---|
| Glidji | Ap (0 - 15) | 1.47 |
| | E (15 - 40) | 1.63 |
| | Bt1 (40 - 95) | 1.56 |
| | Bt2 (95 - 120) | 1.56 |
| Amoutchou | Ah1 (0 - 20) | 1.52 |
| | Ah2 (20 - 35) | NA[a] |
| | E (35 - 50) | 1.46 |
| | Bw (50 - 85) | 1.51 |
| | Bg (85 - 100) | NA |
| Sarakawa | Ah1 (0 - 23) | 1.50 |
| | Ah2 (23 - 40) | 1.50 |
| | BA (40 - 50) | 1.54 |
| | Bt1 (50 - 80) | 1.61 |
| | Bt2 (80 - 112) | NA |

[a] 'NA': 'not available'

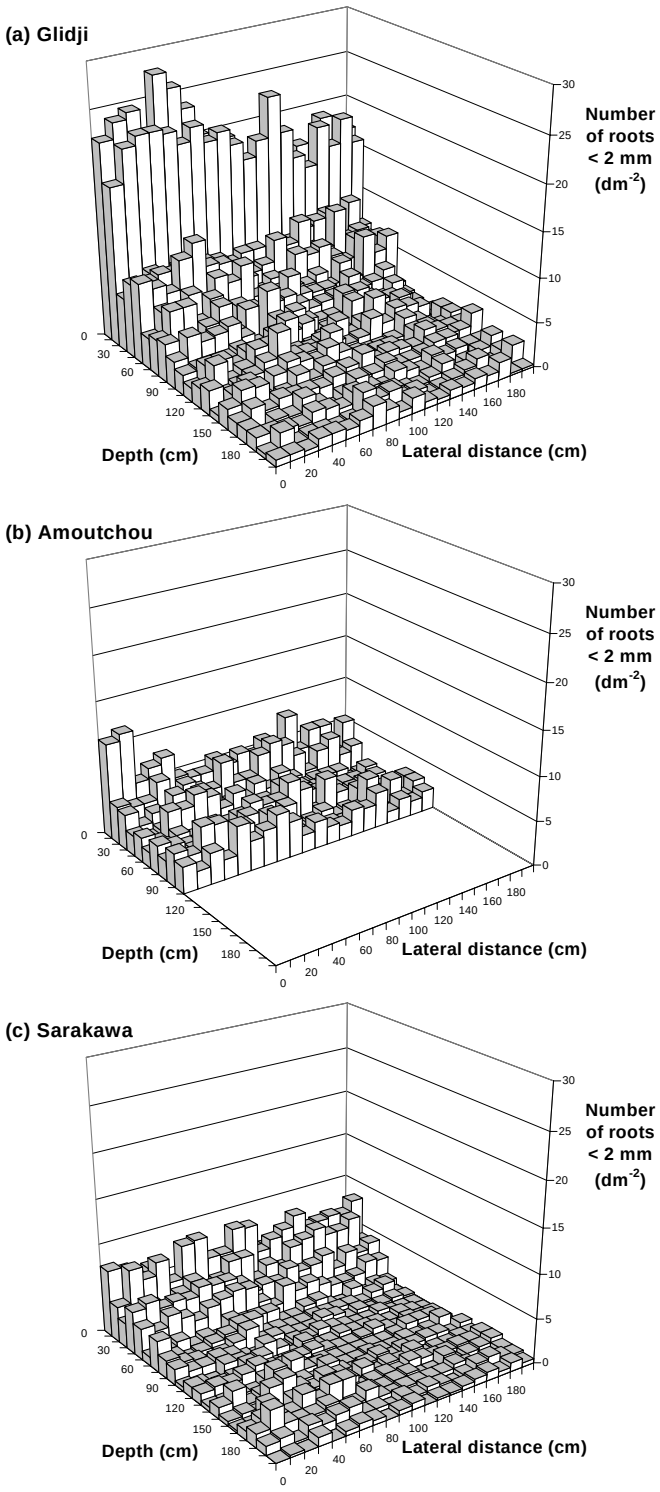


Fig. 1: Abundance of *Senna siamea* roots with a diameter < 2 mm in Glidji (a), Amoutchou (b), and Sarakawa (c) in Togo, West Africa, as influenced by soil depth and distance to the tree base. Values are averaged over the two halves of the two profile pits. Minimal and maximal standard errors of the differences between log(*n*+1)-transformed data are 0.044 and 0.062, 0.045 and 0.069, and 0.039 and 0.055, for Glidji, Amoutchou, and Sarakawa, respectively. Note that in Amoutchou no observations were taken below 100 cm.

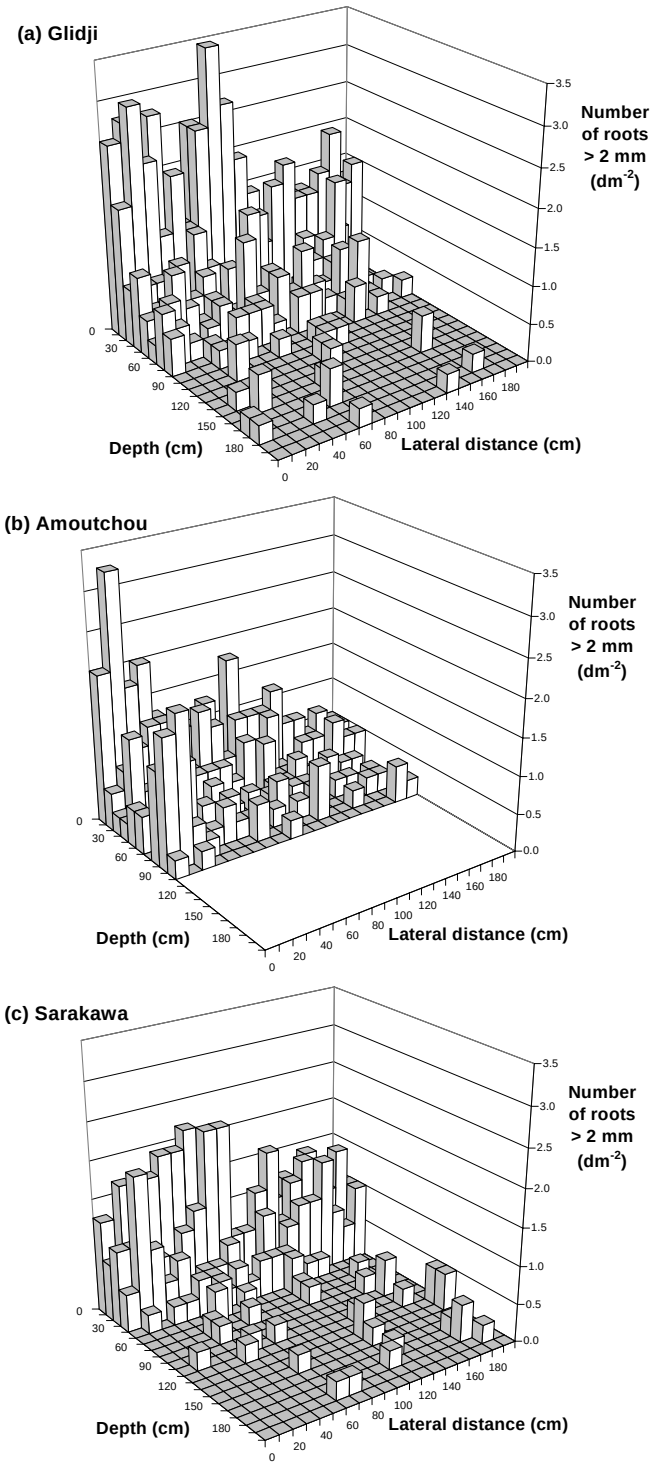


Fig. 2: Abundance of *Senna siamea* roots with a diameter > 2 mm in Glidji (a), Amoutchou (b), and Sarakawa (c) in Togo, West Africa, as influenced by soil depth and distance to the tree base. Values are averaged over the two halves of the two profile pits. Minimal and maximal standard errors of the differences between log(*n*+1)-transformed data are 0.020 and 0.028, 0.028 and 0.044, and 0.018 and 0.026, for Glidji, Amoutchou, and Sarakawa, respectively. Note that in Amoutchou no observations were taken below 100 cm.

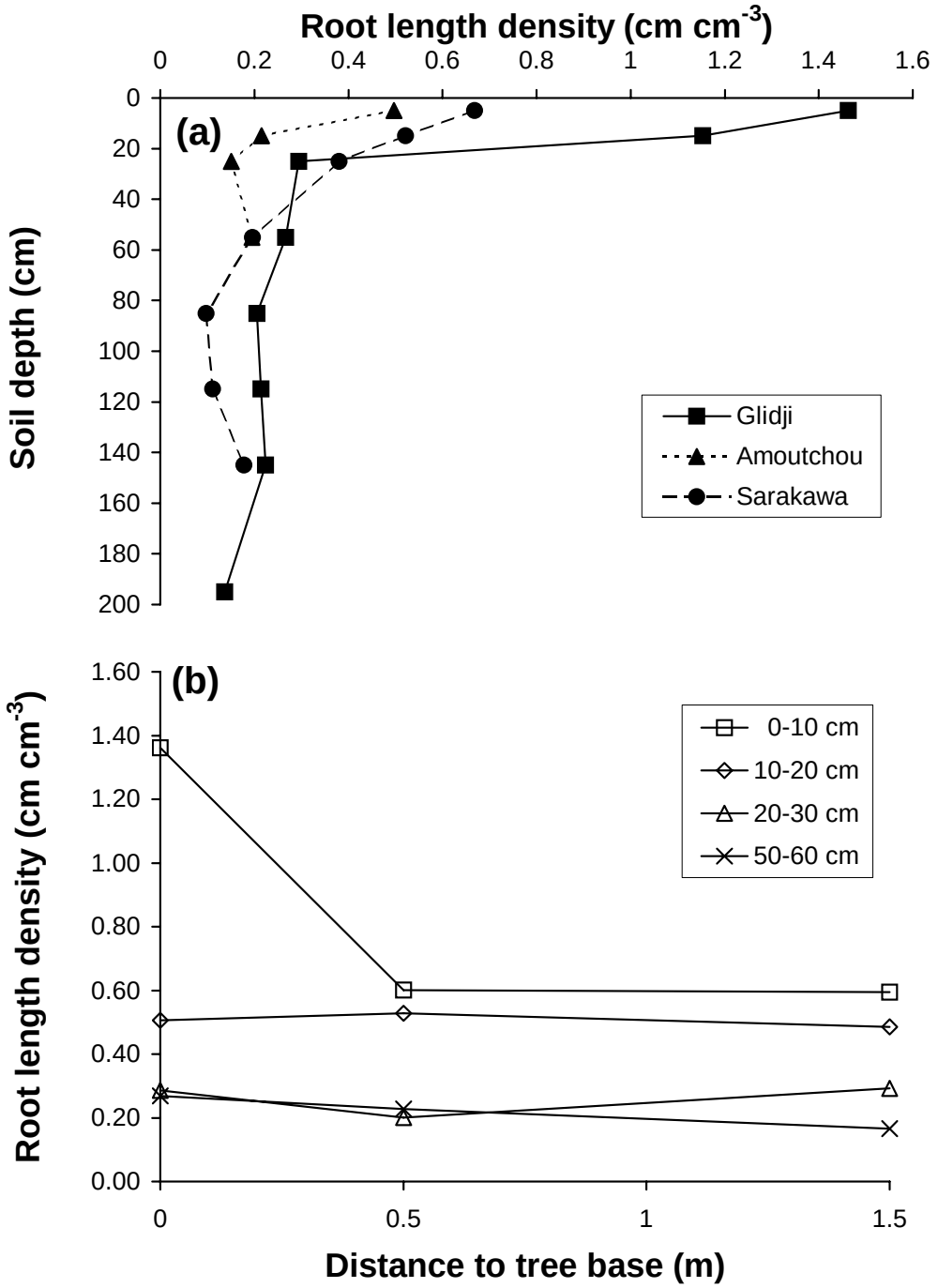


Fig. 3: *Senna siamea* root length density in Glidji, Amoutchou, and Sarakawa in Togo, West Africa, as influenced by soil depth (a) and distance to the tree base (b). The different sites were analyzed together. Minimal and maximal standard errors of the differences between log-transformed data are 0.17 and 0.25 for Fig. 3a and 0.15 and 0.23 for Fig. 3b. The interaction between site, soil depth, and distance to tree base was not significant. Note that in Amoutchou no observations were taken below 100 cm.

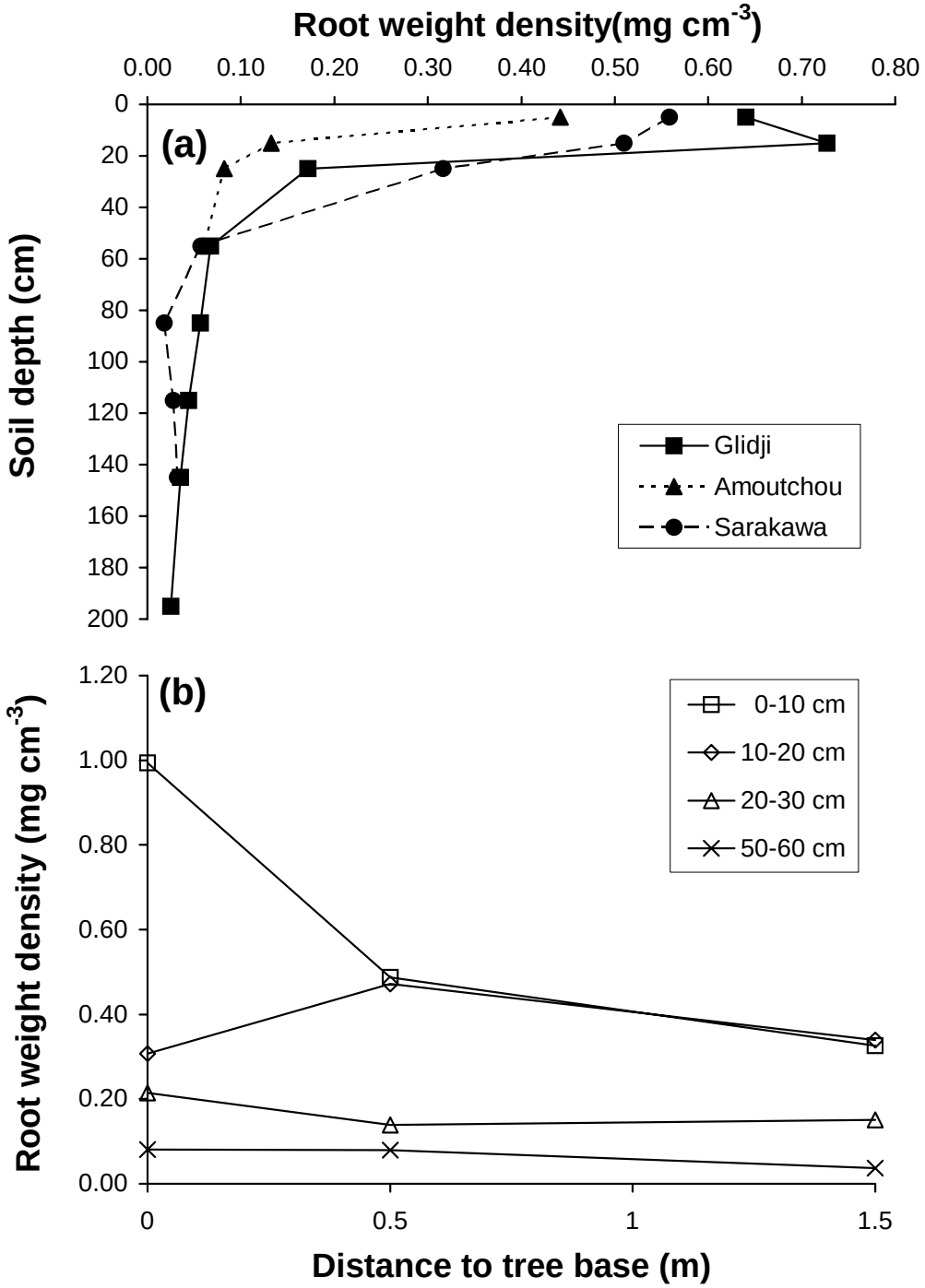


Fig. 4: *Senna siamea* root weight density in Glidji, Amoutchou, and Sarakawa in Togo, West Africa, as influenced by soil depth (a) and distance to the tree base (b). The different sites were analyzed together. Minimal and maximal standard errors of the differences between log-transformed data are 0.27 and 0.37 for Fig. 4a and 0.23 and 0.33 for Fig. 4b. The interaction between site, soil depth, and distance to tree base was not significant.

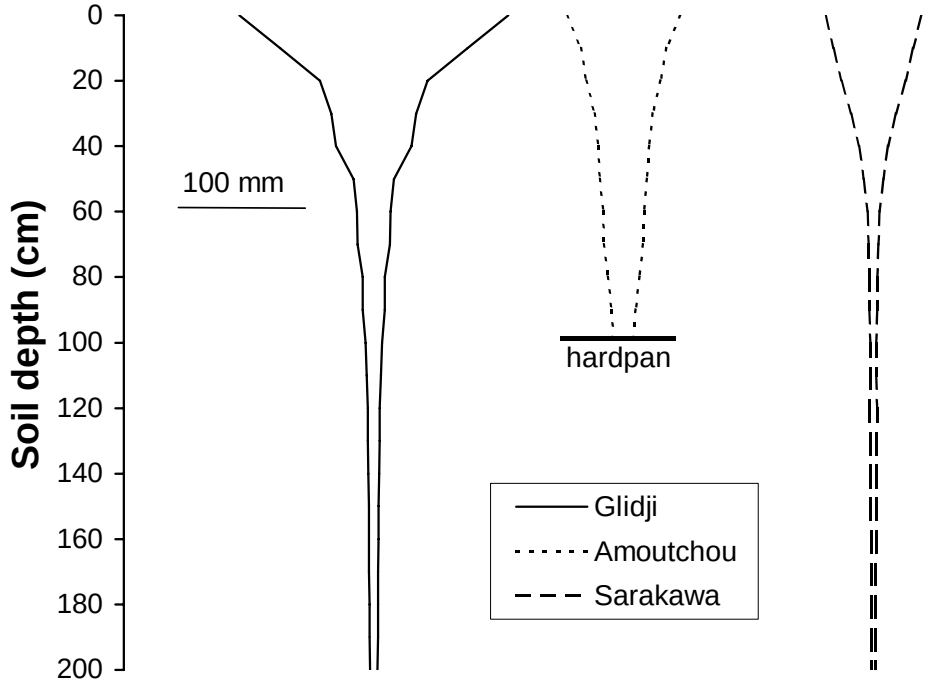


Fig. 5: Diameter of the *Senna siamea* taproot in Glidji, Amoutchou, and Sarakawa in Togo, West Africa. In Amoutchou, a hardpan prevented to measure the taproot diameter below 100 cm. The different sites were analyzed together. The standard error of the difference between log-transformed data to compare sites at similar depths is 0.22 and to compare depths at similar sites is 0.13.

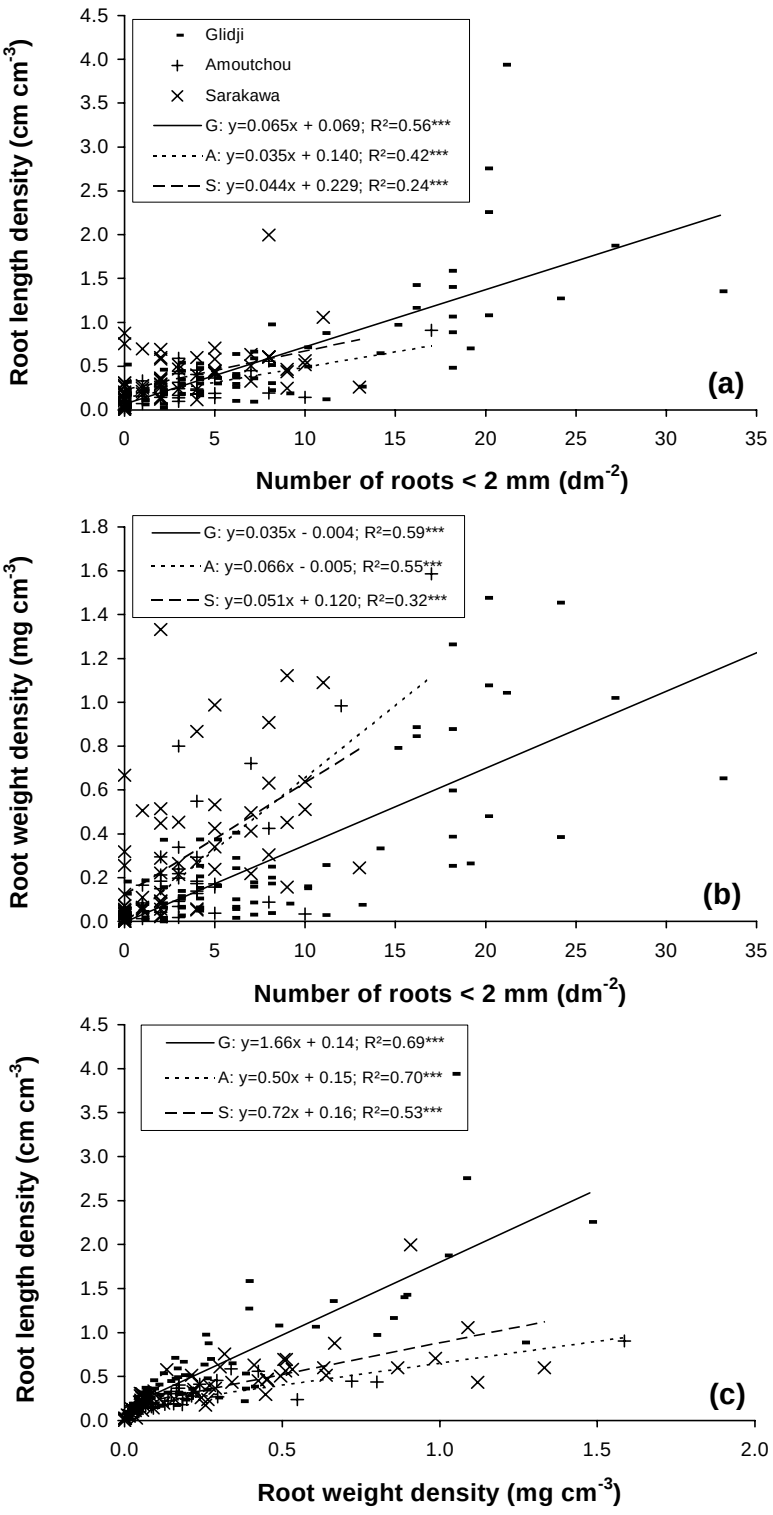


Fig. 6: Linear relationships between log-transformed root length densities and log(*n*+1)-transformed abundances of roots < 2 mm (a), between log-transformed root weight densities and log(*n*+1)-transformed abundances of roots < 2 mm (b), and between log-transformed root length densities and log-transformed root weight densities (c) for data obtained in Glidji, Amoutchou, and Sarakawa in Togo, West Africa.

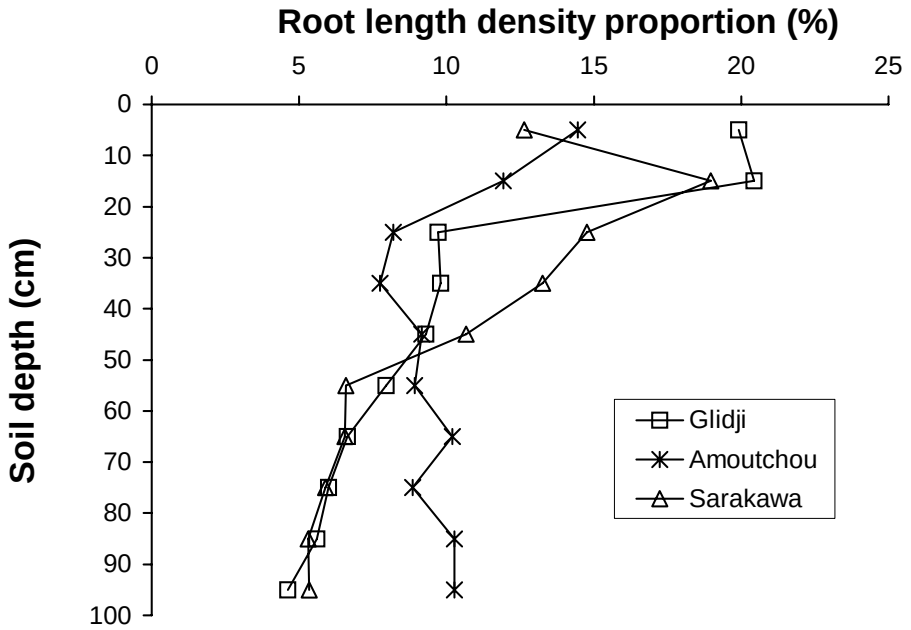


Fig. 7: Proportion of the total root length density of the top 1 m of soil in the various soil layers for the data obtained in Glidji, Amoutchou, and Sarakawa in Togo, West Africa. Root length densities were obtained after converting measured root abundances using the equations presented in Fig. 6a.

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# Economics of Heap and Pit Storage of Cattle Manure for Maize Production in Zimbabwe

[1]H.K. Murwira and [2]T.L. Kudya
[1]Tropical Soil Biology and Fertility Programme, P.O. Box MP228, Mount Pleasant, Harare, E-mail address: hmurwira@zambezi.net
[2]Department of Agricultural Economics and Extension, University of Zimbabwe, P.O. Box MP167, Mount Pleasant, Harare

**Abstract**
This study evaluates the profitability of using aerobic (heap) and anaerobic (pit) composted cattle manure for maize production. Pit storage of manure gave bigger yields of maize than heap storage in the year of application, and is much more profitable. Although the yields from heaped manure increase in the second and third years after manure application, over the three-year period pit storage is more advantageous.

**Key words:** profitability, manure storage, soil fertility, maize

## Introduction

In many areas of Zimbabwe, farmers store manure for up to three months for use on field crops especially maize and finger millet. There are several manure storage techniques used, the predominant being heaping (Nzuma, Murwira and Mpepereki, 1998). Storing in pits (anaerobic composting) is a recent innovation that some farmers have tested (Nzuma and Murwira, 2000). This study assessed the profitability of pit and heap stored manure on maize production over a three-year period.

## Materials and methods

The study was based on trials at Nhapi, Musegedi and Manyani in the Murewa Communal area from 1997/98 to 1999/2000. Manure which had been stored in pits and in heaps was applied at a rate equivalent to 100 $kgNha^{-1}$ in the first season only. No manure was applied to control plots. Ammonium nitrate fertiliser was applied at 100 $kgha^{-1}$ as top dressing yearly to all crops. Maize yield was measured over the three years. Grain price for the three seasons was obtained from the Grain Marketing Board and details of variable inputs were collected from Zimbabwe Farmers Union and the Department of Agricultural and Technical Extension Services.

Information on the labour involved in heap and pit storage was obtained from thirty households which owned cattle. This covered digging and heaping manure and transporting it to the field, the labour and cost of digging a pit, digging manure in the kraal, putting in a pit, covering it and taking manure out of a pit and carrying to the field. Gross margin analysis, Net Present Value (NPV) and Student T- distribution were used. The gross margin was the difference between gross income and total variable costs whilst NPV was calculated as the present worth of benefits less the present worth of costs (Gittinger, 1982).

The costs and benefits were discounted to reflect future values at 70%, this social discount needs to be high because the satisfaction of immediate needs is more urgent for most rural folk than the assurance of longer term benefits and also rainfall is unpredictable (Markandya and Pearce, 1991). Labour costs were deflated using annual inflation rates of respective years from 1998 to 2000 which were 37.2, 58.5 and 55.7 respectively (Reserve Bank of Zimbabwe, 2001). The corrected costs are included in the gross margin budget of these storage techniques during the year of manure application. Costs are in Z$ and a US$1 is equivalent to Z$55 as at August 2000.

## Results and discussion

Of the 30 households interviewed, two families used pits only, four families used heaps only and 24 practised both. The mean number of days and costs of manure storage techniques are in table 1. Heaping required 1.0 to 9.0 days and pitting 2.5 to 11.0 days with means of 3.89 and 4.93 respectively. However,

there was no significant difference between these means ( $\bar{x} = 1.03$, t = 1.759 and p= 0.084).

Deflated costs of storage were used in the T- test. The cost of heaping varied from $18 to $231 and pitting ranged from $15 to $658 with means $87 and $133 respectively. Again, there was no significant difference between these costs ( $\bar{x} = 46.00$ ,t = 1.628, p = 0.110).

In the year of manure application, pit stored manure had the largest gross margin ($2 184) and it was the only viable system (Table 1). Heaping (-$330) and the control (-$1363) both had negative gross margins which mean that they are unviable in this period. The adjusted yield from pit-stored manure was 5290 $kgha^{-1}$ while heaping had 2600 $kgha^{-1}$ (Figure 1).

In a laboratory analysis by Nzuma and Murwira (2000), pit stored manure had a higher N content (2.51% N) compared with 1.12% N for heaped manure at the time of manure application. This resulted in rapid nutrient release from pitted manure during the season hence higher yields. Therefore, manure quality affects profitability by dictating yield level. Heaping produces aerobically decomposed manure which has few nutrients available during the year of application. This would cause higher yield with pits in the first season.

Total costs, benefit streams and net incremental benefits are in Table 2. The profits realised from use of heaped manure increased over the three years while those from pit manure fell. Despite this, Mugwira and Mukurumbira (1986) found that with cattle manure yields are often higher with the second crop compared with the first. Total profit and yield of pit stored manure were greater than heaping because poor quality manure produced by heaping has a more pronounced residual effect than pitted manure. Costs of pit storage were higher ($9223) than for heap storage ($8809). The farmers' profits are not necessarily affected by the residual effect of cattle manure. Because of the residual effect, profits were expected to be greater for heaped manure than for pit stored but discounting of future benefits and costs offset this.

## Conclusion

Pit storage of manure is more profitable for maize than heaping in the year of application and over three-years even though yearly profits and yields decreased. Heaping had a more pronounced residual effect in the second and third seasons.


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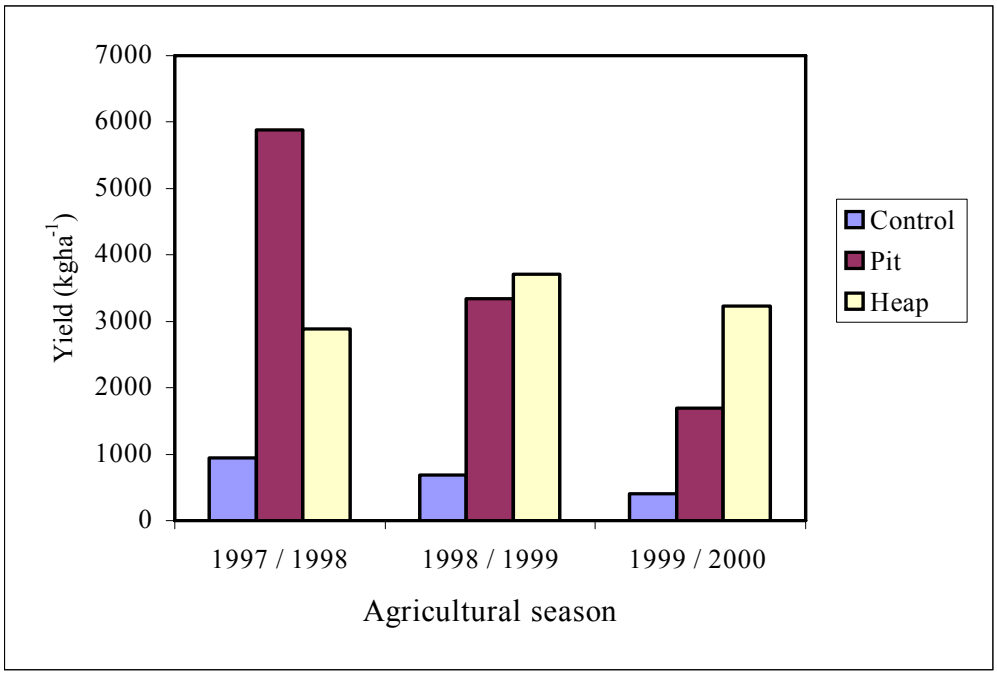


**Figure 1**: Average maize yield obtained from using heap and pit stored manure applied in the first season only

**Table 1**: Profitability of manure options during first year (1997-1998) (Z$)

| Storage System | Total Benefits | Total Costs | Gross Margin | Rate of return ($/$100 Variable Cost) |
|---|---|---|---|---|
| Pit | 6 350 | 4 164 | 2 187 | 52.5 |
| Heap | 3 121 | 3 451 | -330 | -9.57 |
| Control | 1 015 | 2 378 | -1 362 | -57.3 |

**Table 2:** Seasonal costs, benefits and profits during three seasons

| Season | Cost of pitting (Z$) | Benefits of pitting (Z$) | Net incremental benefit (pit) (Z$) | Cost of heaping (Z$) | Benefits of heaping (Z$) | Net incremental benefit - heap (Z$) |
|---|---|---|---|---|---|---|
| 1997-1998 | 4 166 | 6 350 | 2 185 | 3 451 | 3 121 | -330 |
| 1998-1999 | 2 936 | 4244 | 1 308 | 3 038 | 4 714 | 1 676 |
| 1999-2000 | 2 134 | 2 210 | 76 | 2 319 | 4 225 | 1 906 |

*Draft Paper*

**Pathways Towards Integration of Legumes into the Farming Systems of East African Highlands.**

Tilahun Amede
TSBF-CIAT, AHI, Ethiopia

**Abstract**
Food legumes remained to be important components of various farming systems of Eastern Africa, while the attempt to integrate fodder legumes and legume cover crops (LCCs) since 1930s became unsuccessful. Farmers remained reluctant to integrate fodder legumes and LCCs, despite recognising their benefits as soil fertility restorers and high value feeds, mainly due to community/farmer specific socio-economic factors. Farmers' participatory research was conducted in Ethiopian Highlands to understand the processes of integration of legumes of different use into mixed subsistent farming systems. Areka had an altitude of 1990 masl, and rainfall amount of 1300mm, which is characterised by poor access to resources, intensive cropping, land shortage and soil degradation. Firstly participatory evaluation was conducted on the agronomic performance and adaptability of eight legumes during the main and small growing seasons of 2000 and 2001. The treatments were Vetch, Stylosanthus, Crotalaria, Mucuna, Canavalia, Tephrosia, Field pea and Common bean. Following the agronomic evaluation, the perception of farmers to legumes of different use, the socio-economic factors dictating choices and adoption, and potential niches for legume integration into the cropping systems were considered. Dry matter production among legumes was significant regardless of the length of growing period. For short term fallows, 3 months or less, Crotalaria gave significantly higher biomass yield (4.2 t ha $^{-1}$) followed by Vetch and Mucuna (2 t ha$^{-1}$), while for medium-term fallow, 6 months, Tephrosia was best performing species (13.5 t ha$^{-1}$) followed by Crotalaria (8.5 t ha$^{-1}$). The selection criterion of farmers was far beyond biomass production. Farmers identified firm root system, early soil cover, biomass yield, decomposition rate, soil moisture conservation, drought resistance and feed value as important criteria. There was significant difference in soil moisture conservation among LCCs, and decreased in order of Mucuna (22.8%), Vetch (20.8 %), Stylosanthus (20.2 %), bare soil (17.1 %), Crotalaria (14 %), Canavalia (14 %) and Tephrosia (11.9 %), respectively. The overall sum of farmers' criteria showed that Mucuna followed by Crotalaria could be the most fitting species, but farmers finally decided for Vetch, the low yielder, due to its fast growth and high feed value because of their priority to livestock feed than soil fertility. The final decision of farmers for integrating a non-food legume into their temporal & spatial niches of the system depended on land productivity, farm size, land ownership, access to market and need for livestock feed. The potential adopters of LCCs and forage legumes were less than 7%, while 91% of the farmers integrated the new cultivars of the food legumes. After characterising the farming systems of other benchmark sites, those indicators were used for development of decision guides to be used for integration of legumes into multiple cropping systems of East African Highlands.

## 1. Introduction

Food legumes remained to be important components of various farming systems of Eastern Africa as they are the sole protein sources for animals and humans. Besides restoring soil fertility, legumes are grown in rotation with cereals mainly because they accompany the stable cereals in the local dishes. On the other hand, the attempt to integrate fodder legumes and legume cover crops (LCCs) since 1930s became unsuccessful. Farmers remained reluctant to integrate fodder legumes and LCCs, despite recognising their benefits as soil fertility restorers and high value feeds, mainly due to community/farmer specific socio-economic factors. However, as farmers export both grain and stover from the field, the amount of legume residue left to the soil is too small to have a profound effect on restoration of soil fertility.

Degradation of arable lands became the major constraint of production the Ethiopian Highlands, due mainly to nutrient loss resulting from soil erosion, lack of soil fertility restoring resources, and

unbalanced nutrient mining (Amede et al., 2001). However, most farmers in the region have very low financial resources to combat nutrient depletion, and hence research should be directed to seek affordable and least risky, but profitable amendments necessary to keep nutrient balance neutral (Versteeg et al., 1998). In 1999 and 2000, researchers of the African Highlands Initiative (AHI) conducted farmers participatory research on maize varieties on a degraded arable land in Southern Ethiopia, Areka, by applying inorganic fertilisers. Although the soil is an Eutric Nitisol deficit in nitrogen phosphorus (Waigel, 1986), high level application of inorganic N and P did not improve maize yield. Lack of response to inorganic fertilisers because of low soil organic matter content was also reported elsewhere (Swift and Woomer, 1993). Organic inputs could increase the total amount of nutrients added, and also influence availability of nutrients (Palm et al., 1997). However, more than 50% of the organic resource available in the region is maize stalk, of which 80% is used as a fuel wood (Amede et al., 2001). The strong competition for crop residues between livestock feed, soil fertility and fuel wood in the area limits the use of organic ferilizers unless a suitable strategy that builds the organic resource capital is designed. Fallowing for restoration of soil fertility is no more practised in the region due to extreme land shortage.

One strategy could be systematic integration of legume cover crops into the farming system. Organic inputs from legumes could increase crop yield through improved nutrient supply/availability and/or improved soil-water holding capacity. Moreover, legumes offer other benefits such as providing cover to reduce soil erosion, maintenance & improvement of soil physical properties, increasing soil organic matter, cation exchange capacity, microbial activity and reduction of soil temperature (Tarwali et al., 1987; Abayomi et al., 2001) and weed suppression (Versteeg et al., 1998). There are several studies in Africa that showed positive effects of Legume Cover Crops (LCCs) on subsequent crops (Abayomi et al., 2001; Fishler & Wortmann, 1999; Gachene et al., 1999; Wortmann et al., 1994). Studies in Uganda with Crotalaria (Wortmann, et al., 1994; Fishler and Wortmann, 1999), and in Benin with Mucuna (Versteeg et al., 1998) showed that maize grown following LCCs produced significantly higher yield than those without green manure. The positive effect was due to high N& P benefits and nutrient pumping ability of legumes from deeper horizons. However, the success rate in achieving effective adoption of LCCs and forage legumes in Sub-saharan Africa has been low (Thomas and Sumberg, 1995) since farmers prefer food legumes over forage or/legume cover crops in that the opportunity cost is so high to allocate part of the resources of food legumes to LCC. Therefore, there is a need to develop an effective guideline that targets different legume types in different niches of different agro-ecologies and socio-economic strata.

The objective of this paper was, therefore a) to analyse the distribution of legumes in the perennial- based (Enset-based) systems, b) test the performance of legumes under short term and medium term periods, c) identify the potential causes of non-adoption of LCC, and d) develop preliminary decision guides that could be used to integrate LCC in small scale farms with various socio-economic settings.

## 2. Materials and Methods

### *2.1. Location, Climate and Soil*

The research was conducted at the Gununo site (Areka), Southern Ethiopian Highlands. It is situated on 37$^{o}$ 39' E and 6$^{o}$ 51' N, at an altitude range between 1880 and 1960 m.a.s.l The topography of the area is characterised by undulating slopes divided by v-shaped valleys of seasonal and intermittent streams, surrounded by steep slopes.

The mean annual rainfall and temperature is about 1350 mm and 19.5 $^{o}$C, respectively, with relatively low variability, in terms of amount of precepitation, over the years. The rainfall is unimodal with extended growing periods from March to the end of October, with short dry spell in June. The highest rainfall is experienced during the months of July and August and caused soil loss of 27 to 48 t ha$^{-1}$ ( SCRP, 1996). The dominant soils in the study area are Eutric Nitisols, very deep (>130 m), acidic in nature. These soils originated from kaolinitic minerals which are inherently low in nitrogen and phosphorus (Waigel, 1986). Soil fertility gradient decreases from homestead to the outfield due to management effects.

*2.2. Participatory evaluation of LCCs*

The research site has relatively very high human population density with an average land holding of 0.5 ha household$^{-1.}$ Using LCCs for soil fertility purposes is not a common practise in the area. LCCs were introduced into the system in 2000 following a farmers field school (FFS) approach so as to allow farmers to learn and appreciate various legumes uncommon to the area. The farmers research group (FRG) was mainly composed of mainly men, despite the repeated temptation of researchers to include women. The legumes were planted in two planting dates. The on-farm experiments, used simultaneously for FFS and also for evaluation of biomass productivity and after effect of legumes on the following maize crop, were planted on April 25, 2000 and July 1, 2000 and harvested on October 6, 2000 and January 6, 2001, respectively, using recommended seed rates. The interest of the farmers was to evaluate the effect of planting dates and length of fallow period on biomass productivity of respected species, and to identify the best fitting legumes for a short-term fallow (three months) or medium term (six months) fallow. Long-term fallow became impractical due to land scarcity. Thirty interested farmers, who were organised under one farmers research group (FRG), have studied six different species namely, Stylosanthus (*Stylosanthus guianensis*), Crotalaria (*Crotalaria ochroleuca*), Mucuna (*Mucuna pruriens*), Tephrosia (*Tephrosia vogelii*), Vetch (*Vicia dasycarpa*) and Canavalia (*Canavalia ensiformis*). All LCC were exotic species to the system except Stylosanthus. We also included two food legumes, namely common bean (*Phaseolus vulgaris*) and Pea (*Pisum sativum*), in the study that were existing in the farming system. The FRG studied and monitored growth and biomass productivity in short and long seasons of 2000. The researchers were involved mainly in facilitation of continual visits and stimulation of discussions among farmers. Farmers and researchers were recording their own data independently. After intensive discussion, the FRG identified six major criteria to propose one or the other legume to be integrated into the system. Since farmers considered soil water conservation as one important criterion for selecting LCCs, soil water content was determined under the canopy of each species at top 25-cm depth gravimetrically. Sampling was done in relatively dry weeks of November 2000, five months after planting. We considered four samples per plot, weighed immediately after sampling, oven dried the samples with 120 $^{o}$C for a week before taking dry weight. Legume ground cover was determined using the beaded string method, knotted at 10-cm interval and laid across the diagonals of each plot, 12 weeks after planting. A supplemantary replicated on-farm experiment (a plot size of 12 m$^2$, three replications) was conductedto evaluate biomass production of LCCs under partially controlled replicated experiment to verify earlier obtained results. It was also meant to identify the most promising species for short term fallow, as farmers were reluctant to allocate land for LCCs beyond three months. The species were planted on October 12, 2001 and harvested on January 10, 2002. The legumes received phosphorus at a rate of 30 kg/ha $P_2O_5$ at planting. After four months of vegetative growth, the green biomass of the legumes was weighed and incorporated directly to the soil. Maize (var A511) was planted about one month after incorporation on all plots. Three additional nitrogen treatments were included namely, 0 N, 30 N and 60 N per hectare to draw a nitrogen equivalent curve**.**

In August 2002, after farmers monitored the introduced legumes, 26 farmers from four villages selected species of their choice LCC and tested them in their farms together with a food legume, Pea. During the growing seasons of 2000 and 2001, we monitored which farmer selected what, how did they manage the LCCs in comparison to the food legume and for what purpose the legumes were used. Biomass production of the various legumes under farmers' management was also recorded. Besides structured questionnaire and formal survey (Pretty et al., 1995), an informal repeated on-field discussion using transect walks were used to identify the socio-economic factors that dictated farmers to choose one or the other option and to prioritise the most important criteria of decision making using pair wise analysis matrix. More over, farmers invited non-participating neighbouring farmers for discussion; hence the decision made is expected to represent the community.

The tested species were those most favoured by farmers for further integration namely Crotalaria (*Crotalaria ochroleuca*), Mucuna (*Mucuna pruriens*), Tephrosia (*Tephrosia vogelii*), Vetch (*Vicia dasycarpa*) and Canavalia (*Canavalia ensiformis*) replicated three times arranged in a randomised block design. The plot size was 12 m2, with one-meter gangway between treatments. The field was weed free

through out the season by hand weeding. In all cases, phosphorus was applied at a rate of 13-Kg ha-1 to facilitate growth and productivity. Data on biomass production of the species was analysed by ANOVA using statistical packages (Jandel Scientific, 1998).

Using the qualitative and quantitative data obtained from the site, and by considering the hierarchy of indicators identified by farmers, we developed draft decision guides on the integration of legumes into the farming systems of the Ethiopian Highlands.

## 3. Results and Discussion

### *3.1. Land use and Soil fertility management*

The major land use systems in the community include homestead farms, which are characterised by soils with high organic matter content due to continuos application of organic residue. These soils are dark brown to black in colour mainly due to high organic matter content. This part of the farm was used to grow the most important crops such as enset (*Enset ventricosum*), coffee, vegetables, planting materials for sweet potato and raise tree seedlings are grown. In the system only about 3% of the homestead are occupied by legumes intercropped under the enset/ coffee plants (data not presented). Farmers are not applying inorganic fertiliser in this part of the farm. The homestead field is followed by the main field, which is characterised by red soils. Red soils are considered by the farmers as less fertile due to limited application of organic inputs, hence require application of inorganic fertiliser to get a reasonable amount of yield. In this part of the farm, farmers grow maize in association with taro, beans and sweet potato. This is also where legumes are growing most. The outfield is the most depleted and commonly allocated for growing maize or potato using inorganic fertlizers. This plot does not receive any organic manure, legumes are rarely planted and the crop residue is even exported for different purposes. Farmers do not practice intercropping in this part of the land. Although legumes are major components of the system, the primary objective of the farmers is production of food grains as sources of protein followed by feed production as a secondary product, but not soil fertility. That is also partly the reason why the amount of land allocated for legumes decreases with distance from the homestead (decreasing soil fertility).

### *3.2. Participatory Evaluation of Legume Cover Crops and their after effects*

The rainfall distribution was favorable and there was no extended dry spell within the growing season of 2000 and 2001. For the medium-term fallow, Tephrosia produced the highest dry matter biomass yield, 13.5 t $ha^{-1}$ followed by Crotalaria, 9 t $ha^{-1}$. In the three months growing period, the herbaceous legumes varied in biomass productivity significantly. Crotalaria and vetch were fast growing and also early maturing than the others. On the other hand, tephrosia was growing relatively slow at the initial stage of growth, which is reflected in the biomass accumulation. Accordingly, the biomass yield of crotalaria was significantly higher than the other legumes, while the biomass of tephrosia was much lower than all the others (Fig.1). A similar experimental result was also obtained in the previous seasons on onfarm trials. Most of the biomass accumulation in Tephrosia was observed four months after planting. For the short-term fallow, Crotalaria was the best performing species followed by Mucuna and Vetch. On individual farmer's field, Crotalaria was the best performing species regardless of soil fertility. Similar results were reported from Uganda (Wortmann et al., 1994). On the other hand, vetch and mucuna were performing best in fertile corners of the farms. This did not agree with the findings of Versteeg et al., (1998), which indicated that mucuna performed better than other green manures (including crotalaria) to recover completely degraded soils. When those species were planted in the driest part of the season, crotalaria and mucuna performed best and produced up to 2.9 t $ha^{-1}$ dry matter with in three months of time (data not presented). Besides dry matter yield, we measured soil water content under the canopies of LCCs. The data showed that, the highest soil water content was obtained from mucuna and stylosanthus, which could be due to the self-mulching (Table 2). The ground cover (%) was the highest for Mucuna (100 %), and the lowest for vetch (60%). A similar result was obtained for mucuna in western Nigeria (Abayomi et al., 2001). Higher soil water content under mucuna &, stylosanthus implies that these species could improve soil water availability through reduction of evaporative loss if grown in combination with food crops.

The result showed that maize grown after legumes produced significantly higher grain yield than the check (maize grown with out nitrogen fertiliser) and gave a maize yield at least equivalent to 30 kg of N/ha regardless of the legume species (Fig 1). The yield obtained from the plots of vetch, canavalia and mucuna was almost similar, while the yield obtained from crotalaria and tephrosia plots was significantly lower than that of the other species. Although the biomass of crotalaria incorporated to the soil was much higher than the others, the effect was not evident on maize yield. This could be explained by the fact that crotalaria had very high lignin content than the others at the time of harvesting and incorporation, which possibly affected the processes of decomposition and nutrient release.

By considering the type of produce the farmers grow in the neighbouring field of equal size, which was sweet potato, and calcultating the costs and benefits of the LCCs and neighboring field, we found out that the opportunity cost of growing LCCs was much higher than anticipated. The maize yield gain obtained after growing LCCs in a short season should be more than two folds for the farmer to consider growing LCCs as potentially profitable interventions.

Fig. 1. Biomass production of various legume cover crops grown in Nitisols for three or six months of growing period under highland conditions (n=3).

Farmers evaluated the performance of LCCs in the fields individually or in groups through repeated visits. The selection criteria of farmers were beyond biomass production (Table 1). After intensive discussion among them selves, the FRG agreed on seven types of biophysical criteria to be considered for selection of LCCs (Table 1). However, the criteria of choice had different weights for farmers of different socio-economic category. None of the farmers mentioned labour demand as an important criterion. They considered firm root system (based on the strength of the plant during uprooting), rate of decomposition (the strength of the stalk and or the leaf to be broken), moisture conservation (moistness of the soil under the canopy of each species), drought resistance (wilting or non-wilting trends of the leaf during warm days), feed value (livestock preference), biomass production (the combination of early aggressive growth and dry matter production) and early soil cover. For resource poor farmers (who commonly did not own animal or own few) food legumes were the best choices. For farmers who own sloppy lands with erosion problems mucuna and canavalia were considered to be the best: Mucuna for its mulching behaviour and canavalia for its firm root system that reduced the risk of rill erosion. Farmers with exhausted land selected crotalaria, as all the other legumes were not growing well in the degraded corners of their farms. On the other hand, farmers with livestock selected legumes with feed value and fast growth (Vetch and Stylosanths). In general, Vetch was the most favoured legume despite low dry matter production, as it produced a considerable amount of dry matter within a short period of time to be used for livestock feed. It was also easy to incorporate into the soil and found it to be easily decomposable. The over all sum of farmers' ranking, however, showed that mucuna followed by crotalaria are the best candidates for the current farming system of Areka. Since Mucuna is aggressive in competition when grown in combination with other crops (Versteeg et al., 1998) it could be used to increase soil fertility in well established Enset/Coffee fields, while Crotalaria and Canavaia could be used to ameliorate exhausted outfields. Canavalia is found to be best fitting as an intercrop under maize as it has deep root system and did not hang on the stocks of the companion crop (personal observation). The herbaceous LCCs are reported to be of high quality organic resources (Gachene, et al., 1999) to be used as organic fertilisers directly to improve the grain yield of subsequent crops (Caamal-Meldonado et al., 2001; Abayomi et al., 2001).

**Table 1. Farmers' criteria of selection of legume cover crops. According to farmers' ranking 6 was the highest and 1 the lowest (n=25).**

| Species | Firm roots | Early soil cover | Bio-mass | Rate of decom-postion | Moisture conser-vation | Drought resist-ance | Feed value | Sum Total |
|---|---|---|---|---|---|---|---|---|
| Crotalaria | 2 | 6 | 6 | 6 | 2 | 2 | 2 | 26 |
| Vetch | 1 | 5 | 5 | 4 | 1 | 1 | 6 | 23 |
| Mucuna | 6 | 4 | 3 | 3 | 6 | 6 | 4 | 32 |
| Canavalia | 5 | 3 | 4 | 1 | 4 | 5 | 2 | 24 |
| Tephrosia | 3 | 2 | 2 | 2 | 5 | 3 | 2 | 19 |
| Stylosanthus | 4 | 1 | 1 | 5 | 3 | 4 | 5 | 23 |

*3.3. Farmers' Management of LCCs*

After thorough monitoring about the productivity and growth behavior of LCCs in the experimental plots, 26 farmers have tested various LCCs in their own farm. They tried mainly Canavalia, Crotalaria, Mucuna, Stylosanthus and Vetch. We documented that farmers selected the most degraded corners of the farm for growing LCCs and the fertile corners of their land for growing Pea (Table 2). About 50% of the trial farmers allocated depleted lands (degraded and abandoned) for the LCC. Further discussion with farmers revealed that they took this type of decision partly due to fear of risk, and partly not to occupy land that could be used for growing food crops.

**Table 2. Spatial niches identified by farmers for growing Legume Cover Crops or Food legumes (Pea) in the growing seasons of 2000. Data shows number of involved farmers (%) grew legumes at different spatial niches (n=26).**

| Crop type | Sole in fertile soil | Sole in degraded soil | Relay under Maize | Steepy land | Border strips | abandoned land |
|---|---|---|---|---|---|---|
| Legume Cover Crops | 0 | 28.6 | 7.1 | 14.3 | 21.43 | 21.42 |
| Pea | 64.29 | 0 | 35.7 | 0 | 0 | 0 |

From the total respondents, 86.6% of the farmers knew about the role of green manures as soil fertility restorers (Fig. 2). However only 63% of them tested LCCs and of those who tested the green manures only 21 % responded LCCs were effective in improving the fertility status of the soil. About 79% believed that LCCs may not feet into their system mainly because they did not emerge well, or showed poor performance under depleted soils or are competing with food legumes for resources (labour, water and land) (Fig. 2). This was manifested by the fact that almost all of the farmers planted LCCs on the degraded corners of their farm (Table 2), which in turn caused low biomass production and generally poor performance of LCCs (data not presented).

Fig 2. Schemes used for identification of factors of adoption or non-adoption of legume cover crops in multiple cropping systems of Areka.

### 3.3. Socio-economic Factors Dictating Integration of Legumes

Results from informal interviews followed by structured questioner showed that there are 21 different factors that affect the integration of legumes of different purposes. When farmers were asked to prioritise the most important factors that affect adoption and integration of legumes, farmers mentioned a) farm size b) suitability of the species for intecropping with food legumes c) productivity of their land d) suitability for livestock feed e) marketability of the product f) toxicity of the pod to children and animals g) who manages the farm (self or share cropping) h) length of time needed to grow the species and I) risk associated with growing LCCs in terms of introduction of pests and diseases.

Earlier works suggested that farm size and land ownership effect integration of LCCs into small holder farms (Wortmann & Kirungu, 1999). After comparing those factors in a pair wise analysis, four major indicators of different hierarchy were identified (data not presented).

**1)** Degree of land productivity: Farmers in Gununo associated land productivity mainly with the fertility status of the soil and distance of the plot from the homestead. The homestead field is commonly fertile due to continual supply of organic resources. Farmers did not apply inorganic fertiliser in this part of the farm. They remained reluctant to allocate a portion of this land to grow LCCs for biomass transfer or otherwise, but they grow food legumes, mainly beans, as intercrops in the coffee and enset fields. The potential niche that farmers were willing to allocate for LCCs is the most out field.

**2)** Farm size: Despite very high interest of farmers to get alternative sources to inorganic fertilisers the probability that farmers may allocate land for growing LCCs depended on the size of their land holdings. For Areka conditions, a farm size of 0.75 ha is considered as large. Farmers with very small land holdings did not grow legumes as sole crops, but integrate as intercrops or relay crops. Therefore, the potential niches for LCCs are partly occupied unless their farm is highly depleted.

**3)** Ownership of the farm: Whether a legume (mainly LCCs) could be grown by farmers or not depended on the authority of the person to decide on the existing land resources, which is linked to land ownership. Those farmers who did not have enough farm inputs (seed, fertilizer, labour and/or oxen) are obliged to give their land for share cropping. In this type of arrangement, the probability of growing LCCs on that farm is minimal. Instead, farmers who contracted the land preferred to grow high yielding cereals (maize & wheat) or root crops (sweet potato). As share cropping is an exhaustive profit-making arrangement, the chance of growing LCCs in such type of contracts was almost nil. Without ownership or security of tenure, farmers are unlikely to invest in new soil fertility amendment technology (Thomas and Sumberg, 1995)

**4)** Livestock feed: In mixed farming systems of Ethiopia livestock is a very important enterprise. Farmers select crop species/ varieties not only based on grain yield but also straw yield. Similarly legumes with multiple use were more favoured by the community than those legumes that were appropriate solely for green manure purposes.

Above mentioned socio-economic criteria of farmers together with the productivity data from the field were used to develop decision guides to help farmers in selecting legumes to be incorporated into their land use systems as presented in Fig. 3. As mentioned above, farmers considered the degree of land productivity as the most important factor (placed at the highest hierarchy) for possible integration of legumes. Farmers who own degraded arable lands were willing to integrate more LCCs while those who own productive lands of large size wanted to grow food legumes with additional feed values. However, all farmers decided to have food legumes in their system regardless of farm size or land productivity. Beans and Pea are already in the system and farmers already found niches to grow them as they are also parts of the local dish. From the LCCs, farmers favoured vetch as mentioned above. Those farmers who wanted soil improving LCCs selected croletaria, as they found it better performing even under extremely degraded farms. However, about 45% the farmers with degraded arable lands are not willing to integrate LCCs, either because they did not manage their own farm, and practice share cropping /contract or have limited options of household income.

In general, given very high population pressure and associated severe land shortage, farmers in Areka may not allocate full season for LCC, but preferred fast growing LCCs for short term fallow. The probability of integrating LCCs into the system became even less when the land is relatively fertile. As the homestead fields are relatively fertile and used for intercropping/relay cropping purposes, growing LCC on that part of the land may not be the choice of farmers. On the other hand, farmers with large farm size and high degree of land degradation may go for selected LCCs. The potential niche available in the system would be the least fertile most-out field where intercropping is not practised. The most out field is commonly occupied by potato in rotation with maize with relatively less vegetative cover over the years .

The length of the growing period together with the amount and distribution of the rainfall dictates whether the system may allow growing legumes intercroped with maize, intercroped with perennials, or relay cropped with maize or sweet potato. In regions, where the growing season is extended up to eight months, and where the outfield became depleted to sustain crop production, LCCs that could grow under poor soil fertility conditions in drought-prone months would be appreciated. Indeed, crotalaria performed very well under such conditions.

### 3.4. The Decision Guides

We are presenting three guidelines for integration of legumes into the farming systems of multiple cropping, perennial-based systems.
The decision trees were developed based on the following back ground information from the site.

1) Farmers preferred food legumes over non-food legumes regardless of soil fertility status of their farm
2) The above ground biomass of grain legumes (grain & stover) is exported to the homestead for feed and food while the below ground biomass of grain legumes is small to effect soil fertility. The probability of the manure to be returned to the same plot is less as farmers prefer to apply manure to the perennial crops (Enset & Coffee) growing in the home stead.
3) The tested legumes may fix nitrogen to fulfil their partial demand (we have observed nodules in all although we did not quantify N-fixation), but in conditions where the biomass is exported, like vetch for feed, most of the nutrient stock would be exported. Therefore, we did not expect significant effect on soil fertility.
4) LCCs produced much higher biomass when planted as relay crops in the middle of the growing season than when planted at the end of the growing season as short-term fallows due to possible effects of end-of season drought.
5) The homestead field is much more fertile than the outfield; hence those legumes sensitive to water and nutrients will do better in the homestead than in the outfield.

Fig. 3 Guideline for integration food, feed legumes and legume cover crops in small-scale farms.

The first guide (Fig 2) is intended to assist researchers to get feed back information about technologies that were accepted or rejected by the farmers or farmer research groups. This guide will assist researchers not only to identify the major reasons for the technology to be accepted or rejected, but also to prioritise the reasons of resistance by farmers not to adopt the technology. This type of feed back will help to modify/improve the technology through consultative research to make technologies compatible to the socio-economic conditions of the community.

The second guide (Fig 3) integrated both biophysical and socioeconomic indicators. The most important criteria at the lowest level is the presence or absence of livestock in the household followed by who manages the farm, market access, the size of the land holding and the land quality. The factor that dictates the decision at the highest level was land productivity, which was governed mainly by soil fertility status. Growing food legumes was the priority of every farmer regardless of wealth (land size,

land quality & number of livestock). Farmers with livestock integrated feed crops regardless of land size, land productivity and market access to products. However, the size and quality of land allocated for growing feed legumes depended on market access to livestock products (milk, butter and meat). Those farmers with good market access are expected to invest part of their income on external inputs, i.e. inorganic fertilisers. Hence farmers of this category did not allocate much land for growing LCCs, but applied inorganic fertilisers. In the homestead field, there was no land allocated for LCCs in the system, not only because farmers gave priority to food legumes, but it also became very expensive for farmers to allocate the fertile plot of the farm for growing LCCs. The most clear spatial niche for growing LCCs is the most out field, especially in poor farmers' field with exhausted land and limited market-driven farm products. Because the land of most poor house holds was on the verge of being out of production due to the iniquitous nature of land management practices through years long share cropping arrangements.

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*Draft Paper*

**Towards Addressing Land Degradation in Ethiopian Highlands: Opportunities and Challenges**

Tilahun Amede
TSBF-CIAT, AHI, Ethiopia

## Introduction

Land resource degradation is one of the major threats to food security and natural resource base in Ethiopia. Hundreds of years of exploitve traditional land use, aggravated by high human and livestock population density have led to the extraction of the natural capital, which caused the farming of uncultivable sloppy lands and overexploitation of slowly renewable resources. The outcome is that half of the highlands are eroded, of which 15% are so seriously degraded that it will be difficult to reverse them to be agriculturally productive in the near future. In the mountainous highlands, there is a direct link between land-based resources and rural livelihoods. Decline in soil fertility as a result of land degradation decreases crop/livestock productivity and hence household income. Depleted soils commonly reduce payoffs to agricultural investments, as they rarely respond to external inputs, such as mineral fertilizers, and hence reduce the efficiency and return of fertilizer use. Degraded soils have also very poor water holding capacity partly because of low soil organic matter content that in turn reduce the fertilizer use efficiency. There have been various attempts to reduce land degradation in Ethiopia since the 1970s, through national campaigns on construction of terraces, project afforstation programmes and policy interventions. The objective of this paper is to review the various research/development experiences on integrated soil fertility management and synthesize the positive experiences augumented by the experiences of the African highlands initiative on integrated land management in Ethiopian Highlands. The paper will also suggest an outline that could be used by farmers, researchers and policy makers to reverse the alarming trend of land degradation in the mountainous highlands.

This work has consulted the available literature on land degradation and soil fertility management in Ethiopian highlands. While TSBF-CIAT/AHI has been working closely with the Ethiopian Agricultural Research Organisation (EARO) and the Buro of Agriculture, and conducting participatory research in two benchmark sites of the Ethiopian highlands on INRM issues, it became apparent that land degradation is the most fundamental threat for the Ethiopian Agriculture. Based on the systems intensification work that we have been conducting in the two benchmark sites of African highlands initiative, Areka and Ginchi, augmented by secondary data on relevant themes, the following approach was suggested to address land degradation in the country.

## Root Causes of Land Degradation in the mountainous highlands

There are multiple factors that cause land degradation at short and long terms in the region. In Sub Saharan Africa, the major bio-physical agents of land degradation are water erosion, wind erosion and chemical degradation that affected soil loss by 47, 36 and 12%, respectively. Given the mountainous and sloppy landscapes, the major environmental factor that causes considerable soil and nutrient loss within a short period of time is water erosion followed by wind erosion. Most of the Wollo and Shewa highlands became erosion-prone due to high rainfall intensity accompanied by very steeply farmlands. Recent surveys showed that erosion effect is severe in high rainfall areas predominantly covered by nitisols and vertisols. In about 40% of the highlands, the erosion effect was so severe that active erosion was transformed to passive erosion, and hence there are rarely visible signs of sheet or rill erosion, but gullies and land slides. The hazards of erosion in the region was accelerated by socio-economic factors, namely absence of land ownership rights that discourage long term investments, population pressure, lack of alternative income generating options, and weak social capital that failed to protect communal grazing lands, up-slope forest covers and water resources.

Although the degree of soil erosion is highly related to the interaction of Wischmeier factors, the type of land use and management may have played an important role in the Ethiopian highlands. The contribution of different management factors towards land degradation in Africa is estimated to be 49%, 24%, 14%, 13% and 2% for overgrazing, agricultural activities, deforestation, overexploitation and industrial activities (Vanlauwe et al, 2002). The livestock sector is a very important component of the system both as an economic buffer in times of crop failure and economic crisis and as a supportive enterprise for crop production. There is a considerable concern, however, that the number of animals per household in Ethiopian highlands is much higher than the carrying capacity of land resources. Overgrazing due to very high livestock population density in the Amhara region is expected to contribute most to land degradation. For instance, the total annual feed available in the highlands is estimated to be about 9.1 million tones of biomass while the demand is about 21 million tones, double that of the carrying capacity of the land (Betru, 2002). Another very important factor that aggravated land degradation in the Ethiopian highlands is deforestation. The forest cover went down from 40% at the beginning of this century to less than 3% at present, due to ever-growing demand for wood products and very low commitment in planting trees mainly because of the prevailing nationalization of private woodlots in the 1970s and 1980s. Besides, a very high consumption of wood for fuel and housing, wood products, mainly charcoal, became a major cash generating activities in the country in recent years. Deforestation and overgrazing accelerated land degradation in many ways. Firstly a land without vegetative cover is easily susceptible to erosion, both wind and water, and hence causes a considerable nutrient movement. Secondly, a large amount of litter that could have contributed for maintaining soil organic matter and nutrient status is considerably reduced. Thirdly deforestation in the highlands caused lack of fuel wood, and hence farmers use manure and crop residue as cooking fuel, which otherwise could have been used for soil fertility replenishment.

Over-mining of land resources with out returning the basic nutrients to the soil is also an important factor that contributed most for soil fertility decline in the region. For instance, barley is the single dominant crop in the upper highlands of Wollo. The system has very low crop diversity with legume component of less than 3%. The system receives external inputs very rarely with a fertilizer rate of less than 5 kg/ha (Quinones et al., 1997), and the practice of applying this limited amount of mineral fertilizer is a recent practice. Data from the region on the amount of nutrients returned to the soil in comparison to the nutrients lost through removal of crop harvest showed that only 18, 60 and 7 % of nitrogen, phosphorus and potassium is returned to the soil, respectively (Sanchez et al., 1997). Hence there is an over mining of nutrients from the same rhizosphere for years and years.

Another cause of land degradation is lack of early awareness about land degradation by farmers, which is partly associated with the rural poverty. McDonagh, et al., (2001) reported that when farmers were asked to describe their indicators of soil erosion they stated gully/rill formation, exposed underground rocks, land slides, wash away of crops, shallowing of soils and siltation of the soil. Similarly farmers indicators of soil fertility decline include stunted crops, yellowing of crops, weed infestation, and change of soil color to red or grey. These are soil traits that appear in a much later stage of soil degradation, after the soil organic matter and nutrients of the soil are removed. If farmers respond to soil erosion at this stage, the probability of reversing the fertility status to its earlier value would be difficult.

**Towards Integrated Soil Fertility Management**

Application of small amounts of mineral fertilizer alone, as it has been practiced on the 0.5 ha demonstration plots by FAO and the ministry of Agriculture for years, did not improve crop productivity much. The failure of this mono-technology approach calls for an integrated nutrient management that suits local biophysical, social and economic realities. Integrated nutrient management technologies can be nutrient saving, such as in controlling erosion and recycling of crop residues, manure and other biomass, or nutrient adding, such as in applying mineral fertilizers and importing feed stuffs for livestock (Smaling and Braun, 1996).

The traditional field operation in the Ethiopian highlands, which could be characterized by multiple tillage, cereal-dominated cropping and very few perennial components in the system, is very erosive for soils and nutrients. Continual farming in the high lands with out considering conservation measures caused severe land degradation. FAO study in Zimbabwe showed that each hectare of well-managed maize growing land lost 10 tones of soil. Depleted soils commonly reduce payoffs to agricultural investments for various reasons. Degraded soils rarely respond to external inputs, such as mineral fertilizers, and hence reduce the efficiency and return of fertilizer use. Degraded soils have also very poor water holding capacity partly because of low soil organic matter content that in turn reduce the fertilizer use efficiency. Results from the dry regions of Niger, Sadore, showed that application of fertilizer increased the millet yield by 71% and also improved the water use efficiency by 70% (Bationo et al., 1993). Hence improved soil fertility enhances the water use efficiency of crops in drought prone areas. Low soil organic matter accompanied by low soil water content may also reduce the bio-chemical activity of the soil that may affect the above and below ground biodiversity of the system. Degraded soils have also low vegetative cover that may accelerate further soil loss and runoff.

The effect of soil fertility decline goes beyond nutrient and water losses. There are conviencing results showing that the incidence of some pests and disease is strongly associated with decline in soil fertility. Results from the Amhara and Tigrai region showed that the effect of the notorious parasitic weed, striga, on maize and sorghum was severe in nutrient depleted soil (Esilaba, et al, 2001). It was possible to decrease the population & the incidence of striga significantly by improving the fertility status of the soil through application of organic fertilizers. Similarly the incidence of root rots in beans, stem maggots in beans, take all in barely and wheat is associated with decline in soil fertility (Marschner, 1995). The positive effect of application of organic and inorganic fertilizer on the resistance of the host crop is mainly through improving the vigorosity of the plant at the early phonological stages.

Amede et al., (2001) outlined the need for a combination of measures to reverse the trend of soil fertility decline in the African highlands as presented in the following section.

*1. Community-based soil and water conservation measures*

There are about 40 different types of indigenous soil and water conservation practices in different parts of the Ethiopian highlands, ranging from narrow ditches on slopping fields in Wollo highlands to the most advanced & integrated conservation measures in Konso, Southern Ethiopia. However, those indigenous practices are location specific and variable in their effectiveness, and call for closer understanding before any attempt is done for scaling-up. However, there is a consensus among actors that any attempt to protect land resources and improve productivity in the sloppy highlands should integrate system-compatible soil conservation measures. Research conducted in Andit tid and Gununo showed that increasing the vegetation cover of the soil could decreases soil loss and runoff significantly (SCRP, 1996). In Andit tid, the amount of soil loss due to water erosion was 230 t/ha/year under hacked plots. However, it was possible to reduce the soil loss to 30 t/ha or less under crop covers or fallow grasslands (SCRP, 1996). When a cropland covered by crops or grasslands is compared to a frequently hacked farmland, run-off was reduced by about 90 and 100 % and soil loss by 68%, respectively. Hence soil nutrient loss and runoff could be minimized through increasing the frequency of crop cover, especially by those crops with mulching habits and higher leaf area indexs. Moreover, results from SCRP showed that perennial crops like enset and fruit trees or annuals with mulching and runner habits could reduce erosion effects significantly. Recent simulation modules in Northern Ethiopia showed that crop lands allocated for cereal crops like teff were very prone to erosion (Woldu, 2002), and the authors proposed that growing small seeded cereals, like teff, in sloppy farmlands should be discouraged.

There has been an attempt to control soil erosion and rehabilitate degraded lands through construction of farmland terraces in the Ethiopian Highlands starting from the early 1970s. The program was facilitated through the food-for-work scheme of the World Food Program, as a response to the frequent droughts of the 70s and 80s in Ethiopia. The program attempted to construct terraces on about 4

millions of hectares of farm land. In early 1990s, the annual physical construction of farmland terraces reached over 220,000 ha (Lakew, et al, 2000). However, as the campaign was trying to address the problem with out the full participation of the rural community, except selling labor, the farmers considered the activity as an external imposition and hence failed to develop sense of ownership. The consequence being that farmers failed to maintain the terraces and, in some case, farmers have destroyed the terraces for getting another round of payment. When farmers were asked to list the reasons for rejecting soil and water conservation technologies they listed five major driving forces (Amede, 2002, unpublished) namely high labor cost, decreased farm size due to terraces, its inconvenience during farm operations especially for U-turn of oxen plough, and inefficiency of the terraces to stop erosion as they were only physical structures without any biological component and technical follow-ups. By considering those farmers criteria and by adopting participatory planning and implementation approaches farmers have adopted and disseminated soil conservation technologies in one the African Highlands Initiative benchmark sites, Areka (Amede et al, 2001). The major driving force for the adoption of the technology was its integration with high value crops (e.g. bananas, hops) and fast growing drought resistant feeds (e.g. Elephant grass, pigeon pea) grown on the soil bunds. The sustainable integration soil & water conservation technologies also depend heavily on the effectiveness of by-laws that limit free grazing and free movement of animals especially during the dry spells. This requires the empowerment of the local and regional policies so as to facilitate the integration of natural resource management technologies to practices of local communities. Moreover, effective landscape management, in terms of controlling soil erosion, is possible only when there is a community collective action. Unless the landscape is treated as a single unit and involves all potential stakeholders, any individual intervention could provoke social conflicts. For instance, construction of soil conservation bunds and deforestation of forests at the upper slope of the Lushoto highlands, Tanzania, decreased the amount of water flew to the valley bottoms, and affected the vegetable production and income of other farmers.

*2. Integrated Soil Fertility Management options*

Building the organic matter of the soil and the nutrient stock in short period of time requires a systems approach. These include the combination of judicious use of mineral fertilizers, improved integration of crops and livestock, improved organic residue management through composting and application of farmyard manure, deliberate crop rotations, short term fallowing, cereal-legume intercropping and integration of green manures. Because of the inconsistent use of mineral fertilizers and the very limited returns of crop residues to the soil, most of the internal N cycling in small holder systems results from mineralization of soil organic N. Such process may contribute most of the N for the annual crops until the labile soil organic fraction (N-capital) are depleted (Sanchez et al., 1997).

Apart from the occasional application of small amounts of mineral fertilisers, all other organic resources form the principal means of increasing soil nutrient stocks and hence soil fertility restorers in small-scale farms. If these approaches are used in combination and appropriately, they could reverse the trend and consequently increase crop yields and, thereby alleviate food insecurity. However, the continued low yields are an indication of insufficient inputs and/or inappropriate use of these technologies. The majority of the small-scale farmers are still aggravating the soil/plant nutrient deficit through improper land management and over-mining of the nutrient pool. However, there is still an opportunity to replenish the soil nutrient pool using integrated approaches depending on the degree of soil degradation, the production system and the type of nutrient in deficit.

One potential source of organic fertilizer is farmyard manure. There is a large number of livestock in the Amhara region that could produce a considerable amount of manure to be used for soil fertility replenishment. However, there is a strong competition for manure use between soil fertility and its use as a cooking fuel. Recent survey in the upper central highlands of Ethiopia showed that more than 80% of the manure is used as a source of fuel. Only farmers with access to fuel wood could apply manure in their home steads. Experiences from Zimbabwe showed that most manures had very low nutrient content, N fertlizer equivalency values of less than 30%, sometimes with high initial quality that did not

explain the quality of the manure at times of use (Murwira et al., 2002). This could be explained by the fact that most manures were not composed of pure dung but rather a mixture of dung and crop residues from the stall. Besides the quality the quantity of manure produced on-farm is limited. Sandford (1989) indicated that to produce sufficient manure for sustainable production of 1-3 tonnes/ha of maize it requires 10-40 ha of dry season grazing land and 3 to 10 of wet season Range land, which is beyond the capacity of Ethiopian farmers. Moreover, the potential of manure to sustain soil fertility status and productivity of crops is affected by the number and composition of animals, size and quality of the feed resources and manure management. Wet season manure has a higher nutrient content than dry season manure, and pit manure has a better quality than pilled manure. Similarly, Powell (1986) indicated that dry season manure had N-content of 6 g/kg compared with 18.9 g/kg for early rainy season manure when the feed quality is high.

Another potential organic source is crop residue. Returning crop residue to the soil, especially of legume origin, could replenish soil nutrients, like nitrogen. However, there is strong tradeoff for use of crop residue between soil fertility, animal feed and cooking fuel. In the upper Ethiopian highlands crop residues are used as a major source for dry season feed and supplementary for wet season feed. Hence little is remaining as a crop aftermath to the soil. Although legumes are known to add nitrogen & improve soil fertility, the frequency of legumes in the crop sequence in the upper highlands is less than 10%, which implies that the probability of growing legume on the same land is only once in ten years. The most reliable option to replenish soil fertility is, therefore, promoting integration of multipurpose legumes into the farming systems. Those legumes, especially those refereed as legume cover crops, could produce up to 10 ton/ha dry matter within four months, and are also fixing up to 120 kg N per season (Giller, 2002). Those high quality legumes adapted to the Ethiopian highlands include tephrosia, mucuna, crotalaria, canavalia, and vetch (Amede & Kirkby, 2002). However, despite a significant after effect of LCCs on the preceeding maize yield (up to 500% yield gain over the local management) farmers were reluctant to adopt the legume technology because of trade-off effects for food, feed and soil fertility purposes (Amede, unpublished data, 2002). In an attempt to understand factors affecting integration of soil improving legumes in to the farming systems of southern Ethiopia, Amede & Kirkby (2002) identified the most important socio-economic criteria of farmers namely, land productivity, farm size, land ownership, access to market and need for livestock feed. By considering the decision-making criteria of farmers on which legumes to integrate into their temporal & spatial niches of the system, it was possible to integrate the technology to about 10% of the partner farmers in southern Ethiopia.

Organic resources may provide multiple benefits through improving the structure of the soil, soil water holding capacity, biological activity of the soil and extended nutrient release, but it could be unwise to expect the organics to fulfil the plant demand for all basic nutrients. Most organic fertilizers contain very small quantities of some nutrients (e.g. P and Zn) to cover the full demand of the crop, and hence mineral fertiliser should supplement it. Combined application of organic fertilizers with small amount of mineral fertilizers was found to be promising route to improve the efficiency of mineral fertilizers in small holder farms. For instance, Nziguheba et al., (2002) indicated that organic resources enhanced the availability of P by a variety of mechanisms, including blocking of P-sorption sites and prevention of P fixation by stimulation of the microbial P uptake. Long term trials conducted in Kenya on organic and mineral fertiliser interaction also showed that maize grain yield was consistently higher for 20 years in plots fertilised with mineral NP combined with farmyard manure than plots with sole mineral NP or farmyard manure (S.M Nandwa, KARI, unpublished data 1997). Although most farmers are convinced of using farm-based organic fertilisers, they are challenged by questions like which organic residue is good for soil fertility, how to identify the quality of organic resource, how much to apply, when to apply, and what should be the ratio of organics to mineral fertilisers. This calls for development of decision support guides to support farmers' decision on resource allocation and management. Scientists from Tropical Soils Biology and Fertility Institute of CIAT developed decision guide to identify the quality of organic fertilisers based on the polyphenol, lignin and nutrient content as potential indicators (Palm et al., 1997). As those parameters demand laboratory facilities and intensive knowledge, Giller (2000) simplified the guide by translating it to local knowledge as highly astrigent test (high polyphenol content), fibrous leaves

and stems (high lignin content) and green leaf colour (high N content) to make the guides usable to farmers.

In general, there is an increasing trend of mineral fertilizer use in the Ethiopian highlands over the past decades, and fertilizer imports into the country have increased from 47000 tonnes N & P in 1993 to 137 000 tones in 1996 (Quinones et al., 1997). It was mainly as a result of a strong campaign of Sasakawa-Global 2000 in collaboration with the Buro of Agriculture. However, there is a declining trend in fertilisers use in 2001/2002 due to increasing cost of fertilizers, lack of credit opportunities to resource poor farmers and low income return due to market problems.

*3. Systems Approach to INRM*

Sustainable rural development and natural resource management in the region demands an investment in and improvement of the natural capital, human capital and social capital. As the natural capital in the region had multiple problems that needs multiple solutions, there is a strong need for holistic approach to deliver options for clients of various socio-economic categories.

Given the complexity of the problem of land degradation, and its link to social, economical and policy dimensions, it requires a comprehensive approach that combines local and scientific knowledge through community participation, capacity building of the local actors through farmers participatory research and enhanced farmer innovation. This approach requires the full involvement of stakeholder at different levels to facilitate and integrate social, biophysical and policy components towards an improved natural resource management and sustainable livelihoods (Stroud, 2001). Watershed management as a unit of planning and change imposes the need for increased attention to issues of resource conservation and collective action by the community. The issues of land degradation may include afforstation of hillsides, water rehabilitation and/or harvesting and soil stabilization, soil fertility amendment through organic and mineral fertilizers and increasing vegetation cover by systematic use of the existing land and water resources. This could be achieved by working closely with communities and policy implementers in identifying and implementing possible solutions to address land degradation and other common landscape problems, like grazing land improvement, gully stabilization and by monitoring and documenting the processes for wider dissemination and coverage.

Some of the watershed conservation related solutions should be tried and implemented on specific test locations using farmers' own contribution and the INRM team's technical supervision. However, a wider application of these solutions to larger areas may require attracting additional funding investments from the district, donors or other NGOs in the area. The local village communities may also effect changes in the norms and rules governing the use of natural resources in their vicinity. Traditional rules and local by-laws (e.g. written and unwritten and called "afarsata" or awatcheyache) regarding the use and sharing of resources exist in most villages and these need to be identified and studied with a view to effect reform or renew their emphasis in the community. Integration of Agroforestry technologies in the farming systems of the Ethiopian highlands failed because of absence of national and/or local policies /by-laws that prohibit free grazing and movement of animals in the dry season. Experiences from the 1980s campaign of 'Green Campaign' in Ethiopia also showed that it is almost impossible to address the issue of land degradation without the full involvement and commitment of the local community. The local by-laws in resource arrangement and use should be facilitated and supported, as the rules and regulations at the local level could be implemented effectively through elders and respected members of the community with tolerance and respect. There may be a church and/or witchcraft dimensions to these, and there may be changes over time that might help to understand why people are doing what they are doing. In addition, the influence of national and regional policies on local resource management should be understood. These will form an important subject of community wide discussion and deliberation (Stroud, 2001). The current undertaking of soil and water conservation practices through voluntary participation campaign of the community in the northern Ethiopian Highlands is one positive step forward for initiating collective action.

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# Phosphorus use efficiency as related to sources of P fertilizers, rainfall, soil and crop management in the West African Semi-Arid Tropics

Bationo A. [1], and K. Anand Kumar[2]
[1]IFDC/ICRISAT, BP 12404 Niamey – NIGER.
[2]ICRISAT BP 12404 Niamey – NIGER.

## Abstract

The rainfall of agricultural areas of the West African Semi-Arid Tropics varies from 300 to 1200 mm. Although in absolute terms rainfall is low only in the Northen half of the desert margins, the high inter-annual variability associated with eratic distribution of rainfall in space and during the growing season constitute major limitation for agricultural production. Continuous and intensive cropping without restoration of the soil fertility has depleted the nutrient base of most of the soils. For many cropping systems in the region, nutrient balances are negative, indicating soil mining. Among soil fertility factors, phosphorus deficiency is a major constraint to crop production. Phosphorus use efficiency (PUE) is defined as yield increase per kg fertilizer P added, is related to P sources, environmental factors, soil and crop management.

In addition to water soluble P fertilizers, PR sources from Niger (Parc - W PR and Tahoua PR), Mali (Tilemsi PR) and Burkina Faso (Kodjari PR) and modified partially acidulated phosphate rocks (PAPR) effect on P-use efficiency is reported. PAPR improved the PUE of PR sources. Among the four PR sources in the region, Tahoua PR (TPR) recorded highest PUE as compared to Kodjari (KPR) or Parc-W (PRW) sources.

Rainfall received in September at grain filling and maturation stage was best correlated to PUE. There is large difference in PUE of different pearl millet cultivars and values varied from 25 to 77 kg grain. Kg $P^{-1}$.

The hill placement of 4 kg $P.ha^{-1}$ at planting time improved the PUE as compared to present recommendation of 13 $kg.ha^{-1}$ broadcast and also improved the efficiency of phosphate rock.

The rotation of cereals and cowpea and soil amendment with crop residue application increase drastically the PUE in the region.

*Key words : P use efficiency, rainfall, soil and crop management, Pearl millet, Cowpea, West Africa*

## I. Introduction

The West African Semi-Arid Tropics is the home of the world's poorest people, 90% of whom live in villages and depend for their livelihood on subsistence agriculture. In this zone, the length of crop growing season ranges from 75 to 150 days. Recurrent droughts, soils of poor native fertility, wind erosion, surface crusting and low water-holding capacity are the main abiotic constraints to crop production.

In traditional agricultural systems, when crop yields declined to unacceptable levels, over-cropped land was left to fallow until soil fertility was built up, and new land was opened for cultivation. Increasing population pressure is decreasing the availability of land and is leading to reduce duration of fallow relative to the duration of cropping. As a result, shifting cultivation is losing its effectiveness and soil fertility is rapidly declining in many areas. The present farming systems are unsustainable without external inputs of nutrients, will continue to be low in productivity and have long-term destructive potential to the environment. In such systems, plant nutrient balances are negative (Stoorvogel and Smaling, 1990).

Among soil fertility factors, phosphorus deficiency is a major constraint to crop production and response to nitrogen is substantial only when both moisture and phosphorus are not limiting (Traoré, 1974). Although lack of water limits crop production in the drier zones in the Sahel, all available evidences indicates that inherent low fertility (mainly P) is a more serious problem (Breman and de Wit, 1983; van Keulen and Breman, 1990).

For many years, research has been undertaken to assess the extent of soil phosphorus deficiency, to estimate phosphorus requirements of major crops, and to evaluate the agronomic potential of various phosphate fertilizers including phosphate rock (PR) from local deposits (Goldsworthy, 1967a and 1967b; Pichot and Roche, 1972; Thibaut et al., 1980; Bationo et al., 1987; Bationo et al., 1990).

In a survey of the fertility status of representatives sites, Manu et al. (1991) found that the total P in these soils ranged from 25 to 349 mg $kg^{-1}$ with a mean of 109 mg $kg^{-1}$. Available P with Bray P1 was also generally low, ranging from 1 to 30 mg $kg^{-1}$ with an average of 6 mg $kg^{-1}$. However, 77% of samples had available P values of less than 8 mg $kg^{-1}$ which has been determined to be the critical P level required to obtain 90% of the maximum pearl millet yield in the sandy soil of Niger (Bationo et al., 1989a).

The method of Fox and Kamprath (1970) was used to study the P-sorption characteristics of those soils and selected adsorption isotherms are presented in Figure 1. Sorption data were fitted to the Langmuir equation (Langmuir, 1918) and phosphorus adsorption maxima were calculated. From these representative sites, Manu et al., (1991) found that the values of maximum P sorbed ranged from 27 mg $kg^{-1}$ to 253 mg $kg^{-1}$ with a mean of 94 mg $kg^{-1}$. Soils of this region can be considered as having relatively low P sorption capacities compared to clay rich Utisols and Oxisols found in humid tropical regions (Sanchez and Uehera, 1980). As a consequence of the low P retention capacity of these soils, relatively small quantities of P fertilizers will be needed for optimum crop growth.

Phosphorus use efficiency in this paper is calculated by dividing the difference in yield between P-treatment and control with the rate of P applied. In addition to the water soluble P sources such as single superphosphate (SSP) and triple superphosphate (TSP), phosphate rocks (PRs) indigenous to this region such as Tahoua PR (TPR) and Parc-W PR (PRW) from Niger, and Kodjari PR (KPR) from Burkina Faso were evaluated in field trials on the main soil types for crop production. In this region, use of water soluble imported P fertilizers is severely limited because of their high cost. The direct application of PR indigenous to the region may be an economical alternative to the use of more expensive imported P fertilizers. Some PRs may not be suitable for direct application because of their low chemical reactivity (Hammond et al., 1986). Partial acidulation of PR (PAPR) represents a technology that improves the agronomic effectiveness of an indigenous PR at a lower cost than would be required to manufacture the conventional, fully acidulated fertilizers from the same rock (Chien and Hammond, 1978; Hammond et al., 1986; Bationo et al., 1990).

In this paper, after a brief review of the phosphorus use efficiency (PUE) of crops as effected by sources of P fertilizers, we will discuss the effect of rainfall, crop and soil management on Phosphorus use efficiency (PUE).

**Materials and methods**

A) Effect of P sources and rainfall on PUE

*Experiment on the evaluation of different sources of P fertilizers.*

From 1982 a benchmark field trial was initiated on the Sandy Sahelian soils of ICRISAT at Sadoré to evaluate the agronomic efficiency of different sources of P fertilizers. The sources of P fertilizers in those trials were Parc W phosphate rock (Parc W PR), Partially acidulated rock Parc W at 50 % (Parc W PAPR), Triple Superphosphate (TSP), and Single superphosphate (SSP). P was applied at 0, 4.8, 8.8, 13, 17.6 $kg.ha^{-1}$. Pearl millet cultivar CIVT was used as test crop.

Experiment on PUE efficiency in different agro-ecological zones.

In 1996 field trials were conducted at Sadoré, Gobery and Gaya to evaluate the agronomic effectiveness of Kodjari PR (KPR) and Tahoua PR (TPR) compared to single superphosphate (SSP).

*Experiment on the effect of soil and crop management on PUE*
Experiment on placement of P fertilizers
In a researcher managed trial at Karabedji, hill placement of small quantities of fertilizers were evaluated on water soluble and phosphate rock on pearl millet and cowpea. The two PR used were Tahoua phosphate rock (TPR) and Kodjari phosphate rock (KPR).

*Effect of mineral and organic fertilizers, ridging, and rotation of pearl millet and cowpea on PUE.*
In 1998 data were collected in an experiment to evaluate the effect of nitrogen application, crop residue, ridging and rotation of pearl millet with cowpea on PUE.

*Effect of rotation on PUE*
From 1992 to 1995 an experiment was conducted to study the effect of crop rotation of pearl millet and cowpea on PUE at the ICRISAT Sahelian Center. Phosphorus was applied at 0, 6.5 and 13 $kg.ha^{-1}$ as single superphosphate.

**Results and discussion**

*Phosphorus use-efficiency as related to different sources of P fertilizers and rainfall*
For the benchmark experiment was conducted during the period of 1982-1987 SSP outperformed the other sources and its superiority to sulfur-free TSP indicates that with continuous cultivation, sulfur deficiency develops (Frisen, 1991). For both pearl millet grain and total dry matter yields, the relative agronomic effectiveness was almost similar for TSP as compared to PAPR with 50% acidulation (PAPR50) indicating that partial acidulation of PRW at 50% can significantly increase its effectiveness (Figure 2). SSP had the highest PUE values at all rates of P application. Increased rate resulted in a decrease in PUE. For pearl millet grain, application of 4.4 kg P/ha resulted in a PUE of 100 kg grain/kg P, but the PUE decrease to 45 kg grain/kg P at the rate of application of 13 kg P/ha. The difference between the P sources is better resolved at lower application rates of P fertilizers as compared to the higher application rates. The difference between PRW and SSP at 4.4 kg P/ha was 50 kg grain/kg P while at 17.5 kg P/ha, this difference was reduced to only 27 kg grain/kg P (Figure 2).

For the trial for agronomic evaluation of P sources in different agro-ecological zones of Niger, the response of pearl millet to different sources of P fertilizers indicates that TPR agronomic effectiveness outperformed KPR (Figure 3 and Table 1). These results are in agreement with the fact that the molar $PO_4/CO_4$ ratio is 23.0 for KPR and 4.88 for TPR, and TPR also has a higher solubility in NAC. Mokwunye (1995) found that the level of isomorphic substitution of carbonate for phosphate within the lattice of the apatite crystal influences the solubility of the apatite in the rock and therefore controls the amount of phosphorus that is released when PR is applied to soils. Chien (1977) found that the solubility of PR in neutral ammonium citrate (NAC) was directly related to the level of carbonate substitution. As a result of the higher value of Tilemsi PR in NAC, and the high substitution of carbonate for phosphate, Bationo et al. (1997) found that Tilemsi PR can result in net returns and value/cost ratios similar to recommended cotton or cereal complex imported fertilizers.

The PUE at Gobery was 31 kg grain/kg P for TPR, but decreased to 9 kg grain/kg P with KPR application at 17KgP/ha. As soils in Gaya and Gobery are more acidic and receive more rain than the Sadoré site, the agronomic effectiveness is higher at those sites. The ability of the soil to provide the $H^+$ ions is essential to ensure the effectiveness of PR to crops (Chien, 1977; Khasawneh and Doll, 1978). Therefore, acidic soils with a high pH buffering capacity provide an ideal environment for PR dissolution. Results presented for upland rice by Bado et al., 1995 indicate that PUE of the unreactive Kodjari PR on an acidic (PH in $H_20 = 5$) soil is similar to the PUE of the water soluble TSP (Mahaman et al., 1998).

The agronomic effectiveness of the leguminous cowpea is not better than the cereal pearl millet crop (Table 1). This is in contradiction to others reports where legumes have higher strategy to solubilize

PR than cereal by rhizosphere acidulation (Aguilar and van Diest, 1981; Kirk and Nye, 1986; Hedley et al., 1982) and exudation of organic acids (Ohwaki and Hirata, 1992).

The increase in soil pH resulting from flooding of rice fields is expected to depress the dissolution of PR. Enhanced performance of PR in flooded systems has been reported (Hammond et al., 1986). Kirk and Nye (1986) explain the enhance PR performance in flooded soils by arguing that rice roots will acidify surrounding soil and that dissolved organic matter may chelate Ca and P. In the irrigated system the PUE of PR often was higher than TSP (INRAN, 1988).

Using data of PUE at 13 kg P $ha^{-1}$ details from experiment presented in Figure 2 conducted over 10 years period, it was found that the rainfall received in September at grain filling and maturation stage was best correlated to PUE (Figure 4). From the results presented in Figure 4, it could be concluded that PUE of SSP was most affected by the amount of September rainfall due to its higher biomass production as compared PR or PAPR50. The predictions indicate that for SSP, a 40 mm rainfall in September will result in a PUE of 118 kg dry matter/kg P while for 100 mm rainfall the PUE will increase to 160 kg dry matter/kg P.

In the West African Semi-Arid Tropics, both water and nutrients limits crop production, but from multi-location water-balance studies in Niger, it was shown that an important outcome of fertilizer use is an increase in water-use efficiency (Breman and de Wit, 1983; van Keulen and Breman, 1990). In long-term experiments, water-use efficiency (WUE) for grain yield increased dramatically from 5.4 kg $mm^{-1}$ $ha^{-1}$ without the use of fertilizers to 14.4 kg $mm^{-1}$ $ha^{-1}$ with the use of fertilizers. Increased root growth due to P application is associated with greater rooting depth and deeper extraction of moisture during dry spells (Payne and al., 1995). Early vigor and enhanced growth due to P application results in more complete ground cover early in the season, which reduces the proportion of water lost through water evaporation to some extent, thus facilitating effective and efficient use of rainfall.

Although the application of fertilizers improves WUE, the efficiency of fertilizer depends on the amount of rainfall received by the crop. For nitrogen, Bationo et al. (1989b) developed a model relating grain yield of pearl millet to mid-season rainfall (45 days, from mid-July to end of August). This model predicts that response to N in dry years will be limited, with little benefit to the farmers from the investment in N fertilizers.

b) Relationship between crop and soil management on phosphorus use efficiency

Over a period of three years, nine pearl millet cultivars were evaluated to determine their PUE. For both grain and stover, there are very large differences among the nine cultivars for their response to the application of P fertilizer (Figure 5). PUE at 13 kg P $ha^{-1}$ varied among the 9 cultivars from 25 kg grain/kg P for variety ICMV IS 85333 to 77 kg grain/kg P for Haini-Kirei cultivar the local is 3 weeks later to mature and has a very dense root system. Figure 6 shows PUE of different genotypes was significantly correlated with grain yield at 13 kg P $ha^{-1}$ was, and explained 77% of total variation in this relationship. This significant relationship indicates that phosphorus use efficient cultivars can be first identified using their grain yield performance at 13 kg P/ha. The relationship between the PUE of the different genotypes with grain yield in the absence of P application was not significant and only 15% of the total variation could be explained. This observation shows that a cultivar with a high PUE coefficient will not necessarily perform better under low P conditions than the one with a low PUE coefficient. This also implies that genotypes selected for high grain yield under low-P situations will not necessarily be P-use efficient. There is ample evidence that indicates marked differences exist between species and genotypes for P uptake (Föhse et al. 1988; McLachlam, 1976; Caradus, 1980; Nielsen and Schjorring, 1983; Spencer et al. 1980).

For the researcher managed on-farm trials conducted to study interaction between hill placement of small quantities of P fertilizers on the efficiency of water soluble (SSP, 15-15-15) and phosphate rock (PRT and PRW). Results presented in Table 2 and 3 indicate that hill placement increases the agronomic

effectiveness of both water soluble and PR sources for pearl millet and cowpea. Compared to the control, the pearl millet grain yield increased from 281 to 1493 kg $ha^{-1}$ respectively, for the control and the 15-15-15 broadcast plus 15-15-15 hill placed treatments whereas the application of only 15-15-15 yielded 661 kg/ha. The PUE results in Table 3 indicate that hill placement of 4 kg P $ha^{-1}$ with broadcast PRK can improve the PUE of the unreactive PRK. For cowpea fodder, PUE increased from 44 kg/kg P with the addition of KPR only to 93 when KPR is broadcast with hill placement of 15-15-15 (Table 3). Whereas PUE efficiency is 14 for pearl millet grain yield with KPR broadcast it increased to 31 kg grain/kg P when additional hill placement for 15-15-15 is applied (Table 2). Although hill placement alone of 4 kg P $ha^{-1}$ gave high PUE values as compared to broadcast of 13 kg P $ha^{-1}$, this treatment will result in a net negative P balance. With the association of hill placement and low cost PR sources the net balance of P will be positive and soil mining will be avoided. For most of cases, 15-15-15 hill placement efficiency is higher than SSP hill placement. This is due in part to germination failures most likely due to deleterious pH and salt effects on the seedling. The highest effectiveness of NPK placement is also likely due to a stimulation of early root growth by the ammonium component (Marschner et al., 1986), and an enhanced availability of P in the immediate seedling environment. Over the past few years, on-station research at ICRISAT-Niger has focussed on the placement of small quantities of P fertilizers at planting stage in order to develop optimum farmer-affordable P application recommendation. Compared to control, millet grain yield increased between 60 to 70% when 5 kg P $ha^{-1}$ was hill placed, and by 100% when 13 kg P $ha^{-1}$ was broadcast. PUE on total dry matter and grain yield indicate that PUE at 3,5 and 7 kg P $ha^{-1}$ hill application was higher as compared to broadcasting 13 kg P/ha. For example, in 1995, for total dry matter, the PUE for 13 kg P/ha was 159 kg TDM/kg P as compared to 402 kg TDM/kg P with the application of 3 kg P/ha hill placed. This is due in part to the placement of P where the soil is humid as compared to the surface broadcast where some fertilizers will remain in the dry zone of the soil (Muhelhig-Versen et al., 1997).

In long-term soil management trials, application of nitrogen, crop residue and ridging and rotation of pearl millet with cowpea were evaluated to determine their effect on PUE. The results show that soil productivity of the sandy soils can be dramatically increased with the adoption of improved crop and soil management technologies. Whereas the absolute control recorded 33 kg $ha^{-1}$ of grain, 1829 kg $ha^{-1}$ was obtained when phosphorus, nitrogen and crop residue were applied to plots that were ridged and followed leguminous cowpea crop the previous season (Table 4). Results indicate that for grain yield, PUE will increase from 46 with only P application to 133 when P combined with nitrogen and crop residue applications and the crop is planted on ridge in a rotation system.

In a study on the long-term effect of different cropping systems on PUE it was found that rotation of pearl millet with cowpea could significantly increase pearl millet and cowpea production (Figure 7). For pearl millet total dry matter, PUE increased from 149 kg $ha^{-1}$ in the continuous cultivation to 252 kg $ha^{-1}$ in rotation systems. For cowpea fodder, PUE increased from 40 kg $ha^{-1}$ in the continuous cultivation to 65 kg $ha^{-1}$ with rotation.

In a long-term field trials to study the effect of crop residue application on PUE, PUE was 67 kg/kg P when only P fertilizers were applied, its value doubled when P fertilizers were combined with crop residue (Bationo et al., 1985).

**Conclusion**

In the West African Semi-Arid Tropics, lack of volcanic rejuvenation has caused the region to undergo several cycles of weathering erosion, and leaving soil poor in nutrients.

Both total and available P values are very low and P deficiency is a major constraint to crop production. With their sandy texture, these soils have low P retention capacity.

The PUE is highly variable and depends on P sources, rainfall, soil and crop management. In the West African Semi-Arid Tropics there is little research on understanding the factors affecting P uptake

such as the ability of plants to i) solubilize soil P through pH changes and the release of chelating agents and phosphates enzymes, ii) explore a large soil volume, and iii) absorb P from low soil solution P concentration.

Genotypic improvement can come through increased capacity of plants to extract P from the soil or for decreased internal P requirement per unit dry matter produced. The opportunities for increased efficiency of P utilization through cultivar improvement include selection for treatments that favor strong plant demand such as late maturity, increased rootlet activity and increased P solubilization capacity.

The available and total P values are very low in the region. With those extremely low values of total P, it can be questionable to select cultivar adapted to low P condition, as one cannot mine what is not there. Direct application of indigenous PR can be an economic alternative to the use of more expensive imported water-soluble P fertilizers.

The effectiveness of mycorrhizae in utilizing soil P has been well documented (Silberbush and Barber, 1983; Lee and Wani, 1991, Daft, 1991). An important future research opportunity is the selection of plant genotypes that are conducive to colonization by efficient Vesicular-Arbuscular Mycorrhizal (VAM) associations for better utilization of P from PR.

Previous agronomic research has already identified a significant number of technologies to enhance PUE but future research needs to screen technologies under farmer's management in order to recommend with the highest economic returns.

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**Table 1: Relative agronomic effectiveness for pearl millet and cowpea as compared to SSP (%) Of Tahoua phosphate rock (TPR) and Kodjari phosphate rock (KPR) in three agro Ecological zones of Niger**

| | Sadore | | Goberi | | Gaya | |
|---|---|---|---|---|---|---|
| | TPR | KPR | TPR | KPR | TPR | KPR |
| Grain yield (kg/ha) | 63 | 32 | 76 | 41 | 80 | 57 |
| Total biomass (kg/ha) | 65 | 35 | 60 | 40 | 68 | 63 |
| Cowpea fodder (kg/ha) | 43 | 28 | 73 | 51 | 42 | 42 |
| Cowpea total dry matter (kg/ha) | 56 | 40 | 72 | 51 | 52 | 55 |

**Table 2: Effect of different sources* and placement of P** on pearl millet yield and PUE, Karabedji, 1998 rainy season**

| P Sources and method of application | Grain | | TDM | |
|---|---|---|---|---|
| | Yield (kg $ha^{-1}$) | PUE | Yield (kg $ha^{-1}$) | PUE |
| Control | 281 | | 1726 | |
| SSP broadcast* | 535 | 23 | 3726 | 154 |
| SSP broadcast + SSP HP** | 743 | 27 | 5563 | 226 |
| SSP HP | 611 | 83 | 3774 | 514 |
| 15-15-15 broadcast | 660 | 29 | 4226 | 192 |
| 15-15-15 broadcast + 15-15-15 HP | 1493 | 71 | 7677 | 350 |
| 15-15-15 HP | 690 | 102 | 4767 | 760 |
| PRT broadcast | 690 | 31 | 4135 | 185 |
| PRT broadcast + SSP HP | 663 | 22 | 4365 | 155 |
| PRT broadcast + 15-15-15 HP | 806 | 31 | 5061 | 196 |
| PRK broadcast | 465 | 14 | 3302 | 121 |
| PRK broadcast + SSP HP | 747 | 27 | 5052 | 196 |
| PRK broadcast + 15-15-15 HP | 806 | 31 | 5010 | 193 |
| S.E | 84 | | 194 | |

PUE Kg grain/KgP; HP Hill Placed; TDM Total Dry Matter

**For broadcast, 13 KgP/ha was applied *For HP, at 4 KgP/ha SSP Single superphosphate; 15-15-15 compound fertilizer containing 15% N, 15% $P_2O_5$, 15% $K_2O$; TPR Tahoua Phosphate Rock; KPR Kodjari Phosphate Rock

**Table 3: Effect of different sources* of phosphorus and their placement** on cowpea yield and PUE, Karabedji, 1998 rainy season**

| P Sources and method of application | Grain | | Fodder | |
|---|---|---|---|---|
| | Yield (kg $ha^{-1}$) | PUE | Yield (kg $ha^{-1}$) | PUE |
| Control | 505 | | 1213 | |
| SSP broadcast | 1073 | 44 | 2120 | 70 |
| SSP broadcast + SSP HP | 1544 | 61 | 3139 | 113 |
| SSP HP | 1050 | 136 | 2021 | 452 |
| 15-15-15 broadcast | 1165 | 51 | 2381 | 90 |
| 15-15-15 broadcast + 15-15-15 HP | 2383 | 110 | 3637 | 142 |
| 15-15-15 HP | 1197 | 173 | 2562 | 337 |
| PRT broadcast | 986 | 37 | 2220 | 77 |
| PRT broadcast + SSP HP | 1165 | 68 | 3127 | 113 |
| PRT broadcast + 15-15-15 HP | 1724 | 72 | 3163 | 115 |
| PRK broadcast | 920 | 32 | 1791 | 44 |
| PRK broadcast + SSP HP | 1268 | 45 | 2588 | 81 |
| PRK broadcast + 15-15-15 HP | 1440 | 55 | 2792 | 93 |
| *S.E* | *164* | | *313* | |

PUE Kg grain/KgP; HP Hill Placed; TDM Total Dry Matter

**For broadcast, 13 KgP/ha was applied ** For HP, at 4 KgP/ha

*SSP Single superphosphate; 15-15-15 compound fertilizer containing 15% N, 15% $P_2O_5$, 15% $K_2O$; TPR Tahoua Phosphate Rock; KPR Kodjari Phosphate Rock

**Table 4: Effect of mineral fertilizers, crop residue (CR) and crop rotation on pearl millet yield and PUE, Sadore, Niger, 1998 rainy season.**

| Treatment | Without CR, without N | | | | Without CR, with N | | | | With CR, without N | | | | With CR, with N | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TDM | | Grain | | TDM | | Grain | | TDM | | Grain | | TDM | | Grain | |
| | Yield | PUE | Yield | PUE | Yield | PUE | Yield | PUE | Yield | PUE | Yield | PUE | Yield | PUE | Yield | PUE |
| Control | 889 | | 33 | | 2037 | | 58 | | 995 | | 61 | | 1471 | | 98 | |
| 13 kg P/ha | 2704 | 140 | 633 | 46 | 4339 | 177 | 1030 | 75 | 4404 | 185 | 726 | 51 | 240 | 4594 | 1212 | 86 |
| 13 kg P/ha + ridge | 2675 | 137 | 448 | 32 | 4057 | 155 | 946 | 68 | 3685 | 210 | 785 | 56 | 4530 | 235 | 1146 | 81 |
| 13 kg P/ha + rotation | 5306 | 340 | 1255 | 94 | 6294 | 327 | 1441 | 106 | 5392 | 338 | 1475 | 109 | 6124 | 358 | 1675 | 121 |
| 13 kg P/ha + ridge + rotation | 5223 | 333 | 1391 | 104 | 5818 | 291 | 1581 | 117 | 6249 | 404 | 1702 | 126 | 7551 | 468 | 1829 | 133 |
| SE | 407 | | 407 | | 407 | | 407 | | 407 | | 407 | | 407 | | 407 | |

CR Crop Residue; N Nitrogen; TDM Total Dry Matter; PUE (kg grain/kgP); Yield (kg/ha)

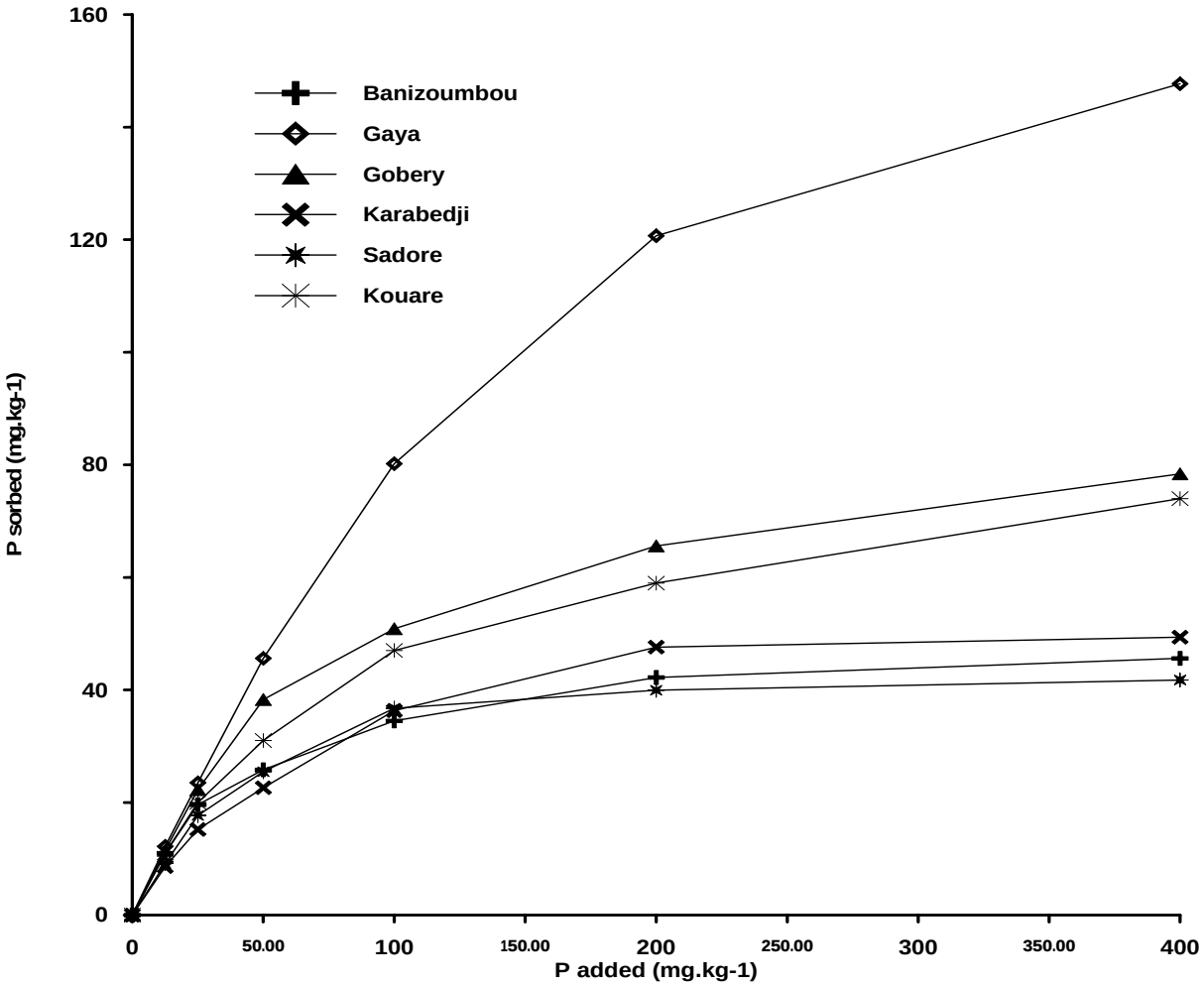


**Figure 1: Phosphorus sorption isotherms of soils samples from six benchmark sites in West Africa (Niger and Burkina Faso).**

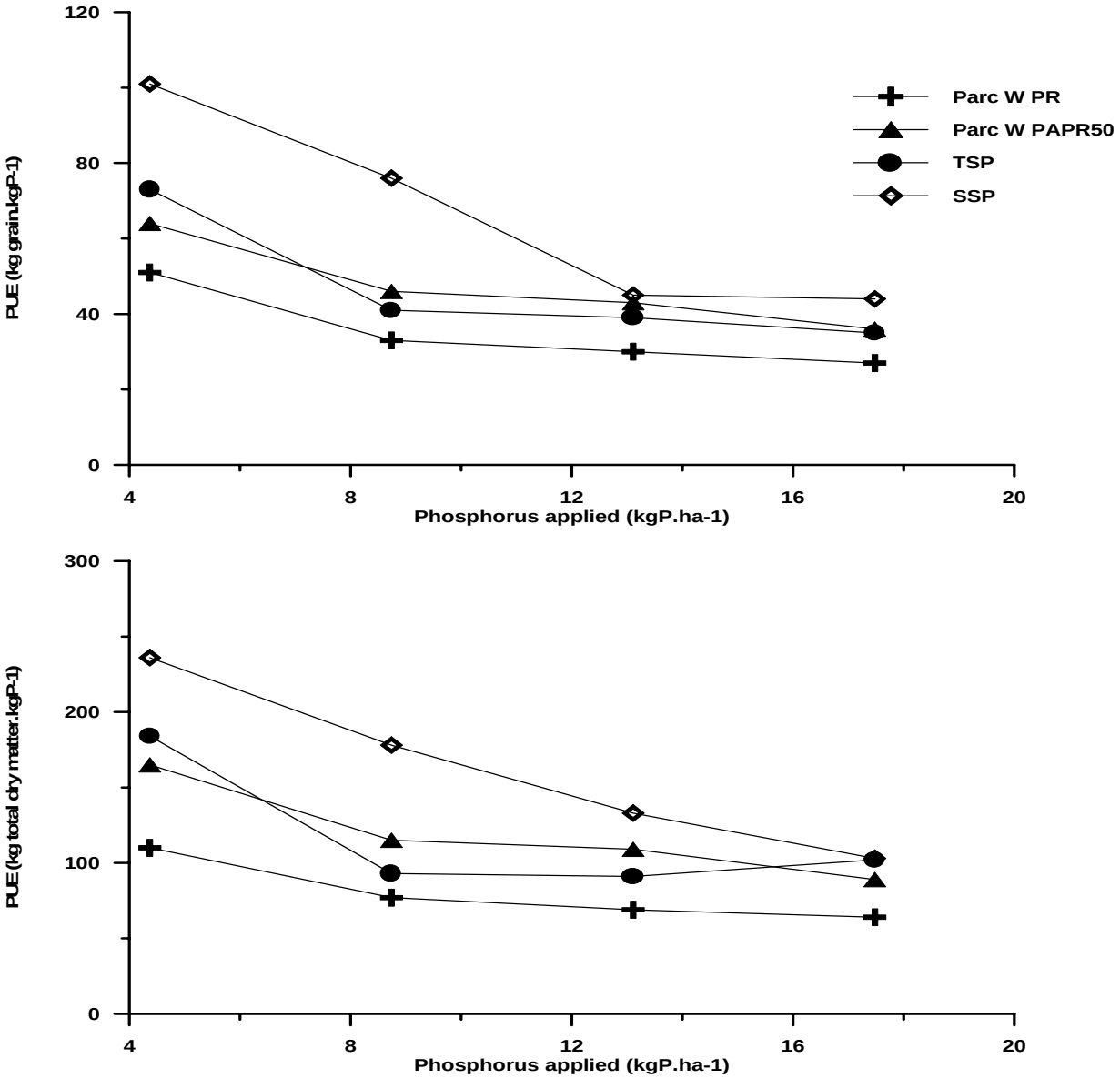


**Figure 2: Relationship between different P sources and rates and PUE for pearl millet grain and total dry matter yields, rainy season, Sadoré, Niger, Average of six years data (1982 to 1987).**

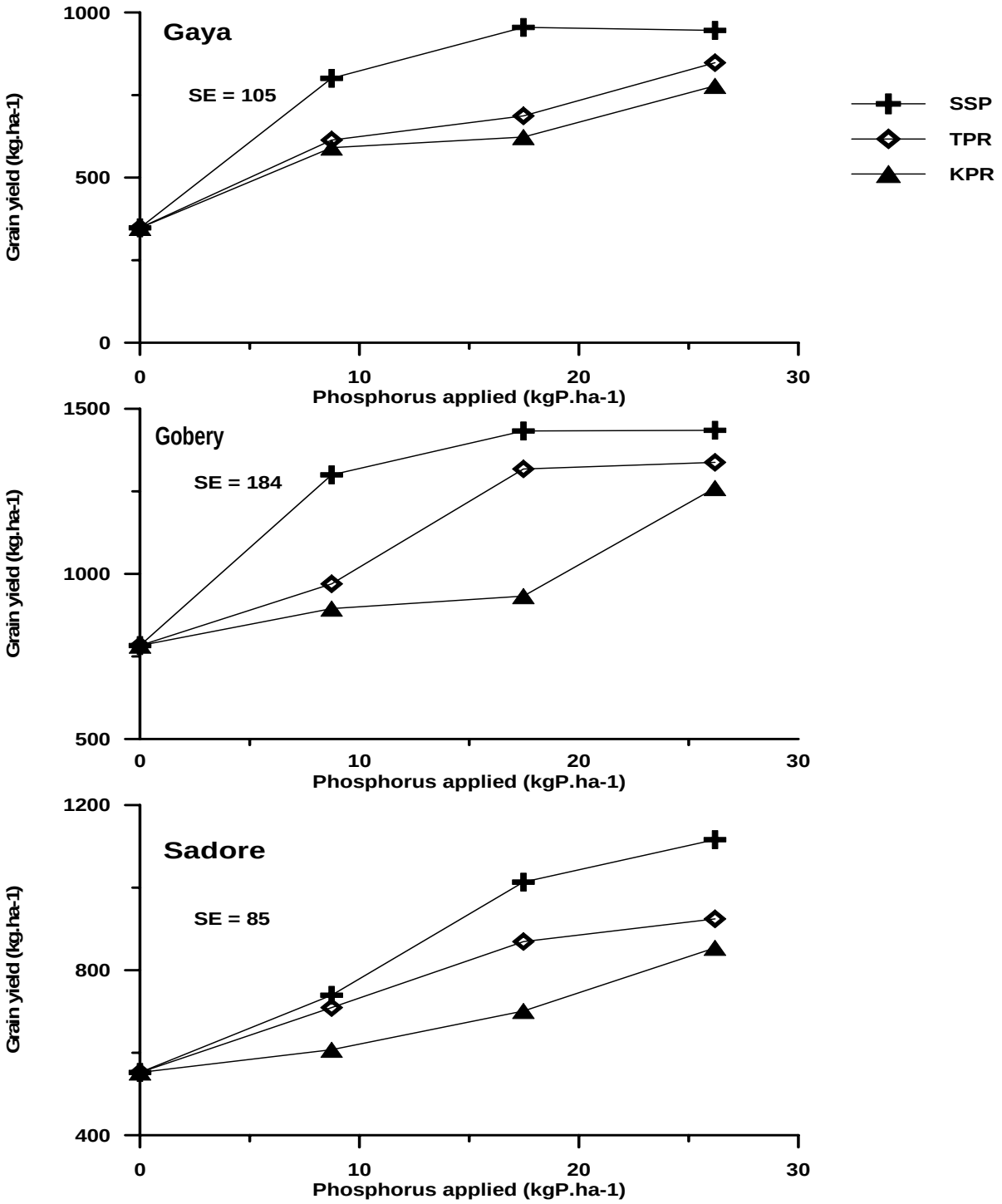


**Figure 3: Relationship between P sources and rates on pearl millet grain yield in three agro-ecological zones of Niger, 1996 rainy season.**

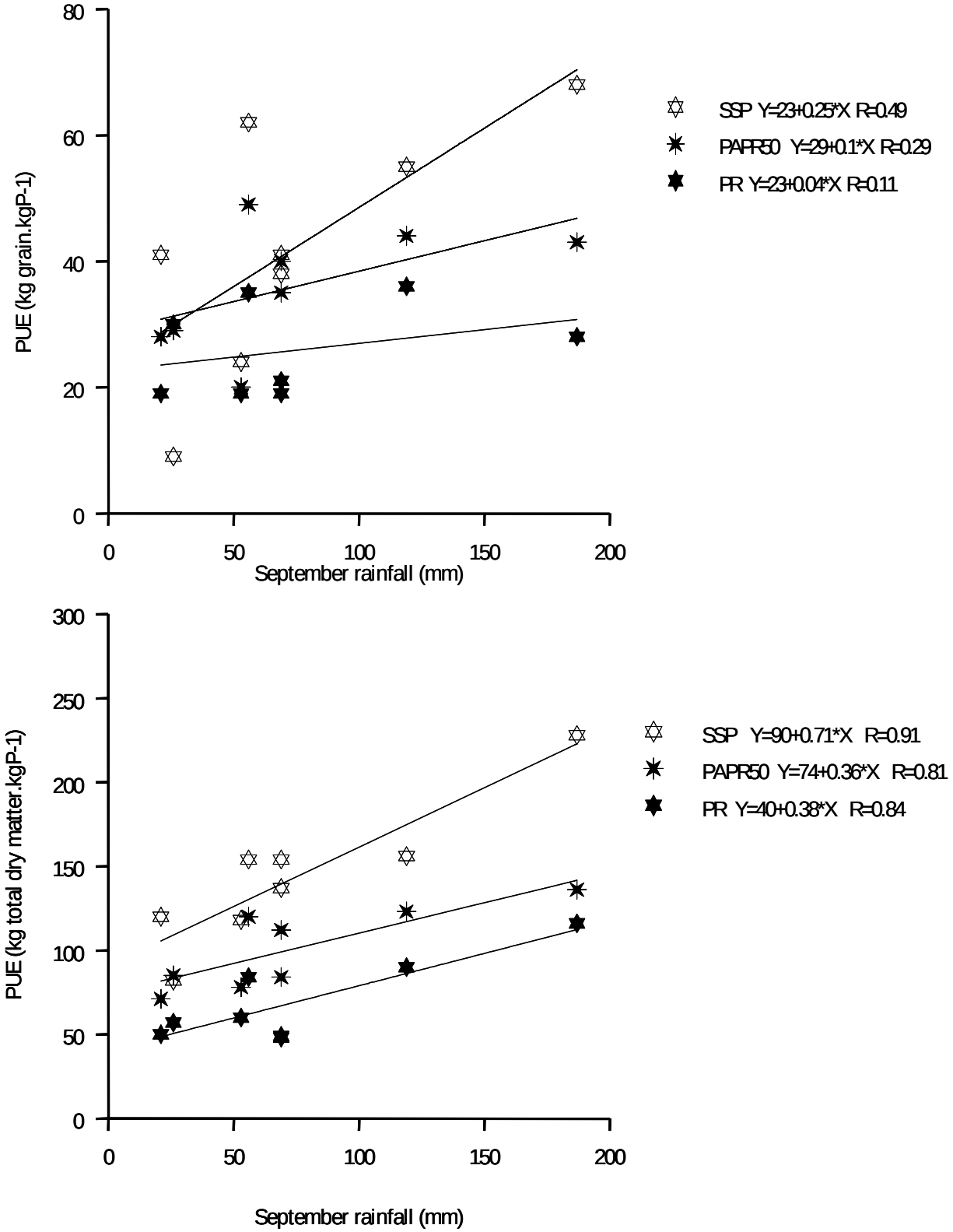


Figure 4: Relationship between September rainfall and PUE for pearl millet grain yield and total dry matter, Sadoré, Niger, 1982-1993 rainy seasons.

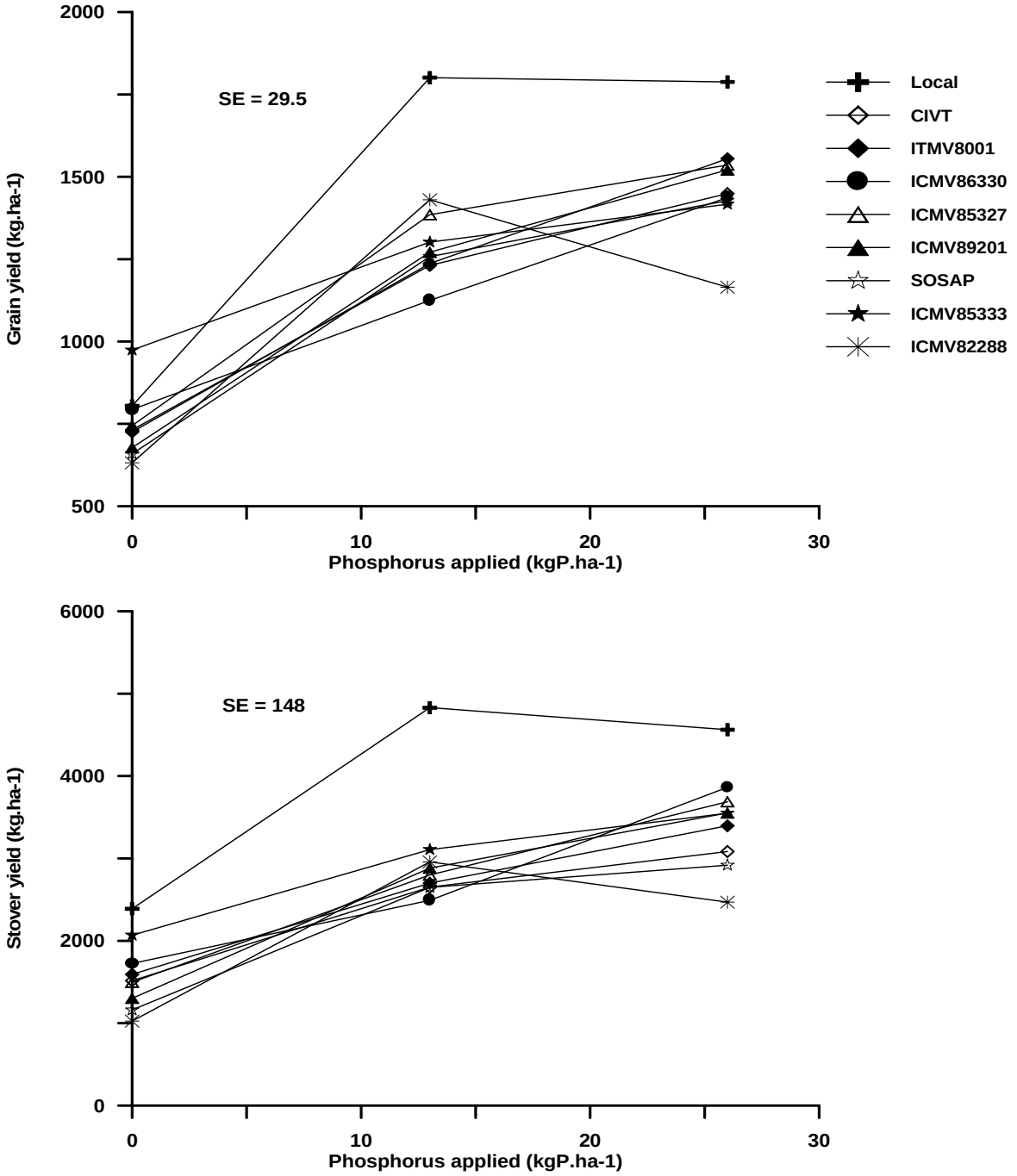


**Figure 5: Relationship between phosphorus applied and grain and stover yields for nine pearl millet cultivars, Sadoré, Niger, rainy season 1991-1993**

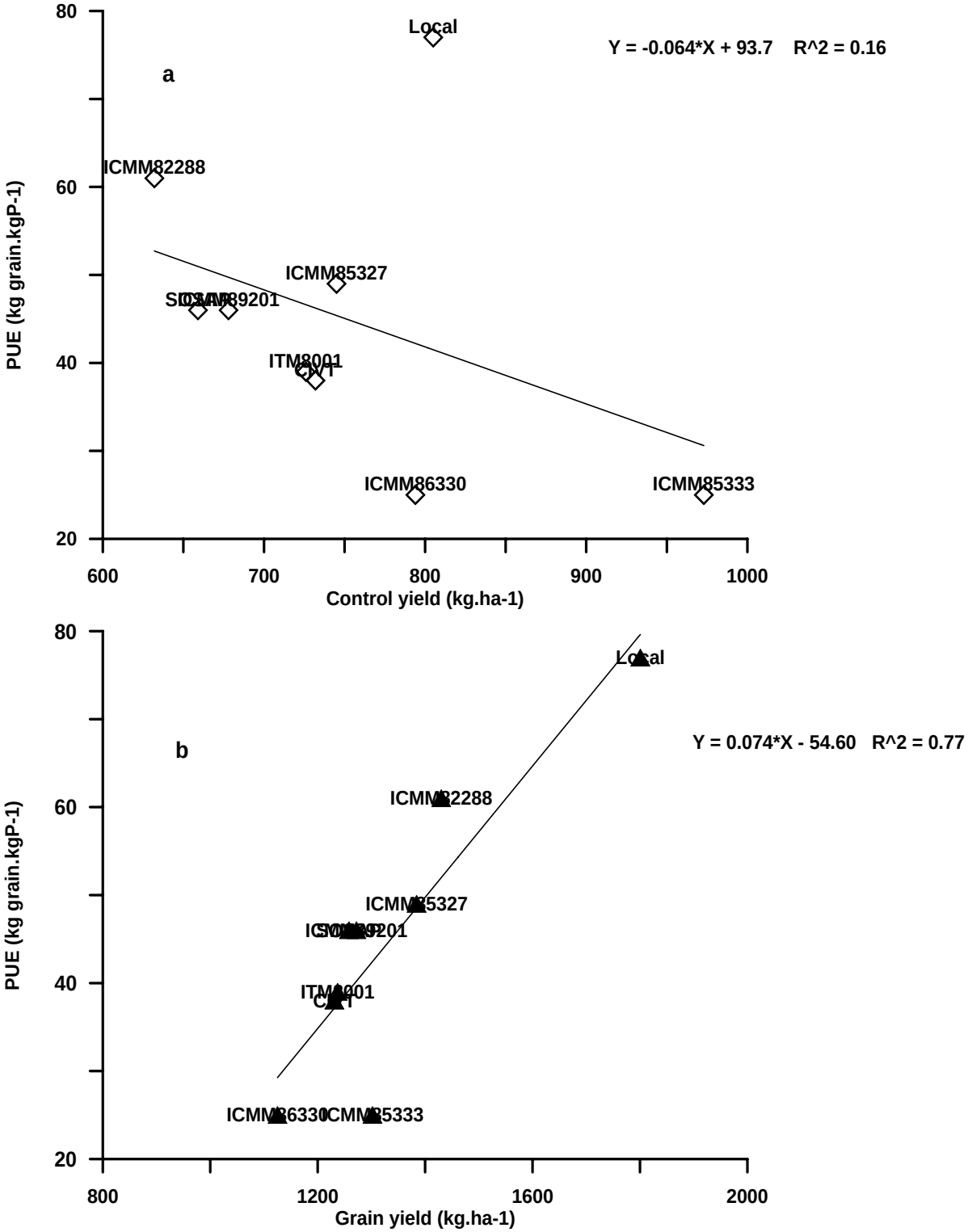


**Figure 6: Relationship between PUE at an application rate of 13 kg P/ha and grain yield of unfertilised (a) and fertilised (b) millet.**

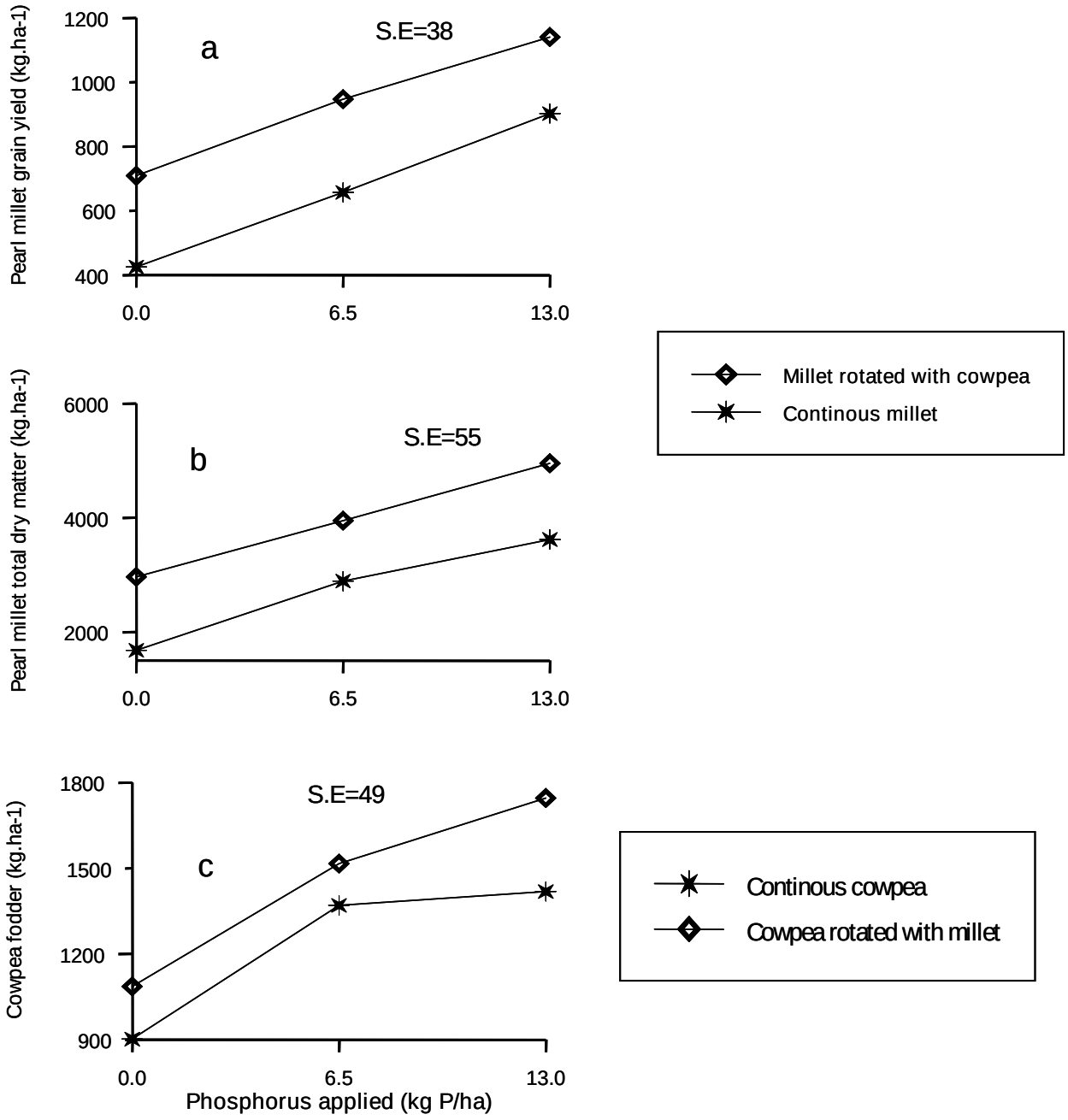


Figure 7: Effect of phosphorus and cropping systems on pearl millet grain (a), total dry matter (b), and cowpea fodder (c) yields, Sadoré, Niger, rainy season 1992-1995.

## Output 2: Improved soil management practices developed and disseminated

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### Use of deep-rooted tropical pastures to build-up an arable layer through improved soil properties of an Oxisol in the Eastern Plains (Llanos Orientales) of Colombia

E. Amézquita[1], R.J. Thomas[2], I.M. Rao[1], D.L. Molina[1] and P. Hoyos[1]
[1] *Centro Internacional de Agricultura Tropical (CIAT), Apartado Aéreo 6713, Cali, Colombia*
[2] *ICARDA, P.O. BOX 5466, Aleppo, Syria (formerly CIAT, Colombia)*

**Abstract**

It is widely believed that tropical soils (mainly Oxisols) have excellent physical characteristics such as high infiltration rates, high permeability of water, good and stable soil structure and that consequently, they can support mechanized agriculture. However in the Eastern Plains (Llanos Orientales) of Colombia, when Oxisols are subjected to tillage using disc harrow, soil physical conditions deteriorate rapidly. We report here that change in land use with deep-rooted tropical pastures can enhance soil quality by improving the size and stability of soil aggregates when compared with soils under monocropping. In addition, rates of water infiltration improved by 5 to 10-fold while rainfall acceptance capacity improved by 3 to 5-fold. We suggest that intensive and sustainable use of these Oxisols, could only be possible if an "arable" or "productive layer" (i.e. a layer with improved soil physical, chemical and biological properties) is constructed and maintained. One option to achieve this arable layer is through the use of introduced tropical pastures with deep rooting abilities that can result in increased soil organic matter and associated improvements in soil physical, chemical and biological properties. One land use option that can achieve these soil improvements is agropastoralism whereby pastures and crops are grown in short-term rotations.

**Keywords:** Soil physical characteristics, Oxisols, Infiltration, Organic matter, Rainfall acceptance, Lower and upper limits of available water

### Introduction

Agricultural sustainability implies that agriculture will remain the principal land use over long periods of time relative to human life-span and it is economically competitive and ecologically acceptable while the soil resource base maintains or even improves its fertility and health (Hamblin, 1991). One of the major challenges for the achievement of sustainable agriculture in the tropics, is the vulnerability of tropical soils to degradation when they are subjected to mechanization for crop production (Thomas et al., 1995; Thomas and Ayarza, 1999; Amézquita *et al.,* 2000). It is widely believed that tropical savanna soils (mainly Oxisols) have excellent physical characteristics such as high infiltration rates, high permeability, good and stable soil structure and therefore can support mechanized agriculture (Sanchez and Salinas, 1981). However, recent work indicated that Colombian savanna soils (Oxisols of Altillanura), have serious physical, chemical and biological constraints for crop and pasture production (Amézquita et al., 1998a). Physically the fertile layer can be shallow with high bulk densities together with weak structure. Tillage (disc harrowing) practices currently used for seedbed preparation could result in surface sealing and low rainfall acceptance capacity (Amézquita *et al.,* 2000). Chemically the soils have low pH values, high levels of exchangeable $Al^{+3}$, low P availability, low base (Ca, Mg and K) saturation and low amounts of organic matter. Also, biologically they show constraints typical of soils with low organic matter such as lower rates of mineralization (Thomas et al., 1995; Lopes *et al.*, 1999).

Physical, chemical and biological conditions of these soils need to be improved in order to increase their productivity. Usually this improvement can be achieved by land preparation and by

application of lime and fertilizer. However, this effect lasts only for a short time and after 4 to 7 years, farmers abandon the degraded land as it is no longer productive and often migrate to other areas. To avoid the continued degradation of these soils and to achieve sustained production, we propose that the construction of an "arable layer", a top layer with improved soil properties, is required (Amézquita *et al.*, 2000).

It has been demonstrated that soil physical conditions are usually best under permanent grassland (or forest) and as soil is cultivated, these conditions deteriorate at a rate dependent of climate, soil texture and management (Lal, 1993; White, 1997). Amézquita *et al*. (1998a), have found significant negative effects of continued cropping on the physical properties of soils in the Llanos. The study by Preciado (1997) from the Casanare region of the Llanos showed that total porosity and macroporosity decrease markedly after 5-7 years of monocropping. Boonman (1997) mentioned similar trends for soils of African savannas.

Ploughing and cultivating new land is usually accompanied by a decline in soil organic matter. When land is ploughed, disruption of peds exposes previously inaccessible organic matter to attack by microorganisms and populations of soil structure-stabilizing fungi and earthworms decrease markedly (White, 1997). Introduced pastures can markedly reverse these trends through improvements in soil aggregation (Drury *et al.*, 1991; Gijsman and Thomas, 1995; Franzluebbers *et al.*, 2000).

The relatively weak structure of savanna soils of Colombia (Oxisols) and their susceptibility to sealing, compaction, and erosion when subjected to tillage can result in negative effects on sustainable productivity of crop-livestock systems (Amézquita, 1998). To overcome these physical constraints, tillage practices should be developed that are based on the concept of development of an "arable layer". The "arable layer" is a surface layer (0-15, 0-25, 0-30 cm depth), with improved soil physical, chemical and biological properties. This is essential for developing a soil that is capable to support sustainable agriculture (Amézquita *et al.*, 2000).

The "arable layer" concept proposed, is based on the combination of: (1) tillage practices to overcome soil physical constraints (high bulk density, surface sealing, low infiltration rates, poor root penetration, etc.). (2) use of chemical amendments (lime and fertilizers) to enhance soil fertility, and (3) use of soil and crop management practices to increase rooting, to promote biostructure, and to avoid repacking of soil after tillage, thus, improving the biological condition of the soil. This concept relies on the use of deep-rooted and acid soil adapted tropical pastures to improve and maintain soil physical conditions via vertical tillage (chisel).

The purpose of this study was to evaluate the influence of deep-rooted tropical pastures in comparison with other land uses such as monocropping of upland rice and native savanna pastures on the build-up of an arable layer through improved soil properties.

## Materials and methods

### *Location*

The experiments were carried out at Matazul farm (4º 9′ 4.9″ N, 72º 38′ 23″ W and 260 m.a.s.l.) located in the Eastern Plains (Llanos) near Puerto López, Colombia. The area has two distinct climatic seasons, a wet season from the beginning of March to December and a dry season from December to March and has an annual average temperature of 26.2 ºC. The area has mean annual rainfall of 2719 mm, potential evapotranspiration of 1623 mm and relative humidity of 81 % (data from the nearby Santa Rosa weather station, located at the Piedmont of the Llanos of Colombia). The soil has low fertility and the availability of P in the soil is low because of the soil's high P fixation capacity (Phiri et al., 2001).

### *Treatments*

To evaluate the impact of deep-rooted pastures on soil physical characteristics, we used the following treatments from long-term experiments:

a) Aggregate size distribution and aggregate stability aspects were studied in an experiment where disturbed and undisturbed introduced pasture systems were compared with rice monocropping on

two sites of contrasting soil texture (Matazul: clay loam; Primavera: sandy loam). Native savanna (undisturbed) system was used as a control. Disturbed pasture received two harrow passes for every two years to reduce surface sealing and compaction.

b) Infiltration rates were measured in an experiment aimed to improve top-soil conditions (cultural profile) using different intensities (1, 2 or 3) of chisel passes (vertical tillage) or different agropastoral treatments (pasture alone, pasture + legume and legumes alone) that were planted after 2 passes of chisel.
c) Measurements on volume and chemical composition of gravitational water were studied in an experiment aimed to understand the processes of soil degradation due to either monocropping of rice or introduced pasture (*Brachiaria dictyoneura* cv. Llanero). Different number of harrow passes (2, 4, 8) were applied every year for a period of two years for each treatment.
d) Root biomass and root volume of *Brachiaria decumbens* were determined in two contrasting textural soils: sandy-loam and clay-loam, under two pasture conditions: productive and degraded (less productive), to compare root growth under these two conditions.

**Evaluated Parameters**

*Aggregate size distribution and aggregate stability*

Ten volumetric soil samples were taken in cylinders (120 mm diameter by 25 mm high) and used for dry aggregate size distribution determinations from each of the following treatments: disturbed pasture, undisturbed pasture, monocrop and native savanna. Disturbed pastures means that two harrowing passes were made every 2 years to loosen the soil to improve pasture productivity. By the time of the evaluation, the experimental plots had 8 years of establishment. In each of the 10 samples taken from each treatment, a test for dry aggregate size distribution (Kemper and Rosenau, 1986; White, 1993; Amézquita et al., 1998b) was made using the total volume of soil collected in the cylinders. Sieves of the following openings were used: >6, 6-4, 4-2, 2-1, 1-0.5 mm, which were fitted to a shaker for 5 minutes.

Aggregate stability was determined also using 10 samples (50 g of soil) for each treatment with a Yoder apparatus (Angers and Mehuys, 1993). A set of sieves with openings of: 2, 2-1, 1-0.5, 05-0.25, 0.25-0.125 and <0.125 mm was used. The amount of sand found in each sieve was discounted from the total weight.

*Infiltration rate*

A double ring devise was used to determine infiltration rates (Bower, 1986). Five tests for each treatment were made. Internal cylinder was inserted into the soil to 5-7 cm soil depth. External cylinder was inserted to 3-5 cm. Water was poured first to the external cylinder to reach a height of about 3 cm within the cylinder and then to the internal cylinder to reach a height of 6 cm from the soil surface. The amount of water entering into the soil was measured at different time intervals during a testing period of two to three hours, until a quasi equilibrium of amount of water entering in function of time was reached.

*Collection of gravitational water*

It is not common to collect and measure the amount and elemental composition of free water (drainage water) from the precipitation that moves down in a soil profile at different depths. In this study we determined the influence of pastures or monocropping of upland rice on the amount of gravitational water and its elemental composition at different soil depths. A pit of 1.8 m length × 0.7 m wide × 0.5 m depth m was dug in each treatment. Funnels filled with clean fine and very fine sand, were wetted to field capacity and then buried in the soil profile at different depths: 3, 5, 10, 15 and 30 cm to collect the gravitational water that passes through each depth, during part of the rainy season. Measurements of the amount of water and elemental composition, were made at different times. During the period of measurements, the pits were protected around and covered with a sheet of zinc to avoid any other water entering into the pit. This methodology assumes that there is a vertical piston like water movement. The accepted rain was assumed to move through the soil profile and reach the funnels that were buried at different depths. Wet sand present in the funnels favors pore continuity for the drainage process.

*Root distribution*

Root sampling was carried out using trench profile method (Schuster, 1964). Three sampling points were randomly located within each treatment of degraded or productive pasture of *Brachiaria decumbens*. A trench of 60 cm wide, 50 cm deep and 60 cm long was dug to determine root penetration and root distribution. Root samples were excavated from the wall of each trench, totalling 3 samples from each treatment. The nail-boards were made of a 2 cm thick plywood board (50 cm wide and 40 cm long). Twelve cm long nails were inserted at 10 cm intervals (10 x 10 cm) through the back of the board and protruded into the frame 10 cm.

Root samples were excavated by pressing the nail-boards into the trench wall and slicing the enclosed soil monolith from the trench wall with a steel blade. The samples were soaked in water for at least 2 h after which the soil was removed from the roots with a fine spray of water. The root samples were photographed. Root volume was determined with a measuring jar filled with water by registering the increase in volume. Root biomass (dry weight) was recorded after oven drying for 2 days at 65°C.

**Results**

*Aggregate size distribution and stability*

*Effect of different management systems.*

The aggregate size distribution under different management systems is shown in Table 1. At Matazul Farm, the percentage of aggregates >6 mm, 6–4 mm and 4–2 mm decreased in intervened systems compared with the native savanna, while those between 2–1 mm, 1–0.125 mm and <0.125 mm increased. This was noted particularly under monocropped rice. At La Primavera Farm, monocropping with rice resuted in a lower percentage of 4–2 mm and higher percentage of 2–1 mm and 1.0–0.125 mm aggregates. In contrast, the undisturbed pasture had a positive effect on soil aggregation, with the highest (non-significant) percentage of aggregates larger than 2 mm.

Table 1. Aggregate size distribution (%) as influenced by soil management system in savanna soils of Colombia

| | % of aggregates of size (mm)* | | | | | |
|---|---|---|---|---|---|---|
| Treatment | >6 | 6-4 | 4-2 | 2-1 | 1-0.125 | <0.125 |
| **Matazul Farm** | | | | | | |
| Undisturbed pasture | 14 b | 11 b | 16 a | 15 b | 32 b | 12 ab |
| Disturbed pasture | 21 a | 11 b | 15 ab | 15 b | 27 c | 11 b |
| Rice monocropping | 7 c | 7 c | 13 b | 17 a | 44 a | 13 a |
| Native savanna | 22 a | 14 a | 16 a | 11 c | 24 c | 10 b |
| **La Primavera Farm** | | | | | | |
| Undisturbed pasture | 14 a | 15 a | 26 a | 17 b | 22 b | 5 b |
| Disturbed pasture | 6 b | 7 c | 17 ab | 22 a | 37 a | 11 a |
| Rice monocropping | 13 a | 12 b | 15 b | 18 b | 31 a | 10 a |
| Native savanna | 11 a | 11 b | 26 a | 18 b | 24 b | 9 ab |

** Values within an aggregate size class and farm followed by the same letter are not significantly different at p<0.05.*

The results on aggregate stability are presented in Table 2. Aggregate stability values at Matazul Farm were greater for native savanna than for intervened systems. The percentage of stable aggregates larger than 2 mm was significantly greater in relation to other treatments. At La Primavera Farm, undisturbed pasture and native savanna both had a higher percentage of aggregates larger than 2 mm diameter.

Table 2. Percentage of stable aggregates under different management systems on a Colombian savanna Oxisol

| | % of stable aggregates of size (mm)* | | | | | |
|---|---|---|---|---|---|---|
| Treatment | >2 | 2-1 | 1-0.5 | 0.5-0.25 | 0.25-0.125 | <0.125 |
| **Matazul Farm** | | | | | | |
| Undisturbed pasture | 75 c | 7.2 a | 4.0 a | 1.6 a | 1.6 a | 10.0 ab |
| Disturbed pasture | 79 bc | 4.5 b | 2.7 b | 1.2 b | 0.9 ab | 11.4 a |
| Rice monocropping | 84 b | 3.6 b | 2.6 b | 1.2 b | 0.9 ab | 7.8 ab |
| Native savanna | 93 a | 1.2 c | 0.6 c | 0.3 c | 0.3 b | 4.2 b |
| **La Primavera Farm** | | | | | | |
| Undisturbed pasture | 94 a | 1.0 c | 0.5 c | 0.5 b | 0.2 b | 3.7 b |
| Disturbed pasture | 78 c | 7.6 a | 3.7 a | 1.3 a | 1.2 a | 8.7 a |
| Rice monocropping | 84 b | 4.4 b | 2.3 b | 0.8 ab | 1.0 a | 7.8 a |
| Native savanna | 93 a | 1.7 c | 0.6 c | 0.3 b | 0.2 b | 4.4 b |

** Values followed by the same letter are not significantly different at p<0.05.*

*Infiltration rates*

Infiltration rates, determined under different management system treatments in an experiment aimed to create an arable layer, are shown in Table 3. In relation to native savanna the treatments that included introduced pastures showed higher and more stable rates. Particularly higher rates of infiltration were found under *A. gayanus* pasture.

Table 3. Rate of water infiltration (cm. $h^{-1}$) as influenced by different treatments in the experiment on building an arable layer (Matazul Farm)

| | Infiltration rate (cm $h^{-1}$) | |
|---|---|---|
| Treatment | 1998 | 1999 |
| Rice-soybean rotation | | |
| 1 chisel pass | 2.0 c | 5.5 bc |
| 2 chisel passes | 1.6 c | 7.4 bc |
| 3 chisel passes | 2.2 c | 7.5 bc |
| Rice + Pastures | | |
| a) Early incorporation of residues | | |
| *A.gayanus (Ag)* | 17.0 a | 15.0 a |
| *Ag*+legumes (Kudzu + *D. ovalifolium*) | 8.8 abc | 5.6 bc |
| Legumes (Kudzu + *D. ovalifolium*) | 9.7 abc | 6.8 bc |
| b) Late incorporation of residues | | |
| *A.gayanus (Ag)* | 8.5 abc | 9.4 b |
| *Ag*+legumes (Kudzu + *D. ovalifolium*) | 6.5 bc | 5.2 bc |
| Legumes (Kudzu + *D. ovalifolium*) | 14.2 ab | 3.1 c |
| Native savanna (control) | 1.7 c | 3.7 bc |
| Significance level | 0.07 | 0.006 |

** Values followed by the same letter are not significantly different at p<0.05.*

*Gravitational water*

The amount of gravitational water draining at different soil depths as a function of soil management system is shown in Table 4. Little water was collected in the top layers of soil of savanna while greater amounts were collected at 15 cm soil depth. The treatment sown to upland rice with 8 harrow passes, did not allow the movement of free water through the soil. With 16 harrow passes more water was able to enter into the soil especially in the top two layers.

Under introduced pastures, the amount of free water entering and moving through the soil profile was extremely high (480 $cm^3$ vs 0 $cm^3$ with 8 harrow passes and 490 $cm^3$ vs 100 $cm^3$ with 16 harrow passes) in comparison with upland rice.

The chemical composition of the water collected at different soil depths under upland rice and pastures is shown in Table 5. Higher amounts of nutrients, especially at the first two depths were found under rice.

*Root distribution*

Examination of soil monoliths collected through profile wall technique showed marked differences in root penetration and root distribution between a degraded pasture and a productive pasture of *Brachiaria decumbens* (Figure 1). Differences in root biomass and root volume at different soil depths, as influenced by soil texture (clay-loam and sandy-loam) are shown in Table 6. Clearly the productive pasture showed greater abundance and distribution of root systems than the degraded one.

**Discussion**

Good soil management should aim to create optimum physical conditions for plant growth (White, 1977). These include: a) adequate aeration for roots and microorganisms. b) adequate available water, c) easy root penetration, d) rapid and uniform seed germination, and e) resistance of the soil to slaking, surface sealing and accelerated erosion. Results from this study indicate that change in land use as deep-rooted tropical pasture can enhance soil quality by improving the size distribution of stable aggregates when compared with soils under continuous upland rice monocropping. The greater percentage of stable aggregates with introduced pastures compared with monocropping indicates that any kind of soil disturbance negatively affects aggregate stability, possibly through its influence on soil organic matter (Hamblin, 1985; Lal, 1993) or some of its components (Caron *et al.*, 1992). Compared with native savanna, introduced pastures also showed higher and more stable rates of water infiltration, particularly with *A. gayanus* pasture. These results reconfirm the benefits of introduced pastures in improving soil quality (CIAT, 1998; Gijsman and Thomas, 1996).

The improvement of the structural condition of soils by pastures, when they are used for grazing, normally change to less beneficial values of porosity, infiltrability, etc., as a consequence of trampling. However, strategies to maintain a good soil structural quality can be developed with proper grazing management.

Little amount of gravitational water was collected in the top layers of soil of native savanna while greater amounts were collected at 15 cm soil depth suggesting the existence of preferential flow. This could be due to the wetting mechanisms dominant in the natural savannas. The treatment sown to upland rice with 8 harrow passes, did not allow the movement of free water through the soil, probably as a result of surface sealing that impeded the entrance of water. Under 16 harrow passes more water was able to enter into the soil especially in the first two depths, showing that there was a better rainfall acceptance under this treatment. The greater amounts of gravitational water entering and moving through the soil profile of introduced pasture in comparison with monocropping of upland rice indicates that introduced pastures are a very good alternative to improve and maintain the amount of macropores (pores that permit the free movement of water). This result confirms the beneficial effects of agropastoral system for improvement of these soils (Angers, 1992). Results on the chemical composition of the gravitational water collected indicate the beneficial effects of introduced pastures both on water and nutrient redistribution in the top-soil layers. However, it is important to note that pastures were sown a year before rice. `

Table 4. Gravitational water collected (ml) at different soil depths for different systems of soil management (Matazul Farm)

| Depth (cm) | Amount of water collected (ml) | | | | |
|---|---|---|---|---|---|
| | | Rice | | Pasture | |
| | Native savanna | 8 harrow passes | 16 harrow passes | 8 harrow passes | 16 harrow passes |
| 3 | 3 | 0 | 100 | 480 | 490 |
| 5 | 2 | 0 | 136 | 480 | 490 |
| 10 | 4 | 1 | 0 | 480 | 447 |
| 15 | 490 | 2 | 0 | 440 | 132 |
| 20 | 1 | 0 | 0 | 40 | 78 |
| 30 | 0 | 3 | 0 | 0 | 460 |

Table 5. Elemental composition of gravitational water collected at different depths and management systems (Matazul Farm)'

| Crop | Depth (cm) | N | K | Ca | Mg | Al | Electrical conductivity ($\mu S\ cm^{-1}$) | pH |
|---|---|---|---|---|---|---|---|---|
| | | ($mg\ L^{-1}$) | | | | | | |
| Rice | 3 | 8.5 | 12.0 | 2.9 | 0.5 | 6.0 | 103.8 | 5.8 |
| | 5 | 2.8 | 10.4 | 6.0 | 1.0 | 17.5 | 90.0 | 6.0 |
| Pastures | 3 | 1.7 | 4.1 | 1.7 | 0.5 | 2.2 | 463.0 | 5.9 |
| | 5 | 2.9 | 0.6 | 1.6 | 0.3 | 1.4 | 29.5 | 6.2 |
| | 10 | 2.0 | 1.4 | 0.8 | 0.2 | 0.4 | 288.0 | 6.1 |
| | 15 | 2.0 | 2.6 | 2.8 | 0.4 | 0.6 | 47.5 | 6.6 |
| | 20 | 2.7 | 1.5 | 2.3 | 0.4 | 0.5 | 56.3 | 6.7 |
| | 30 | 4.8 | 3.8 | 3.7 | 1.0 | 1.7 | 79.0 | 6.6 |

Table 6. Root biomass (g) and root volume ($cm^3$) of *Brachiaria decumbens* at different soil depths as influenced by level of pasture productivity (degraded or productive) on two soil types.

| Soil depth (cm) | Sandy-loam | | | Clay-loam | | |
|---|---|---|---|---|---|---|
| | Degraded | Productive | $LSD_{0.05}$ | Degraded | Productive | $LSD_{0.05}$ |
| Root biomass (g) | | | | | | |
| 0-15 | 0.7 | 1.3 | 0.64 | 1.0 | 1.7 | NS |
| 15-25 | 0.2 | 0.2 | NS | 0.3 | 0.3 | NS |
| 25-40 | 0.1 | 0.3 | 0.08 | 0.2 | 0.2 | NS |
| Root volume ($cm^3$) | | | | | | |
| 0-5 | 6.5 | 9.7 | NS | 8.5 | 15.7 | 5.6 |
| 15-25 | 2.2 | 2.7 | NS | 2.7 | 2.6 | NS |
| 25-40 | 1.2 | 2.7 | 0.8 | 2.1 | 2.1 | NS |

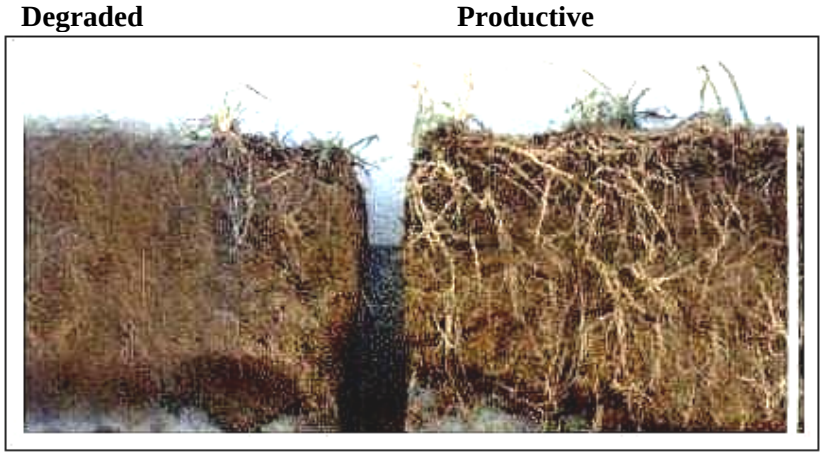


Figure 1. Root distribution under degraded and productive *Brachiaria decumbens* pasture.

Four aspects of the research deserve to be emphasized. First, the methodology used was appropriate as it was possible to collect drainage water and differentiate between treatments. Second, there was a very high variability in the way the water moved into the soil (preferential flow). Third, the amount of nutrients that moved from one depth to the other was a function of the total amount of water draining through soil profile. Fourth, the greater capacity of the pastures for facilitating a better movement and distribution of nutrients and water could be used for improving soil physical conditions.

## Conclusions

This study shows that change in land use as introduced pastures can enhance soil quality by improving the size distribution of stable aggregates, water infiltration rates and rainfall acceptance capacity when compared with soils under monocropping. We suggest that the intensive and sustainable use of these soils, is only possible if an "arable" or "productive layer" is produced and maintained i.e. a layer with little physical, chemical and biological constraints. One option to achieve this arable layer is the use of introduced pastures with deep rooting abilities that can result in increased soil organic matter and associated improvements in soil physical and chemical properties. One land management option that can achieve these improvements is agropastoralism whereby pastures and crops are grown in short-term rotations.

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# Sustainability of Crop Rotation and Ley Pasture Systems on the Acid-Soil Savannas of South America

E. Amézquita[1], D.K. Friesen[2], M. Rivera[1], I.M. Rao[1], E. Barrios[1], J.J. Jiménez[1], T. Decaëns [3] and R.J. Thomas[4]

[1]*Centro Internacional de Agricultura Tropical (CIAT), A.A. 6713, Cali, Colombia.*
[2]*IFDC-CIMMYT, P.O. Box 25171, Nairobi, Kenya (formerly IFDC/CIAT).*
[3]*Université de Rouen, F-76821 Mt Saint Aignan Cedex, France.*
[4]*ICARDA, P.O. Box 5466, Aleppo, Syria (formerly CIAT, Colombia).*

## Abstract

Intensification of agricultural production on the acid-soil savannas of south America (mainly Oxisols) is constrained by the lack of diversity in acid (aluminum) tolerant crop germplasm, poor soil fertility and high vulnerability to soil physical, chemical and biological degradation. The use of high levels of inputs and monocropping is thought to be unsustainable since it may result in deterioration of soil physical properties as well as escalation of pest and disease problems. Traditional grazing systems on native savanna species have very low productivity. Improved legume-based pastures can actually improve the soil resource base but require investments in inputs for establishment, which are unattractive to graziers. Other alternatives include establishment of pastures in association with rice (agropastoral systems) as well as rotations with grain legumes or green manures. Systems such as these may attenuate or reverse the deleterious effects of monocultures while permitting intensified agricultural production. To monitor the sustainability of such systems, biophysical measures are required as 'predictors' of system performance and 'health'. In 1993, a long-term field experiment was established in Carimagua, Colombia, (4°36'N, 71°19'W) to study the influence of various systems on soil quality and system productivity on a savanna Oxisol. Soil biophysical properties were measured in potentially degrading and non-degrading production systems. In this paper, we report results obtained during the first five-years of experimentation on the impact of these diverse systems (rice monoculture, rice–cowpea rotation, rice–green manure rotation, rice–agropastoral rotation and native savanna) on soil quality and rice production. Increasing intensity of production system (with concomitant use of inputs) resulted in improved indicators of soil fertility. Cultivation resulted in improved soil physical characteristics, primarily because of the degraded nature of the soil under native savanna. In contrast, soil organic matter declined with increasing intensity of cultivation as did populations of macrofauna in the different systems. Only in the agropastoral system were soil organic matter and macrofaunal activity enhanced. This study provides important indicators for resource management on savanna Oxisols.

**Keywords:** agro-pastoral systems, crop rotation, soil degradation, soil improvement, soil physical vulnerability, tropical savanna

## Introduction

The neotropical savannas occupy 243 million hectares in South America and are one of the most rapidly expanding agricultural frontiers in the world (Thomas and Ayarza, 1999). Oxisols predominate in the hyperisothermic savannas and cover an area of 17 million hectares in Colombia alone. Intensification of agricultural production in this ecosystem requires acid soil (aluminum) tolerant crop germplasm, soil fertility improvement and management of highly vulnerable physical properties (Amézquita, 1998; Guimaraes et al., 1999). Monocropping systems with high levels of inputs and excessive cultivation may

be unsustainable since they may cause deterioration of soil physical properties as well as escalation of pest and disease problems.

Improved legume-based pastures are considered least harmful to the soil resource base but require investments in inputs for establishment that are unattractive or beyond the means of graziers. Establishment of pastures in association with rice (to defray the cost of inputs) is a potential alternative that has seen significant adoption by farmers in frontier areas of the Colombian Llanos (Sanz et al., 1999). Alternative systems incorporating components that attenuate or reverse the deleterious effects of monocultures are required, and biophysical measures of sustainability need to be developed as 'predictors' of system 'health' to sustain agricultural production at high levels while minimizing soil degradation.

Grain legumes, green manures, intercrops and leys are possible system components that could increase the stability of systems involving annual crops (Karlen et al., 1994). To test the effects of these components on system sustainability and to identify indicators of soil quality, a long-term field study was implemented in 1993 on a Colombian Oxisol under native savanna grassland using a selection of alternatives based on these components (Friesen et al., 1997). The study has extended through almost two cycles of the principal rotation, i.e., the agropastoral system, recognizing that the degrading or beneficial effects of various agricultural practices are often subtle and only manifest themselves over long periods. This paper presents results from the initial 5-year phase of the experiment, focusing on systems based on upland rice with emphasis on systems' effects on: (a) productivity; (b) soil fertility indicators; (c) soil physical attributes; (d) associated soil organic matter quality; and (d) soil biological health.

## Materials and Methods

### *Site description and experimental design*

The experiment was established on a well-drained silt clay loam (Tropeptic Haplustox, isohyperthermic) under native savanna grassland at Carimagua (4°37'N, 71°19'W, 175 m altitude) in the Eastern Plains of Colombia. The mean annual rainfall is 2240 mm with a mean temperature of 27°C. The experiment is laid out in a split-plot design with four replications in which alternative systems (in sub-plots, size 0.36 ha) based on upland rice or maize (main plots) are compared (Friesen et al., 1997). Only rice-based systems are reported here. They include rice monoculture, rice rotated with cowpeas (for grain), cowpea green manure (GM) or "improved" grass-legume pasture leys. Cowpea or GM rotations occurred within each year, i.e., rice was sown in the first season (semester) and the legumes in the second season annually. Pastures were sown simultaneously under rice in 1993 and again in 1998, and grazed in the intervening 4 years. Native savanna plots were maintained for baseline comparisons. Cropped systems were limed with 500 kg $ha^{-1}$ of dolomite prior to establishment and maintained thereafter with annual applications of 200 kg $ha^{-1}$. Each rice crop received 80 kg-N $ha^{-1}$ (split: 20+30+30), 60 kg-P $ha^{-1}$ and 100 kg-K $ha^{-1}$. Legumes (cowpeas or GM) received 20 kg-N $ha^{-1}$, 40 kg-P $ha^{-1}$ and 60 kg-K $ha^{-1}$. Pastures were fertilized biennially with 20 kg-P $ha^{-1}$. Plot sizes of 200 m × 18 m (3600 $m^2$) were used to allow for grazing by cattle and the use of conventional machinery which impact directly on soil physical properties especially. A description of treatments is provided in Table 1.

### *Soil and plant sampling and analytical procedures*

Soils were sampled before planting rice each year from different systems including native savanna. The samples were air-dried, and visible plant roots were removed before they were gently crushed to pass a 2-mm sieve. The following chemical analyses were carried out: pH (1:1 soil:$H_2O$ ratio), exchangeable Al and Ca extracted in 1M KCl, and available P by the Bray-2 method. Soil pore-size distribution was determined from the moisture characteristic curves using undisturbed soil cores (50 mm × 25 mm) taken from the 0-10, 10-20 and 20-40 cm soil layers of each replicate (Phiri et al., 2001). Saturated soil cores were weighed and then subjected to different tensions (5, 10, 100, 300 and 1500 kPa). Pore-size distribution was calculated using the Kelvin equation. Pores were divided into macropores (>50 μm; drained at a tension of ≤6 kPa), mesopores (50-0.2 μm; water retained at >6 kPa but <1500 kPa) and micropores (<0.2 μm; water retained at >1500 kPa).

Table 1. Treatment description: First agropastoral cycle (five years).

| Treatment No. | System | Description |
|---|---|---|
| 1 | Native savanna | Managed traditionally by burning annually during dry season; not grazed. |
| 2 | Rice-agropastoral rotation | *Brachiaria humidicola / Centrosema acutifolium / Stylosanthes capitata / Arachis pintoi* cocktail sown with rice in year-1 and 6; grazed to maintain legume content. |
| 3 | Rice monoculture | Rice grown in monoculture; one crop per year in the first semester; second semester weedy fallow turned in with early land preparation at end of rainy season. |
| 4 | Rice-cowpea (grain) rotation | Rice (1st semester) and cowpea (2nd semester) in 1-year rotation; residues incorporated prior to planting in following season. |
| 5 | Rice-cowpea (green manure) rotation | Rice (1st semester) and green manure (2nd semester) in 1-year rotation. Legumes incorporated at maximum standing biomass levels in late rainy season. |

*Soil organic matter quality*

Soil samples were taken for the 0-10 cm and 10-20 cm layers of each treatment in February 1998 in order to characterize the impact of production system on soil organic matter quantity and quality. Total soil C and N were determined by combustion on a Leco CHN analyzer and C:N ratio calculated. Size- density fractionation of soil organic matter (SOM) was done using the Ludox Method to separate three size-density fractions: LL (>150 µm, <1.13 g $cm^{-3}$), LM (>150 µm, 1.13-1.37 g $cm^{-3}$) and LH (>150 µm, >1.37 g $cm^{-3}$) identified as most promising by Barrios et al. (1996).

*Earthworm populations under different systems*

In June 1994 and June 1996 (rainy season), the earthworm community, comprising eight species native to the savanna ecology, were sampled by taking 25×25×30 cm soil monoliths at 50 to 120 points on a regular grid in each plot of each system. Samples were taken quickly, sorted and earthworm species identified and counted at each point. Earthworm biomass was estimated using available data of mean weights of each species at the period of sampling (Decaëns and Jiménez, 2002).

*System productivity*

Rice grain yields were measured each year in at least four 5m × 5m quadrats located randomly in each plot prior to harvesting the rice crop with a combine harvester. Grain, straw and weeds were separated, weighed and subsampled for moisture content and chemical analysis.

**Results**

*Impact of systems on soil fertility indicators*

Soil chemical characteristics under the different systems is shown in Figure 1 where systems are arranged from left to right in order of increasing intensity of input use and cultivation. Temporal changes in soil pH and exchangeable Al were very similar in all systems, with the exception of the inexplicably high Al values in the surface soil under pasture in the later years. The temporal fluctuations in soil pH and exchangeable Al observed in all soil layers can probably be attributed to variability associated with factors such as burning and temporary anaerobic conditions due to high rainfall which directly impact on soil pH and, consequently, soluble Al.

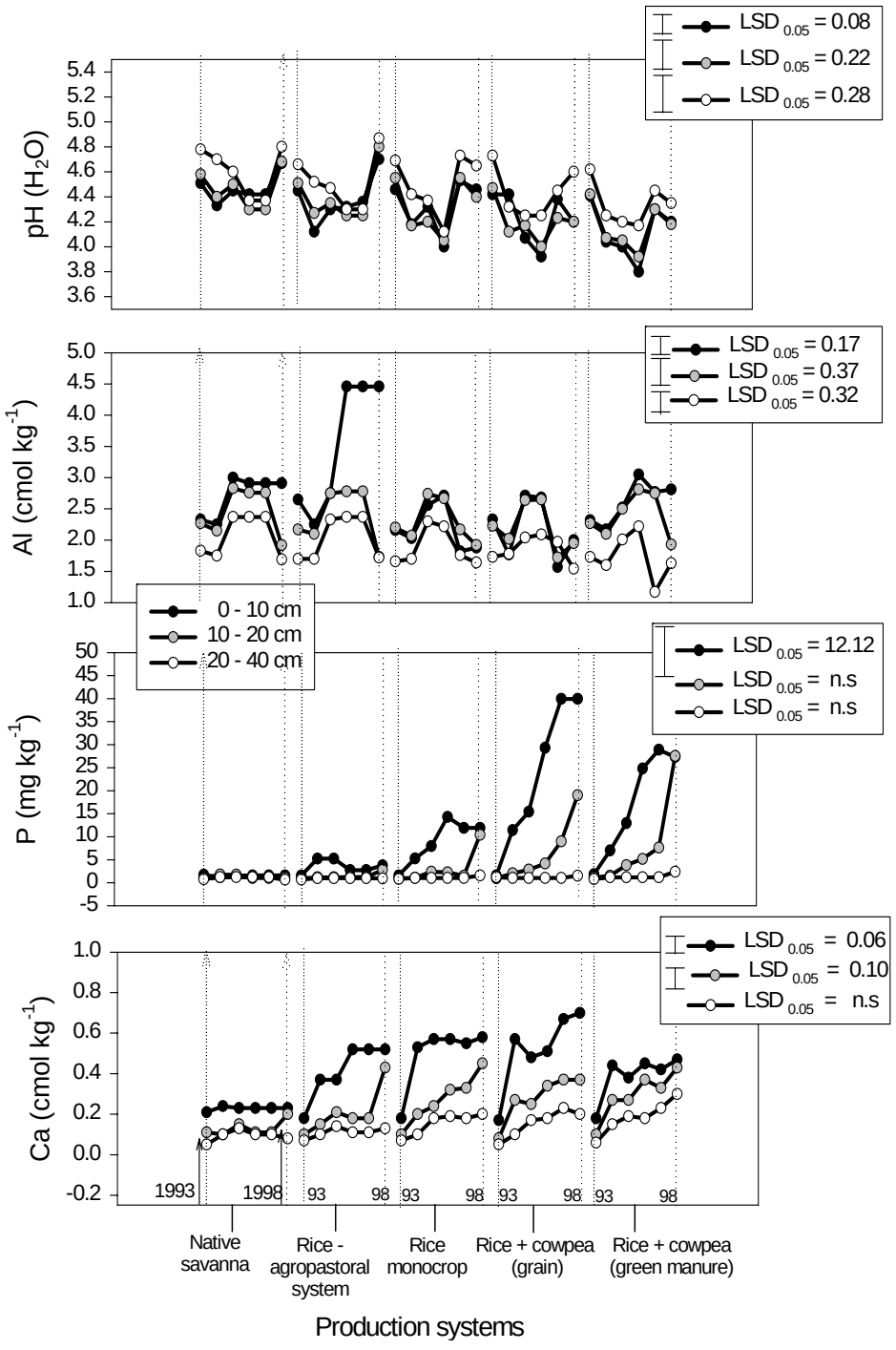


Figure 1. Changes in soil chemical characteristics under different rice-based production systems during five years (1993-98).

Soil fertility indicators for P and Ca generally reflected increasing system intensity. In the absence of inputs to the native savanna system, no significant changes in available P or exchangeable Ca were observed during the five years of experimentation. P availability remained at low levels at all depths (0-10, 10-20 and 20-40 cm), and exchangeable Ca was higher in the surface soil (0-10 cm) than in subsoil layers. Under the rice-agropastoral system, available P and exchangeable Ca levels increased modestly with time in response to the initial applications of lime and P to the pioneer rice crop and the small biennial maintenance applications to the pasture thereafter. The resultant levels of available P (about 10 mg $kg^{-1}$) are considered adequate for acid soil adapted forage germplasm.

Under rice-monocrop system, P availability increased during the first three years in response to P fertilization but failed to reflect P additions in the latter two years, especially in the surface soil layer (0-10 cm). This could be due to P removal by weeds which became increasingly prevalent as the experiment progressed, and to P fixation by soil incorporated from subsoil layers through excessive ploughing (Friesen et al., 1997). The increase in available P in the 10-20 cm layer in 1998 supports this interpretation. Exchangeable Ca increased in all soil layers in response to annual lime applications. In the surface soil, the largest increase occurred in the first year and remained unvarying thereafter. Instead, annual Ca inputs were reflected in the 10-20 and 20-40 cm layers which progressively increased during the 5-year period, presumably due to leaching from the surface soil.

Changes in soil pH and exchangeable Al were not well correlated with exchangeable Ca, contrary to expectations, probably due to the very low lime rates applied and Ca leaching as a neutral cation with nitrate or chloride which would not affect pH. Changes in exchangeable Ca under the rice-cowpea rotation were very similar to those under rice monoculture although movement of Ca into the subsoil was slightly less, perhaps due to scavenging by deep cowpea roots and cycling of Ca back to the surface through cowpea residues. In contrast, levels of available P in the 0-10 cm layer increased much more sharply over time and were accompanied by increased levels of available P in the subsurface 10-20 cm layer. These increases in available P reflect the additional applications of P fertilizer to cowpea component of the rotation while subsoil increases were probably the result of the increased frequency of cultivation required for the cowpea crop.

The rice-GM system was the most intensely cultivated. Although inputs of lime and P fertilizer were the same as for the rice-cowpea system, there were some notable differences in available P and exchangeable Ca dynamics between the two. Exchangeable Ca in the 0-10 cm layer did not rise to the levels observed in either the rice monoculture or the rice-cowpea system, although changes in the subsoil layers were very similar. This can be explained by an increased rate of leaching of soluble Ca through the soil profile with the much higher nitrate concentrations generated by mineralization of ammonia produced by decomposing GM residues (Friesen et al., 1998). Available P followed a similar temporal trend to that observed in the rice-cowpea system in the first three years. However, in the latter two years, the increased intensity of tillage apparently caused some incorporation of P into the subsoil layer, resulting in a reduced level of available P in the surface soil and an increased level in the subsoil.

*Impact on soil physical characteristics*

The impact of the different crop rotation and ley pasture systems on some soil physical characteristics 5-years after establishment is shown in Table 2. In general, the saturated hydraulic conductivity of this Oxisol under native savanna is low in the surface soil and even lower in the subsoil layers. A hydraulic conductivity of 10 cm $h^{-1}$ would be considered critical for the prevailing climatic conditions at Carimagua (2700 mm $year^{-1}$ rainfall with high intensity 100-120 mm $h^{-1}$ of rain storms). Most of the observed values were below this critical value. These results indicate that this soil has limited ability for downward movement of water, resulting in temporary waterlogging during intense storms. Infiltration of water through the soil profile is more critical with depth. Thus, any soil management strategy must include improvement of soil hydraulic conductivity. The various rice-based systems had no significant impact on hydraulic conductivity of the surface soil layer after 5 years of tillage at increasing levels of intensity. Measured two years later, chisel ploughing to 30 cm in the annual rotations and monoculture systems caused increased hydraulic conductivity in the 10-20 cm layer but not the 20-40 cm

layer. Rooting of cowpeas in the subsoil apparently aided in maintaining the effects of chiseling more than rice alone.

Table 2. Impact of different crop rotation and ley farming systems on certain soil physical characteristics at 5 years after establishment of the experiment.

| Depth (cm) | Treatment | Hydraulic conductivity (cm $h^{-1}$) | Bulk density (g $cm^{-3}$) | Macroporosity (%) |
|---|---|---|---|---|
| 0-10 | Native savanna | 5.1 | 1.24 | 14.6 |
| | Rice–Agropastoral | 3.9 | 1.31 | 12.3 |
| | Rice monoculture | 5.3 | 1.17 | 19.6 |
| | Rice–cowpea | 7.4 | 1.29 | 14.6 |
| | Rice–GM | 6.1 | 1.19 | 14.4 |
| | $LSD_{0.05}$ | NS | 0.09 | 5.1 |
| 10-20 | Native savanna | 0.9 | 1.31 | 11.3 |
| | Rice–Agropastoral | 0.5 | 1.37 | 7.8 |
| | Rice monoculture | 5.9 | 1.23 | 15.9 |
| | Rice–cowpea | 14.4 | 1.23 | 17.1 |
| | Rice–GM | 13.5 | 1.25 | 17.2 |
| | $LSD_{0.05}$ | 11.4 | 0.09 | 5.3 |
| 20-40 | Native savanna | 0.4 | 1.42 | 7.2 |
| | Rice–Agropastoral | 3.0 | 1.35 | 11.0 |
| | Rice monoculture | 0.8 | 1.47 | 6.5 |
| | Rice–cowpea | 1.9 | 1.34 | 11.3 |
| | Rice–GM | 3.7 | 1.31 | 12.4 |
| | $LSD_{0.05}$ | NS | 0.12 | 5.2 |

GM = cowpea green manure.

Statistically significant differences were found in bulk density among systems at different depths but the values found for 0-10 and 10-20 cm soil layers could be considered non-limiting for root growth and distribution. Below 20 cm soil depth where tillage implements (disc harrows) used for land preparation are not expected to have any direct impact, bulk density values were generally higher than those found in the ploughed layers. However, they were not substantially different than native savanna at that depth, indicating that land preparation was not causing added compaction in subsoil layers.

Although some statistically significant differences in macroporosity were found among the different systems, values in the 0-10 and 10-20 cm soil layers are considered non-limiting for root growth and distribution. Below this depth, some values lower than the critical level (10%) were observed. Monocropping of rice resulted in marked decrease of macroporosity for 20-40 cm soil depth when compared with rotation systems.

*Impact on soil organic matter fractions*

Trends among systems in total soil organic C and SOM fractions (i.e., LL-C) were generally the same (Table 3). However, SOM fractions were more sensitive to the effects of production system than conventional measures of total soil C. LL-C content revealed greater differences among treatments at 0-10 cm soil depth and also found significant effects at 10-20 cm depth. This agrees with results of Barrios et al. (1996, 1997) where the LL-C fraction was identified as a sensitive indicator of SOM changes due to soil and crop management not detected by total soil C.

Surface soil (0-10 cm) LL-C was usually higher than that of the sub-soil. Both total C and LL-C were highest in the agropastoral system and became progressively lower in the annual rice-based systems, in step with increasing intensity of cultivation in the order:

*Rice monocrop (1 cultivation $yr^{-1}$) > rice-cowpea (2 $yr^{-1}$) > rice-GM (3 $yr^{-1}$)*

Despite the large quantities of crop and GM residues incorporated into these systems, only the agropastoral system succeeded in building total SOM content; all other systems experienced declining total C values. Only the rice-GM system showed an increase in LL-C at 10-20 cm depth.

Table 3. Soil total C, light SOM fraction C (LL-C) and C:N ratio in surface and sub-soil layers of rice-based systems.

| Treatment | Total soil C | | *LL-C fraction* | | C:N ratio | |
|---|---|---|---|---|---|---|
| | 0-10 cm | 10-20 cm | 0-10 cm | 10-20 cm | 0-10 cm | 10-20 cm |
| Native savanna | 23950 ab* | 18200 a | 595 b | 217 ab | 15.8 b | 17.0 a |
| Rice–agropastoral | 25450 a | 18925 a | 794 a | 239 ab | 18.9 a | 18.1 a |
| Rice monocrop | 22450 bc | 19975 a | 497 bc | 167 bc | 16.4 b | 17.2 a |
| Rice–cowpea | 22700 bc | 18725 a | 419 c | 101 c | 16.4 b | 17.5 a |
| Rice–GM | 21075 d | 21050 a | 301 d | 335 a | 13.8 c | 17.1 a |

*Within columns, means followed by the same letter are not significantly different according to LSD (0.05).

Soil C:N ratio was significantly reduced in the surface soil of the rice-GM system, corresponding to the inputs of high quality organic residues. On the other hand, C:N ratio increased significantly in the agropastoral system, probably due to the high litter production of the grass component with its high C:N ratio. Lower soil C:N ratios in the rice-GM system are indicative of higher potential soil N availability, which can be equated with improved plant nutrition or alternatively greater potential for N loss from the system. High rates of legume residue decomposition in this experiment were reported previously (Friesen et al, 1998) and explain the failure to generate an increased SOM content in this system despite the high organic matter inputs.

*Impact of systems on soil macrofauna (earthworms)*

Intensification and land use system affected earthworm communities in different ways. One year after breaking native savanna (1993), a drastic reduction in earthworm density and biomass was observed in the established rice monocrop and agropastoral systems. Two years later (1996), earthworm density and biomass decreased sharply along a gradient in which highly intensified annual crop systems had deep detrimental impacts that were more accentuated in the rotations (i.e. systems that were tilled 2 or 3 time per year) – down to 3 individuals $m^{-2}$ and 0.1 g $m^{-2}$ in the rice-GM rotation from 50 individuals $m^{-2}$ and 3.2 g $m^{-2}$ in the native savanna (Decaëns and Jiménez, 2002).

Earthworm species responded differently to intensification. Only one species, the small endogeic *Ocnerodrilidae* sp., seemed to be enhanced by the conversion of the savanna into annual crops which usually led to a drastic reduction of the number of species. Three species, *Andiodrilus* n. sp., *Aymara* n. sp. and *Glossodrilus* n. sp. often disappeared from the soil of these systems (Decaëns and Jiménez, 2002), although those species with a high surface mobility were able to colonize the agroecosystems again. Other species showed a high population growth potential that allowed them to recover to their population density before the perturbation. Sensitive species disappeared after pasture establishment but richness was recovered 3 years later.

*Impact of systems on rice productivity*

Average rice grain yields fluctuated from year to year in response to differences in moisture availability and, more importantly, increased competition from weeds (data not shown). The latter also resulted in increased variability and an inability to detect significant differences among systems in later years (Table 4). Rice-legume (cowpea or GM) rotations tended to produce greater yields throughout the 4-year period following establishment in 1993; however, these were only statistically significant in 1994.

With the exception of 1995, average rice grain yields did not show any apparent decline with time in any of the three annual production systems.

Table 4. Grain yields of upland rice from different rice-based systems.

| Treatment | 1993[§] | 1994 | 1995 | 1996 | 1997 |
|---|---|---|---|---|---|
| | ---------- (Mg grain ha$^{-1}$) ---------- | | | | |
| Rice–agropastoral | 3290b* | - | - | - | - |
| Rice monoculture | 2820a | 2120a | 1280 | 3220 | 3090 |
| Rice–cowpea rotation | 2820a | 3210b | 1380 | 2520 | 5070 |
| Rice–GM rotation | 2820a | 3380b | 2140 | 3230 | 5430 |
| Level of significance | 0.02 | 0.01 | 0.27 | 0.28 | 0.24 |
| CV (%) | 6 | 12 | 46 | 22 | 39 |

[§] rice yields in monoculture and rotations measured as one plot in Year 1.
[*]Within columns, means followed by the same letter are not significantly different according to LSD (0.05).

**Discussion and Conclusions**

This 5-year field study examined the effects of contrasting rice-based production systems on rice productivity and indicators of soil chemical/fertility, physical and biological health. Increased intensity of fertilizer inputs associated with increased system intensity generally resulted in commensurate increases in soil fertility under those systems. A previous report (Friesen et al, 1998) showed increasing levels of inorganic N in soil profiles to 1-m depth under rice monoculture < rice-cowpea < rice-GM, with significant and substantial leaching due primarily to legume residues in the latter two systems. The long-term consequences and externalities of improved N fertility in such systems cannot be discounted.

Soil physical characteristics were generally improved with increasing system intensity, probably due to the degraded nature of the soils under native savanna. Cultivation generally helped to create an 'arable layer' (Phiri et al, 2001) by incorporating immobile nutrients such as P to depth in this infertile Oxisol. However, these beneficial effects can only be considered short-term. Cultivation also resulted in declining levels of SOM, particularly in the LL-C fraction, which may have consequences on soil structure in the longer term.

Soil macrofauna were the most adversely affected by production systems. Cultivation caused drastic reductions in earthworm populations and biomass, more severely so with increasing intensity and frequency. Since soil macrofauna have direct beneficial effects on many soil characteristics that affect its long term productivity (such as nutrient cycling, soil structure, soil water dynamics, bulk density and root penetrability), managing systems in ways that minimize the impact on macrofaunal populations will be an essential consideration in the sustainable use of this agroecosystem. Within the context of the savannas, Jiménez et al. (2001) proposed a hypothetical conservative agricultural production system to preserve benefits of soil fauna which integrated: (i) native vegetation plots possibly used as extensive pastures and as a reserve of biodiversity; (ii) permanent pastures for livestock systems that allow the establishment of important native earthworm biomass; (c) agro-pastoral systems with annual crops managed in rotation with temporary pastures and located contiguously to permanent pastures to maximize migration of populations. Integration of more intense production systems which build the 'arable layer' but thereafter revert to more conservative tillage practices may be viable alternatives whose sustainability should be examined at the landscape scale.

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*Agriculture, Ecosystems and Environment (in review)*

# Fallow management for soil fertility recovery in tropical Andean agroecosystems in Colombia

Edmundo Barrios , Juan G. Cobo, Idupulapati M. Rao, Richard J. Thomas, Edgar Amézquita, Juan J. Jiménez
Centro Internacional de Agricultura Tropical (CIAT), A.A. 6713, Cali, Colombia

## Abstract

Andean hillsides dominate the landscape of a considerable proportion of Cauca Department in Colombia. The typical cropping cycle in the region includes monocrops or intercrops of maize (*Zea mays* L.), beans (*Phaseolus vulgaris* L.) and/or cassava (*Manihot esculenta* Crantz). Cassava is usually the last crop before local farmers leave plots to natural fallow until soil fertility is recovered and a new cropping phase can be initiated. Previous studies on land use in the Río Cabuyal watershed (6500 ha) show that a considerable proportion of land (about 25-30%) remains under natural fallow every year. The focus of our studies is on systems of accelerated regeneration of soil fertility, or improved fallow systems, as an alternative to the natural regeneration by the native flora. Fallow improvement studies were conducted on plots following cassava cultivation. The potential for soil fertility recovery after 12 and 28 months was evaluated with two fast growing trees, *Calliandra calothyrsus* Meissn (CAL) and *Indigofera constricta* L.(IND), and one shrub, *Tithonia diversifolia* (Hemsl.) Gray (TTH), as slash/mulch fallow systems compared to the natural fallow (NAT). All planted slash/mulch fallow systems produced greater biomass than the natural fallow. Greatest dry biomass (16.4 Mg $ha^{-1}$ $yr^{-1}$) was produced by TTH. Other planted fallows (CAL and IND) produced about 40% less biomass than TTH and the control (NAT) about 75% less. Nutrient levels in the biomass were especially high for TTH, followed by IND, CAL, and NAT. The impact of fallow management on soil chemical, physical and biological parameters related to residual soil fertility during the cropping phase was evaluated. Soil parameters most affected by slash/mulch fallow systems included soil total N, available N (ammonium and nitrate), exchangeable cations (K, Ca, Mg and Al), amount of P in light fraction, soil bulk density and air permeability, and soil macrofauna diversity. Results from field studies suggest that the *Tithonia* slash/mulch fallow system could be the best option to regenerate soil fertility of degraded volcanic-ash soils of the Andean hillsides.

**Key words**: *Calliandra*, fallows, *Indigofera*, slash and mulch, soil quality, *Tithonia*

## Introduction

In the humid tropics, a substantial proportion (36%) of agricultural land is on steep or very steep slopes (Wood et al., 2000). In mountainous regions of developing countries, these lands often play a central role in rural food security and increasingly supply urban and/or export food and forest product markets. Andean hillsides contribute to food production through agricultural systems but these systems are characterized by low productivity and limited use of nutrient inputs. They harbor a large proportion of the rural poor and are an important source of water for the urban population and agricultural and industrial activities downstream (CIAT, 1996a). Densely populated hillsides in the humid and sub-humid tropics are considered to be areas where diversification of cropping systems to include trees and shrubs could improve soil fertility, increase production of fuel-wood, and result in better watershed management (Young, 1997).

Traditional agricultural systems in Colombia's tropical hillsides are based on shifting cultivation that involves slashing and burning of the native vegetation, followed by continuous cultivation and abandonment after 3-5 years because of low crop yields (Knapp et al., 1996). Leaving degraded soils to "rest" or "fallow" is a traditional management practice throughout the tropics for restoration of soil

fertility lost during cropping (Sánchez, 1995). Successful restoration of soil fertility normally requires a long fallow period for sufficient regeneration of the native vegetation and establishment of tree species (Young, 1997). Increased pressure on land as a result of population growth has limited the possibility for long fallow periods. When purchasing power is low, one alternative to traditional fallows is to improve fallows with plants that replenish soil nutrient stocks faster than plants in natural succession (Barrios et al., 1997). Planted fallows are an appropriate technological entry point because of their low risk for the farmer, relatively low cost, and potential to generate additional products that bring immediate benefit while improving soil fertility (i.e. fuel-wood).

Slash and mulch agroforestry systems include alley cropping systems where pruned biomass from tree rows is applied in the alleys between the rows before planting (Kang et al., 1990). Alternatively, biomass transfer systems include the harvesting and transporting of biomass from one farm location (e.g., live fences) to another as a source of nutrients for the crop (Jama et al., 2000). Fallow enrichment of traditional slash/mulch systems of 'frijol tapado' in Costa Rica have also shown the importance of the inclusion of trees as a source of biomass and nutrients during soil fertility recovery (Kettler, 1997). In the Honduran 'quezungual' system trees are left in cropped fields and pruned periodically to keep competition low while providing plant residues for soil cover and as a source of nutrients (Hellin et al., 1999).

The volcanic-ash soils in Colombian hillsides generally contain high amounts of soil organic matter (SOM) but nutrient cycling through SOM in these soils is limited because most of it is chemically protected, which limit the rate of its decomposition (Phiri et al., 2001). The slash/mulch fallow system described in this work has the spatial design features of an agroforestry planted fallow system but involves prunings with the resulting biomass applied to the same fallow plot. This system is expected to accelerate nutrient recycling through increased biological activity in soils with high inherent nutrient reserves but low nutrient availability. In this paper we explore the agronomic features of this system as well as its impact on soil fertility recovery as measured by some soil chemical, physical and biological parameters before a cropping phase of maize.

## Materials and Methods

*Site description*

The study was conducted on two farms in Pescador, located in the Andean hillsides of the Cauca Department, southwestern Colombia (2º48' N, 76º33' W) at 1505 m above sea level. The area has a mean temperature of 19.3°C and a mean annual rainfall of 1900 mm (bimodal). The experiment started in November 1997 and the fallow phase concluded after 27 months (FebruaryMarch 2000).

Soils in the area are derived from volcanic-ash deposition and are classified as Oxic Dystropepts in the USDA classification, with predominant medium to fine textures, high fragility, low cohesion, and shallow humic layers (IGAC, 1979). Soil bulk density is close to 0.8 Mg $m^{-3}$. Soils in the top 20 cm are moderately acid ($pH_{H20}$ = 5.1), rich in soil organic matter (C = 50 mg $g^{-1}$), low in base saturation (57%) and effective CEC (6.0 cmol $kg^{-1}$), and also low P availability (Bray-II P = 4.6 mg $kg^{-1}$). Low soil P availability is the result of high allophane content (52-70 g $kg^{-1}$) which increases soil P sorbing capacity (Gijsman and Sanz, 1998).

*Experimental design*

Experiments were set up at two locations in the Cauca Department hillsides on degraded soils previously cultivated with cassava for three years. Experiment BM1 was established at San Isidro Farm in Pescador. It was established as a random complete block (RCB) design with four treatments and three field replications. Treatments included two tree legumes, *Indigofera constricta* (IND) and *Calliandra calothyrsus* (CAL), one shrub, *Tithonia diversifolia* (TTH), and a natural regeneration or fallow (NAT). Plant species were selected on the basis of their adaptation to the hillside environment, ability to withstand periodical prunings, and the contrasting chemical composition of their tissues. The plot size was 18 m by 9 m. Experiment BM2 was established at the Benizio Velazco Farm also in Pescador. It was also established

as a RCB design with three treatments due to limited space available and three field replications. Treatments included IND, CAL and NAT with same plot size and management as in BM1.
Glasshouse grown two-month old *Indigofera* and *Calliandra* plants, inoculated with rhizobium strains CIAT 5071 and CIAT 4910 respectively and a common *Acaulospora longula* mycorrhizal strain, were planted in the field at 1.5 x 1.5 m spacing for treatments IND and CAL respectively. *Tithonia* cuttings were initially rooted in plastic bags before transplanting to the field using a 0.5 x 0.5 m spacing. During the first two months all planted fallows were frequently weeded to facilitate rapid establishment, thereafter no additional weeding took place. The natural regeneration treatment, NAT, received no management at all and served as control since this is the common practice of local farmers once their soils have become unproductive. Treatments IND and CAL were pruned to 1.5 m height at 18 months after planting and weighed biomass was laid down on the soil surface. In the TTH treatment, plants were pruned to 20 cm six times, starting six months after planting, and weighed biomass laid on the soil surface. Pruning intensity in TTH was guided by farmers concern that this common weed may become too competitive if allowed to produce seeds. In the case of IND and CAL the strategy was to reduce the impact of prunings on stem diameter increase and thus value as fuel wood at the end of the fallow phase. Whole plot measurement of biomass production during each pruning event was carried out and a composited sub-sample taken for laboratory analyses before laying down the pruned biomass on the soil surface. All above-ground biomass was harvested after 27 months with the conclusion of the fallow phase and left on the soil surface until soil sampling.

*Chemical analysis of plant materials*

Subsamples of each plant material evaluated were analyzed for total carbon (C), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg). All plant material was ground and passed through a 1 mm mesh before analysis. C, N and P were determined with an autoanalyzer . Potassium, Ca and Mg were determined by wet digestion with nitric-perchloric acid followed by atomic absorption spectrometry (CIAT, 1993).

*Soil sampling and analytical procedures*

High soil variability has been identified as a major limitation to evaluation of soil management strategies because of the difficulty in finding significant treatment differences in the area of study. Several measures were taken to address this potential limitation including splitting field replications in half and treating them as subplots from the beginning of the experiment, grid sampling for a composite subplot sample, and using covariance analysis.

Twenty-five samples were collected in a grid pattern and composited for each subplot at 0-5, 5-10 and 10-20 cm respectively after 12 and 28 months under the four fallow treatments. Plant litter on the soil surface was carefully removed before collecting the soil samples. Samples from each plot were air-dried, visible plant roots removed, and the samples gently crushed to pass through a 2-mm sieve.

Whole soil was ground with a mortar and pestle to <0.3 mm and then analyzed for C, N, and P. Total organic C was determined by wet oxidation with acidified potassium dichromate and external heating followed by colorimetry (Anderson and Ingram, 1993). Total N and P whole soil were determined by digestion with concentrated sulfuric acid using selenium as a catalyst, followed by colorimetric determination with an autoanalyzer. Bray P and exchangeable K were extracted with Bray II solution followed by colorimetric and atomic absorption determination respectively. Exchangeable Ca and Mg, and Al were extracted with 1M KCl solution and determined as described before (CIAT, 1993). Nitrate and ammonium were extracted in 1M KCl solution and determined by colorimetry with an autoanalyzer. .

Separate soil samples were taken from each field replication after 28 months to assess soil physical, chemical and biological parameters at the end of the fallow period. Soil bulk density was determined every 5 cm soil depth by using 50 mm long cores with 50 mm internal diameter (Blake and Hartge, 1986). Measurements for other physical parameters used similar cylinders as those indicated above. Hydraulic conductivity was measured on undisturbed core samples using a constant head of water (Klute and Dirksen, 1986). Air permeability was determined by measuring the rate of air flowing in a core

sample equilibrated at a suction of 7.5 KPa, using a Daiki DIK-5001 apparatus. Residual porosity was calculated as percentage of porosity remaining in the soil after subjecting it to a 20 KPa confined pressure at a suction equivalent to field capacity (Hakansson, 1990). Soil samples for chemical analyses were taken at three soil depths (i.e. 0-5, 5-10 and 10-20 cm).

Special attention was paid to the soil macrofauna communities (i.e. soil invertebrates larger than 2 mm) in BM1. The sampling was performed using the method recommended by the Tropical Soil Biology and Fertility Programme (TSBF) (Anderson and Ingram, 1993). In each fallow system and repetition two samples of 25 cm x 25 cm x 30 cm were taken at regular 5 m intervals. A metallic frame was used to isolate soil monoliths that were dug out with a spade and divided into 4 successive layers (i.e., litter, 0-10, 10-20, 20-30 cm). Each layer was then carefully hand-sorted in large trays and all macro-invertebrates seen with the naked eye were collected, counted, weighed and preserved in 75% alcohol, except for the earthworms which were previously fixed in 4% formalin for 2 or 3 days.

In the laboratory, invertebrates were then identified into broad taxonomic units (Orders or Families), counted and further grouped in 7 larger units, i.e., earthworms (Oligochaeta), termites (Isoptera), ants (Hymenoptera), beetles (Coleoptera), spiders (Arachnida), millipedes (Myriapoda), and "other invertebrates". Density and biomass of each of these 7 major groups were determined in each slash/mulch fallow system. Biomass was expressed as fixed weight in alcohol, 19% lesser than live weight for earthworms and termites, 9% for ants, 11% for Coleoptera, 6% for Arachnida and Myriapoda and 13% for the "other invertebrates" (Decaëns et al., 1994).

*Statistical analyses*

Analyses of variance (ANOVA) for plant biomass and nutrient data from BM1 and BM2 experiments were conducted to determine the impact of experimental site and management regime on planted fallow species. Covariance analyses were conducted on soil data from the BM1 and BM2 experiments to determine the effect of fallow systems on soil parameters. In the case when covariance analysis for a parameter showed no significance, the Tukey's Studentized Range Tests were used to compare treatment means; conversely, when covariance analysis for a parameter was significant, the General Linear Models Procedure of Least Square Means (LSM) was used to compare treatment means. ANOVA for soil physical parameters were used to compare treatment means at the end of the fallow period for BM1 and BM2 respectively. All statistical analyses were conducted using the SAS program (SAS Institute, 1990).

## Results and Discussion

*Initial soil conditions*

Experimental sites were of the same soil type and had a similar recent cropping history as stated above; nevertheless, they showed differences in certain soil parameters probably as a result of previous differences in soil management. Soil at BM1 experimental site was generally more acid, had a lower total C, higher total P, and considerably higher Bray P and exchageable Al than soil at the BM2 experimental site (Table 1).

*Biomass production*

Total biomass production of the different slash/mulch fallow systems evaluated was higher in BM1 than in BM2, independent of treatment (Fig. 1). In BM1 the order of total biomass production was TTH>IND,CAL,NAT, while in BM2 the order was CAL,IND>NAT. Published values for leguminous trees in different agroforestry systems indicate average annual additions of dry matter biomass up to 20 Mg $ha^{-1}$ $yr^{-1}$ (Young 1997). The highest total biomass production, 17.1 Mg $ha^{-1}yr^{-1}$, corresponded to *T. diversifolia,* and was likely a result of fast growth and ability to withstand coppicing about every three months. This value is comparable to the mean dry biomass production of 18.0 Mg $ha^{-1}yr^{-1}$ for *Leucaena*

*leucocephala* and greater than the 11.3 Mg $ha^{-1}yr^{-1}$ reported for *Senna siamea* in alley cropping systems (Van der Mersch et al., 1993). The mean biomass production of *C. calothyrsus* was 9.8 Mg $ha^{-1}yr^{-1}$ and 9.0 Mg $ha^{-1}yr^{-1}$ for *I. constricta*. The natural fallow (NAT), which represents the traditional fallow practice by local farmers, was dominated by herbaceous plants like *Panicum viscedellum* Scribn, *Emilia sonchifolia* (L.) DC., *Hyptis atrorubens* Poit, *Mellinis minutiflora* Beauv, *Richardia scabra* L., *Panicum laxum* SW and *Pteridium aracnoideum* (Kaulf.) Mabon. (Zamorano, 2000), and showed the lowest mean biomass accumulation (5.5 Mg $ha^{-1}yr^{-1}$). The difference observed in annual increments of dry matter production between IND and CAL as affected by experimental site suggests that *I. constricta* is more responsive to better soil conditions found in BM1 than *C. calothyrsus* while the latter is more tolerant to poorer soil conditions found in BM2. However, further multi-location testing of these species is needed to better define the environmental niches for these slash/mulch fallow species.

Table 1. Initial soil conditions for plow layer (0-20 cm) at experimental sites in BM1 and BM2

| | pH | C tot | N (mg $kg^{-1}$) | | | P (mg $kg^{-1}$) | | Ca | K | Mg | Al |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | ($H_20$) | (mg $kg^{-1}$) | total | $NO_3$ | $NH_4$ | total | Bray | (cmol $kg^{-1}$) | | | |
| BM1 | 4.67 | 52674 | 4240 | 25.10 | 12.30 | 653.2 | 10.83 | 1.70 | 0.40 | 0.65 | 1.92 |
| BM2 | 5.28 | 61741 | 4249 | 23.54 | 10.10 | 485.5 | 1.59 | 1.79 | 0.30 | 0.57 | 0.50 |

*Amount of nutrients in the biomass*

The relative contributions of nutrients through slash/mulch fallow management, expressed as percent of control (NAT), were generally highest in TTH (Table 2). Relative N contributions were highest in BM2 for both CAL and IND compared to BM1. This is possibly a result of the considerably lower (i.e. 40%) total aboveground biomass production in NAT in BM2 compared to BM1, because actual N inputs values were similar for both species in both experiments (data not shown). Research on the impact of nutrient contributions to the soil through the application of organic materials usually focus on N, increasingly on P, and least frequently on K, Ca or Mg. Nitrogen contributions through prunings of *L. leucocephala* and *S. siamea* in alley cropping systems were shown to contribute 307 kg $ha^{-1}$ and 197 kg $ha^{-1}$ respectively (Van der Mersch et al., 1993). Nitrogen contributions through slash/mulch systems TTH, IND and CAL in this study were 36%, 5% and 0.5% higher than for the *L. leucocephala* alley cropping systems mentioned above. Published values indicate that leguminous trees in alley cropping systems can contribute as much as 358 kg N, 28 kg P, 232 kg K, 144 kg Ca and 60 kg Mg per hectare (Palm, 1995). Nevertheless, nutrient availability in the soil is regulated to a large extent by the chemical composition or quality of plant tissues because they affect the rates of decomposition and nutrient release (Cadisch and Giller, 1997). All species used in this experiment have a N content greater than 2.5% which has been suggested as a conceptual threshold for N mineralization resulting in increased soil N availability to arable crops within a growing season (Palm et al., 2001). Nevertheless, while *T. diversifolia* and *I. constricta* decompose quickly because of their low lignin (6.9%, 4.6% respectively) and polyphenol (8.6%, 8.7%) contents and high *in vitro* dry matter digestibility (IVDMD) (72.4%, 77.4%), decomposition is slower in *C. calothyrsus* because of high lignin (14.5%) and polyphenol (18.4%) contents and low IVDMD (28.1%) (Cobo et al., 2002a). Recent studies also showed that fast decomposing, high quality plant materials (i.e. IND, TTH) generated high short-term N availability but low crop uptake; while slow decomposing, lower quality plant materials (i.e. CAL) resulted in greater N crop uptake presumably as a result of improved synchrony between soil nutrient availability and crop demand (Cobo et al., 2002b). Additional benefits from slash/mulch fallow systems include the contribution to soil nutrient pools from fine roots through root turnover and root dieback caused by pruning of above ground biomass. The importance of fine root and mycorrhiza turnover has generally been under emphasized as it has been shown in forest systems that

they can contribute up to 4 times more N and up to ten times more P than above ground litterfall (Bowen, 1984). There is little information on the amount of nutrients supplied through roots in agroforestry systems (Palm, 1995). Root biomas of trees is usually between 20-50% of aboveground biomass, giving shoot:root ratios ranging from 4:1 to 1.5:1, but the proportion of roots becomes higher on nutrient- and/or water-limited soils (Young, 1997).

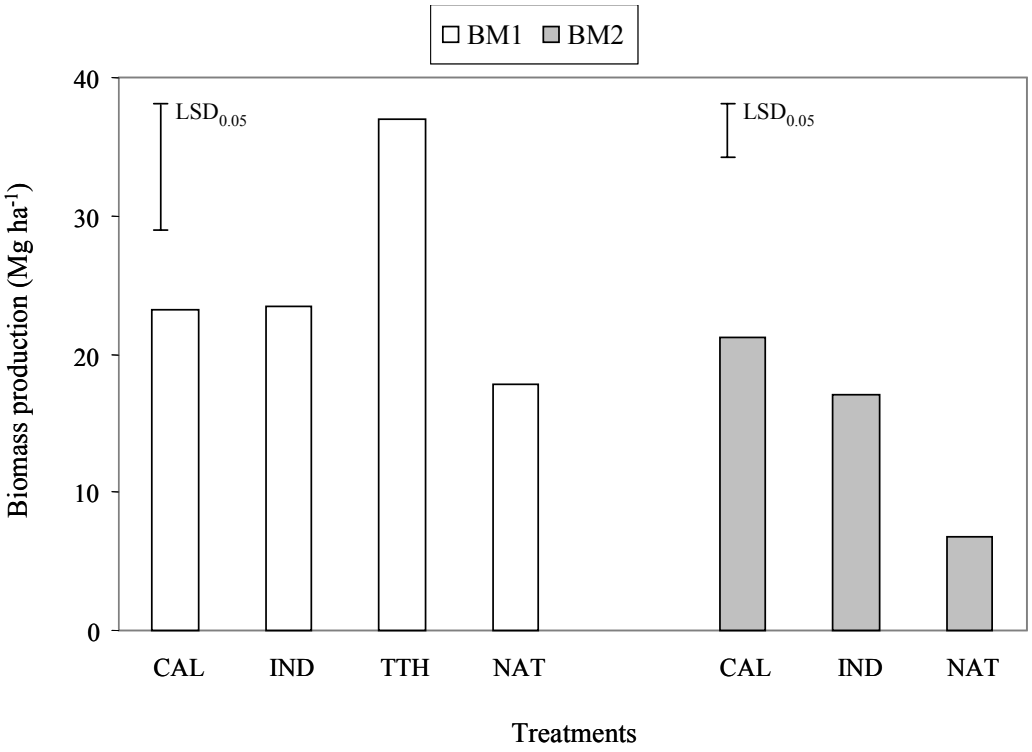


Fig. 1. Dry matter aboveground production by slash/mulch and natural fallow systems at the BM1 and BM2 sites after 27 months.

One important difference between slash/mulch fallow systems and biomass transfer systems is related to their long-term impact and sustainability. Slash/mulch fallow systems are likely to promote soil nutrient availability through remobilization of nutrients from less available soil nutrient pools. This may be a result of priming effects on soil mineralization processes triggered by labile C added with prunings as well as by root death and decomposition following slash/mulch. A considerable proportion of nutrients released is likely to be reabsorbed by the standing root biomass of fallow species and lead to new biomass growth. This cycle repeats with each slash/mulch event as nutrient recycling constitutes the basis of the functioning and sustainability of this cropping system. On the other hand, biomass transfer systems lead to variable levels of nutrient mining because they generate negative nutrient balances in soils under hedges and thus their long term use is limited as indicated by Gachengo et al. (1999) and Jama et al. (2000).

Table 2. Differences in total aboveground nutrient contributions by slash/mulch fallow systems compared to the natural fallow at BM1 and BM2 experiments

| Experiment | Treatments | % of control (NAT) | | | | |
|---|---|---|---|---|---|---|
| | | N | P | K | Ca | Mg |
| BM1 | CAL | 176 | 5 | -1 | 58 | 21 |
| | IND | 217 | 43 | 17 | 130 | 62 |
| | TTH | 215 | 225 | 283 | 351 | 223 |
| BM2 | CAL | 606 | 120 | 138 | 269 | 311 |
| | IND | 608 | 164 | 199 | 507 | 540 |

*Soil chemical parameters in slash/mulch planted fallow systems*

Soil parameters showing significant differences among treatments included total N, available N (nitrate), exchangeable K, Mg, and Al for BM1 and available N (amonium, nitrate), and exchangeable K and Ca for BM2 (Table 3). Significant differences for most parameters, however, occurred after 12 or 28 months. The only parameters showing consistent significance across fallow age were total N in BM1 and exchangeable K in both BM1 and BM2. Because of high spatial variability, which is the characteristic feature of these hillside soils, significant changes are of considerable importance.

Table 3. Effects of four fallow systems on soil fertility parameters for plow layer (0-20 cm) at 12 and 28 months after establishment [ab].

| | | Means | | Significance level | | | |
|---|---|---|---|---|---|---|---|
| | | 12 | 28 | 12 months | | 28 months | |
| Exp | Parameter | months | months | Cov* | Treat* | Cov | Treat |
| BM1 | Ntot (mg $kg^{-1}$) | 4147 | 4645 | 0.317 | 0.050 | 0.099 | 0.043 |
| | $NO_3$ (mg $kg^{-1}$) | 8.67 | - | 0.161 | < 0.001 | - | - |
| | K (cmol $kg^{-1}$) | 0.46 | 0.45 | < 0.001 | 0.101 | < 0.001 | 0.031 |
| | Mg (cmol $kg^{-1}$) | - | 0.58 | - | - | < 0.001 | 0.052 |
| | Al (cmol $kg^{-1}$) | 1.61 | - | 0.011 | 0.028 | - | - |
| BM2 | $NH_4$ (mg $kg^{-1}$) | 14.1 | - | 0.547 | 0.040 | - | - |
| | $NO_3$ (mg $kg^{-1}$) | - | 21.7 | - | - | 0.077 | < 0.001 |
| | K (cmol $kg^{-1}$) | 0.34 | 0.34 | 0.012 | 0.063 | 0.001 | 0.039 |
| | Ca (cmol $kg^{-1}$) | 2.24 | - | < 0.001 | 0.080 | - | - |

[a]For initial values refer to Table 1 [b]Data were subjected to covariance analysis.

***Cov = Covariable; Treat = Treatment**

Treatments means for soil parameters indicated are presented in Tables 4 and 5. Total soil N was highest ($P < 0.05$) in TTH, and CAL showed the second highest value after12 and 28 months of fallow duration (Table 4). After 12 months, NAT presented the lowest soil total N while IND had the lowest soil total N at the end of the fallow period (28 months). The beneficial effects of *T. diversifolia* on soil nutrients observed in the present study confirm previous published results of Gachengo et al. (1999), also on P-fixing soils. *T. diversifolia* is highly effective in scavenging soil nutrients as previously reported by

Jama et al. (2000). This may be a result of profuse rooting systems in association with native mycorrhizae as well as the capacity to stimulate mineralization of adsorbed P and utilize organic phosphorus. *C. calothyrsus* and *I. constricta*, on the other hand, are both N-fixers deriving respectively 37 and 42 % of their N from the atmosphere (CIAT, 1996b).

Table 4. Effect of fallow species on soil total N, amonium and nitrate for plow layer (0-20 cm) after 12 and 28 months of fallow period[abc]

| | | Fallow period | | | | |
|---|---|---|---|---|---|---|
| | | 12 months | | | 28 months | |
| Exp | Treat | Ntot (mg $kg^{-1}$) | $NH_4$ (mg $kg^{-1}$) | $NO_3$ (mg $kg^{-1}$) | Ntot (mg $kg^{-1}$) | $NO_3$ (mg $kg^{-1}$) |
| BM1 | TTH | 4390 | - | 6.61 | 4913 | - |
| | CAL | 4366 | - | 7.42 | 4717 | - |
| | IND | 4008 | - | 12.6 | 4266 | - |
| | NAT | 3824 | - | 8.07 | 4683 | - |
| | *SED* | *169* | - | *1.69* | *159* | - |
| BM2 | CAL | - | 14.8 | - | - | 22.9 |
| | IND | - | 14.6 | - | - | 32.2 |
| | NAT | - | 13.0 | - | - | 8.10 |
| | *SED* | - | *0.96* | - | - | *4.54* |

[a]For initial values refer to Table 1

[b]Tukey's Studentized Range Tests was used to compare treatments means when covariable was not statistically significant ($P < 0.05$).

[c]For each parameter only treatment means are presented when their effect was shown significant in Table 3

After 12 months, slash/mulch fallow systems containing TTH showed the highest exchangeable K and lowest exchangeable Al ($P < 0.05$) in BM1 (Table 5). Studies in acid soils of Burundi have also found a reduction in exchangeable Al by green manure additions, suggesting complexing of Al by organic materials (Young, 1997). In BM2 highest exchangeable K and Ca values were found in IND and NAT respectively. At the end of the fallow phase (28 months), exchangeable K was highest for TTH overall, but the trend for the common treatments among BM1 and BM2 was the same, with NAT and IND contributing significantly ($P < 0.05$) more than CAL. Exchangeable Mg in BM1 showed the same trend as K with the difference that the IND fallow system led to the lowest soil values. The high concentration of cations, especially K in *T. diversifolia* biomass (Table 2), and the pruning management in TTH is likely to be responsible for the highest contribution to soil exchangeable cations by this slash/mulch fallow system.

The lack of significant changes in soil P parameters as a result of the slash/mulch fallow systems evaluated may, however, be influenced by the relative low amounts of P added to the soil compared with other nutrients like N and K (Palm et al., 1995) and also could be due to soils with a high P-sorption capacity (Rao et al., 1999).

Table 5. Effect of fallow species on soil exchangeable cations for plow layer (0-20 cm) after 12 and 28 months of fallow period[abc]

| Exp | Treat | Fallow Period | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 12 months | | | | | | 28 months | | | |
| | | Al (cmol kg$^{-1}$) | | K (cmol kg$^{-1}$) | | Ca (cmol kg$^{-1}$) | | K (cmol kg$^{-1}$) | | Mg (cmol kg$^{-}$ | |
| BM1 | TTH | 1.24 | b | 0.54 | a | - | - | 0.60 | a | 0.67 | a |
| | NAT | 1.84 | a | 0.48 | ab | - | - | 0.49 | ab | 0.64 | a |
| | IND | 1.88 | a | 0.38 | b | - | - | 0.36 | b | 0.48 | b |
| | CAL | 1.49 | ab | 0.43 | ab | - | - | 0.34 | b | 0.53 | ab |
| BM2 | NAT | - | - | 0.33 | ab | 2.32 | a | 0.38 | a | - | - |
| | IND | - | - | 0.39 | a | 2.19 | b | 0.36 | a | - | - |
| | CAL | - | - | 0.30 | b | 2.22 | ab | 0.29 | b | - | - |

[a]For initial values refer to Table 1

[b]Least Square Means (LSM) was used to compare treatment means when covariable was statistically significant ($P < 0.05$). Means in a column followed by the same letter do not differ significantly at $P = 0.05$.

[c]For each parameter only treatment means are presented when their effect was shown significant in Table 3

Soil fractionation generally increases the capacity to detect soil changes in SOM as a result of treatment compared to bulk soil measures (Barrios et al., 1996; 1997). Recent results from Phiri et al. (2001) focusing on soil organic matter (SOM) (Meijboom et al., 1995) and P fractions (Tiessen and Moir, 1993), rather than conventional chemical analyses (e.g., Bray II P), indicate significant differences among treatments in experiment BM1 after 12 months. The slash/mulch fallow species in TTH, IND and CAL had an overall positive effect on soil fertility parameters when compared with the natural unmanaged fallow (NAT). *T. diversifolia* showed the greatest potential to improve SOM, nutrient availability, and P cycling because of its ability to accumulate high amounts of biomass and nutrients. The amount of P in the light (LL) and medium (LM) fractions of SOM correlated well with the amount of "readily available" P in the soil (Fig. 2). It is suggested that the amount of P in the LL and LM fractions of SOM could serve as sensitive indicators of "readily available" and "readily mineralizable" soil-P pools, respectively, in the volcanic-ash soils studied.

*Soil physical parameters in slash/mulch planted fallow systems*

Bulk density values reported for BM1 and BM2 are relatively low and are in agreement with published values for other volcanic ash soils (Shoji et al., 1993). After 28 months of fallow with the four systems, significant differences ($P < 0.05$) in bulk density were only found for the 0-5 cm soil depth of experiment BM2 (Table 6). While CAL and NAT were not different, IND showed significantly higher bulk density values (Table 7). A parameter showing significant treatment effects can result from low random error (i.e. bulk density) or a large separation of treatment means (i.e. air permeability) (Mead et al., 1993). The increased bulk density observed could be the result of a decrease in SOM levels. Although SOM levels in IND were lowest but not statistically significant (data not shown) in BM2, significantly lowest ($P < 0.05$) total N values were found in IND compared to other system treatment for BM1 (Table 4). Since soil total C and soil total N are highly correlated (Wild, 1988) we can assume that the *I. constricta* slash/mulch fallow generally promoted a reduction in SOM resulting in an increased soil bulk density.

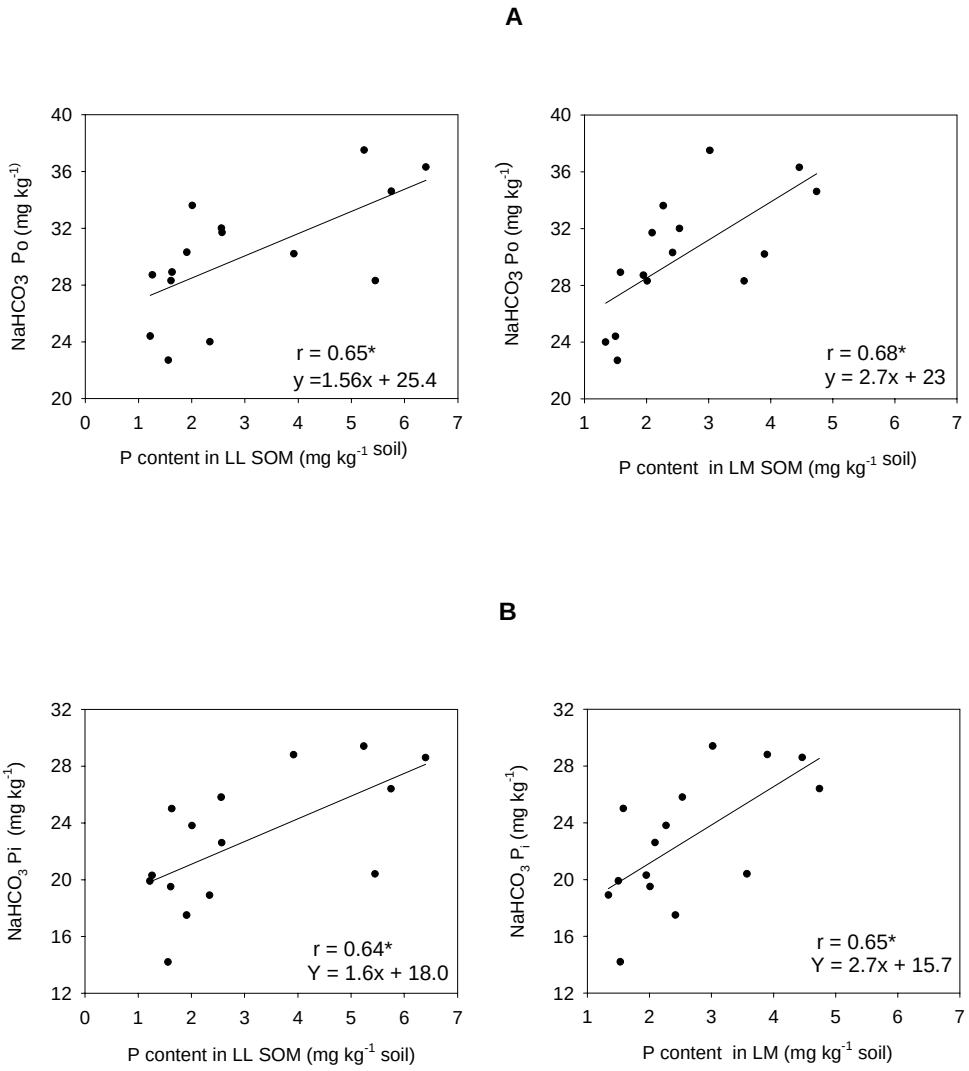


Fig. 2. The relationship between P content in the light (LL) and intermediate (LM) soil organic matter (SOM) fractions and sodium bicarbonate (NaHCO3) extractable organic P (A) and inorganic P (B) at BM1 after 12 months. The asterisk (*) indicates significance at a = 0.05.

Soil air permeability was sensitive to treatment differences in BM1 (Table 6). This parameter measures the resistance of soil to air-flow and is associated to bulk density and hydraulic conductivity. While TTH showed the highest values, CAL and NAT showed intermediate values and IND the lowest values (Table 7). These results indicate that TTH improved structural stability of surface soil presumably as a result of changes in pore size distribution which allowed better air flow while IND led to greater resistance to air flow than the control NAT.

Table 6. Probability table for effect of four fallow treatments on soil physical parameters in BM1 and BM2 after 28 months[a]

| Soil Depth (cm) | Bulk density (Mg $m^{-3}$) | | Hydraulic conductivity (cm $h^{-1}$) | | Air permeability (75 cm suction) (cm $h^{-1}$) | | Residual porosity (%) | |
|---|---|---|---|---|---|---|---|---|
| | BM1 | BM2 | BM1 | BM2 | BM1 | BM2 | BM1 | BM2 |
| 0-5 | 0.289 | 0.036 | 0.844 | 0.695 | 0.018 | 0.775 | 0.413 | 0.552 |
| 5-10 | 0.474 | 0.581 | 0.379 | 0.152 | 0.273 | 0.747 | 0.104 | 0.554 |
| 10-15 | 0.124 | 0.449 | 0.693 | 0.354 | 0.412 | 0.763 | 0.595 | 0.503 |
| 15-20 | 0.118 | 0.149 | 0.424 | 0.488 | 0.199 | 0.566 | 0.167 | 0.578 |

[a]Data were subjected to analysis of variance

*Soil macrofauna in slash/mulch planted fallow systems*

The characterization of the soil macrofauna communities after 28 months of slash/much fallow treatments in BM1 showed taxonomically and functionally diverse taxa. A total of 22 taxonomic units (TU) were found. Macro-invertebrate total density ranged from 376.8 individuals (ind.) $m^{-2}$ in TTH to 304.8 ind. $m^{-2}$ in CAL. Conversely, macro-invertebrate biomass ranged from 18.2 g $m^{-2}$ in IND to 6.1 g $m^{-2}$ in TTH (Fig. 3). Other invertebrates corresponded to some nematodes (Mermithidae), hemipterans (Hemiptera) , snails (Gastropoda) and grasshoppers (Orthoptera). Termites (Isoptera) were almost absent from all fallow treatments, being less than 1% of total macro-fauna abundance.

Table 7. Effect of four fallow treatments on soil bulk density and air permeability at 0-5 cm soil depth in BM1 and BM2 after 28 months[a]

| | Experiment | |
|---|---|---|
| | BM2 | BM1 |
| Treatment | Bulk density (Mg $m^{-3}$) | Air permeability (cm $h^{-1}$) |
| CAL | 0.7 | 50.5 |
| IND | 0.8 | 33.8 |
| NAT | 0.69 | 64.7 |
| TTH | - | 91.6 |
| *SED* | *0.03* | *12.6* |

[a]For each parameter only treatment means are presented when their effect was shown significant in Table 6

The main groups of soil macro-invertebrates were rather abundant, especially ants (Hymenoptera). The abundance of ants, comprised of several species, was highest in TTH (254.8 ind.$m^{-2}$) and lower in IND and NAT (176 ind.$m^{-2}$). Earthworm density was lowest in TTH (19.2 ind.$m^{-2}$) and highest in IND (106.8 ind.$m^{-2}$). These two taxa were the main components of total macro-invertebrate biomass in all systems ranging from 46.9% in TTH to 73.1% in IND in the case of earthworm biomass. We found the

exotic earthworm species *Pontoscolex corethrurus* (Glossoscolecidae) that is commonly found when tropical natural ecosystems are replaced by different production systems (Fragoso et al., 1999). In some Amazonian agroecosystems, the presence of this exotic has had a negative effect on soil properties, mainly due to loss of the original earthworm diversity rather than to the mere presence of this earthworm (Chauvel et al., 1999). Larvae of beetles (Coleoptera) were also highly abundant and their biomass was lowest in IND (78.8 g $m^{-2}$) and highest in TTH (120.8 $gm^{-2}$).

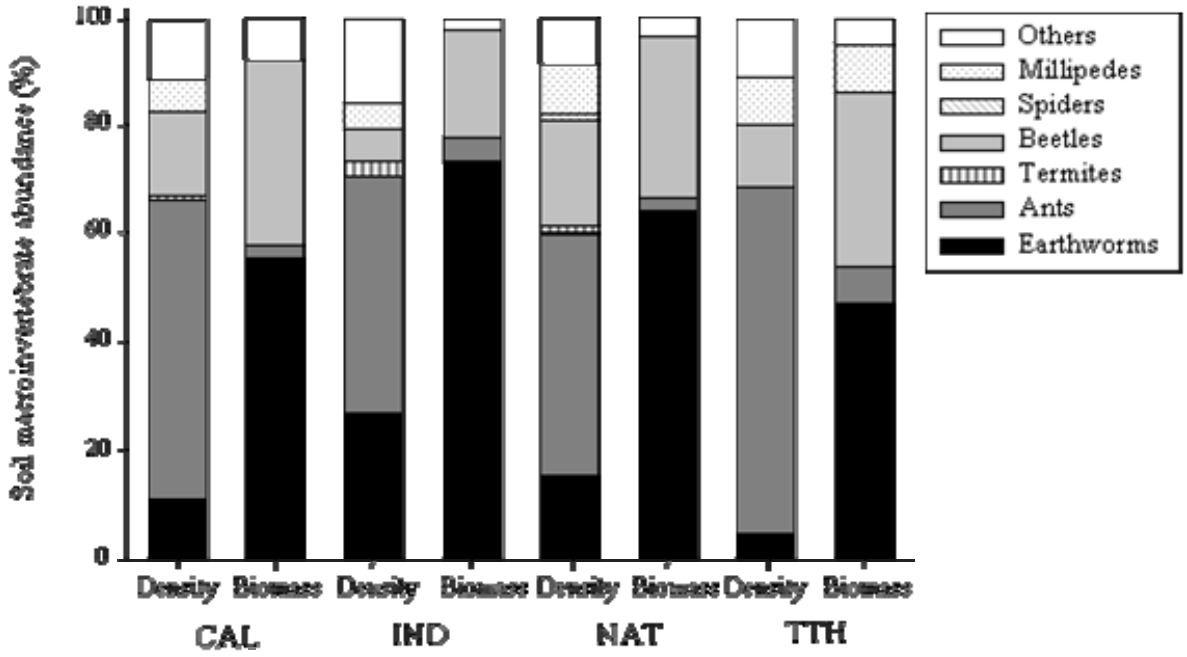


Fig. 3. Density and biomass of soil macroinvertebrate communities in the slash/mulch fallow systems at the BM1 site at the end of the fallow phase.

The impact of slash/mulch treatment differences is consistent with other results presented and suggest three generally distinct groups TTH, CAL+NAT, and IND. High ant activity in TTH, as indicated by high density, suggests that we may be underestimating the potential impact of *T. diversifolia* additions because a considerable proportion may be exported by ants to their nests. On the other hand, earthworm activity is well known for stimulating N mineralization rates (Barois et al., 1987; Lavelle et al., 1992; Decaëns et al., 1999; Rangel et al., 1999) and the observation of particularly high numbers of individuals in IND coincides with the observation of a reduction in total soil N and an increase in soil available N. The conspicuous presence of *P. corethrurus* in IND and the observation that compact casts increase soil compaction (Hallaire et al., 2000), because of the limited presence or absence of soil fauna able to decompact such casts (Blanchart et al., 1997, P.Lavelle pers.comm.), suggests that increased soil bulk density observed in IND may have been mediated by increased activity of this species.

Some groups of soil macroinvertebrates may have beneficial effects on some soil parameters evaluated but others, on the contrary, may cause damage since they constitute soilborne pests. Therefore, it is necessary to increase the level of resolution of identifications studies to the species level. This seems to be of particular relevance when using soil macrofauna as biological indicators of soil functioning and health (Pankhurst et al., 1997). Nevertheless, since information on soil fauna was not available at the beginning of the experiment and was limited to BM1, conclusions regarding the impact of production systems on the soil macrofauna communities must be considered preliminary.

## Conclusions

Slash/mulch planted fallow systems evaluated in this study were more productive in terms of biomass production and nutrient recycling than the traditional practice of natural regeneration by native flora, suggesting that the objective of increased nutrient recycling was achieved. This study attempted to integrate understanding of the impacts of slash/mulch planted fallow systems on soil quality by simultaneously evaluating the chemical, physical and biological dimensions of the soil. The TTH slash/mulch fallow system proved to be the best option to recover the overall soil fertility of degraded soils following cassava monocropping in the study area. Nevertheless, its use may be limited in areas with seasonal drought as it is not very tolerant to extended dry periods. The CAL slash/mulch fallow system proved to be the most resilient as it produced similar amounts of biomass independent of initial soil quality and thus a candidate for wider testing as a potential source of nutrient additions to the soil and fuelwood for rural communities. The slower rates of decomposition in CAL, compared to IND and TTH, suggest that benefits provided may be longer lasting and potential losses would be reduced through improved synchronization between nutrient availability and crop demand. The IND slash/mulch fallow, on the other hand, showed more susceptibility to initial soil quality and this may limit its potential for extended use.

Increased soil bulk density as a result of decrease in SOM, observed in slash/mulch planted fallows using IND, was possibly mediated by the presence of large populations of the endogeic earthworm *P. corethrurus*. This earthworm species is known to stimulate N mineralization and to be responsible for soil compaction when a diverse macrofauna community capable of ameliorating soil physical structure is limited or absent. Although increased available N may have positive short-term impacts, the significant decrease in total soil N suggests that considerable N losses may be occurring during the fallow phase and benefits to subsequent cropping could be limited. Further multilocation testing is needed to confirm these observations, and also to study the 'fallow effect' on crop yield as well as the economic feasibility of slash-mulch fallow systems.

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# Sequential phosphorus extraction of a $^{33}$P-labeled oxisol under contrasting agricultural systems

S. Buehler[1], A. Oberson[1], I.M.Rao[2], E. Frossard[1] and D.K. Friesen[3]

[1]Institute of Plant Sciences, Swiss Federal Institute of Technology (ETH),
Eschikon 33, 8315 Lindau, Switzerland
[2]Centro Internacional de Agricultura Tropical, CIAT, A.a. 6713, Cali Colombia
[3]formerly IFDC/CIAT, now IFDC/CIMMYT Kenya, P.O. Box 25171, Nairobi, Kenya

## Abstract

Chemical sequential extraction is widely used to divide soil phosphorus (P) into different inorganic and organic fractions, but the assignment of these fractions to pools of different availability, especially for low P tropical soils, is still matter of discussion. To improve this assignment, the effect of land-use systems and related P fertilizer inputs on size of P fractions and their isotopic exchangeability was investigated. A Colombian Oxisol, sampled from a long-term field experiment with contrasting management treatments was labeled with carrier free $^{33}$P and extracted after incubation times of 4 hours, 1 and 2 weeks. Phosphorus concentrations (inorganic=$P_i$ and organicP=$P_o$) and $^{33}$P recovery in fractions sequentially extracted with resin ($P_i$), 0.5 *M* $NaHCO_3$ (Bic-$P_i$, Bic-$P_o$), 0.1 *M* NaOH ($P_i$, $P_o$), hot concentrated HCl ($P_i$, $P_o$) and residual P were measured at each time. Resin-$P_i$, Bic-$P_i$, NaOH-$P_i$ and hot HCl-$P_i$ were increased with fertilization, with highest increase for NaOH-$P_i$. The recovery of $^{33}$P in the two soils with annual fertilizer inputs and large positive input-output P balances indicate that resin-$P_i$, Bic-$P_i$ and NaOH-$P_i$ contained most of the exchangeable P. In these soils the label moved with increasing incubation time from the resin to the Bic-$P_i$ and NaOH-$P_i$ fraction. As the $^{31}$P content of these fractions remained constant, the transfer of $^{33}$P suggests P exchange among these fractions. The organic or recalcitrant inorganic fractions contained almost no exchangeable P. In contrast, in soils with low or no P fertilization, more than 14% of added $^{33}$P was recovered in NaOH-$P_o$ and HCl-$P_o$ fractions two weeks after labeling, showing that organic P dynamics are important when soil Pi reserves are limited.

**Key words:** Oxisol, land-use system, sequential P fractionation, short term P dynamics, $^{33}$P labeling, metallic (oxy)hydroxides, soil microbial biomass

**List of abbreviations:** Bic-P: 0.5 *M* $HCO_3$-extractable P, CIAT: Centro Internacional de Agricultura Tropical, CORPOICA: Corporacion Colombiana de Investigacion Agropecuario, $C_p$: P concentration in the soil solution, $P_i$: inorganic P, $P_o$: organic P, SA: specific activity ($^{33}$P/$^{31}$P)

## Introduction

Phosphorus (P) is an essential nutrient for plants and often the first limiting element in acid tropical soils. Profound understanding of the P dynamics in the soil/plant system and especially of the short- and long-term fate of P fertilizer in relation to different management practices is essential for the sustainable management of tropical agroecosystems (Friesen et al., 1997). Chemical sequential extraction procedures have been and still are widely used to divide extractable soil P into different inorganic and organic fractions (Chang and Jackson, 1957; Bowman and Cole, 1978; Hedley et al., 1982; Cross and Schlesinger, 1995). The underlying assumption in these approaches is that readily available soil P is removed first with mild extractants, while less available or plant-unavailable P can only be extracted with stronger acids and alkali. In the fractionation procedure developed by Hedley et al. (1982) and modified by Tiessen and Moir (1993), the P fractions (in order of extraction) are interpreted as follows. Resin-$P_i$ represents inorganic P ($P_i$) either from the soil solution or weakly adsorbed on (oxy)hydroxides or

carbonates (Mattingly, 1975). Sodium bicarbonate 0.5 *M* at pH 8.5 also extracts weakly adsorbed $P_i$ (Hedley et al., 1982) and easily hydrolysable organic P ($P_o$)-compounds like ribonucleic acids and glycerophosphate (Bowman and Cole, 1978). Sodium hydroxide 0.5 *M* extracts $P_i$ associated with amorphous and crystalline Al and Fe (oxy)hydroxides and clay minerals and $P_o$ associated with organic compounds (fulvic and humic acids). Hydrochloric acid 1 *M* extracts $P_i$ associated with apatite or octacalcium P (Frossard et al., 1995). Hot concentrated HCl extracts $P_i$ and $P_o$ from more stable pools. Organic P extracted at this step may also come from particulate organic matter (Tiessen and Moir, 1993). Residual P, i.e. P that remains after extracting the soil with the already cited extractants, most likely contains very recalcitrant $P_i$ and $P_o$ forms.

Several studies related these different P fractions in tropical soils to plant growth (Crews, 1996; Guo and Yost, 1998) or showed the influence of land-use and the fate of applied fertilizers (Iyamuremye et al., 1996; Linquist et al., 1997; Lilienfein et al, 1999; Oberson et al., 1999), and partly resulted in contrasting assignments of fractions to pools of different availability. By comparing the amounts of P extracted from the surface horizons of Brazilian Oxisols that had been under different land-use systems for 9-20 years, either unfertilized or with mineral P fertilizer application, Lilienfein et al. (1999) showed that most of the fertilizer was recovered in the Bic- and NaOH-$P_i$ fractions, irrespective of the land-use system (resin-$P_i$ was not measured). In a 4-year field study conducted on a Hawaiian Ultisol, Linquist et al. (1997) recovered one year after fertilizer application almost 40% of the applied triple super phosphate (TSP) fertilizer in the hot HCl and $H_2SO_4$ fractions. Oberson et al. (1999) showed that in an Oxisol managed as a legume-grass pasture for 15 years resin-$P_i$, Bic- and NaOH-$P_i$ as well as NaOH-$P_o$ levels were maintained at a higher level over the whole year in comparison to the same soil with the same total P content but managed as a grass only pasture. Iyamuremye et al. (1996) found an increase of resin-$P_i$, Bic-$P_i$ and -$P_o$ as well as NaOH-$P_i$ after addition of manure or alfalfa residues to acid low-P soils from Rwanda. In the study of Guo and Yost (1998), resin-$P_i$, Bic- and NaOH-$P_i$ were most depleted by plant uptake on highly weathered soils. NaOH-$P_i$ was important in buffering available P supply while significant depletion of organic fractions could rarely be measured.

A possible method to gain information about the availability of different P fractions is to label soil P, fertilizers or plant residues before applying the sequential fractionation scheme (MacKenzie, 1962; Weir and Soper, 1962, Dunbar and Baker, 1965). Two studies followed the movement of labeled P from plant residues to soil P fractions applying a modified Hedley (Daroub et al., 2000) or the Chang and Jackson (1957) fractionation procedures (Friesen and Blair, 1988). They found that at six or eleven days, respectively, after plant residue addition between 20 and 50 % of the label was extractable as $P_i$ with a resin (Daroub et al., 2000) or with $NH_4Cl$ and $NH_4F$ (Friesen and Blair, 1988). For longer incubation periods up to 34 days, Daroub et al. (2000) showed a subsequent movement of the label from the resin-$P_i$ fraction to the NaOH-$P_i$ fraction. The results obtained in these studies suggest that, in tropical soils, the amounts of P in the different pools measured by sequential P extraction procedures and the fluxes of P between pools are controlled both by physico chemical factors (sorption/desorption) and by biological reactions (immobilization/mineralization). However, the importance of these different reactions for different land-use systems, such as monocropping, pasture or intercropping, remain largely unknown.

The objective of this study was to assess the effect of different land-use systems (native savanna, rice monocropping, rice green manure rotation, grass legume pasture) on some physico chemical and biological reactions involved in P cycling in a Colombian Oxisol. Surface soil sampled in the different cropping systems was labeled with carrier-free radioactive P ($^{33}P$). After various incubation times, P was sequentially extracted by the modified Hedley procedure (Tiessen and Moir, 1993) and $^{31}P$ and $^{33}P$ were measured in each fraction.

## Materials and Methods

Soils included in the study were sampled during the rainy season in September 1997 from a field experiment (Friesen et al., 1997) located at CORPOICA-CIAT (Corporacion Colombiana de Investigacion Agropecuario; Centro Internacional de Agricultura Tropical) research station, Carimagua, Meta, Colombia

(4°30'N, 71°19'W). Mean annual temperature is 27° C, average rainfall 2200 mm. The soils are well drained Oxisols (Kaolinitic isohyperthermic Typic Haplustox) of clay loam texture (Table 1).

The surface soil layer (0-20 cm) was sampled in the long-term "Culticore" field experiment, which was established in 1993 with the objective to test the effect of different farming systems on plant productivity and soil fertility (Friesen et al., 1997). The experiment had a split-plot design with four replicates with treatment sub-plots of 0.36 ha size. The soil samples used for this study were taken at random in two replicates of each treatment and the replicates were mixed for the laboratory analysis. For our study, the following treatments were included.

1. SAV (Native savanna): native grassland annually burned in February, not grazed; no fertilizer application.
2. GL (Grass-legume pasture): rice in 1993, with undersown pasture, since then grass-legume pasture with *Brachiaria humidicola* CIAT 679, *Centrosema acutifolium* CIAT 5277, *Stylosanthes capitata* CIAT 10280, and *Arachis pintoi* CIAT 17434. The pasture was partly resown for renovation in June 1996 with legumes (the same *Arachis pintoi*, additionally *Centrosema acutifolium* cv Vichada CIAT 5277 and *Stylosanthes guianensis* CIAT 11833). Grazing intensity was on average 2.7 steers $ha^{-1}$ during 15 d followed by a 15 d ley regrowth phase.
3. CR (Continuous rice): rice (*Oryza sativa* cv Oryzica Sabana 6, cv Oryzica Sabana 10 since 1996) grown in monoculture; one crop per year followed by a weedy fallow incorporated with early land preparation at the beginning of the rainy season before sowing rice.
4. RGM (Rice green manure rotation): Rice followed by cowpea (*Vigna unguiculata*, var. ICA Menegua) in the same year. The legume was incorporated at the maximum standing biomass level in the late rainy season before sowing rice in the following rainy season.

Before establishing the treatments, GL, CR, and RGM on savanna, the soil was conventionally tilled after burning the native vegetation. At the beginning of the experiment all treatments except SAV were limed using 500 kg dolomitic lime $ha^{-1}$. Fertilization of rice was 80 kg N ha $year^{-1}$ (urea, divided among three applications), 60 kg P ha $year^{-1}$ (triple superphosphate), 99 kg K as KCl, 15 kg Mg and 20 kg S (as $MgSO_4$) and 10 kg Zn $ha^{-1}$ at establishment and according to plant needs afterwards. With cowpea additionally 20 kg N and 40 kg P ha $year^{-1}$ and 60 kg K, 10 kg Mg, 13 kg S and 10 kg Zn $ha^{-1}$ at establishment and in adequate rates afterwards were applied. The introduced pasture (GL) received additional fertilization only in 1996 (per ha: 20 kg P, 20 kg Ca (lime), 10 kg Mg (lime), 10 kg S (elemental) and 50 kg K (KCl)). Phosphorus input-output balances were estimated by subtracting the P removed from the system by grain and/or with animal live weight gains from the P applied in mineral fertilizers. Phosphorus exports in grain were calculated by multiplying weighed rice grain yields with measured P contents in grains. P exported in the animals was assumed to be 8 g per kg of live weight gain. Live weight gains in GL were on average 68 kg $ha^{-1}$ $yr^{-1}$ (Oberson et al., 2001). Cultivated soils were tilled to a maximum of 15 cm depth.

Topsoil samples (0-20 cm) were air-dried and sieved at 2 mm before they were used for chemical analysis in the analytical service laboratory of CIAT or shipped to Switzerland where they were stored in air-dried condition until use for the fractionation experiment in 2000.

*Soil Characterization*

Bray-II P was extracted using dilute acid fluoride (0.03 *M* $NH_4F$, 0.1 *M* HCl) at 1:7 soil solution ratio using 2 g soil and 40 sec shaking time. Total soil P ($P_{tot}$) was determined on samples of 0.25 mg soil with addition of 5 mL concentrated $H_2SO_4$ and heating samples to 360° on a digestion block with subsequent stepwise (0.5 mL) additions of $H_2O_2$ until the solution was clear (Thomas et al., 1967).

Table 1. Selected chemical and physical properties of the surface soil (0-20 cm) of studied Colombian Oxisol under different gricultural systems. Values are the average of four analytical replicates, except Fe- and Al-contents (three replicates#).

| Treatment † | Total C | Total N | pH in water | Al-Saturation | $Fe_{d}$ ‡ | $Fe_{ox}$§ | $Al_{d}$‡ | $Al_{ox}$§ | Clay | Bulk density |
|---|---|---|---|---|---|---|---|---|---|---|
| | g $kg^{-1}$ | | | % | g $kg^{-1}$ | | | | % | Mg $m^{-3}$¶ |
| SAV | 27 | 1.64 | 4.8b | 86.8b | 26.7 | 3.6 | 7.8 | 2.0 | 35.0a | 1.27 |
| GL | 29 | 1.55 | 4.9b | 71.7a | 26.4 | 3.6 | 7.7 | 2.0 | 39.3b | 1.27 |
| CR | 26 | 1.45 | 4.3a | 75.4a | 26.2 | 3.7 | 7.6 | 2.0 | 39.9b | 1.21 |
| RGM | 26 | 1.49 | 4.3a | 76.3a | 26.9 | 3.5 | 7.8 | 2.0 | 39.0b | 1.24 |

† see Table 1.
‡ Extraction with dithionite.
§ Extraction with oxalate.
# Means followed by the same letter are not significantly different ($P$=0.05) by Tukey's multiple range test. The absence of ` letter in a column shows that no significant differences were observed between the treatments

Microbial P, C and N ($P_{Chl}$, $C_{Chl}$ and $N_{Chl}$) were determined on the same moist, preincubated samples as for the sequential P fractionation by extraction, of chloroforme fumigated and unfumigated samples, with Bray I (0.03 *M* $NH_4F$, 0.025 *M* HCl) ($P_{Chl}$) (Oberson et al., 1997) or $K_2SO_4$ ($C_{Chl}$ and $N_{Chl}$) (Vanceet al., 1987). No k-factors (Brookes et al., 1982; Hedley and Stewart, 1982; McLaughlin et al., 1986) were used to calculate $P_{mic}$, $C_{mic}$ or $N_{mic}$ from measured $P_{Chl}$, $C_{Chl}$ and $N_{Chl}$ as there exist no proper estimates for these acid tropical soils (Gijsman et al., 1997). $P_{Chl}$ was corrected for sorption of released P according to Oberson et al. (1997). Dithionite-citrate-bicarbonate extractable and oxalate extractable Fe and Al ($Fe_d$, $Fe_{ox}$, $Al_d$, $Al_{ox}$) were determined according to Mehra and Jackson (1960) and McKeague and Day (1966). The mineralogy of the soils was determined on total soil samples, pretreated with $H_2O_2$ to remove organic C, using X-ray diffraction analysis (XRD) (Table 1). The samples were ground under acetone in a tungsten carbide vessel of a vibratory disk mill (Retsch RS1) for 10 minutes. Longer grinding times were not applied due to the detrimental effect that further grinding can have on the crystallinity of minerals, especially Fe (hydr)oxides (Weidler et al., 1998). For the Cu Kα, the Bragg-Brentano geometry was chosen as an XRD routine setup. The measurement were carried out on a Scintag XDS 2000 equipped with a solid state detector from 2 to 52 °2 \θ with steps of 0.05 °2\θ and counting times of 16 seconds.

*Sequential P Fractionation of Labeled Soils*

Before starting the sequential P fractionation, the soils were preincubated in a climate chamber (24°C and 65 % relative atmospheric humidity, no light) for two weeks in portions of 100 g at 50% of their water holding capacity (300 g water $kg^{-1}$ soil dry weight). Soil water content was controlled and adjusted every other day by weighing.

Subsamples of preincubated soils were labeled in portions of 15 g with 120 MBq $^{33}P$ $kg^{-1}$ which were added with 10 µl deionized water per g soil. The mass of P introduced with the $^{33}P$ label can be neglected (<2.5 x $10^{-3}$ □g P $g^{-1}$ soil, Amersham product specification, July 2000). Therefore, the term 'P concentration' always refers to $^{31}P$ and specific activities (SA) are calculated as:

$$SA\ (Bq\ \square g^{-1}\ P) = {}^{33}P/{}^{31}P \qquad [Eq.\ 1]$$

Soil P was fractionated sequentially with three replicates per soil following the modified method of Hedley et al. (1982), as described in Tiessen and Moir (1993), with $HCO_3$-saturated resin strips (BDH # 55164, 9 x 62 mm), followed by 0.5 *M* $NaHCO_3$ (referred to as Bic-P), 0.1 *M* NaOH, (these first three steps each with an extracting time of 16 h) and concentrated hot HCl at 80° C for 10 minutes. The step using diluted cold HCl was omitted, as Ca-phosphates are only present at very low levels or are absent in highly weathered acidic soils (Agbenin and Tiessen, 1995), as shown for the soils used in this study by Friesen et al. (1997). Residual P was extracted as described previously for determination of $P_{tot}$.

The amount of soil extracted was doubled from 0.5 to 1 g using the original volumes of extractants (2 resin strips in 30 mL $H_2O$, 30 mL $NaHCO_3$, 30 mL NaOH, 15 mL concentrated HCl, 5 mL conc. $H_2SO_4$) in order to get higher $^{33}P$-concentrations in the extracts. This was preferred to the alternative of higher label application as the radiation might affect microbes (Halpern and Stöcklin, 1977). After each extraction, the samples were centrifuged at 25000 x g for 10 minutes before filtering the solutions of the Bic- and the NaOH-extraction through 0.45 □m pore size millipore filters (Sartorius, cellulose acetate), and the hot HCl and residual P extract through a Whatman filter Nr. 40.

Phosphorus concentration in all extracts was measured after neutralization by the Murphy and Riley (1962) method. This method was used directly, after neutralization of the extracts, for the P recovered from the resin strip and for $P_i$ determination in the HCl extract. Organic matter was first precipitated by acidification in the Bic- and the NaOH-extracts prior to $P_i$ determination (Tiessen and Moir, 1993). Total P ($P_t$) in the Bic-, the NaOH- and the HCl-extracts was measured after digestion of $P_o$ with potassium persulfate (Bowman, 1989). Organic P was calculated as the difference between total P and $P_i$ in the Bic-, NaOH- and hot HCl extracts.

To partition soluble $^{33}P_i$ and $^{33}P_o$ in the Bic-, the NaOH- and the hot HCl-extracts into separate solutions before counting, 5 mL of the extracts were shaken with acidified ammonium molybdate dissolved in isobutanol (Jayachandran et al., 1992). With this method, $P_i$ is extracted into the isobutanol while $P_o$ remains in the aqueous phase. The complete recovery of $P_i$ in the isobutanol phase was verified with the addition of a standard amount of $^{33}P$ in 0.5 *M* $HCO_3$, 0.1 *M* NaOH and in 2.3 *M* HCl; recovery rates of added $^{33}P$ in the isobutanol phase were between 97 % and 103 %, which was not significantly different from 100%. Counts in the aqueous phase were 1.1 % ($HCO_3$), 0.3 % (NaOH) and 0.1 % (HCl) of the original solutions showing that hardly any $P_i$ goes into this phase. Determination of total P in the aqueous phase is not possible because the presence of the molybdate interferes with the analysis (Jayachandran et al., 1992).

The radioactivity in each phase was determined with a liquid scintillation analyzer (Packard 2500 TR) using Packard Ultima Gold scintillation liquid in the ratio (extract to liquid) 1:5. The values were corrected for radioactive decay back to the day of soil labeling. All extracts were tested for possible quenching effects by adding defined $^{33}P$ spikes. Quenching in the acid resin eluate could be prevented by dilution of 250 □l eluate with 750 □l deionized water for counting. The quench effect in the hot concentrated HCl extract could be avoided by counting in the solutions separated with acidified isobutanol because the separated phases were not affected by quenching. All other extracts were not affected by quench effects.

The recovery of the label as sum of all fractions, including residual P, was never complete. Therefore, subsamples of the soil residue after final acid digestion were dried and weighed into scintillation vials. These subsamples were then counted after addition of 1 mL water and 5 mL of scintillation cocktail.

*Isotopic Exchange Kinetics*

The procedure of isotopic exchange kinetics was used to assess the exchangeability of $P_i$ in the soils sampled in the different land-use systems. The method was conducted as described by Fardeau (1996). Suspensions of 10 g of soil and 99 mL deionized water were shaken for 16 h on an overhead shaker to reach a steady state equilibrium for $P_i$. Then, at t = 0, 1 mL of carrier free $H_3{}^{33}PO_4$ tracer solution containing 1.2 MBq was added to each continuously stirred soil water suspension. Three subsamples were taken from each sample after 1, 10 and 100 minutes, immediately filtered through a 0.2 μm pore size micropore filter, and the radioactivity in solution was measured by liquid scintillation as described previously. To determine the $^{31}P$ concentration in the soil solution ($C_p$, mg P $L^{-1}$) 10 mL of the solution were filtered through a 0.025 μm filter (Schleicher & Schuell, NC 03) at the end of the experiment. The smaller filter pore size was used to exclude any influence of suspended soil colloids on $C_p$ determination (Sinaj et al., 1998). The P concentration in the filtrate was measured in a 1 cm cell using the Malachite green method (Ohno and Zibilske, 1991) with a Shimadzu UV-1601 spectrophotometer. As the concentrations in the solutions of SAV and GL were close to the detection limit, they were additionally measured in samples concentrated by evaporation (5:1). This procedure resulted in $C_p$ values that were not significantly different from the non-concentrated solutions.

Assuming that at any given exchange time the specific activity (SA) of inorganic phosphate in the solution is equal to the SA of the total quantity of phosphate which has been isotopically exchanged, it is possible to calculate the amount of isotopically exchanged P ($E_t$, mg P $kg^{-1}$ soil). The amount of P exchangeable within one minute ($E_1$), indicating the immediately available P, is expressed as (Fardeau, 1996):

$$E_1 = R \times 10 \times C_p / r_1 \qquad \text{[Eq. 2]}$$

where R is the introduced radioactivity and $r_1$ is the radioactivity remaining in solution after 1 minute of isotopic exchange. The factor 10 results from the soil solution ratio of 1:10.

*Statistical Analysis*

The effects of land-use systems and incubation time after labeling on P fraction size were tested by two-way ANOVA and Tukey's multiple range over all treatments and times of fractionation. A separate

one-way ANOVA was used to test the difference on label recovery and fraction size between samples labeled in soil water ratio 1:10 and samples labeled in incubated moist state 4 hours after labeling. Percentage recovery data were log-transformed to meet the requirements of analysis of variance. Time and soil treatment influences on the Sas of each fraction were tested by a two-way ANOVA and, as the interaction time X treatment was significant for all fractions, the treatment influence was tested for each repitition in time of sequential fractionation, separately.

**Results and Discussion**

The mineralogy and the Fe and Al (oxy)hydroxides contents of the surface soil from the four treatments was normal for this type of soil (Gaviria, 1993). On average of all treatments, the soil contained 68% quartz, 23% kaolinite, 4% anatase, 3% gibbsite, 2% rutile, and <1% vermiculite. There were no significant differences among the different land-use systems (SAV, GL, CR, RGM). This implies that any difference seen in the P dynamics among land-use systems was mainly due to the land-use system and not to differences in the soil mineralogy.

*Total Soil P and P Balance Induced by the Different Treatments*

The amounts of total P directly extracted from the soil samples ($P_{tot}$) were not significantly different from the sum of P ($P_{sum}$) extracted in the different fractions of the sequential extraction for SAV and CR while the direct extraction led to significantly higher values ($P$<0.05) for GL and RGM (Table 2). To evaluate whether differences in total P content in soils were related to P fertilization, the increase in $P_{tot}$ content (calculated as the difference between total P extracted from fertilized GL, CR or RGM) and $P_{tot}$ extracted from non fertilized SAV was compared to the estimated P balance of these treatments (significant correlation, $r^2$=0.87; $P$<0.001). The increases in $P_{tot}$ were of the same order of magnitude as the calculated P balance. Given the imprecision of the methods used to determine total P contents (O'Halloran, 1993) and of the estimations made to calculate the P balance, these results suggest that most of the P added with fertilizers and not taken up by plants remained in the surface layers of the studied soils. Except for the CR soil these results agree well with Oberson et al. (2001). In their study only about half of the calculated positive P balance was recovered in total P. The sampling depth of 0-10 cm might explain this difference: soil tillage may have mixed P in the 0-10 cm soil layer with soil in the 10-20 cm layer, resulting in incomplete recovery of P in the 0-10 cm sampling depth.

Table 2. P status and calculated P balances of the studied Oxisol under different land-use systems. Total P as sum of the sequential P fractionation ($P_{sum}$) or extracted directly with $H_2O_2$ and $H_2SO_4$ ($P_{tot}$).

| Treatment† | Bray II P‡ | $P_{sum}$ ‡ | Δ $P_{sum}$§ | $P_{tot}$ ‡ | Δ $P_{tot}$§ | P-Balance¶ |
|---|---|---|---|---|---|---|
| | mg $kg^{-1}$ | | | | | |
| SAV | 0.9a | 165aA | 0 | 172aA | 0 | 0 |
| GL | 2.0b | 190bA | 25 | 213bB | 41 | 28 |
| CR | 17.2c | 290cA | 125 | 293cA | 121 | 92 |
| RGM | 35.5d | 335dA | 170 | 376dB | 205 | 153 |
| F-test (soil) | *** | *** | | *** | | |

† see Table 1.

‡ P concentrations followed by the same lower case letter (within columns) or upper case letter (comparison of $P_{sum}$ and $P_{tot}$ within rows) are not significantly different ($P$=0.05) according to Tukey's test.

§ Δ P calculated as the difference between $P_{sum}$ or $P_{tot}$ of fertilized treatments – SAV.

¶ Calculated by subtracting the P removed by grain and/or animals from the P applied with mineral fertilizer.

*Isotopic Exchange Characteristics*

The effect of the four land-use systems on $P_i$ exchangeability in the surface layer of the studied soil is presented in Table 3. The ratio $r_1/R$, which is inversely correlated to the P sorbing capacity of soils (Frossard et al., 1993), was below 0.05 for all treatments suggesting that these soils have a high P sorbing capacity (Frossard et al., 1993). Furthermore, the $r_1/R$-values of the four treatments were positively correlated with the directly extracted total soil P ($r^2$=0.76 $P$<0.001). This suggests that the different land-use systems have resulted, through their different P fertilization and cropping, in different sorption rates of $P_i$ on soil minerals. Since in Oxisols P sorption is governed by the Al and Fe (oxy)hydroxides, these treatments probably induced different degree of $P_i$ saturation on the soil metallic (oxy)hydroxides such as gibbsite, which was identified in the soil from these treatments.

The $P_i$ concentration in the soil solution ($C_p$) was close to the detection limit in SAV, GL and CR treatments (Table 3). Although significantly different between all treatments, $C_p$ was significantly increased only in the RGM treatment ($P$<0.001). In SAV, GL and CR, $C_p$ was much lower than the critical concentration needed to sustain optimal growth for a large range of crops (Kamprath and Watson, 1980; Fox, 1981). The $P_i$ concentration in the soil solution was not correlated with the total soil P content. The clear $C_p$ increase in RGM was therefore not only due to an increase in total P but also to other mechanisms. The strong increase in soil biological activity observed in land-use systems including legumes might partly explain this higher $C_p$ value (Haynes and Mokolobate, 2001; Oberson et al., 2001). The variation in the amount of $P_i$ isotopically exchangeable in one minute ($E_1$) followed the same trend as the variation in $C_p$.

Table 3. Parameters of isotopic exchange †

| Treatment‡ | $r_1/R$§ | $c_p$ ¶ (mg $l^{-1}$) | $E_1$ # (mg $kg^{-1}$) |
|---|---|---|---|
| SAV | 0.02a | 0.0015a | 0.7a |
| GL | 0.03a | 0.002b | 0.6a |
| CR | 0.04a | 0.003c | 0.8a |
| RGM | 0.055b | 0.015d | 2.7b |
| F-test | *** | *** | *** |

† Values are the average of three replications.
‡ see Table 1.
§ ratio of radioactivity remaining in soil solution to radioactivity added at time 0 after 1 minute of isotopic exchange.
¶ P concentration in the soil solution measured at soil:water ratio 1:10.
# Quantity of P exchangeable within 1 minute.

*P Concentrations in Different Fractions of the Sequential Extraction*

The positive P balances of the fertilized GL, CR and RGM treatments resulted in significantly higher P concentrations ($P$<0.001) compared to the savanna soil in all fractions except the organic fractions and residual P (Table 4). This agrees with the results of Friesen et al. (1997) and Oberson et al. (2001), who fractionated P forms according to the same method in the same field experiment, and studies conducted in other tropical soils (Beck and Sanchez, 1994; Linquist et al., 1997). Our results show that

Table 4 Distribution of P in various fractions of the modified Hedley fractionation in different agricultural systems with and without P application on an Oxisol, at three times of incubation after mixing the soils for label application.

| Treatment ‡ | Incubation Time | resin $P_i$ | Bicarbonate $P_i$ | Bicarbonate $P_o$ | NaOH $P_i$ | NaOH $P_o$ | Hot HCL $P_i$ | Hot HCL $P_o$ | Residual $P_t$ | Total P | Total $P_o$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | mg kg-1 | | | | | | | | | |
| SAV | 4 hours | 0.9 g† | 1.4 g | 12.4 | 22 de | 46 | 37 b | 6.1 ab | 44 ab | 172 ef | 65 |
| GL | 4 hours | 2.0 ef | 2.8 fg | 11.8 | 27 de | 56 | 34 b | 8.6 a | 43 b | 185 ef | 76 |
| CR | 4 hours | 4.8 d | 9.7 def | 15.0 | 102 b | 48 | 56 a | 9.1 a | 49 ab | 298 cd | 72 |
| RGM | 4 hours | 10.0 b | 21.4 bc | 6.7 | 100 bc | 62 | 65 a | 5.2 abc | 47 ab | 321 abc | 74 |
| SAV | 1 week | 2.0 ef | 4.3 fg | 5.7 | 20 e | 42 | 36 b | 4.1 bc | 42 b | 157 f | 52 |
| GL | 1 week | 2.4 e | 6.4 efg | 10.0 | 33 d | 47 | 38 b | 3.3 bc | 43 ab | 184 ef | 61 |
| CR | 1 week | 8.0 c | 14.3 cde | 14.3 | 89 c | 47 | 53 a | 2.5 bc | 50 ab | 279 d | 64 |
| RGM | 1 week | 16.4 a | 29.8 a | 12.8 | 119 a | 40 | 63 a | 3.3 bc | 54 ab | 338 ab | 56 |
| SAV | 2 weeks | 2.0 ef | 4.1 fg | 6.3 | 20 e | 42 | 36 b | 4.1 bc | 48 ab | 164 f | 52 |
| GL | 2 weeks | 4.2 d | 6.4 efg | 10.3 | 33 d | 49 | 38 b | 2.9 bc | 62 a | 207 e | 62 |
| CR | 2 weeks | 7.5 c | 16.6 cd | 11.0 | 90 bc | 56 | 58 a | 1.2 c | 61 ab | 305 bcd | 68 |
| RGM | 2 weeks | 15.8 a | 27.5 ab | 15.9 | 118 a | 45 | 63 a | 4.3 bc | 62 a | 354 a | 65 |
| Treatment | | *** | *** | n.s. | *** | n.s. | *** | ** | n.s. | *** | n.s. |
| Time | | *** | *** | n.s. | n.s. | n.s. | n.s. | *** | *** | * | n.s. |

*,**,*** Significant at the 0.05, 0.01, and 0.001 probability level, respectively

† values within a column followed by the same letter do not differ significantly (*P*=0.05) according to Tukey's test.

‡ see Table 1.

resin-$P_i$, Bic-$P_i$ and NaOH-$P_i$ increased with P fertilizer input, with the NaOH-$P_i$ fraction being the main sink for the applied P. This P sink function of the NaOH-$P_i$ fraction can be explained by the adsorption of $P_i$ through ligand exchange with hydroxyl groups (Sposito, 1989) located on the surface of Fe and Al (oxy)hydroxides (Ainsworth et al., 1985; Parfitt, 1989; Torrent et al., 1992) and by the desorption of $P_i$ from the surface of (oxy)hydroxides in the presence of 0.5 *M* NaOH (Houmane et al., 1986; Cross and Schlesinger, 1995).

During the continuous 2-week incubation of the soil samples, the resin and the Bic-$P_i$ fractions increased significantly ($P<0.05$) between the first and second fractionation date for all soils (between 4 and 14 mg $kg^{-1}$ for the sum of resin and Bic-$P_i$). There was no significant and corresponding decrease in any fraction although total extractable $P_o$ tended to decline (between 8 and 18 mg $kg^{-1}$) for all soils (Table 5). The absence of significant compensating movements of P out of $P_o$ fractions may be due to the high variability of the results, especially for the organic fractions where coefficients of variation for Bic-$P_o$ were between 13 and 70 % and for NaOH-$P_o$ between 7 and 45 %. Since $P_o$ is determined by the difference between $P_t$ and $P_i$ there are multiple sources of error. High variability of repeated measuring of Bic- and NaOH-$P_o$ were reported in Magid and Nielsen, (1992). Problems in the determination of $P_i$ are mentioned in Tiessen and Moir (1993), especially the possibility that $P_i$ is precipitated along with the organic matter upon acidification and erroneously determined as $P_o$ ($P_t$-$P_i$). On the other hand, $P_o$ compounds could be hydrolyzed in the acidic solution during the measurement of P during the colorimetric essay (Condron et al., 1990; Gerke and Jungk, 1991).

Increases in resin and Bic-$P_i$ between 4 hours and 1 week of incubation suggest that mineralization of $P_o$ led to the release of labile $P_i$ from $P_o$ fractions. As the first fractionation was started 4 hours after labeling, the disturbance by mixing the soil with the label and the momentarily increased humidity might additionally have stimulated the microbial activity despite of the preincubation. A temporary stimulation of the microbial activity by the thorough mixing when labeling soil was indicated in microbial turnover studies conducted on soils from the same field experiment (Oberson et al., 2001). This assumption seems likely, as there were little changes in fraction sizes between the second and the third fractionation indicating a stabilization of the system.

*Distribution of $^{33}P$ Among P Fractions and Dynamics over Time*

The fraction of $^{33}P$ recovered in the resin-$P_i$ fraction 4 hours after labeling varied between 22 % in SAV and 60 % in RGM (Figure 1). The $^{33}P$ recovery in this fraction was positively correlated to the content of total P of the soils ($r^2=0.87$; $P<0.001$, 4 h after labeling). The corresponding decrease of $^{33}P$ in the resin fraction in RGM and CR corresponded with an increase in label recovery in Bic- and NaOH-$P_i$, while in SAV and GL the decline in resin $^{33}P$ was accompanied by an increase in $^{33}P$ in NaOH-$P_o$ (GL also NaOH-$P_i$), HCl-$P_i$ and residual-P. For SAV and GL, the label recovered in the resin-$P_i$, and Bic-$P_i$ did not change much between the 1st and the 2nd week and the amount of $^{33}P$ in NaOH-$P_i$ was stable over the entire incubation time. This shows that in SAV and GL the label was rapidly exchanged between these fractions and that equilibrium with the (labeled) soil solution was reached. In contrast, $^{33}P$ in the Bic-$P_i$ and the NaOH-$P_i$ of CR and RGM was still increasing after one week while the resin-$^{33}P_i$ continued to decrease, showing that the exchange between these fractions was incomplete.

The data for $^{33}P_o$ were, because of the determination after the separation from Pi with the isobutanol method, not affected by the inherent problems in determination of the $P_o$ fractions in the Hedley fractionation scheme as described previously. Only small amounts of the label were found in organic fractions after 4 hours, but there were already significant differences in NaOH-$^{33}$Po ($P<0.001$) in the order: SAV (4%) ≈ GL (2%) > CR (0.4 %) ≈ RGM (0.1 %).

This might be due to differences in microbial activity as observed by Oberson et al. (2001) in the same field experiment. Actually, the microbial biomass in incubated soils, indicated by measured $P_{Chl}$, $C_{Chl}$ and $N_{Chl}$ values, was significantly different between the soils (Table 5), despite the fact that the samples had been stored in air-dried condition for more than three years before being used in this study. The assumption that recovery of the label in organic fractions was actually due to active processes and not to

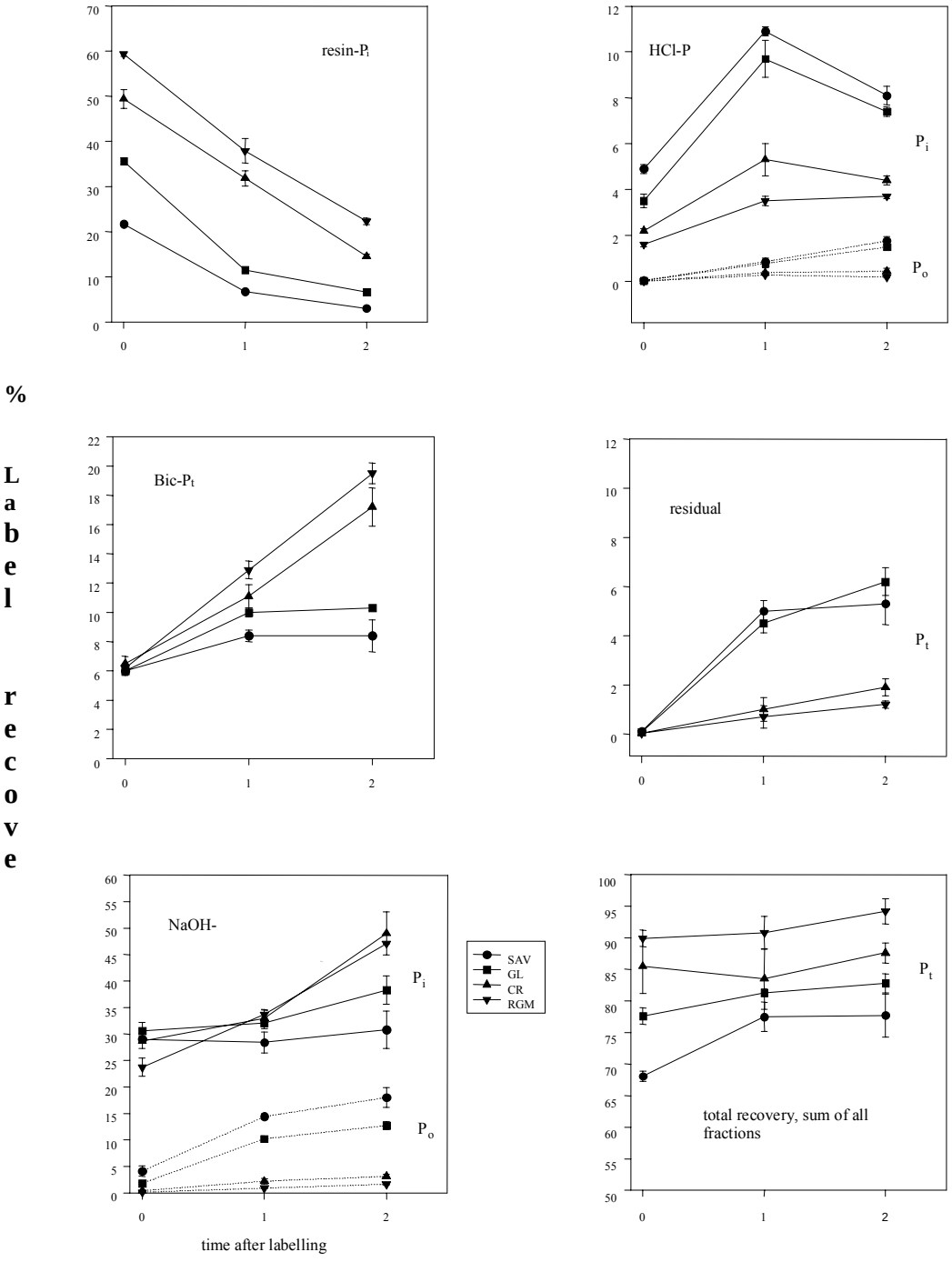


Fig. 1 Percentage of label recovery in the different fractions of the sequential P extraction and in the sum of all fractions at 4 hours, 1 and 2 weeks after labeling soil (Means of three replicates± SD)

any analytical artifact is supported by the observed increases of NaOH-$^{33}P_o$ and HCl-$^{33}P_o$ for all soils over time. The total recovery of 20 % (SAV) or 14% (GL), respectively, of the label in organic fractions two weeks after labeling shows that these compartments have to be taken into account to understand the fate of P in these very low-P soils (Tiessen et al., 1984; Beck and Sanchez, 1994; Linquist et al, 1997).

Table 5. Size of the soil microbial biomass nutrient pool in different agricultural systems after 20 days of incubation of the formerly air-dried soils. Values are the averages of three replicates†.

| treatment ‡ | $C_{Chl}$ | $N_{Chl}$ | $P_{Chl}$ |
|---|---|---|---|
| | mg $kg^{-1}$ | | |
| SAV | 88.7a | 13.7a | 1.6a |
| GL | 80.8a | 13.5a | 1.2ab |
| CR | 72.9a | 8.5b | 0.7b |
| RGM | 48.2b | 6.1b | 0.5b |
| F-Test | ** | *** | *** |

**,*** Significant at the 0.01, and 0.001 probability levels, respectively.
† Means followed by the same letter are not significantly different (*P*=0.05) by Tukey's multiple range test.
‡ see Table 1.

The proportion of label in the hot HCl and residual P fractions increased significantly with incubation time in all soils. This contradicts the prevailing opinion of recalcitrance of the P in these fractions (Guo and Yost, 1998; Neufeldt et al., 2000). While the total P content in the residual fraction varied significantly with time (Table 4), this was not the case for hot HCl extractable $P_i$, while hot HCl extractable Po tended to decrease. This suggests that the movement of the label to these fractions was not due to net P-movement but to exchange processes.

*Total $^{33}P$ Label Recovery*

At all sampling times during the incubation study, in total between 67 % and 94 % of the applied $^{33}P$ label could be recovered in the sum of all fractions (Fig. 1). This sum was generally in the order SAV<GL<CR<RGM. These incomplete recoveries can be explained by the fact that the method used to assess total P or residual P was not efficient enough to extract all P. Comparative studies have shown that total P can only be reliably extracted by alkali fusion (Syers et al., 1967; Bowman, 1988), which could not be used in this work. The analysis of soil residues after the acid extraction of residual P (Table 6) indicated indeed that significant amounts of the label remained unextracted, these being higher for SAV and GL than CR and RGM. Although counting of $^{33}P$ bound to solid phases is generally possible, problems of phase, impurity, self absorption of scintillations by the soil particles or color quenching effects (Gibson, 1980) are difficult to correct, as these influences might be highly variable between samples. However, the recovery of standard additions of $^{33}P$ to our soil residues was complete and the correlation of the measured radioactivity in the different soil treatment residues with the sample weight was linear (data not shown), thus confirming the qualitative information obtained from the counting of the soil residues.

Altogether the results suggest that the transfer of $^{33}P$ among the different fractions determined by the sequential extraction was strongly dependent on the degree of saturation of soil Al and Fe (oxy)hydroxides with $P_i$, and therefore on the bonding energy of $P_i$ to the soil minerals. It is indeed known that a high $P_i$ saturation of metal oxide surfaces causes a more negative charge on the surface and prevents the specific sorption of further $P_i$ ions (Ryden et al., 1977; Bowden et al., 1980). In the P poor soils (SAV and GL), most $P_i$ would be sorbed with such a high energy that their exchangeability would be very limited. A specific sorption of $^{33}P$ to the surface of Al and Fe (oxy)hydroxides of these soils, although unlikely (Frossard et al., 1994), cannot be excluded (Barrow, 1991). In contrast, in the P rich soils (CR and

RGM), the annual P additions might have resulted in the build up of relatively larger quantities of $P_i$ exchangeable with $^{33}P$.

Table 6. Radioactivity measured in soil solid residues by scintillation counting after extraction of residual P by sequential P fractionation starting 1 week after soil labeling

| Soil treatment | Bq $g^{-1}$ soil (decay corrected)† | % of initial label |
|---|---|---|
| SAV | 2251 (111) | 4.4% |
| GL | 1843 (357) | 3.6% |
| CR | 427 (215) | 0.8% |
| RGM | 348 (140) | 0.7% |

†Average of three replications, standard error in brackets.
decay corrected to the day of soil labeling.

*Specific Activities in the Fractions Determined by the Sequential Extraction*

The highest specific activities (SA) observed in this incubation experiment were obtained in the resin extract after 4 hours of incubation (Table 7). This is consistent with the assumption that the amount of P desorbed from the soil by a resin is in very rapid exchange with $P_i$ in the soil solution, as suggested by other studies (Amer et al., 1955; Bowman and Olsen, 1979; Tran et al., 1992; Schneider and Morel, 2000). The subsequent decrease in the SA of resin-$P_i$ reflected the process of isotopic exchange between $^{33}P$ and stable $P_i$ located on the soil's solid phase (Fardeau, 1996). The order of the SAs in the $P_i$ fractions after 4 hours of incubation followed the extraction sequence (resin-$P_i$>Bic-$P_i$>NaOH-$P_i$>HCl-$P_i$>residual P), showing that the strongest reactants extracted either large quantities of slowly exchangeable P or a large quantity of P in which only a small part was rapidly exchangeable. After 2 weeks the SAs of resin-$P_i$, Bic-$P_i$ and NaOH-$P_i$ became closer, suggesting that equilibrium with respect to P transfer between these fractions was being approached. The SAs of resin-$P_i$, Bic-$P_t$ and NaOH-$P_i$ were not significantly different in SAV and GL while the SA of resin-$P_i$ was still significantly higher than the SA of Bic-$P_i$ and NaOH-$P_i$ in CR and RGM. These observations show that it is not possible to discuss the exchangeability of a certain P fraction without relation to a defined time of exchange (Fardeau et al., 1996).

Although the SAs of the NaOH-$P_o$ and HCl-$P_o$ fraction were relatively low they showed that, depending on land-use, these fractions were connected through active processes with the soil solution, most probably through microbial activity (Oehl et al., 2001). This indicates that the determination of plant available P with short-term isotopic exchange experiments might lead to errors since the dynamics of organic P forms are excluded.

## Conclusions

The effect of contrasting land-use systems on the P fractions extracted by the sequential fractionation procedure was assessed in an Oxisol during a 2-week incubation on soils labeled with carrier free $^{33}P$. The results show that in the studied Oxisol, the quantities of $^{31}P$ and $^{33}P$ recovered in the different fractions were strongly dependent on the total P content of the soil, which was determined by the amount of P added by fertilizers and by plant P uptake.

Table 7. Specific activities ($^{33}P/^{31}P$) in isotopic exchange soil solution and in extracts of the Hedley sequential fractionation in the labeled Oxisols derived from different agricultural systems at different times after labeling. †

| Time | treatment | resin $P_i$ | Bic-$P_i$ | NaOH-Pi | NaOH-Po | HCl-Pi | HCl-Po | residual P |
|---|---|---|---|---|---|---|---|---|
| | | kBq mg $P^{-1}$ | | | | | | |
| 4 hours | SAV | 32.9 AA | 5.9 aC | 1.8 aD | 119 x $10^{-3}$ aE | 180 x $10^{-3}$ aE | 8 x$10^{-3}$ F | 3 x$10^{-3}$ aF |
| | GL | 24.5 BA | 3.3 bB | 1.6 aC | 44 x $10^{-3}$ bE | 138 x $10^{-3}$ bD | 3 x$10^{-3}$ F | 3 x$10^{-3}$ aF |
| | CR | 13.8 CB | 1.3 cC | 0.4 bD | 11 x $10^{-3}$ bF | 54 x $10^{-3}$ cE | 0 | 1 x $10^{-3}$ bF |
| | RGM | 7.9 dA | 0.6 cB | 0.3 bC | 3 x $10^{-3}$ bE | 33 x $10^{-3}$ dD | 0 | 1 x $10^{-3}$ bF |
| | F-test ¶: | *** | *** | *** | *** | *** | n.s. | *** |
| 1 week | SAV | 5.1 AbA | 2.7 aA | 1.9 aB | 480 x $10^{-3}$ aC | 430 x $10^{-3}$ aD | 280 x $10^{-3}$ E | 157 x $10^{-3}$ aF |
| | GL | 6.4 AA | 2.2 bB | 1.3 bD | 293 x $10^{-3}$ bE | 436 x $10^{-3}$ aE | 497 x $10^{-3}$ DE | 140 x $10^{-3}$ aF |
| | CR | 5.3 AbA | 1.1 cC | 0.5 cD | 64 x $10^{-3}$ cE | 138 x $10^{-3}$ bE | 271 x $10^{-3}$ DE | 26 x $10^{-3}$ bE |
| | RGM | 3.1 BcA | 0.6 cC | 0.4 cD | 35 x $10^{-3}$ cE | 76 x $10^{-3}$ bE | 159 x $10^{-3}$ DE | 18 x $10^{-3}$ bE |
| | F-test: | * | *** | *** | *** | *** | n.s. | *** |
| 2 weeks | SAV | 2.1 ABC | 1.6 aB | 2.1 aAB | 587 x $10^{-3}$ aC | 290 x $10^{-3}$ aD | 566 x $10^{-3}$ C | 154 x $10^{-3}$ aE |
| | GL | 2.1 B | 1.4 aC | 1.6 aBC | 357 x $10^{-3}$ bD | 249 x $10^{-3}$ bD | 741 x $10^{-3}$ D | 135 x $10^{-3}$ aE |
| | CR | 2.6 A | 1.1 abB | 0.7 bB | 70 x $10^{-3}$ cD | 99 x $10^{-3}$ cC D | 22 x $10^{-3}$ D | 43 x $10^{-3}$ bD |
| | RGM | 1.9 A | 0.8 bBC | 0.5 bC | 48 x $10^{-3}$ cDE | 75 x $10^{-3}$ cD | 56 x $10^{-3}$ DE | 26 x $10^{-3}$ bE |
| | F-test‡: | n.s. | * | *** | *** | *** | n.s. | *** |

*,**,*** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

† All values are the average of three replicates. Decay corrected to the day of soil labeling.

‡ ANOVA was calculated separate for each time, means followed by different lower case letters within one column at one time are significantly different ($P$=0.05) by Tukey's test. The same is valid for means within one row followed by different upper case letters.

In the two soils fertilized annually with P and with a large positive P input-output balance, most of the $P_i$ was stored in the resin-$P_i$, Bic-$P_i$ and NaOH-$P_i$ fractions. The use of carrier free $^{33}P$ confirmed that, under all land-use systems studied, these soil P fractions contained most of the exchangeable P and that $^{33}P$ was transferred from the soil solution first to the resin fraction and then to the Bic-$P_i$ and NaOH-$P_i$ fraction. This suggests that, when this Oxisol is regularly fertilized, P is stored in these three fractions while the plants might take up P from the same fractions. In the two other soils, which had either never been fertilized or had been fertilized only once at the beginning of the field trial, the transfer of $^{33}P$ in these three fractions (i.e. resin-$P_i$, Bic-$P_i$ and NaOH-$P_i$) was less clear, suggesting that the soil $P_i$ was much less exchangeable. In these soils, however, the transfer of $^{33}P$ into organic P fractions was more important (up to 20 % of the label was found in the organic P fractions two weeks after labeling). As the pool sizes of these organic fractions did not change significantly over time of incubation, the label recovery indicates relatively quick cycling processes, probably mostly of microbial P. In such low P soils, these processes are relevant and should be considered when estimating soil P availability for plants.

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# Constructing an arable layer through chisel tillage and agropastoral systems in tropical savanna soils of the Llanos of Colombia

S. Phiri[1,2,3], E. Amézquita [2], I.M. Rao[2], and B.R. Singh[1]

[1]Agricultural University of Norway, P.O. Box 5028, NLH, N-1432 Aas, Norway; [2]Centro Internacional de Agricultura Tropical (CIAT), Apartado Aéreo 6713, Cali, Colombia; [3]Misamfu Regional Research Centre, Kasama, Zambia

## Abstract

Integration of crop and livestock systems (agropastoralism) is a key strategy for intensifying agricultural production on infertile acid savanna soils, and for reversing problems of soil degradation in the tropics. The main objective of this study was to evaluate the impact of strategies including vertical tillage (1, 2 or 3 passes of chisel), crop rotations (rice-soybean), and agropastoral systems (rice-grass alone pasture; rice-grass/legume pasture) on the build-up of an arable layer and on grain yields of upland rice and soybean. We assessed the build-up of an arable layer in terms of improved soil physical characteristics (bulk density, penetration resistance), soil nutrient availability, soil phosphorus (P) pools, plant growth, and nutrient acquisition during the fourth year after the establishment of different treatments on native savanna soil. The soil used in this study was an Oxisol in the eastern plains (Llanos orientales) of Colombia. Agropastoral treatments (rice-grass alone pasture; rice-grass/legumes pasture) with vertical tillage decreased soil bulk density in the 0-20 cm soil layer by 12% when compared with the unmanaged native savanna. Consistent with bulk density, penetration resistance was also markedly decreased for 0-20 cm depth. Three passes of chisel (rice-soybean rotation) and pasture treatments (grass alone and grass/legume) improved the availability of Bray (II) P, K, Ca, and Mg in the 0-5 cm layer. The biologically available resin-$P_i$ and $NaHCO_3$-$P_i$ each represented 5% of the total P and were significantly affected by chisel down to 10-20 cm depth. The moderately resistant NaOH-P represented, on average, 33% of total P in the 0-20 cm soil layer, and both NaOH-Pi and NaOH-Po were significantly affected by chisel tillage. Results on grain yields of upland rice showed that three passes of chisel could have a negative effect on grain yield, and that yields which declined over time declined more in agropastoral treatments than in rice-soybean rotation. These results indicate that the use of vertical tillage and agropastoral treatments can contribute to the build-up of an arable layer in low fertility savanna soils of the Llanos of Colombia as indicated by improved soil physical properties and nutrient availability. However, to take advantage of the constructed arable layer to improve crop yields, there is a need for developing better crop management strategies to control weeds.

**Key words:** Acid soils, crop-pasture systems, crop rotations, soil P pools, vertical tillage

## Introduction

Tropical savannas cover 45% of the land area in Latin America, or 243 million hectares (Mha), mainly in Brazil (200 Mha), Colombia (20 Mha), and Venezuela (12 Mha). The soils are mainly Oxisols and Ultisols, which are characterized by low nutrient reserves, high acidity (pH 4.0-4.8), high aluminum (Al) saturation (up to 90%), high phosphorus (P) fixing capacity (Sánchez & Logan, 1992), and a low capacity to supply P, K, Mg and S. In addition to soil chemical constraints, these soils also exhibit high bulk density, high resistance to root penetration, low rates of water infiltration, low water holding capacity, and low structural stability (Amézquita, 1998a, b; Phiri et al., 2001a). These chemical and

physical constraints have to be alleviated in order to make these infertile soils productive and sustainable for agriculture.

These soils have traditionally been used for extensive cattle ranching on native forage, dominated by *Andropogon* and *Trachypogon* grasses, with low management and almost no purchased inputs (Fisher et al., 1994). Native pasture productivity on these soils is correspondingly low.

Land demand for intensive agricultural production on these soils has increased in the past 20 years. However, intensified agricultural production is usually constrained by poor soil chemical and physical properties. Traditional methods of cultivation by disc harrowing often lead to soil structural deterioration and erosion (Preciado, 1997; White, 1997 ). Research in the eastern plains (*Llanos Orientales*) of Colombia has shown that these soils are susceptible to physical, chemical, and biological degradation once brought into cultivation (Amézquita, 1998a, b). One of the effects of increasing land preparation is reduction in soil volume due to the decrease in size of soil aggregates. As a consequence, it causes changes in total porosity and pore-size distribution, affecting the flow of water and nutrients. Total porosity, water holding capacity, and macroporosity decline as cultivation is prolonged (McBratney *et al.*, 1992; Preciado, 1997; Amézquita, 1998a). Plowing causes disruption of peds, and this exposes previously inaccessible organic matter to attack by microorganisms while the population of structure-stabilizing fungi and earthworms decrease markedly (White, 1997). These changes result in soil degradation, which reduces water infiltration and increases the loss of soil and plant available nutrients by soil erosion and surface runoff (Amézquita & Londoño, 1997; Amézquita & Molina, 2000).

The practicality of rehabilitating degraded lands depends on the cost relative to the output or environmental benefits expected (Scherr & Yadav, 1996) and their influence on yields. The impact of soil degradation should be assessed in relation to critical limits to crop growth of key soil properties. Identification of appropriate methods of soil restoration is facilitated by knowledge of the key soil properties that influence soil quality and their critical limits in relation to the severity of soil degradation (Lal, 1997).

To achieve improved and sustainable crop and pasture production and to avoid degradation, key soil properties such as soil's physical constraints must be alleviated by appropriate tillage and cropping practices (Amézquita, 1998a; Phiri et al., 2001a). A highly successful strategy for intensifying agricultural production in a sustainable manner and reversing problems of soil degradation involves the integration of crop-pasture systems (agropastoralism) (Vera et al., 1992; Rao et al., 1993; Thomas et al., 1995). This strategy is based on the assumption that a beneficial synergistic effect on production and on soil quality occurs when annual and perennial species are combined in time and space (Spain, 1990; Lal, 1991). Available nutrients are used more efficiently and the chemical, physical and biological properties of the soil are improved.

Phosphorus is among the nutrients that most limits crop production on acid savanna soils (Rao et al., 1999). Studies on P cycling in long-term (16-year-old) introduced pastures in the 'Llanos' of Colombia indicate that legume-based pastures maintain higher organic and available P levels more consistently than grass alone or native pastures (Oberson et al., 1999). Greater turnover of roots and aboveground litter in legume-based pastures could provide steadier organic inputs and, therefore, higher P cycling and availability (Friesen et al., 1997; Rao, 1998; Oberson et al., 1999). Failure of P to enter organic P pools is thought to indicate a degrading system due to low level of P cycling (Friesen et al., 1997; Oberson et al., 2001).

To overcome soil constraints and improve soil quality for agricultural productivity, there is potential for improved soil management through vertical tillage using a chisel plow (Amézquita, 1998a). In this study, we tested the hypothesis that vertical tillage combined with adequate fertilizer inputs to adapted crop and pasture germplasm will improve root growth which could avoid soil compaction and improve root turnover and accumulation of soil organic matter. We also hypothesized that this integration of soil tillage and soil fertility together with vigorous root systems of introduced pasture species could result in the build-up of an arable layer. The arable layer is defined as a surface layer (0-15, 0-25 or 0-30 cm depth depending on cropping system) with minimum soil physical, chemical, or biological constraints.

We believe that the buildup of an arable layer is essential for low fertility acid soils to support sustainable agriculture (Amézquita, 1998b).

The "arable layer" concept proposed here is based on combining: (1) adapted crop and forage germplasm; (2) vertical tillage to overcome soil physical constraints (high bulk density, surface sealing, low porosity and infiltration rates, poor root penetration, etc.); (3) use of chemical amendments (lime and fertilizers) to enhance soil fertility; and (4) use of agropastoral systems to increase rooting, to promote soil biological activity, and to avoid soil compaction after tillage.

The main objective of this study was to evaluate the impact of different strategies of vertical tillage (1, 2, or 3 passes of chisel), crop rotations (rice-soybean), and crop-pasture rotations (rice-grass alone pasture; rice-grass/legume pasture) for 4 years on the buildup of an arable layer. Build-up of the arable layer was assessed in terms of improved soil physical characteristics (bulk density, penetration resistance), soil nutrient availability, soil P pools, plant growth, and nutrient acquisition.

## Materials and Methods

As part of a major effort to improve quality of native savanna soils for agricultural production in the Llanos of Colombia, a field experiment was established in May 1996 to determine the impact of vertical tillage, application of soil amendments and fertilizers, crop rotations and crop-pasture rotations on the buildup of an arable layer. The experiment tested two methods: (i) vertical tillage (using chisel) at different intensities (1, 2 and 3 passes) plus crop rotations to improve soil physical conditions in a crop rotation (rice-soybean) system; and (ii) vertical tillage plus use of adapted crop and forage germplasm associations (rice-grass/legumes) to improve soil through vigorous root growth, organic matter accumulation, maintenance of soil structure, and improved soil fertility.

### *Site description*

The experiment was carried out at Matazul farm (4º 9′ 4.9″ N, 72º 38′ 23″ W and 260 m.a.s.l.) located in the Eastern Plains (Llanos) near Puerto Lopez, Colombia. The area has two distinct climatic seasons, a wet season from the beginning of March to December and a dry season from December to the first week of March, and has an annual average temperature of 26.2 ºC. The area has a mean annual rainfall of 2719 mm, potential evapotranspiration of 1623 mm and average relative humidity of 81% (data from the nearby Santa Rosa weather station, located at the Piedmont of the Llanos of Colombia). Before treatment application, the area was under native savanna pasture, consisting for the most part of native savanna grasses. The land is generally flat (slope < 5%), the soil is deep, well structured and has a particle size distribution in the first 10 cm of about 34% clay, 28% silt and 38 % sand (loam texture). The soil has low fertility, particularly low available P because of the soil's high P-fixation capacity. It was classified as Isohyperthermic Kaolinitic Typic Haplustox in the USDA soil classification system (Soil Survey Staff, 1994).

### *Treatments and experimental design*

Use of acid-soil adapted upland rice and tropical forage germplasm in crop-pasture rotations has been demonstrated to be agronomically and economically viable on the infertile acid soils of the South American savannas (Vera et al., 1992; Rao et al., 1993; Thomas et al., 1995). Based on this strategy, the following treatments were designed to buildup an arable layer:

- Upland rice (*Oryza sativa* L. cv. Savanna 6)-soybean (*Glycine max* cv. Soyica Altillanura 2) rotation with 1, 2, or 3 passes of chisel before rice planting in May of each year for 4 years. Soybean was planted in October and harvested in December of each year.
- Rice-grass alone [*Andropogon gayanus* (Ag)] pasture, and rice-grass/legumes [*Pueraria phaseoloides* (Pp*)* + *Desmodium ovalifolium* (Do)] pasture with two passes of chisel before planting rice and pasture in May each year for 4 years. In both pasture systems, after harvest of rice in September, the pasture was allowed to grow until November. Pasture biomass was incorporated with two passes of

disc harrow in November (end of rainy season) and also before planting rice and grass alone pasture association in May (early rainy season) each year.

- Native savanna was used as a control to compare the impact of the above treatments with the natural (undisturbed) soil conditions.

During the first two years, incidence of weeds in all introduced treatments was low and we did not apply any herbicides to control weed growth. During the next two years, however, we had to apply different herbicides (propanil, glyphosate, or 2,4-D) at recommended rates to control weeds in rice and soybean. The amount of aboveground biomass incorporated was between 3.5 to 4.5 Mg $ha^{-1}$ of grass biomass for grass alone pasture and between 3.0 to 4.0 Mg $ha^{-1}$ of grass biomass and 0.4 to 0.6 Mg $ha^{-1}$ of legume biomass for grass/legumes pasture. Both grass alone and grass/legumes pastures were left ungrazed. We are aware of the fact that the agropastoral treatments in terms of incorporation of pasture biomass every year may neither be economical in short-term nor may reflect the current farmer practices. But we consider this as an important approach for improving soil conditions over a shorter time period than other options.

Vertical tillage was applied in the following sequence: disc harrow, chisel(s), disc harrow to allow good seedbed preparation and sowing with a planting machine. Chisels were applied to a depth of 25 to 30 cm with a distance between chisels of 60 cm. The length of the chisel was 60 cm. Disc harrowing was applied to a depth of 7 to 10 cm with a distance between discs of 12 cm. The diameter of the disc was 60 cm.

Dolomitic lime at a level of 1.5 Mg $ha^{-1}$ to rice-soybean rotation and 0.5 Mg $ha^{-1}$ to rice-pasture associations was applied via broadcast and incorporated with disc harrow one month before planting. Each year, at the time of planting, rice-soybean rotation and rice-pasture associations received (kg $ha^{-1}$) 80 N (urea), 50 P (TSP), 100 K (KCl), 5 Zn ($ZnSO_4$). Soybean was planted each year after rice with residual soil fertility. Nitrogen and K were split-applied at 4 and 8 weeks for N and 0, 4 and 8 weeks for K after planting rice or rice-pasture associations.

The experiment was laid down in a randomized complete block design with three replications in May, 1996. The individual plot size was 50 x 30 m. A composite soil sample consisting of 50 cores from each plot was collected in a grid pattern. These samples were air-dried, visible plant roots were removed, and soil gently crushed to pass a 2-mm sieve. The <2-mm fraction was used for subsequent chemical analysis. Measurements of soil physical characteristics (bulk density, penetration resistance) were carried out during the fourth year (June 1999) after establishment. Bulk density was determined using the core method and penetration resístanse was measured using a cone penetrometer (DIK-5521, Daiki Rika Kogyo Co., Ltd., Japan) (Amézquita, 1998b). Soil nutrient availability, shoot biomass production, root length, plant nutrient composition, and shoot nutrient uptake were determined for each treatment in September 1999. Soil and plant nutrient analyses and nutrient uptake were determined as described in Rao et al. (1992). Root length was measured using a root length scanner (Rao, 1998). Grain yield of upland rice and soybean were recorded after harvest each year (Sanz et al., 1999). The harvested area for grain yield determination was 2 qudrats of 5 x 5 $m^2$ in each plot.

*Phosphorus fractionation and analysis*

A shortened and modified sequential P fractionation as per the method of Tiessen and Moir (1993) was carried out on 0.5-g sieved (<2-mm) soil samples. In brief, a sequence of extractants with increasing strength was applied to subdivide the total soil P into inorganic ($P_i$) and organic ($P_o$) fractions (Phiri et al., 2001b). The following fractions were included: (1) Resin $P_i$, anion exchange resin membranes (used in bicarbonate form) were used to extract freely exchangeable $P_i$. The remaining $P_o$ in the extract of the resin extraction step was digested with potassium persulfate ($K_2S_2O_8$) (Oberson et al., 1999). (2) Sodium bicarbonate (0.5 *M* $NaHCO_3$, pH = 8.5) was then used to remove labile $P_i$ and $P_o$ sorbed to the soil surface, plus a small amount of microbial P (Bowman and Cole, 1978). (3) Sodium hydroxide (0.1 *M* NaOH) was used next to remove $P_i$, more strongly bound to Fe and Al compounds (Williams & Walker, 1969) and associated with humic compounds (Bowman & Cole, 1978). (4) The residue containing insoluble $P_i$ and

more stable $P_o$ forms (residual P) was digested with perchloric acid ($HClO_4$). To determine total P in the $NaHCO_3$ and NaOH extracts, an aliquot of the extracts was digested with $K_2S_2O_8$ in $H_2SO_4$ at >150 °C to oxidize organic matter (Bowman, 1989). Organic P was calculated as the difference between total P and $P_i$ in the $NaHCO_3$ and NaOH extracts, respectively. Inorganic P concentrations in all the digests and extracts were measured colorimetrically by the molybdate-ascorbic acid method (Murphy & Riley, 1962). All laboratory analyses were conducted in duplicate, and the results are expressed on an oven-dry basis.

*Statistical analysis and data presentation*

Analyses of variance were conducted (SAS/STAT, 1990) to determine the significance of the effects of vertical tillage system and crop-pasture rotations on soil and plant parameters. Planned F ratio was calculated as TMS/EMS, where TMS is the treatment mean square and EMS is the error mean square (Mead et al., 1993). Where significant differences occurred, least-significant-difference (LSD) analysis was performed to permit separation of means. Unless otherwise stated, mention of statistical significance refers to $\alpha = 0.05$.

**Results and Discussion**

*Soil physical properties*

Bulk density values of different soil layers during the fourth year (June 1999) after establishment of the field experiment are shown in Table 1. Note the high bulk densities in the native savanna that served as a control treatment. Compared with native savanna, bulk density was reduced by the agropastoral and rice-soybean rotations. Consistent to the bulk density values, native savanna soil layers exhibited less total porosity (results not shown), which regulates the entry of water and the flux of air into the profile. Root growth is inhibited when bulk density exceeds 1.4-1.6 Mg $m^{-3}$ and is suppressed at densities near 1.8 Mg $m^{-3}$ (Heilman, 1981; Mitchell et al., 1982). Agropastoral (crop-pasture) treatments, in general, had 16% lower bulk density in the 0-10 cm soil layer and 13% lower in the 10-20 cm soil layer than those of the native savanna. In the subsoil layers, all treatments presented significantly lower values of bulk density than those of native savanna (Table 1). Previous research showed that legume-based pastures contribute to improved quantity and quality of soil organic matter with depth due to vigorous rooting ability of forage components (Fisher et al., 1994; Rao et al., 1994; Rao, 1998). Suitably low bulk densities are of great importance for soil management in this type of soil as they are indicative of factors that regulate root growth, infiltration, and water movement in the soil, which in turn affects nutrient availability in soil and nutrient acquisition by plants (Rao, 1998).`

Results on penetration resistance at different soil layers are shown in Figure 1. In relation to native savanna, all the treatments decreased penetration resistance, particularly in topsoil layers (0-20 cm). These results suggest that it is possible to improve soil physical conditions to enhance water and nutrient availability, which favor rooting of the crop and forage components. The improved soil quality should allow these soils to support greater crop and pasture productivity (Amézquita, 1998b). Lack of additional effects of tillage on rice-soybean rotation compared with rice-pasture treatments (Table 1) indicates that either two passes of the chisel were sufficient in both systems or that deep rooting of introduced pasture species might have contributed biological tillage to improve soil quality. Both tillage and agropastoral treatments improved soil conditions, but whether one treatment is more beneficial than another over a longer period needs to be evaluated further.

*Soil chemical properties*

Soil chemical characteristics and root length distribution for different soil layers during the fourth year (September 1999) are shown in Table 2. As expected, compared to native savanna where nutrient availability was low and Al levels high, the different crop rotation and agropastoral treatments improved nutrient availability and reduced Al levels. The higher rate of dolomitic lime application (1.5 Mg $ha^{-1}$) to rice-soybean rotation reduced the exchangeable Al level and increased the exchangeable Ca and Mg levels

in comparison with the agropastoral treatments (0.5 Mg $ha^{-1}$). Exchangeable Al levels decreased in the first two layers, but remained at similar values of native savanna below these depths.

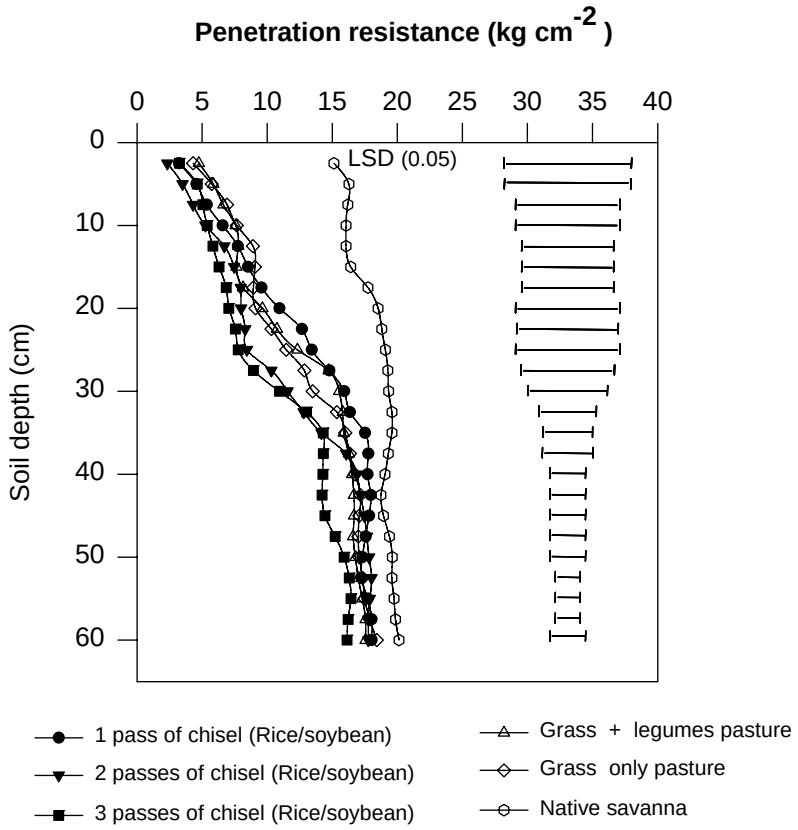


Figure 1. Penetration resistance (measured at field capacity) with soil depth during the fourth year (June 1999) after establishment of different tillage and agropastoral treatments. LSD values are at 0.05 probability level.

Differences in available P between rice-soybean rotations and agropastoral treatments were probably the result of differences in the rate of lime applied, which may have affected P sorption in soil. Other nutrients, such as K, Ca and Mg, accumulated in the topsoil. Nutrient values tended to be greater in the 0-5 cm layer as compared to subsoil layers. Available K was 2 to 4 times greater than that of native savanna (0.09 $cmol_c\ kg^{-1}$). Availability of Ca and Mg was 4 to 10 times higher than that of native savanna. These results suggest that application of lime and fertilizer could markedly improve soil fertility, particularly in topsoil. Chisel treatments were moderately effective to incorporate lime and P to deeper layers. Total C and total root length across the soil profile up to 40 cm soil depth were greater in agropastoral (rice-grass/legumes) treatment than those of rice with vertical tillage.

***P fractionation***

To simplify interpretation of results, the P fractions were divided into three groups using a criterion similar to that given by Bowman and Cole (1978) and by Tiessen et al. (1984). The three groups were: (1) biologically available P, (2) moderately resistant P, and (3) sparingly available P.

Table 1. Bulk density (Mg $m^{-3}$) of soils in profiles during the fourth year (June 1999) after establishment of different rice/soybean rotation and agropastoral systems compared with native savanna. LSD values are at 0.05 probability level.

| Soil depth (cm) | System | | | | | | LSD (0.05) |
|---|---|---|---|---|---|---|---|
| | Rice/soybean rotation | | | Rice + pastures (Agropastoral) | | Native savanna (control) | |
| | 1 pass of chisel | 2 passes of chisel | 3 passes of chisel | Grass only (Ag) | Grass + legumes (Ag + Pp + Do) | Savanna | |
| 0-5 | 1.36 | 1.36 | 1.33 | 1.37 | 1.38 | 1.61 | 0.11 |
| 5-10 | 1.49 | 1.42 | 1.46 | 1.44 | 1.39 | 1.64 | 0.09 |
| 10-20 | 1.54 | 1.57 | 1.50 | 1.55 | 1.56 | 1.73 | 0.08 |
| 20-40 | 1.60 | 1.60 | 1.57 | 1.56 | 1.62 | 1.73 | 0.06 |
| LSD (0.05) | 0.16 | 0.18 | 0.16 | 0.15 | 0.19 | 0.09 | |

Ag = *Andropogon gayanus;* Pp = *Pueraria phaseoloides;* Do = *Desmodium ovalifolium*.

*Biologically available P* ($H_2O$-$P_o$, resin-$P_i$, and $NaHCO_3$-$P_i$, and -$P_o$) is available or becomes available to plants in a short time (from days to a few weeks) (Cross and Schlesinger, 1995). The resin and the bicarbonate $P_i$ consists of labile $P_i$ and represents soil solution P, soluble phosphates originating from calcium phosphates, and weakly adsorbed $P_i$ on the surfaces of sesquioxides or carbonates (Mattingly, 1975).

The $H_2O$-$P_o$ and bicarbonate-$P_o$ are considered "readily mineralizable" and related to P uptake by plants (Fixen & Grove, 1990). This $P_o$ fraction includes nucleic acid-P, sugar-P, lipid-P, phytins, and other high-molecular-weight P compounds (Bowman & Cole, 1978). The "readily mineralizable" $H_2O$-$P_o$ represented, on average, 1% of the total soil P and was uniformly distributed throughout the profile and across the tillage systems (Figure 2A). The resin and the bicarbonate $P_i$, on average, represented 4 and 6%, respectively, of the total soil P in the 0-5 and 0-10 cm soil depths. The profile distribution of these fractions is shown in Figure 2B, C. These fractions decreased rapidly with increasing soil depth and were affected by the tillage system employed up to the 10-20 cm soil depth. The highest values were obtained in the agropastoral treatments followed by the three-chisel-passes treatment to crop-rotation.

The $NaHCO_3$-$P_o$ represented about 2.5 % of the total soil P and did not differ much with increasing soil depth (Figure 2D). For the most part, there were no treatment effects and a gradual decline was observed with increasing soil depth. On average, the "biologically available" P represented 11-15% and 7-10% of the total soil P in the 0-20 and 20-40 cm soil layers, respectively. These results indicate that agropastoral treatments and 3 passes of chisel to crop rotation increased biologically active $P_i$ but had little effect on $P_o$. It is also important to note that the effects on biologically available P fractions were not significant below 20 cm soil depth except for $NaHCO_3$-$P_i$.

*Moderately resistant P* includes the NaOH-$P_o$ and NaOH-$P_i$ fractions that are not immediately available to plants, but have the potential to become available in a medium term (from months to a few years) through biological and physico-chemical transformations (Cross & Schlesinger, 1995). This fraction is thought to be associated with humic compounds, and amorphous and some crystalline Al- and Fe-phosphates (Bowman & Cole, 1978). The moderately resistant P fraction represented 30-35% and 20-25% of the total soil P in the 0-20 and 20-40 cm soil layers, respectively. The large amount of P recovered from this fraction can be attributed to the high contents of Al- and Fe-oxides associated with Oxisols. Both the NaOH-$P_i$ and the NaOH-$P_o$ were affected by treatments (Figure 3A, B). The greatest effect was

Table 2. Chemical characteristics of soil layers and total root length distribution during the fourth year (September 1999) after establishment of different agropastoral treatments. Root length values are for upland rice in the case of rice/soybean rotation and upland rice + pastures in the case of agropastoral systems. LSD values are at 0.05 probability level.

| Soil/plant parameters | Soil depth (cm) | System | | | | | | LSD (0.05) |
|---|---|---|---|---|---|---|---|---|
| | | Rice/soybean rotation | | | Rice + pastures (Agropastoral) | | Native savanna (control) | |
| | | 1 pass of chisel | 2 passes of chisel | 3 passes of chisel | Grass only (Ag) | Grass + legumes (Ag + Pp + Do) | Savanna | |
| PH | 0-5 | 5.7 | 5.8 | 5.7 | 5.1 | 5.1 | 4.6 | 0.49 |
| | 5-10 | 5.7 | 5.9 | 5.5 | 5.0 | 5.0 | 4.6 | 0.52 |
| | 10-20 | 5.1 | 5.3 | 5.1 | 4.8 | 4.8 | 4.7 | 0.24 |
| | 20-40 | 4.9 | 5.0 | 4.9 | 4.8 | 4.8 | 4.8 | 0.08 |
| | LSD (0.05) | 0.7 | 0.7 | 0.6 | 0.2 | 0.2 | 0.2 | |
| C (g $kg^{-1}$) | 0-5 | 20.1 | 18.3 | 21.3 | 19.9 | 21.7 | 16.3 | 2.11 |
| | 5-10 | 18.4 | 18.3 | 20.4 | 19.1 | 21.8 | 10.9 | 3.98 |
| | 10-20 | 15.0 | 15.5 | 17.3 | 14.9 | 17.6 | 6.7 | 4.19 |
| | 20-40 | 12.8 | 12.3 | 13.8 | 13.2 | 13.7 | 3.7 | 4.11 |
| | LSD (0.05) | 5.2 | 4.5 | 5.4 | 5.1 | 6.2 | 8.7 | |
| P (mg $kg^{-1}$) | 0-5 | 34.8 | 34.6 | 46.2 | 19.6 | 15.1 | 3.7 | 16.36 |
| | 5-10 | 20.7 | 15.5 | 16.9 | 7.2 | 4.6 | 2.0 | 7.92 |
| | 10-20 | 3.2 | 4.5 | 1.6 | 2.4 | 1.2 | 1.4 | 1.33 |
| | 20-40 | 1.8 | 1.5 | 1.0 | 1.5 | 0.6 | 1.1 | 0.45 |
| | LSD (0.05) | 24.9 | 23.8 | 33.7 | 13.3 | 10.7 | 1.8 | |
| K ($cmol_c$ $kg^{-1}$) | 0-5 | 0.20 | 0.33 | 0.24 | 0.17 | 0.24 | 0.09 | 0.08 |
| | 5-10 | 0.12 | 0.14 | 0.15 | 0.09 | 0.10 | 0.05 | 0.03 |
| | 10-20 | 0.07 | 0.02 | 0.07 | 0.06 | 0.06 | 0.04 | 0.02 |
| | 20-40 | 0.05 | 0.04 | 0.06 | 0.04 | 0.04 | 0.02 | 0.01 |
| | LSD (0.05) | 0.11 | 0.23 | 0.13 | 0.09 | 0.14 | 0.05 | |
| Ca ($cmol_c$ $kg^{-1}$) | 0-5 | 2.23 | 1.69 | 1.72 | 0.66 | 0.77 | 0.15 | 0.83 |
| | 5-10 | 1.54 | 1.37 | 1.41 | 0.43 | 0.60 | 0.12 | 0.63 |
| | 10-20 | 0.54 | 0.60 | 0.21 | 0.21 | 0.19 | 0.11 | 0.21 |
| | 20-40 | 0.19 | 0.13 | 0.18 | 0.13 | 0.09 | 0.11 | 0.04 |
| | LSD (0.05) | 1.48 | 1.13 | 1.27 | 0.38 | 0.52 | 0.03 | |
| Mg ($cmol_c$ $kg^{-1}$) | 0-5 | 0.95 | 0.76 | 0.75 | 0.29 | 0.37 | 0.08 | 0.35 |
| | 5-10 | 0.68 | 0.68 | 0.67 | 0.19 | 0.30 | 0.06 | 0.29 |
| | 10-20 | 0.34 | 0.36 | 0.16 | 0.13 | 0.13 | 0.05 | 0.13 |
| | 20-40 | 0.14 | 0.12 | 0.12 | 0.08 | 0.06 | 0.04 | 0.04 |
| | LSD (0.05) | 0.57 | 0.47 | 0.53 | 0.14 | 0.23 | 0.03 | |
| Al ($cmol_c$ $kg^{-1}$) | 0-5 | 0.43 | 0.31 | 0.37 | 1.25 | 1.09 | 1.98 | 0.69 |
| | 5-10 | 0.62 | 0.31 | 0.42 | 1.56 | 1.35 | 1.93 | 0.70 |
| | 10-20 | 1.35 | 0.94 | 1.25 | 1.56 | 1.25 | 1.69 | 0.27 |
| | 20-40 | 1.46 | 1.25 | 1.25 | 1.56 | 1.14 | 1.25 | 0.16 |
| | LSD (0.05) | 0.82 | 0.75 | 0.79 | 0.25 | 0.18 | 0.53 | |
| Root length (km $m^{-2}$) | 0-5 | 1.7 | 2.9 | 2.0 | 2.2 | 3.4 | 1.8 | 0.70 |
| | 5-10 | 0.6 | 2.4 | 1.2 | 1.8 | 2.6 | 1.2 | 0.81 |
| | 10-20 | 0.9 | 1.4 | 1.3 | 2.0 | 2.4 | 0.8 | 0.65 |
| | 20-40 | 0.8 | 1.8 | 1.2 | 1.5 | 2.1 | 0.4 | 0.66 |
| | LSD (0.05) | 0.8 | 1.1 | 0.6 | 0.5 | 0.9 | 1.0 | |

Ag = *Andropogon gayanus,* Pp = *Pueraria phaseoloides;* Do = *Desmodium ovalifolium.*

observed with the three chisel passes with crop rotation and the grass/legumes pasture treatments. The greater $P_o$ contribution to the NaOH fraction by agropastoral systems, the two-chisel-passes and the three-chisel passes with crop rotation could be highly desirable because the NaOH-$P_o$ fraction is usually more stable than $NaOHCO_3$-$P_o$ and may represent a relatively active pool of P in tropical soils under cultivation, especially those not receiving mineral P fertilizers (Tiessen et al., 1992). These results indicate that vertical tillage with three-chisel-passes with crop-rotation and two-chisel-passes with grass/legumes pasture treatments can markedly improve P availability through moderately resistant P pools.

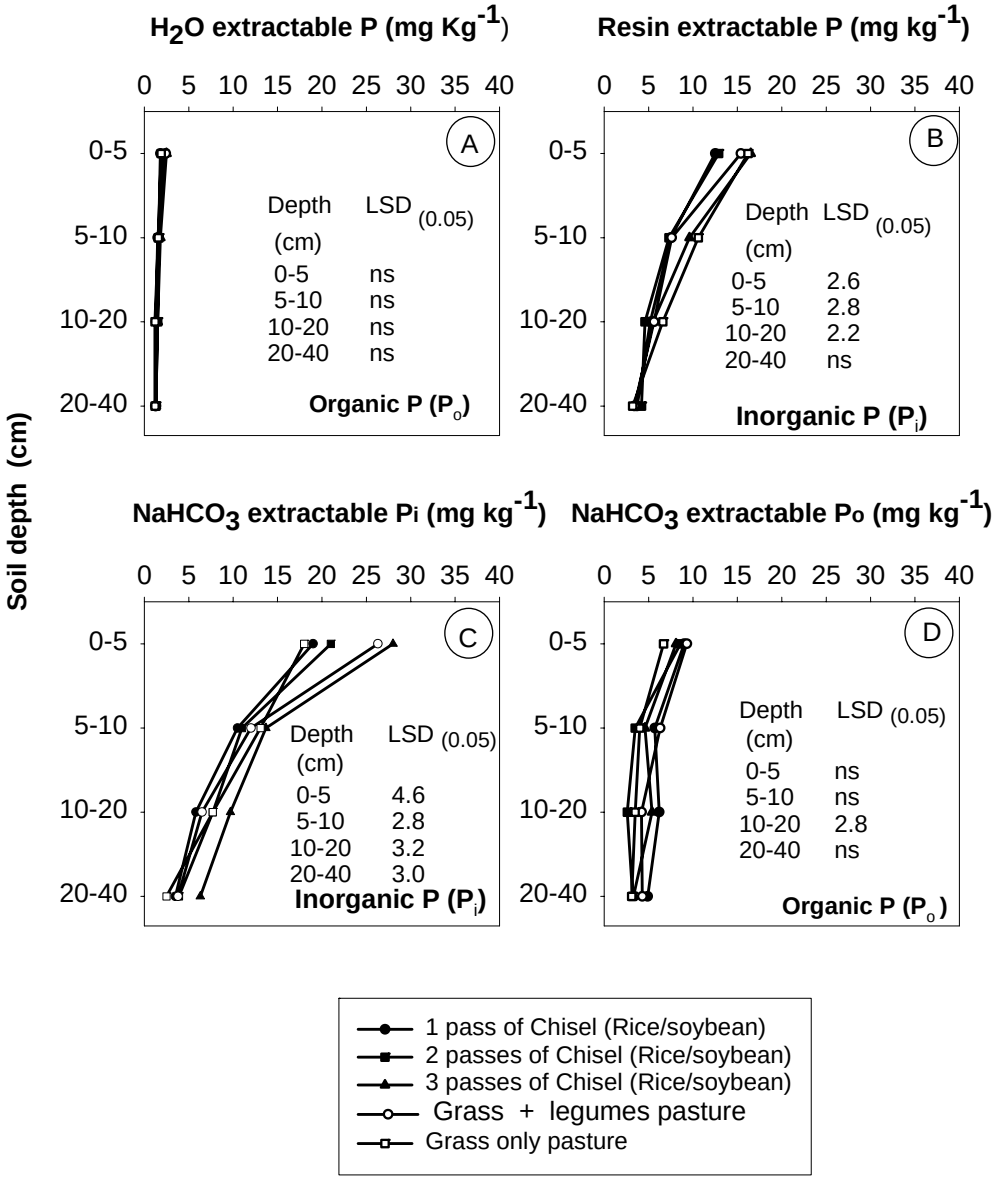


Figure 2. Distribution of the biologically available P fractions in soil profiles during the fourth year (September 1999) after establishment of different tillage and agropastoral treatments. Biologically available P fractions in 0 to 10 cm soil depth in native savanna plots were 7.1, 3.3, 7.1 and 5.4 mg $kg^{-1}$ for $H_2O$-$P_o$, resin-$P_i$, and $NaHCO_3$-$P_i$, and $NaHCO_3$-$P_o$, respectively. LSD values are at 0.05 probability level; ns = not significant.

The *sparingly available P* includes the HCl-P (not done in this study) and the Hedley et al. (1982) residual-P. The sparingly available P is not available on a short time scale such as one or more crop cycles, but a small fraction of this pool may become available during long-term soil P transformations. In general, this fraction was slightly affected by tillage system in the top 0-5 cm soil layer (Figure 4A) and then remained fairly consistent through the rest of the soil profile. However, it represented about 49% and 73% of the total P in 0-20 and 20-40 cm soil layers, respectively. This fraction is mainly composed of the stable humus fraction and highly insoluble $P_i$ forms (Hedley et al., 1982) and was not affected by chisel, crop rotation and agropastoral treatments in the short-term.

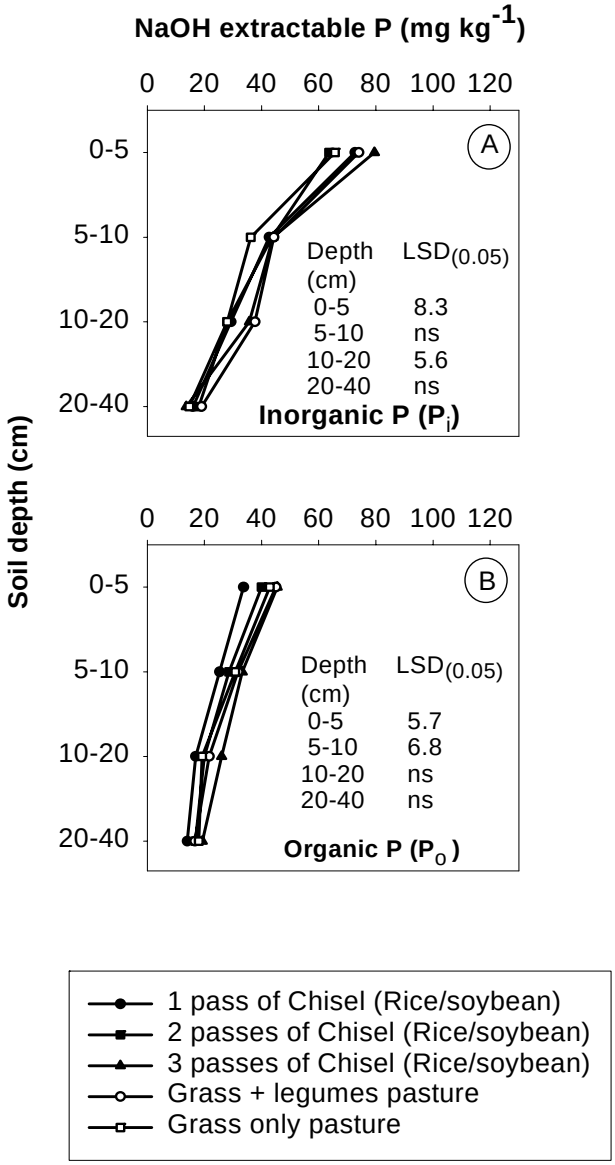


Figure 3. Distribution of the moderately resistant P fractions in soil profiles during the fourth year (September 1999) after establishment of different tillage and agropastoral treatments. Moderately resistant P fractions in 0 to 10 cm soil depth in native savanna plots were 16.1 and 25.5 mg $kg^{-1}$ for NaOH-$P_i$ and NaOH-$P_o$, respectively. LSD values are at 0.05 probability level; ns = not significant.

We also looked at the sum of the soil Po fraction ($H_2O$-$P_o$ + $NaHCO_3$-$P_o$ + NaOH-$P_o$) to detect any significant effects of treatments on $P_o$ that were not evident in the individual fractions. The sum of the soil $P_o$ fraction was, on average, 16% of the total P in the top 0-5 cm soil layer and decreased steadily to an average of 13.5% at the 20-40 cm soil layer (Figure 4B). The greatest amounts were obtained in the agropastoral systems, and the two-passes-of-chisel and three-passes-of-chisel treatments of crop rotation. The one-chisel pass treatment with crop rotation had the lowest effect on this fraction. Oxisols have high P-sorbing capacity resulting from their high Al and Fe content. Therefore, the increase of total $P_o$ resulting from treatment effects is desirable because the P maintained in organic pools may be better protected from loss through fixation than P flowing through inorganic pools in soil. Adsorption of P occurs mainly through processes in the soil, and as such minimizing P interaction with the soil is an important management tool for increasing P cycling.

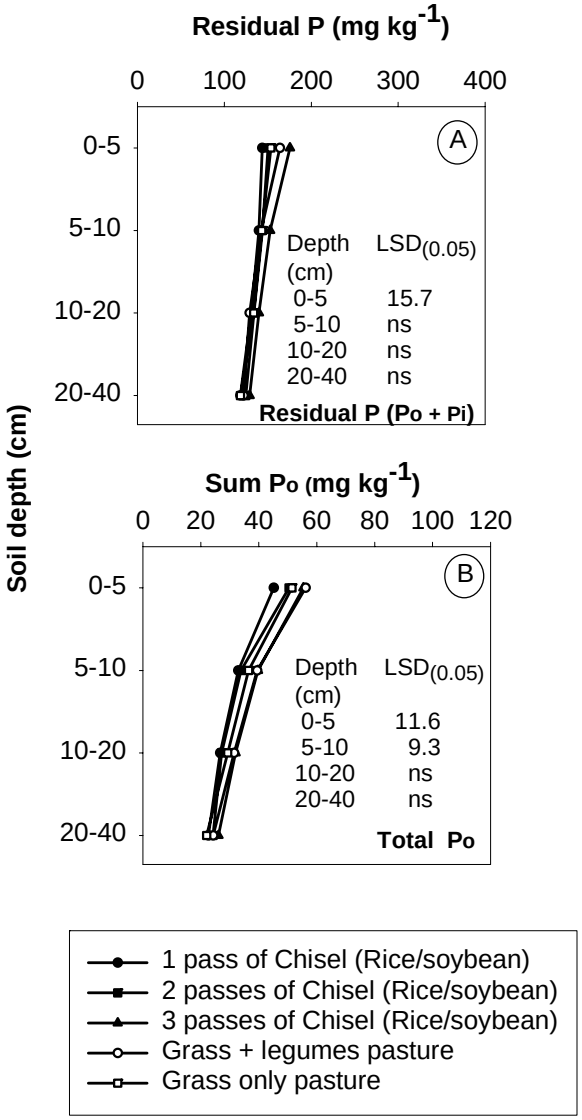


Figure 4. Distribution of the residual P and sum of soil Po in soil profiles at four years after establishment of different tillage and agropastoral treatments. Residual and sum of soil Po fractions in 0 to 10 cm soil depth in native savanna plots were 144 and 38.0 mg $kg^{-1}$ for residual P and total $P_o$, respectively. LSD values are at 0.05 probability level; ns = not significant.

*Crop yield, plant growth and total nutrient acquisition*

The trend in rice and soybean grain yields as a function of time is shown in Table 3. It was not possible to maintain yields of either crop in any of the treatments used. During the first year, yields of rice and soybean were relatively high, but they declined with time irrespective of the treatment, with the steepest rate of decline being recorded in the rice-pasture systems. The yield decline with rice may have been due to increase in weed biomass, which had a trend of 35, 320 and 704 kg $ha^{-1}$ for the years 1996, 1997 and 1998, respectively, in rice crop across treatments. Soybean was relatively less affected by weeds and it failed to produce any grain during 1998 due to severe drought conditions. Shoot biomass of rice was less when associated with pasture components than under chisel treatments with crop rotation (Table 4). This could be mainly due to the competition of pasture components for nutrients, water and light. These results indicate that decrease in rice yields was much greater in agropastoral treatments than in rice-soybean rotation. On average, an increase in the number of chisel passes from 1 to 3 did not significantly affect rice biomass or grain yield production. Amézquita (1998a) reported that three passes could be excessive for these soils causing a collapse of soil volume.

Shoot biomass of rice was greater with rice-soybean rotation than with rice/pasture treatments (Table 4). This was mainly due to the competition of pasture components for nutrients, particularly K and Ca which showed greater uptake in rice/pasture treatments than in rice-soybean rotation (Table 4). Previous research showed that pasture legumes could be of great importance in stimulating soil biological activity, nutrient cycling and addition of organic matter to the soil, which have beneficial effects on the production system (Rao et al., 1994; Thomas et al., 1995; Fisher et al., 1999; Sanz et al., 1999). Rao (1998) reported that the deep root systems of improved tropical forages are efficient in extracting nutrients from subsoil and recycling them throughout the plant and back to the soil through the death of plant tissue. Legumes also improve nutrient cycling and the nutritive value of forage. The agropastoral systems had greater root length compared to 1 pass of chisel treatment, particularly in the subsoil layers (Table 2). This is desirable as the turnover of roots through time contributes not only to nutrient cycling but also to soil improvement via positive changes in soil porosity and carbon sequestration in soil (Aerts et al., 1992; Rao et al., 1993; van de Geijn & van Veen, 1993; Veldkamp 1993; Cadisch et al., 1994; Fisher et al., 1994; Rao 1998).

## Conclusions

This study indicated that vertical tillage with 2 chisel passes for rice/soybean rotation or agropastoral treatments improved soil physical and chemical characteristics. However, these improved soil conditions did not translate into improved and sustained grain yields of either upland rice or soybean. This might have occurred because of crop management, particularly with the increase in incidence of weeds over time. Further research work is needed to develop appropriate crop management to benefit from the improved soil conditions. Buildup of an arable layer requires improvement of soil physical, chemical and biological conditions. Introduction of tropical pasture components with legumes into the production system could provide adequate soil physical conditions, to improve nutrient acquisition and recycling, and to facilitate accumulation of better quality and quantity of soil organic matter leading to the buildup of an arable layer. This study provides experimental evidence to promote the concept of building-up an arable layer in tropical Oxisols using vertical tillage and agropastoral treatments. But to improve and sustain crop production on infertile Oxisols of the tropics, there is a need to develop better crop management strategies to overcome weed problems. We suggest that the buildup of an arable layer is a prerequisite to move towards no-till or direct drilling systems to minimize environmental degradation in savanna soils of the Llanos of Colombia.

Table 3. Rice and soybean grain yield (kg $ha^{-1}$) as a function of time. LSD values are at 0.05 probability level.

| System | Treatment | Rice | | | | LSD | Soybean | | | | LSD |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1996 | 1997 | 1998 | 1999 | (0.05) | 1996 | 1997 | 1998 | 1999 | (0.05) |
| Rice-soybean rotation | 1 pass of chisel | 3240 | 2760 | 2064 | 1219 | 1398 | 1930 | 1330 | - | 1273 | ns |
| | 2 passes of chisel | 3650 | 2890 | 1720 | 1447 | 1636 | 1830 | 1280 | - | 1272 | ns |
| | 3 passes of chisel | 3310 | 3080 | 1455 | 1147 | 1757 | 1830 | 1260 | - | 1315 | ns |
| Rice + pastures (Agropastoral) | Grass only (A.g.) | 3180 | 1730 | 422 | 374 | 2111 | - | - | - | - | |
| | Grass + legumes (Ag + Pp + Do) | 3300 | 1760 | 724 | 736 | 1933 | - | - | - | - | |
| LSD (0.05) | | 227 | 805 | 852 | 530 | | ns | ns | - | ns | |

Ag = *Andropogon gayanus;* Pp = *Pueraria phaseoloides;* Do = *Desmodium ovalifolium*.
ns = not significant.

Table 4. Plant growth and total nutrient acquisition by different crop rotation and agropastoral systems during the fourth year (September 1999) after establishment of different treatments. Values of shoot nutrient uptake are for upland rice only in the caseof rice/soybean rotation and for upland rice + pasture species in the case of agropastoral treatments. LSD values are at 0.05 probability level.

| Systems | Treatments | Shoot biomass | | Shoot nutrient uptake | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Rice | Pasture | N | P | K | Ca | Mg |
| | | ---------- (kg ha$^{-1}$) ---------- | | | | | | |
| Rice/soybean rotation | 1 pass of chisel | 3990 | - | 41 | 7.2 | 39.7 | 6.1 | 7.3 |
| | 2 passes of chisel | 4210 | - | 50 | 8.0 | 42.9 | 7.2 | 8.1 |
| | 3 passes of chisel | 4370 | - | 50 | 7.3 | 42.8 | 6.6 | 7.7 |
| Rice+pastures (Agropastoral) | Grass only (Ag) | 2280 | 2120 | 54 | 6.6 | 66.3 | 10.3 | 7.7 |
| | Grass + legumes (Ag + Pp + Do) | 2420 | 3140 | 65 | 7.7 | 71.6 | 12.9 | 8.6 |
| LSD (0.05) | | 1480 | ns | ns | ns | 26.0 | 3.4 | ns |

Ag = *Andropogon gayanus;* Pp = *Pueraria phaseoloides;* Do = *Desmodium ovalifolium*.
ns = not significant.

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**Networks of Agricultural Information Dissemination in Emuhaya, Western Kenya**

Michael Misiko (TSBF-CIAT), Joshua J. Ramisch (TSBF-CIAT) and Leunita Muruli (University of Nairobi).

**Summary:** Researchers interested in technology dissemination are increasingly targeting farmer-to-farmer extension techniques. However, farmer networks form for a variety of reasons, and different actors perceive their benefits in many different ways. This paper describes the role of social networks in soil fertility management among small-scale cultivators in Western Kenya. Data for the study were collected from farmers using a semi-structured questionnaire, group discussion, in-depth interviews and direct observation. By and large, agricultural activities still dominate the agenda of rural community institutions. However, the exchange of soil fertility is increasingly accorded low priority in social interactions between farmers, because of poor returns from farming under current conditions of land and labour scarcity. Many farmers put greater priority on using networks for business, formal employment, politics (favours, handouts, appointments, etc.) or infrastructure development. . Networks of farmers are formed on the basis of friendship, proximity and buffering against uncertainty. These factors are effective reminders of the value of networking within community institutions. These findings have important implications for agricultural technology dissemination and adoption in developing countries.

## 1. Introduction and Objective

The complexity, diversity and peculiarity of rural communities are increasingly being appreciated in research and development work. Social dynamics, like geographical, cultural, soils' physical and biological aspects of a given community pattern agricultural practices. This paper gives a systematic view and analysis of social networks in community institutions and demonstrates their importance and significance in the process of dissemination of agricultural knowledge.

This paper is a result of a study within a BMZ-funded Project of the Tropical Soil Biology and Fertility (TSBF) Programme. The project sought to involve community institutions in the dissemination of agricultural technologies, and therefore studied mechanisms that could be effective in a socially heterogeneous farming community (Emuhaya, Vihiga District, Western Kenya). Some of the important matters brought to light in this study include:

- There were strong social networks among local farmers. Important soil fertility knowledge given to the few farmers who had been involved closely in research and extension filtered to many other farmers through networks.
- However, the content and scope of the knowledge was curbed in the process of dissemination. This resulted from the nature of the existing research links, which currently emphasise vertical rather than effective horizontal sharing of information.
- The wide variety of social problems facing local farmers constrained their search for soil fertility knowledge. Farmers' efforts were diverted to short-term endeavours that ranked as more important.

The understanding gained on networks in community institutions has provided a stage for wider and more meaningful involvement of farmers in research and extension. This paper (i) describes networks among farmers, (ii) demonstrates the importance of networks in community institutions and (iii) explains the function networks play in disseminating agricultural technologies among rural farmers.

## 2. Recent Perspectives on Networks

> "…[I]t is clear that agriculture today is often individualistic, with farming households increasingly going it alone. But in times of trouble, such as following a drought … and labour is critical to ensure a good harvest, networks are re-established and co-operative behaviour is very evident. Social networks based on lineage relations and friendship thus

may not be critical to agricultural production in all years as they were in the past, but they are certainly of vital importance as a means of offsetting extreme hardship' (Scoones *et al* 1996:35).

Social networks have an important role in the lives of rural communities. In the recent past, research has been done to understand networks and how they function. This knowledge needs to be synthesised, developed and analysed with the view of enhancing dissemination and adoption of agricultural technologies. Lack of understanding or inadequate appreciation of networks will impede dissemination of soil knowledge.

Existing networks can be exploited through engaging community groups (IIRR, 1998). Because group members are themselves typically linked by a variety of network ties, individuals within the group are able to call on collective resources, such as reciprocal labour exchange (Sikana, 1995; Scoones *et al* 1996). Well-functioning groups develop a spirit of "…unselfconscious showing, sharing, and checking… [such] Groups have an overlapping spread of knowledge which covers the wider field and crosschecks" Chambers (1992:41). That implies that farmers of different sorts in such institutions share different types of knowledge and demonstrate or verify it in the process of interaction. By introducing technologies to strong groups comprised of well-networked individuals, researchers may have at their disposal a strong framework and impetus for the adoption of technologies (Sharp and Kone, 1992: 8).Even if strong groups permit the successful diffusion of technologies, researchers and extensionists must be wary of calling immediately for the strengthening (or establishment) of new community institutions. Farmers' institutions have developed and operate within a local context where they may be effective, but farmer groups on their own rarely have influence on higher-level decisions concerning policy. Similarly, because most of the rural population is resource poor, their institutions frequently have weak financial bases. This constant vulnerability does not allow such institutions to bargain with external donors or agencies on equal terms, and leaves them open to having priorities imposed upon them. Since many governmental and non-governmental organisations are eager set up *their own* farmers' organisations and to shape them in line with their ideas and ideologies, it is therefore crucial to establish practical guidelines through a truly inclusive and acceptable arrangement (Pertev and King, 2000). Empowerment should be about organisation, strengthening networking at grassroots structures. Allowing or enabling democratic control of members on these structures will help establish trust and effective vertical relationships.

Although "communities" (or even farmer groups) may have boundaries and memberships that appear discrete and accessible to outsiders, social networks are not confined solely to those units. Rural people participate and invest in a diversity of social networks, whose value lies exactly in their wide thematic scope and geographic coverage (Adamo, 2001). It is ultimately going to be more sociologically and culturally sensitive, as well as more sustainable, to identify the range of local networks that could be used as potential entry points for different research activities (Sikana, 1995).However, it is unrealistic to expect that the interests and priorities of farmers' existing institutions will necessarily correspond with those of researchers. For example, Verma (2001) observed in Western Kenya that soil fertility concerns were not top priority for many farmers, even though land per capita is diminishing and the soil fertility in this region is under serious pressure. Greater worries about disease or marital security in fact constrained many households' efforts to conserve soil fertility. Truly participatory technology design will emphasise farmers choosing research activities relevant to their needs that also build on their knowledge of the farming system and their familiarity with local technologies (Haverkort, 1991).

## 3. Methodology

The process of study involved both individual actors and collectives in an effort to assess their links and roles, and to outline opportunities of better engaging community institutions for research and extension. To get a comprehensive view of the process of sharing of soil fertility knowledge, this study targeted community institutions, interviewing members of these institutions and focussing on key informants.

Ten community institutions were purposively selected on the basis that (i) they were engaged in agricultural activities, (ii) held regular meetings, (iii) had been in existence for more than one year and (iv) engaged in information dissemination in several ways. Seventy-eight questionnaire respondents were

randomly sampled from 334 members of these selected institutions. Seventy-eight (23%) was representative given the nature of the study, physical size and population density of the area. The purpose of the study was to maximise access to qualitative information from a group of respondents knitted in social networks. The researcher therefore deliberately selected a diversity of informants who were most likely to provide articulate answers, explanations, descriptions, proposals, and experiences concerning the complex issues of social networks. Eleven key informants were selected purposively. These informants included people with leadership roles and responsibilities (*Maguru*), those respected in the community, people who had worked in that community and had accumulated essential knowledge and experience in local agricultural aspects, with valuable opinion on community organisations. Some had participated in the project before and had valuable opinion on agricultural research. The researcher carried out several informal interviews, focus group discussion (*FGD*) and group interviews, engaged repeatedly in participatory learning and observed various phenomena to verify or identify data.

The study (and therefore this paper) was largely based on qualitative data: on open conversations[1], in-depth and group interviews, comparisons more than counting, informal *FGD* and brainstorming, stories, exchanges and consensus where necessary. Analysis was therefore largely on the spot, while the study occurred.

3.1 – Study Area – Social. The study was conducted in Ebusiloli sub-location of Emuhaya Division in Vihiga District. The Luyia speaking people called **Abanyore** inhabit Emuhaya. They formed a close community in which there was much sharing of life between families and neighbours (Osogo, 1965). Today, a strong individualism is replacing this community consciousness. Since independence, their social system has noticeably transformed and the predominant religion is Christianity (Muruli *et al*, 1999).

In 1995, Vihiga District had 948 registered women groups with membership of 28,440. There were 557 self-help groups (no membership given) and 168 youth groups with registered membership of 4,543 (Republic of Kenya, 1997). Information acquired from the divisional headquarters of Emuhaya during the study show that there were seven registered groups in Ebusiloli (Courtesy: Ministry of Social Services, Emuhaya Division). According to Muruli *et al* (1999), more than sixty three per cent of farmers in the area actively participate in different kinds of registered and unregistered community institutions.

3.2 – Study Area – Physical. Emuhaya has loamy sands that support the growing of maize, sweet potatoes, coffee, beans, finger millet, sorghum, sugar cane, and horticultural crops (Republic of Kenya, 1997). However, these soils are quickly losing their fertility through leaching and over-cultivation due to limited land sizes per household coupled with low usage of suitable farming innovations. Vihiga district has an annual population growth rate of three per cent. Emuhaya's population density is about 1197 people $km^{-2}$ (Republic of Kenya, 1997).

## 4. Social Networks: Is There Room for Soil Fertility Knowledge?

Although networks are the implicit cornerstones of the farmer-to-farmer strategy for disseminating soil knowledge being preferred in many projects, many academic analyses of social networks create a romantic picture that may not be regarded as very useful by agricultural workers. Such texts may for example display a harmonious existence and functioning of networks in community institutions. Such information may not outline specific areas that can be exploited to enhance dissemination of agricultural knowledge. Of course, forming social networks is not an end in itself. The communication of information and reciprocity of networks are in reality a survival mechanism for many poor farmers. They provide the means to acquire material and non-material benefits.

Results from the *FGD*, the study survey and in-depth interviews show that networks play a

[1] The researcher recognized the essence of getting farmers' message clearly and as accurately as possible. Before any *FGD*, interview or meeting he met with some participants to train them in note taking so that he would concentrate on keeping conversations flowing. However, the researcher wrote down brief notes on important issues in a small notebook. Key vernacular terms were written. Maintaining conversation flow in discussions is vital if one hopes to keep participants *interested* in the study.

dominant role in agricultural production. The question remains, however, whether room exists for soil fertility knowledge in these social networks? Soil fertility knowledge may be spread or utilised depending on the type and strength of networks in operation. The following expressions by two farmers attest to this.
Boaz:

> "… [S]ome people are just friends. They do not share a lot and that is why they do not work closely. But me, I value my friends and neighbours very much. We exchange items like the 'black beans' (*KK15)* and soil knowledge from the research people and contribute a lot to our farmers' research group. The group and also my youth group are very beneficial. I also participate in *barazas* of *Maguru* [village headmen]. They [*Maguru*] are [also] useful because they help us to deal with thieves…."

Alexander:

> "Our group is made up of people with similar interests who know one another well. When there is a demonstration here [researchers have a trial plot on their family farm], all members attend and learn something. We have been planning to try some of those technologies [leguminous cover crops such as *Desmodium*] on our group's plot but we do not have enough farm and money and prefer to plant *Napier* grass for sale. …[B]ut we cannot convince others who are not in our group to do what we do not do. They will say, 'If it is good why have you not tried it?' So that is hard, when they see the things [improved fallows] on the trial plot they say, 'You [the family] have been given money for this research and we have not."

These verbatim accounts show that soil fertility knowledge is likely to spread faster among farmers bonded by strong networks, who will share valued information amongst themselves. However, as the second farmer implies, even information that is known to be potentially useful will not spread without it also being *seen* to be beneficial. In this case, because the soil fertility practices being researched were not perceived to offer immediate financial gain, farmers of that group were not keen to try them. This reluctance within the group of research farmers effectively blocked the further sharing of useful soil fertility practices, even though the research farmers might have been part of extensive and strong networks.

This suggests that farmers would more likely engage in social talk about something immediately tangible, like a good yielding crop variety, than they would about something more abstract or complicated, such as a management practice that would directly support that crop by improving soil fertility. It is easier to talk about the benefits of a technology than it is to explain exactly how those benefits were obtained. Nevertheless, most of these new technologies rely on sound management. Because farmers will master this management at differing rates, many may not feel confident enough to discuss soil fertility management, especially the new practices that research is still yielding. Unfamiliar technologies (such as planting of *Desmodium* sp.) will therefore not enter easily into local discourse and practice. However, *Crotalaria ochroleuca*, another of the improved fallow species being researched and disseminated is well known by farmers because it is locally eaten as a vegetable. However, if it is known and liked then not enough quantities may be left in the farm to mature so as to contribute to soil fertility. Farmers may generally view it and discuss it as food, not a soil fertility management plant. Therefore knowledge about it may not necessarily be inclined toward improvement of soil fertility.

One benefit of strong social networks is the provision of social fora to express or explore new ideas. While most farmers did not necessarily have access to such venues, two examples show how strong networks did allow valuable soil fertility information to be exchanged between members and sometimes used on collective plots. For instance, the 19 members of Emanyonyi Women Group spent between ten and sixteen hours (11-20%) of their working daytime in a week together. Discussion of soil fertility was part of their deliberations on the agricultural and forestry projects that generated their collective income. Each and every member was an *official* in some capacity. Because this group had several ventures, all the members had to actively contribute labour, cash and importantly information or logistics. Their stronger networks had not just inculcated discussion of soil fertility information; they attracted outside support (especially training and exchange visits). Similarly, Escrava Youth Group whose members were young (18-35), perceived soil fertility research as an opening to enhance returns from their farm projects. During a visit to their plot, the researcher noticed that they had embraced some of the biomass transfer practices that were under research. Most members of this group did not own individual

plots, yet their willingness and ability to share soil fertility knowledge was astounding. Only two of the 17 members were participating in TSBF trials, but the level of awareness among the rest was significant due to their attitudes. Networks as strong as those found within these two groups act as invaluable 'talking spaces' and provide counsel to members. It is important for locals to be able to present and discuss new ideas especially in their own language and setting. This may present one way of understanding how farmers conceptualise and use new soil fertility ideas.

Farmers with strong networks were able to exchange valuable knowledge on soil fertility (i.e.: *biomass* transfer and fallow cropping practices) and take certain collective investment risks. In such cases, the general 'farming' talk also led to tangible exchanges such as seed, agricultural labour, cash, manure, land use and other resources. Unlike average networks, strong networks allowed for a relaxed form of balanced *reciprocity* where one did not necessarily have to 'reply' immediately or directly. For example, one would volunteer one's farm for collective farming without expectation of direct payment from members. One was clearly aware that some members did not have sizeable farm to allow for collective activities.

**5. The Essence of Networks**

In spite of the decline in soil fertility and the ensuing low farm yields, farming remains a treasured activity, even if it is not one that receives adequate national support. Most people in the study area practised at least some form of farming regardless of their main occupation. One adaptive research farmer, Nashon, portrays this in the following explanation:

> "I discuss many things with people. I sit in the [farmers research] group, and I know most of us want to spend a lot of energy on small businesses or to look for office work [i.e.: formal employment]. As you have known, our farms are very small and we are very interested in growing [i.e.: getting money] because we are very poor. This work you are doing will help us also, to train our people in agriculture, to teach us soil fertility practices so that we can increase our maize harvest. Let me tell you something, we feel very fastened to farming even though our maize [harvest] is pitiable. Yet one's own harvest is very precious. If your children want to roast [maize], they will not steal from your neighbour's farm [if your farm has any maize on it?]. So you see, soil fertility is important because if you fail to plant, or do not harvest anything, your child may become a thief and people will say you are lazy. So for me, I ask for soil fertility information from you the agriculture people [researchers and extension agents] and my friends [locals] to help us…."

As this commentary shows, farmers engage in agriculture not because it is inherently profitable but because it is an essential part of life. In this respect, it is wrong to conceive of peasant cultivation as a 'technical industry' *per se*, since it is also clearly a socially-based activity. Informal discourse within farmers' networks is commonly about what are accepted norms. Resources were 'injected into the soil' even when returns were small, in part because someone who 'failed' to demonstrate capacity as a 'farmer' would risk criticism as 'lazy', a 'thief', etc. Clearly the discussion of new soil fertility practices would fall within such local 'normal' discourse, but quantifying these discussions would be difficult.

Nashon is however uses his local networks only cautiously, since he preferred not to rely on locals for important information. He stated that there are certain hindrances to the flow of useful knowledge within his experience of networks, especially related to the sharing of gossip (*etsimbemba*):

> "You hear 'So and so said this or that': how do you rely on that? *Avanti vayansa okhuchaya* (others will despise you), instead of learning something from you. *Valala vali nende omwoyo kwe imbotokha nende wivu* (others have bad feelings and are jealous), others are false pretenders (*vachuaji*), they pretend they know it all and few are delinquent (*avahalifu*)."

Such feelings were particularly common among men. Many farmers cited such explanations as obstacles to the establishment of stronger networks with certain people in some community institutions. Farmers would rather keep away from those they regarded as pernicious, even if it meant foregoing access to useful information. An implication of this wariness is that in selecting resource people researchers need to be keen to avoid putting locals regarded as 'unpleasant' on the frontline. If they have bad reputation, the project will not have a good standing and locals may not feel enthusiastic about the research.

On the other hand, some issues were perceived as so fundamental that farmers were encouraged to unite and create stronger networks. The main reasons behind strong networks of interaction in community institutions gathered in the sample survey have been given in Table 1 below.

**Table 1: Percent Distribution of Reasons for Participation in Community Institutions**

| Exchange/Benefit | Responses | Percent of Responses |
|---|---|---|
| Improve livelihood | 49 | 28.5% |
| Cash – credit, assistance, savings | 36 | 20.9% |
| Agricultural development | 35 | 20.3% |
| Assistance – in distress | 27 | 15.7% |
| Advice and information (general) | 15 | 8.7% |
| Administrative issues, *Maguru* | 6 | 3.5% |
| Links to donor and agricultural organisations | 3 | 1.7% |
| Employment, to earn some money | 1 | .6% |

The most commonly mentioned motive for participation in community institutions was to improve members' livelihoods. Table 1 also reveals that at the grassroots, agriculture is an integral part of the broader system of economic and social contexts that shape involvement in social networking. . *FGD*, group discussion and informal interviews showed that earnings from other occupations such as formal employment and business are used to improve soil fertility. For instance, poor performance in business or a delay in salary payment affected purchase of fertiliser or seed. Therefore, networks formed on non-agricultural exchanges directly or indirectly support agricultural production. It therefore implies that narrow observation and dealing with local institutional networks as if they were purely 'agricultural' in orientation can be misleading.

**6. Networks in Community Institutions**

The history of an institution's development, and the nature of its members' networks significantly influenced the sharing of valuable knowledge, collective action and attitudes and behaviour. The main reason behind the existence of strong networks was the need to improve livelihood foundations. The strength of these networks depended on actors' trust in each other. If this trust was significant, they would invest their time and money together in group activities, one consequence of which would be the sharing of soil fertility knowledge.

Nevertheless, the process of inception of the various institutions that existed was not unilinear. The strongest community institutions resulted from one or two individuals inviting their close friends who shared similar problems and aspirations. Leadership in such situation was achieved through mutual agreement, willingness and suitability. Duties would be delegated to any chosen member and everyone's input in drawing a constitution was valued. Constitutions were precise, mutual agreements, normally as written documents, but a few were verbal. They outlined the objectives, procedures and conduct of members in an institution.

Researchers facilitated the creation of one farmers' research group, while other institutions were mobilised by local resource persons, church leaders, opinion leaders or even politicians. All the institutions that were selected for study had been in existence for over two years. The oldest was a labour group that had been in existence for over 25 years. Institutions that were formed and defined by narrow schemes such as to gain access to campaign money shortly before the 1997 presidential funds drives did not last long. They were mobilised by politicians and packed by people who did not have strong networks. Soon after inception, jostling for leadership and access to funds ruined them.

There were several factors that were favourable for the existence of an institution. The overriding factors included the desire and dedication of actors in networks. Actors relied on existing traditions, and social and cultural attitudes conducive to co-operative participation and common social action. One

discussant (Gerishon[2]) reflects this in the following remark:

> "Our people have always had reasons to co-operate. Since the time of my great-great-grandparents, Abanyore have assisted each other in wars, famine, building huts, farming, hunting, raising children and so on. Many of those things are done individually now while others no longer matter. But, you never know. You may fall sick or even die tomorrow…. I have to maintain some relationship with some people, in the event that I need help they should be willing and available to assist me."

The success of strong groups also tended to be self-reinforcing since, when members' financial stake in their group was significant they tended to participate actively in an effort to ensure that the group operated efficiently.

The strength and nature of interactions within local institutions was significantly shaped by proximity. Most residents had been living in the study area among their lineage relatives for many generations. As a result, local level networks were considered strong. For example, members of Alexander's youth group live nearby and formed a very active institution. However, like other groups, the quality of networks was determined by friendship based on age and socio-economic factors.

Table 2 shows that friendship was very important for determining group membership, especially within women and youth groups. Women groups, followed by youth groups, were identified as having the strongest network ties. These two drew membership from across the study area and beyond. Women were more available than men for meetings, able to work with young members, and had fewer leadership wrangles or funds mismanagement problems. Theoretically, networks were vast and primarily open. For instance it was not possible to map out all networks of a member of a community institution. But the nature of networks and goals of an individual defined the level of freedom to move in and/or out of an institution. For instance, a man of sixty-eight years was unlikely to share or discuss goals and aspirations with his twenty-year-old daughter in law. Other than age, this would also be culturally abhorrent.

**Table 2: Composition of Community Institutions**

| Type of Institutions | Close Friends | General Friends | Close Relatives | Clan Members |
|---|---|---|---|---|
| Women Groups | 31 | 8 | 3 | 6 |
| Youth Groups | 21 | 10 | 2 | 16 |
| Farmers RG and Self-help Groups combined | 11 | 10 | 2 | 16 |
| Totals | 63 | 28 | 7 | 38 |

Many of the respondents belonged to more than one institution. However, this did not necessarily reward them with soil fertility knowledge. Members almost always affiliated closely with cliques of their closest friends. In fact, there was evidence of lack of practise and even awareness of notable activities done in other institutions in spite of the fact that some members belonged to both institutions. For instance, one institution had very strong networks that were evident from frequent weekly meetings, loyal contribution of subscriptions, high attendance in meetings, participation in collective activities and sharing of important farming and other knowledge. Members of this group had been trained in tree planting, improvement of soil fertility through improved fallow systems and biomass transfer, basketry and so on. Some of these skills and knowledge had not spread to neighbouring institutions to which some of the members belonged. It is possible that the content of the information that had percolated was very ordinary. It would take a longer period (more than one year) for a remarkable amount of soil knowledge to pass to other institutions and for them to use it.

[2] Gerishom (62) worked with the Railways corporation in Uganda and Kenya before his retirement. He is a committee member of a water project in his village and his wife is a key member in one of the most active women groups in Ebusiloli. He is very knowledgeable about the social history of his people, and his ability to critique, use proverbs, analogies and comparisons from afar was impressive. He has a zero gazing unit and part of his farm-plot is used for TSBF trials (BMZ Project). Unlike other verbatim, his has been directly written in grammatical English because it was entirely recorded in English.

One explanation for the low exchange of ideas was that the new practices were not seen to promise good enough economic returns to compete with other group investment opportunities. Local farmers noted that agriculture is very difficult to capitalise. For example, farmers have trouble obtaining credit for new farm ventures because the profits to the lender are not assured. Furthermore, it was not feasible for most households or groups to engage *only* in agricultural activities, since land pressure is intense and it was difficult to acquire sizeable farms (over one acre). Even if farmers planted cash crops like kale or other vegetables, the amount they would fetch was little. Such collective proceeds would be meagre when subdivided among members of a given institution. Therefore, networks were not used exclusively for agricultural work. For example, if members set one day a week to work on their group plot, they would spend the rest of the week on other enterprises like selling maize or firewood beside the road. The desire for cash (specifically capital) was important in this respect. There was a resolve to engage in small businesses within homesteads or at local market centres and many groups intended to purchase plots, to construct shops, rental rooms, eating rooms, and so on. Such ventures were seen to be more profitable uses of local 'farm' plots than using that land for agriculture.

Smaller institutions of about fifteen were more organised and committed to their course. It is however not possible to map out the boundaries of networks and thus determine an ideal size of farmers' institution. This study points out that it is preferable to work with institutions shaped out of a 'natural' process rather than try to create networks on the basis of research needs. If the goals of research cannot fit somewhere within the wider objectives and aspirations of local farmers, then there is arguably no business to be done with those farmers.

In circumstances where local institutions are not already strong, creating or strengthening those existing networks can be worthwhile. It is not uncommon to find farmers who live nearby, share common agricultural problems and have strong networks, but who are yet to form an organised institution. In other words, the formation of a group does not happen spontaneously, it often takes the initiative of a local opinion leader or someone else to facilitate.

**7. The Strength of Networks**

According to Ritzer (1992), the strength of networks is directly dependent on the returns accruing from them. In reality, farmers do not mechanically act in social networks while making cost-benefit analyses. For instance, most farmers understand that seeking and maintaining links with researchers and extension workers can assist them to improve their soil management practices, among other benefits. Yet even where the researcher-farmer relationship is strong, it does not follow that information shared between them will spread to other farmers. The nature of farmer-to-farmer interactions is a function of local social relations, as explained by this fifty-six year old *Liguru (*village leader) Bernard:

> "Many farmers in your projects do not want others to know what they are doing or how they are benefiting. They feel privileged and under no obligation to spread the knowledge they are given. They wish to stay on top by being advantaged in such ways…. Not all are like that, but it is hard to know. You [researchers] should do things openly. You should involve many people. Let us see, who has joined us here since you came? They [farmers] think it is a private deal between you and me. Those who come may not want soil fertility information but to know our affairs".

The acute under-utilisation of existing technologies is often construed as 'conservatism' or 'traditionalism' on the part of rural farmers. However, as Bernard's comments show, new ideas are not like seeds that can be sown on neutral ground. Instead, they are always being planted in environments where the "safeguarding of vested interests and a *way of life* is very conscious"( Mbithi, 1974: 60).

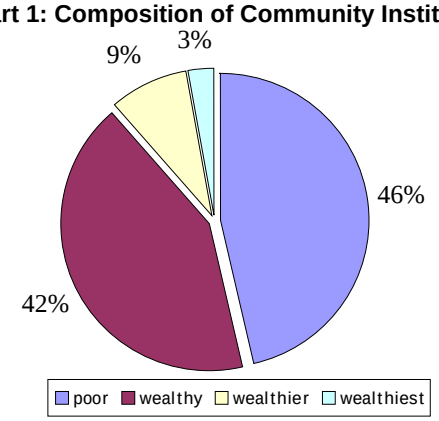
Networks are dynamic. Regardless of the rules and codes of conduct within community institutions, the networks between members are never constant. The more committed members are to their institution the stronger their networks. The more they exchange information and achieve their goals, the higher the chance that they will remain in those institutions for long.

Congenial discourse within an institution creates an air conducive for association, but people will enter and leave institutions as they choose. Fortunes of members keep changing with new experiences, beliefs, opportunities, and even assumptions. In the face of such potential fluidity, an institution's

organisation is important. Within institutions that had strong networks, members had unambiguous but to all intents and purposes transcending roles. In institutions where the role of each member was noteworthy, members had a feeling of value and merit. Such groups could endure without significant turnover of membership. However, most institutions did not function like this: rather, they had a small, core membership that provided continuity and direction. Most of these institutions were made of economically poor farmers. Such groups would not persist without the constant initiative of relatively stable members to invite, mobilise and encourage others to join or even remain in those institutions.

Informal interviews, in-depth interviews and discussions showed that relatively richer farmers were seen as sources of casual employment, money handouts, food, tools, and so forth. Contribution of resources to institutions was supposed to be uniform for all members in given institutions. Nevertheless, relatively prosperous members of community institutions were expected to be 'monetary pillars' in times of difficulty. Chart 1 below shows the distribution of members of institutions in various social classes as perceived by farmers. These data were gathered in wealth ranking exercises that were carried out during the study. While poorer farmers acknowledged that there were also members who were knowledgeable in soil conservation, their value to the group as 'knowledge reservoirs' was rarely acknowledged or explicitly valued. The low flow of valuable knowledge from resource persons was also made notable as a result of their small number.

**Chart 1: Composition of Community Institutions**




Discussion also revealed that women were more likely than men to share resources in institutions. While soil fertility found its way (explicitly) on to the agenda of their discussions on relatively few occasions, women's strong networks were however built upon the understanding that they were more vulnerable to hunger and other local problems than men. It therefore became necessary for them to discuss crop performance. Furthermore, women's position in the homestead was precarious, as their stability depended considerably on their husbands' decisions. If they transferred savings to their homesteads, those savings would be counted as their husbands'. It was therefore rational to keep some of their savings with the group so as to safeguard it. Consequently, regardless of how women were perceived (wealthy or poor), their involvement in community institutions was beneficial. For instance, women perceived as relatively well off had children in schools and their parcels of farmland were relatively larger. If their husbands declined to hire labour, they were made to turn to their institutions for labour. In worse circumstances, poor women received comfort from these institutions. They would for example withdraw their investment in the event that they were divorced[3] to 'look for life' elsewhere. The proceeds of institutions were not necessarily immediate or for immediate use. As Kanogo and Maxon (1992), (in Nangendo, 1994:353)

[3] Abanyore are patriachal and patrilocal. When a woman is divorced or 'flees away', she is therefore expected to live elsewhere. Normally, young women would return to their parents or remarry. But those over forty-five would find it hard to settle back in their parental homes or to remarry. They would turn to their savings in groups to start business or resort to other dealings.

say, members of these groups:

> "pooled labour resources and shared the proceeds of that labour, and this produced a spirit of sharing and unity. People joined these groups even if they did not immediately need the services provided."

Hartwig (2000:34) observed in a similar vein that:

> "The groups are open to precisely those women who … progressing from dealing with specific problems in the women's work and life, provides the stimulus to exchange information and develop their education."

**8. Reaching the Wider Community**

To a casual observer, the networks in local institutions are besieged by competition just as much as co-operation. It was however found that competition in these institutions acts as a reminder that farmers do not always network because they are homogenous, but rather because they want to fight poverty. This finding is reflected in this revelation of a sixty-year-old key informant (Repha):

> "Members of my group have different behaviour but have similar ambitions. We therefore share agricultural information. All the people you see sitting together in community institutions recognise that they cannot succeed by sitting on others (undermining others). … [Y]ou give some people around here information, they refuse to use and instead visit me at night[i.e.: steal her crops]. Such are the people who want money from researchers, though they need information urgently. If you get even five people who are serious, work with them. Do not follow masses, your success will be small. Work with few groups and if others *see results*, they will move closer, like now, many of them want to know about the black beans (*KK15*). …[I]t is not that they are not involved, they do not involve themselves. I always invite them to my farm whenever visitors (researchers) come. Few come, some do not, yet they all want to *see results*."

Her emphasis on tangible results reinforces that that research must be seen (and known) to benefit especially poor farmers. If the agricultural technologies that research is generating can be shown to be useful and sustainable, then researchers may rely on networks to reach the wider community. During the study period, it was found that farmers were willing to participate in collective research activities if research would directly benefit them especially in the short term. Some of the cover crops (especially *Desmodium,* planted with *Napier* grass etc.) were appreciated. Some farmers liked this particular leguminous cover crop because it would increase the harvest of *Napier* grass, which is an important cash crop to many institutions that were studied. However farmers were disheartened due to unavailability of seed. Moreover, if these legumes could be consumed (like *Crotalaria*) it would be pointless to vigorously disseminate knowledge on their usefulness. Such knowledge would spread quickly through social networks and farmers would first adopt them as food crops regardless of what scientists told them.

**Table 3: Farmers' Identified Sources of Agricultural Information in Western Kenya**

| Information Source | Information Frequency | Information Source | Information Frequency |
|---|---|---|---|
| Ministry of Agriculture (government extension service) | 649 | Research institutions | 148 |
| Schools | 396 | Stockists | 94 |
| Other government bodies | 329 | Informal networks | 1523 |

The importance of informal ways of information dissemination and sharing are difficult to overstate. Table 4 below shows results from a survey carried out by TSBF in 1998, which included the study area. Informal networks were mentioned more than twice as often as being a source of agricultural information than the government extension service (the next most cited source).

Despite its prevalence, the success of research and dissemination using informal channels is not straightforward. For instance, knowledge transmission is not based on simple communication channels,

conduits or linkages, it involves human agency and occurs within socially and politically constituted networks of different actors, organisations and institutions. Thus, communication occurs through the discontinuous, diffuse, value-bound interactions of different actors and networks (IIRR, 1998; Scoones and Thompson, 1993). At the same time, researchers should not expect that the content of 'their' information would pass through networks unaltered. For information to be locally relevant, it must be continuously tested and validated. Researchers relying on local networks for knowledge diffusion must also embrace the idea that the learning process involved will be 'two-way', with lessons to be learned by both farmers and researchers.

Because networks depend on the decisions of individual actors, distribution and content of knowledge cannot be precisely monitored. Network channels filter information differently to different actors. Effective dissemination of information will therefore have to rely on involving collectives. Relying on stronger networks in community institutions represents best the promise of wider reach to poor farmers. Giving information to as many farmers as possible at once improves the chances of information spreading widely through existing social networks (Grigg, 1995).

**9. Participation Facilitates Learning**

Farmer-to-farmer extension that involves community institutions provides a variety of both formal and informal settings for farmers to learn and share knowledge through participation. Researchers have been working with community institutions in the study area in a variety of activities. The most important venues cited by respondents included: demonstrations mentioned forty-three times (55.1%), field days mentioned thirty-seven times (47.4%), farm visits mentioned thirty-six times (46.1%) and training workshops mentioned twenty-two times (28.2%). These activities presented convenient avenues for researchers to interact with farmers while farmers also got to learn from each other. Although farmers lived close by to one another, in normal, daily interactions they reported rarely finding such valuable occasions or venues to learn new ideas (or even unlearn poor practices). Although researchers considered such 'on-farm' work to be less formal than their other types of interactions, farmers strongly associated such fora with technical knowledge. The talk by both farmers and technical staff was not general; it was direct and vital in enabling farmers to separate facts and reality from rumours. Farmers got to learn with confidence – information validated as 'science'- and to assess things through their own eyes. Such fora also encouraged change, unlike informal interaction where conformity with the status quo was often the norm.

Despite the high status afforded to the formal activities, all seventy-eight farmers reported sharing the bulk of their information through informal activities. Such activities included group meetings, interaction at local market centres, farmer-to-farmer visits, singing and so on. For instance, when outside 'visitors' came to the village, women would sing songs containing soil fertility messages. While this certainly served to entertain, it was also a very powerful means of disseminating soil fertility knowledge. One may conclude that those songs bear witness that women had taken into account the soil fertility practices that research was yielding. The songs also further strengthen networks among members and encouraged visitation.

During formal events such as demonstrations, consultations between farmers and specialists in a less formal, impromptu atmosphere before dispersing helps answer questions that could not have been addressed during the formal programme of the occasion. This presents an ideal arena for farmers, especially those who would not normally speak in public gatherings (such as poorer women and children) to appropriately learn.

Researchers need to take explicit steps have to respect women by listening to their side. Otherwise women's often-placid approach may sometimes be mistaken for ignorance or disinterest. Because resource poor farmers (especially women) are besieged by numerous problems, scientists and extension agents should expect them to bring up topics that are not directly connected with soil fertility. Being the topic of the day, soil fertility may only act as an 'entry point' for dealing with broader development issues. In the midst of what appeared to be a soil-focused discussion, a participant may, for example, ask for a water or dairy project. Such concerns are common and, while seemingly 'off-topic',

the outsiders' remarks on them will be keenly noted. Farmers may afterward reflect on what they *did not hear* from the researcher, and it is important to bear in mind that such dialogue is not uniquely a 'research' endeavour, but part of a longer-term social relationship. It is neither realistic, nor practical to assume that a topic like soil fertility will feature in every social encounter, as demonstrated by this comment by a farmer (Jairo):

> "I cannot introduce a technical subject like use of fertiliser on the market or while taking *busaa* [a local beer] with my friends. They are supposed to be here listening [referring to a field day]. Furthermore they are not children to be taught on the proper practice anywhere…. However, you [researchers] should keep up, I have observed an increase in the number of attendance by farmers. Also, your activities have encouraged more [community] discussion on agriculture and trees [agroforestry]."

While it is entirely legitimate to focus on soil fertility research, crusading to keep farmers consistent may push them away or simply turn them into 'followers'. For instance, at the outset of this study the researcher explained to farmers that he had gone to the community 'to learn'. However, from rapport development up until the end of the work, farmers expected him to be an instructor. During formal interviews, respondents would keep 'other' issues to themselves. But when interacting informally, they would for example say, "Ooh, it is good you are with us. We look forward to your help…" or, "Take these vegetables, you are a good young person, you can make a wonderful son-in-law…." Farmers who were able to express their various 'off-topic' feelings or remarks and questions were then more willing than before to discuss soil fertility issues. The researcher had penetrated their networks somewhat by allowing the informal 'talk' to be his 'entry point'.

There is also a need to understand that different farmers learn well in different settings. Understanding the learning styles of the farmers who researchers and development agents deal with can assist them to establish suitable platforms and processes. Chart 1 (above) showed that more than three quarters of local farmers were resource poor. The interview process found that most of them preferred a balance between the informal forms of knowledge dissemination that were typical within their groups and more formal means. The following is an example of informal aspects as suggested by a farmer during an *FGD*:

> "…. Those [farmers] who are using your ideas [soil fertility practices] can be selected as examples to show the way. Also, all participating farmers should be awarded certificates. Certificates will remind us about your work and encourage us to talk about it openly."

Such encouragements, while perhaps seeming trivial to an outsider, would actually be like 'adding value' to any information that is provided. Locally, education is highly regarded and any proof that one is knowledgeable may enhance one's confidence. This may not directly contribute to a change in farming practices, but if it can generate enthusiasm in research activities so can it improve communication in social networks.

## 10. Conclusion and Way Forward

While every farmer involved in this study was involved in social networks, the use of these networks for farmer-to-farmer extension is as complicated as the networks themselves. To disseminate agricultural knowledge through channels that have evolved for a multitude of social, cultural, and economic reasons, one needs to understand the local institutions, agricultural practices and preferences of local farmers. Therefore, researchers and extension workers need to understand the social interactions within local institutions and how these institutions can better serve memberships from varying socio-economic backgrounds.

There is also a need to involve farmers in community institutions directly in the dissemination of knowledge. Transferring more of the research and dissemination process off-station and into farmers' hands should not just be viewed as a cost-saving measure, but one of legitimate empowerment. Currently, local innovation is being hampered by the farmers' (often-justified) anticipation that the researched soil fertility technologies generate poor returns. If farmers can monitor and evaluate their

activities, the costs and benefits of innovations can be better understood and a subsequent generation of more relevant and effective technologies will result. We can also expect to see greater farmer commitment and thus the greater involvement of their social networks. Such an evolution may involve unlearning old practices on the part of both development agents and farmers. It was observed in this study, as in previous ones, that greater facilitation and involvement of farmers as full partners in research and dissemination would enhance innovation of indigenous technologies. Researchers and extension agents also need to acknowledge that the *sharing* of information through networks is by definition a 'two-way' learning process, which ultimately generates important understanding of local realities. Questions that need to be clearly understood include: how and when do farmers innovate, who amongst them is foremost in innovating and how do they trust technologies from within and outside and share them amongst themselves?

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***Draft***

**Decision Support Systems for Integrated Soil Fertility Management**

J.J. Ramisch and M. Misiko
TSBF-CIAT, PO Box 30677, Nairobi, Kenya

**Rationale:** Adaptation by farmers of research-designed technologies is crucial for increasing the relevance and therefore adoption of technologies. Adaptive research has to be linked to increasing the capacity of service providers and farmers to disseminate this new information and to ensure effective information flow between research and extension.

Since May of 2002, four interactive participatory events have occurred at a TSBF-farmer demonstration plot in Emuhaya, W. Kenya. Efforts have been made to describe and explain to a wider audience (local farmers) TSBF's process of soil fertility research in W. Kenya. Key among the explanations were that TSBF in conjunction with local farmers and other research institutions have identified soil infertility and related problems as major and are researching on alternative or/and potential solutions.

Some of the technologies that have been researched are being illustrated on the demonstration plot in Emuhaya. These activities include i) improved fallows ii) efficient recycling of residues iii) use of inorganic and organic fertilisers iv) traditional practices like natural fallows and use of indigenous plants among other technologies. On July 31, 2002 farmers and researchers held an evaluative field day and discussions at the demonstration site. Farmers expressed the main areas of strength and pointed out improvements that were needed. On August 16, 2002, farmers and TSBF staff harvested maize on the demonstration plot in Emuhaya. On August 22, 2002 a community discussion was held involving different types of farmers and TSBF staff to assess achievements, limitations and lessons achieved from the activity. On the former day, a pre-harvest evaluation was done, and also ranking of the different plots under different treatments. On the later day, in-depth deliberations were held about the plot and way forward. This was a furtherance of preliminary discussions that had been held during different stages of the demonstration.

The technologies that were demonstrated on the plot include i) efficient recycling of crop residues ii) use of inorganic and organic fertilisers and their iii) different combinations iv) biomass transfer and use of legume trees. Also tackled, and not demonstrated, include use of indigenous plants as manures.

**Findings:** There was a step-wise pre-harvest review of plots under different treatments by farmers and TSBF staff. Many of the attendants had visited the plot before and many had participated in various or different activities at the site and were already acquainted with the plots. A summary of all activities that had been done on and at the demonstration plot was given and the plots were briefly described; the different treatments included:

| | Low quality (maize stover) ↓ | Intermediate quality (FYM) ↓ | High quality + polyphenols (*Calliandra calothyrsus*) ↓ | High quality (*Tithonia diversifolia*) ↓ | Control plot (no organic) ↓ |
|---|---|---|---|---|---|
| No N or P → | | | | | |
| + Urea only → | | | | | |
| + Urea, +TSP→ | | | | | |

A rapid pre-harvest assessment of plots was held; first, amongst the first five (with organic inputs only); second, between plots with organic inputs alone and those with different inorganic fertilisers added; and three, amongst those with inorganic fertilisers. This was done to illustrate nutrient

contributions of selected inputs.

All maize plants on every plot were counted. After getting the sum of maize on every subdivision, farmers systematically harvested the crop, starting with the control and weighing both stover and maize. Various observations were made, and notes on the following taken by farmers: Differences in dryness, weight, appearance; Effect of striga, other weeds and pests.

Most maize had been twisted, lying on the ground due to a past storm. Low harvest was also blamed on late planting and a long dry spell in June. Farmers said that under normal local circumstances one would likely get some harvest, however small, and not to completely miss out even when no input is applied as happened under the control plot.

**Discussions:**

Variability within plots: The soil type on the plot is called *ingusi. Ingusi* is yellowish brown to dark brown, clayey soils. It occurs commonly in Emuhaya according to the soil study that was done in February 2002. Striga was very prevalent on plots with high fertility, especially where TSP was applied. This contributed to low harvests on those plots. It was clarified that inorganic fertilisers do not 'bring' or increase striga weed as expressed by few farmers during the discussion. Rather, fertility conditions needed by striga were created on those spots where TSP was used.

Ranking of treatments: Plots were ranked on the basis of: Green leaves – before drying; Thick and long leaves; Height of stalks relative to seed type (hybrid etc.); Bigness of maize, and cobs; Germination rate; Rate of growth, especially after germination, is determinant; Number of cobs on every plant; Number of lines of maize on every cob, especially important in selection of planting seed [12-14 lines (hybrid 513), 16 lines or even more (pioneer usually has one cob with large seeds). Number of lines is relative to type of seed. Also size of every seed matters. Small seeds are good for roasting]; Weight of maize, through estimation by hand and observation.

Farmers used these criteria to rank the various plots. The table below shows results of the ranking. The Table also displays results of previous ranking that had been done and documented two weeks before harvest.

**Table 1: Rank of Organic Resources that were used**

| **Rank** | **1** | **2** | **3** | **4** |
|---|---|---|---|---|
| Pre-harvest | FYM | *Tithonia* | *Calliandra* | Stover |
| Post harvest | *Tithonia* | FYM | *Calliandra* | Stover |

Table 1 shows a shift in ranks, between FYM and *Tithonia*. This change came as a result of weighing; maize on *Tithonia* plot was heavier than that on FYM plot. During preliminary ranking, FYM was seen to have had a more positive role in the context of the demonstration trial. Then, the overall aspect was the size and not weight of maize cobs. On the basis of this, FYM had *performed* better because it would result in higher yield.

The order of ranks was respectively similar for plots with organic resources listed above with TSP alone, and TSP and DAP added. It was easier for farmers to tell differences between segments with organic resources only, unlike comparison between those with inorganic fertilisers. Farmers therefore deduced that certain mineral components (i.e.: P) can only be adequately sourced from inorganic fertilisers. P had been unknown to majority of farmers before prior demonstration events were held.

**Lessons and conclusions:**

- Good harvest (quality and quantity) depends on:
    - Availability of rain, type of rain

    - Timing of planting (recommend that TSBF plant at same time as the majority of farmers to enable them to better compare with and borrow ideas from trial site).
    - Type of soil (recommend that TSBF locate trial sites on each of the major local soil types).
- Appropriate use of high quality resources like *Tithonia* was seen to have a bigger potential locally. However, labour to harvest *Tithonia* was highlighted as a constraint.
- Use of stover as fertiliser was seen as less promising option. Stover is used as fodder and as fuel material, and because it is usually available in small quantities, abandoning it in the field is not very feasible. Other ways to use it more productively should be devised, or to feed it to livestock and to use the resultant dung as FYM.
- The site allowed farmers to better learn how to tell whether plant material is good manure e.g. softness, quick to rot, easy to tear, bitter taste. *Masatsi, mirembe che sisungu* etc.

**Observations:**

- There is lack of cash to use available technologies, especially because of lack of P in most local soils and the need to buy P-containing fertilisers.
- Farmers' comments that the demonstration plots should be 'large' reflect concerns that local farms display considerable variability in soil quality even over small distances and that it is difficult to extrapolate performance from 3 x 3 m plots. This variability results from concentration of resources on certain sections of the plot – driven by labour shortage, on the basis of what section is more promising. These sites tend to be where there is more fertility and where farmers tend to plant first. There are certain sections (especially near the house) where organic materials are dumped regularly.
- There was much interest in doing more demonstrations; with the current awareness, more farmers are likely to attend and learn from the process.
- Disease and funerals affected attendance in field days at the plot

*Soil Biology and Fertility (submitted)*

**Mucuna pruriens and Canavalia ensiformis legume cover crops: Sole crop productivity, nutrient balance, farmer evaluation and management implications**

Delve[1], R.J. and Jama[2], B.
[1]Tropical Soil Biology and Fertility Institute of International Centre for Tropical Agriculture, PO Box 6247, Kampala, Uganda
[2] International Centre for Research in Agroforestry, PO Box 30677, Nairobi, Kenya

**Abstract**
The high costs of inorganic fertilizers in Uganda limits their use by resource-poor smallholder farmers. There is also little practical knowledge existing in Uganda about the management of herbaceous legume cover crops that often are promoted as low-cost alternatives. Therefore, the effects of a one season sole-crop fallow of *Mucuna pruriens* and *Canavalia ensiformis* legume cover crop on a following maize crop and topsoil N, P and K balances were assessed for 2 seasons in two locations, Osukuru ($0^o$ 39/ N, $34^o$ 11/ E) and Kisoko ($0^o$ 43/ N, $34^0$ 06 / E) of Eastern Uganda. During land preparation, 50 or 100% of the aboveground biomass of Mucuna and Canavalia was manually incorporated into the topsoil (0 to 15 cm depth) using a hand hoe. Mucuna and Canavalia aboveground biomass production was not affected by the initial soil fertility of the sites and produced 6 t $ha^{-1}$ at Osukuru and 7 t $ha^{-1}$ at Kisoko. Incorporation of 50% or 100% of the *in-situ* aboveground biomass significantly increased maize grain by up to 118% and stover yields by up to 75% compared to farmer practice in the first season after incorporation in nearly all treatments. No significant increases in maize grain or stover yields were observed in the second season after application. No significant differences were also observed between 50% and 100% *in-situ* biomass incorporation on maize grain and stover yields, giving resource poor farmers the option of alternative uses for the additional 50% of the biomass, for example, biomass transfer to other parts of the farm, for compost making or for livestock feed. In the first season after incorporation of the legume cover crops, addition of 100% and 50% of the aboveground biomass resulted in a positive nutrient balance for N only. Additions of 100% of the aboveground biomass of either Mucuna or Canavalia were needed for a positive nutrient balance for K, whereas none of the treatments produced a positive balance for P, thus suggesting the need for inorganic P fertilizers additions in order to mitigate depletion in the long run. Farmers had multiple criteria for assessing the different species and used these to select the potential species that fitted within their production systems and production objectives.

*Keywords: soil fertility, legume cover crops, Mucuna, Canavalia, nutrient budgets*

**Introduction**
The depletion of much of sub-Saharan Africa's soils through continuous cropping and decreasing nutrient inputs has been widely reported over the last 10 years. All land on the African sub-continent that is classified as very suitable for cultivation was already under cultivation 15 years ago (FAO, 1986). Farmers are increasingly intensifying their agricultural production activities, for example, through the more efficient utilization of animal manures, crop residues and forages and other organic resources. At the same time, use of inorganic fertilizers is decreasing such that organic resources are often the only source of nutrient inputs for farmers (Giller *et al.*, 1997). Resource-poor farmers face difficult decisions over the use of scarce nutrient sources in their production systems. In addition, land constraints force them to trade-off land use in terms of food crop production, fallowing and animal feed supply, amongst others.

Much research has highlighted the benefits of fast-growing legume cover crops (LLCs) to supply nitrogen fixed biologically from the atmosphere to a following non-legume crop in a rotation (e.g. Fujita et al., 1992; Gachene et al., 2000; Giller et al., 1997; Palm et al. 1997). Short growth duration legumes have been used to replenish soil fertility in many parts of Africa (Gutteridge, 1992; Dreschel *et al*., 1996;

Luna-Orea *et al*., 1996; Jama and Nair, 1996; Gachene and Palm, 1999; Rao and Mathuva, 2000; Kayuki and Wortmann, 2001). LCCs refer to the production and incorporation into the soil of leguminous crops that have been grown to enhance the yield of following crops (Lathwell, 1990). Maximum benefit of this approach is seen where the biomass is incorporated into the soil early giving rapid release of nitrogen but farmers often have other priorities in their production system. This can be in terms of a demand for livestock feed, for production of a durable mulch or to control weeds like couch grass. This implies that the farmer may not always manage for the optimal but balance the needs of their farming enterprise. An understanding of how much of the biomass should be incorporated to increase maize yields, where and how this biomass can be produced and what are the alternative uses of the biomass are critical to targeting these legume cover crop technologies.

In Uganda smallholders dominate the agricultural sector with over 90% of crops being produced on household farms averaging less than 2 ha (Appleton, 1998). More than 60% of the land is under cultivation with declining fallow length and increasing periods of continuous cultivation (HASP, 2000). This has greatly reduced crop yields, in addition to increasing pest and weed problems (NARO, 2001). The fallow period has reduced from about 10-12 years of secondary forest fallow in the early 1980s to 3-5 years at present, with the number of crop cycles between a 10-12 year fallow increasing from 2-3 to 4-7 during the same period (Boonman, 1999). Due to these land constraints, the utilization of biomass transfer and legume cover crops was investigated as options for soil fertility management and also in terms of the niches on-farm where they can be grown to fit within the existing production system. Critical to targeting these legume cover crop technologies is an understanding of how much of the biomass should be incorporated to increase maize yields, where and how on the farm this biomass can be produced, what are the alternative uses of the biomass and what are the opportunities and constraints to technology adoption identified by farmers.

The objectives of the study were, (i) to evaluate the effects of *Mucuna pruriens* and *Canavalia ensiformis* on maize yields, and nutrient balances, (ii) to determine the effects of different management options for Mucuna and Canavalia (full vs. partial incorporation of above-ground biomass into the soil) in farmer-managed trials in maize-based system of eastern Uganda and (iii) use farmer evaluations of the technologies to assess their potential adoption and to identify areas of adaptive research.

## Materials and Methods

*Site description*

Farmer managed on-farm experiments were conducted on five farmers' fields in each of two sub-counties (Kisoko and Osukuru) in Tororo District, Eastern Uganda. Both sub-counties are 1000-1200 m.a.s.l., receive bimodal rainfall of 1000-1200 mm per year and maize, groundnuts and cassava are the main crops. The two sites differ in their geographical position with Kisoko being about 20 km North of Osukuru with soil fertility and rainfall, particularly the chance of extended dry spells increasing as you go North. The soils are generally sandy clay loams (Kandiusalf) and have good pH and are generally low in organic C, N and P. The sites significantly differ in their clay content (16.3 vs. 31.3) and total soil N (0.05 vs. 0.11) for Kisoko and Osukuru respectively with all other parameters being non-significant (Table 1).

*Experimental design*

Following the harvesting of an unfertilised maize crop, Mucuna (75 cm by 60 cm) and Canavalia (75 cm by 30 cm) were planted as sole crop fallows for one season. No amendments were added to the soil at the time of legume planting so that the legume cover crops would be produced under farmers' conditions. At the beginning of the next season the legume cover crops LCC were cut, allowed to wilt for five days and incorporated into the soil at either 50% or 100% of the *in-situ* produced biomass. The treatments were as follows: 1) absolute control, 2) fertilized control, with P and K application, 3) 100% of above-ground Mucuna biomass incorporated, 4) 50% of above-ground Mucuna biomass incorporated, 5) 100% of above-ground Canavalia biomass incorporated and 6) 50% of above-ground Canavalia biomass incorporated. A basal application of TSP (80 kg P $ha^{-1}$) and Muriate of potash (60 kg K $ha^{-1}$) was

broadcast and incorporated to a depth of 15 cm in all plots except treatment one. Farmers managed the experiments and conducted weeding and other management practices as they would for their own farm.

*Experimental design – planting and harvest*
A RCBD was used with five replicates, with each of the five farms acting as a replicate. Maize (hybrid Longe1) was sown at a spacing of 0.75 m by 0.25 m, with two seeds per hole and was thinned to one seed per hole after two weeks (53,200 plants $ha^{-1}$). Plots were kept weeded during the farmers normal weeding operations. At physiological maturity net plots (3.75 m by 4 m) were harvested and the weight of maize stover, grain and cobs recorded. Sub-samples were collected, chopped and dried at 70°C for 48 hours. After harvest, all plots were cleared of weeds and crop residue and hand ploughed. In the following two seasons maize (hybrid Longe1) was sown to investigate the residual benefits of the LCCs.

*Soil and plant analysis*
Soil samples (0-15cm) were collected at the beginning of the experiment and bulked by sub-county for analysis. Samples were analysed for pH (water), Total N (Kjeldahl digestion), Total C (Walkley-Black), extractable P (Olsen and Sommers, 1982), macronutrients (extracted in $NH_4Oac$; atomic absorption spectrophotometer) and texture. LCC plant samples were analysed for total N (Kjeldahl) and total P and K (Kjeldahl; atomic absorption spectrophotometer; Parkinson and Allen, 1975).

*Farmer participatory evaluation*
Farmer participatory evaluations were conducted using open questions and probing questions. Qualitative data was also collected on farmer criteria used in selection of LCCs technologies and on innovations made by farmers.

*Statistical analysis*
Data were analysed by the SAS General Linear Models procedure (SAS Institute Inc., 1988). ANOVA was used for mean separation and significance is reported at the $P<0.05$ level.

**Results**
*LCC biomass production and nutrient content*
Comparative analysis of the macronutrient content of the LCC's shown there was only a significant difference in the plant species for their Calcium contents (Table 2). There were no significant differences in location or in the species by location interaction. Similarly, there were no significant species or location differences in the biomass production of the two LCCs, nor in the amount of N applied in the experimental design. The amount of biomass produced was not significantly different but for both locations Mucuna and Canavalia exceeded 6 t DM $ha^{-1}$ and 7 t DM $ha^{-1}$ in Kisoko and Osukulu, respectively.

*Maize production*
There was no significant difference between the sites except for stover production in the first season (Table 3). Therefore data was combined for further statistical analysis. No significant increases between the control and the positive control (with P and K addition) were observed indicating that the site was N limiting and not P or K deficient.

In the first season, at both sites, all treatments (except 50% incorporation of Canavalia biomass in Osukulu) gave significantly higher grain and stover yields compared to the control (Table 3). In all cases where biomass production was significantly higher than the control, the yield increase was more than 100% higher than the control treatment. Incorporation of 100% rather than 50% of the biomass produced in the plot did not significantly increase maize grain yields compared to the control (Table 3). In the second residual season no significant differences were observed for maize grain and stover production between treatments. Combined yields over the two seasons showed significant increases in maize grain yield for all treatments except for maize stover production for maize grain with the 50% Canavalia

incorporated treatment. The total dry matter yield of grain and stover over the two seasons was highly significant ($P<0.001$) for all treatments (Table 3).

*Nutrient balance*

The farmers normal practice of growing maize without additions of organic or inorganic fertilizers not surprisingly resulted in negative nutrient balances for N, P and K (Fig. 1). In the first season after incorporation of the LCCs, addition of both 100% and 50% of the aboveground biomass reversed this negative nutrient balance for N only. Additions of 100% of the aboveground biomass of either Mucuna or Canavalia were needed for a positive nutrient balance for K, whereas none of the treatments produced a positive balance for P (Fig. 1). Nutrient balances were not calculated for the residual seasons as there were no significant differences in maize grain and stover yields.

*Farmer participatory evaluation*

Farmers assessment of the LCCs species revealed many positive and negative aspects for each species (Table 4). Many positive criteria were mentioned by farmers that were expected for these species, for example, improved soil fertility, provides livestock fodder. More interesting from the research prospective were the negative aspects. For example, Mucuna and Canavalia were notably disliked because their seeds are not edible yet they looked very attractive to eat, and are produced in large numbers, even in dry seasons. Mucuna was further disliked for its unsuitability for intercropping and because it can harbour snakes if planted near the homesteads.

**Discussion**

*Legume biomass production*

The lack of significant differences in biomass yield of the mucuna and canavalia (Table 2) at the sites in spite of Kisoko being more deficient in N (Table 1) would suggest that similar BNF among the two species at both sites. Biomass dry matter productivity averaging 6.8 t DM $ha^{-1}$ for Mucuna and 7.0 t DM $ha^{-1}$ for Canavalia in six months compares with other reported data. For *Mucuna pruriens* other authors have reported varying sole crop one-season biomass production figures. Mucuna produced 1.3-3.50 t DM $ha^{-1}$ and in some cases up to 9 0 t DM $ha^{-1}$ in one season in Rwanda (Drechsel, *et al.*, 1996); an average of 5.7 t DM $ha^{-1}$ across five sites in Malawi (Kumwenda and Gilbert, 2000) and an average of 4-7 t DM $ha^{-1}$ from sites across Kenya (Dyck, 1997).

Comparative data for Canavalia ensiformis has been much harder to find. Gachene et al. (2000) report production figures of 3-6 t DM $ha^{-1}$ in six months. These different production figures are due to differences and variations in soils, rainfall, seasons and management of the legumes for the different citations.

*Grain and stover yield*

All significant treatments increased maize grain yields by between 106% and 118% in the first season, these yield increases more than compensate the farmer for the loss of one seasons production of maize whilst the legume cover crop is being grown. Kumwenda and Gilbert (2000) reported maize grain yield increases averaging 180% following Mucuna incorporation in five sites across Malawi. Whilst other studies have not reported such yield increases of above 100% and therefore did not find that the extra maize yield compensated for the land being out of production for one season (Drechsel, *et al.*, 1996). Also, work in Uganda work with different legumes found that maize yield increases varied by season and legume species but on average did not consistently return yield increases of above 100% (Fishler, 1997; Tumuhairwe, 2001).

Although the grain and stover results were not significant in the second season it has to be remembered that farmers under their own conditions, with individual farmers as replicates, conducted this work. Therefore, the level of error would be expected to be higher than a replicated on-station or a replicated on-farm experiment. The second season results were significant ($P<0.10$) for maize grain and stover yield, giving the farmer a two-season benefit.

Where the yield increases do not compensate for the loss of maize production during the season of LCC production there is unlikely to be any adoption in areas of high population density where there is a high demand every season for cropping land. The advantages of LCC can best be utilized where land is out of production due to low fertility or high pest/disease pressures or where it would be left in a natural fallow system. In addition, the significant increases in associated maize stover provide increased options for the farmers. The extra stover can be used in livestock feed or bedding, soil erosion control, compost making or mulching the banana crop.

Another very important conclusion of this work is that incorporation of 50% or 100% of the *in-situ* produced biomass produces a maize grain and stover yield that is not-significantly different from each other. This again then provides the farmers with increased options for their resource management. For example, this would allow the farmer to produce the biomass in one place and to apply the biomass over twice the area for maize production. Alternatively they might want to use 50% for incorporation and the remaining 50% for livestock feed, sale to other farmers or to produce hay for dry season feed. Increasing the resource management options and therefore the production options of the farming enterprise is critical where land sizes and fallow areas are small and little area is available for non-food crop production and where cash is not-readily available to buy inputs for crop and livestock production.

**Nutrient balances**

The N fixed by LCCs during the fallow period may not a net addition to the system if increases in the following crop yields removes more N than is added by the legume. The large applications of N in the LCC biomass (Table 2) will be exposed to leaching as decomposition occurs, especially during the tropical storms that characterise the beginning of the rainy season. Much work has been conducted on decomposition and nutrient release rates for legumes, with different rates being reported. For example, more than 50% of N, P, K and Mg from Desmodium and Pueraria being released in four weeks (Luna-Orea et al., 1996); 60% of N from Leucaena and Senna in the first four weeks (Jama and Nair, 1996). Drechsel, *et al.* (1996) concluded that as sowing starts immediately after the first lasting rainfall, it is impossible to optimize the time of green manure incorporation before sowing. This may be true but there are management options available to reduce leaching of N and increase synchrony of release with demand. For example, incorporation of sorghum straw and green manures significantly delayed and reduced leaching of nitrate, by around 30%, of the mobilized legume nitrogen (Hagedorn, 1995 in Dreschel *et al.* 1996). Similarly, other nutrient balance studies in Uganda have reported negative balances for a range of cropping systems (e.g. Bekunda and Woomer, 1996; Wortmann and Kaizzi, 1998).

*Farmer participatory evaluation*

There was no doubt among the farmers that the LCCs technologies work and were better than the traditional practice as far as improving soil fertility was concerned. In terms of costs, it was reported that the use of LCCs and biomass transfer species offered a low input technology to the farmers, as most of them could not afford use of inorganic fertilizers especially on the low value crops like maize. Farmers evaluation however raised many concerns over the adoptalibility of the technology. Farmers observed that the use of LCCs required a substantial amount of land for production and for sole crop production this is left under fallow with no food crop being produced, high labour for clearing and ploughing in the vegetation, and patience in attaining the results (Table 4). In addition, the single purpose use of the LCC was mentioned as a negative aspect in terms of the adoption of the technology.

**Conclusion**

In the on-farm experiments reported here in two areas of Uganda, the use of *Mucuna pruriens* and *Canavalia ensiformis* significantly increased the following maize yields in the first season ($P<0.05$) and in the residual season ($P<0.10$). Farmer evaluations of the technology highlighted some negative aspects of this technology, for example, it needs increased management by the farmer as well as increasing the labour input into the cropping system, in addition, many farmers do not have the opportunity to leave land

fallow for one season to produce the LCC. This method of soil fertility improvement is just one of the many options available to farmers and the exact production system the farmer develops will depend on many other issues, for example, access to inorganic fertilizers, the need for firewood, livestock feed or grain legume production. Farmer evaluations identified research gaps with this technology that are now being investigated in further on-farm experimentation. LCC species, however, still remain a strategic opportunity for the many farmers that have no access to fertilizers or animal manures and who have available land.

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Table 1: Soil characterisation in Kisoko and Osukuru sub-counties in Eastern Uganda

| Location | pH | Total N | Total C | Total P | Ca | Mg | K | P | Clay | Sand | Silt |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (%) | (%) | (%) | -----cmol $g^{-1}$------ | | | (ppm) | ----------%--------- | | |
| Kisoko | 6.80 | 0.05 | 0.66 | 0.02 | 3.77 | 0.80 | 0.26 | 7.97 | 16.3 | 64.7 | 19 |
| Osukuru | 6.11 | 0.11 | 1.32 | 0.10 | 6.46 | 1.76 | 0.37 | 33.2 | 31.3 | 51.1 | 17.6 |
| $LSD_{0.05}$ | ns | 0.04 | ns | ns | ns | ns | ns | ns | 10.6 | ns | ns |

Table 2: Legume cover crop nutrient analysis, biomass production and amounts of N added in the treatments for the two sub-counties.

| Location name | Total N (%) | | Total P (%) | | Ca | | Mg | | K | | Biomass (kg DM ha$^{-1}$) | | Applied-N (kg ha$^{-1}$) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Can[1] | Muc[2] | Can | Muc | Can | Muc | Can | Muc | Can | Muc | Can | Muc | Can | Muc |
| Kisoko | 2.9 | 2.4 | 0.13 | 0.20 | 4.2 | 1.6 | 0.40 | 0.35 | 1.0 | 1.2 | 6626 | 6111 | 190 | 153 |
| Osukuru | 3.1 | 2.5 | 0.27 | 0.20 | 4.8 | 1.3 | 0.50 | 0.25 | 1.5 | 1.4 | 7435 | 7502 | 228 | 188 |
| LSD (0.05) | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| | ***Significance level*** | | | | | | | | | | | | | |
| Plant species | 0.18 | | 0.97 | | 0.0005 | | 0.13 | | 0.92 | | 0.86 | | 0.37 | |
| Location | 0.67 | | 0.32 | | 0.81 | | 1.00 | | 0.23 | | 0.42 | | 0.39 | |
| Location * Species | 0.82 | | 0.32 | | 0.50 | | 0.31 | | 0.65 | | 0.83 | | 0.98 | |

[1] Can=*Canavalia ensiformis*
[2] Muc = *Mucuna pruriens*

**Table 3: Maize grain and stover yields following application of Mucuna and Canavalia in Osukuru sub-county, Tororo District**

| Treatment description | Grain Crop1[1] | Grain Crop2[2] | Grain Crop1+Crop2 | Stover Crop1 | Stover Crop2 | Stover Crop1+Crop2 | Sum Stover + Grain, all crops |
|---|---|---|---|---|---|---|---|
| | ---------- t DM $ha^{-1}$ ---------- | | | | | | |
| 100% Canavalia | 3.5 | 3.3 | 6.9 | 4.0 | 4.5 | 8.6 | 15.5 |
| 100% Mucuna | 3.7 | 3.7 | 7.3 | 4.2 | 4.3 | 8.2 | 15.6 |
| 50% Canavalia | 3.0 | 3.3 | 6.4 | 3.5 | 4.2 | 7.4 | 13.8 |
| 50% Mucuna | 3.5 | 3.3 | 6.9 | 4.0 | 4.1 | 8.0 | 14.9 |
| Control F P | 1.7 | 2.2 | 3.9 | 2.4 | 2.9 | 5.0 | 8.9 |
| Control P K | 2.3 | 2.8 | 5.1 | 2.7 | 3.6 | 6.3 | 11.5 |
| | Significance level | | | | | | |
| Site (0.05) | 0.18 | 0.62 | 0.09 | 0.01 | 0.72 | 0.25 | 0.12 |
| Treatment (0.05) | <0.0001 | 0.08 | 0.0001 | 0.02 | 0.07 | 0.03 | 0.001 |
| Site $LSD_{0.05}$ | ns | ns | ns | 0.75 | ns | ns | ns |
| Treatment $LSD_{0.05}$ | 0.73 | ns | 1.40 | 1.18 | ns | 2.08 | 3.11 |

[1] Crop1 = the first crop after incorporation of the legume cover crop
[2] Crop2 = the second crop after incorporation of the legume cover crop

**Table 4. Farmers' assessment of the LCCs species for soil fertility improvement**

| LCC/shrub | Positive aspects | Negative aspects |
|---|---|---|
| *Mucuna pruriens*<br><br>Local name: none | ✓ Improves soil fertility<br>✓ Suppress weeds effectively<br>✓ Produce high biomass<br>✓ Quick maturing | x Not edible<br>x Not good for intercropping (Climbs the crops)<br>x Requires high labour for clearing and incorporation<br>x Can harbour snakes if planted near the home |
| *Canavalia ensiformis*<br><br>Local name: Yathipendi (medicine for banana) or Akengu ka angu (trap for the hyena) | ✓ Improves soil fertility<br>✓ Has fodder value<br>✓ Suppresses weeds<br>✓ Easy to multiply (high seed production)<br>✓ Good for intercropping | x Not edible<br>x Difficult to incorporate |

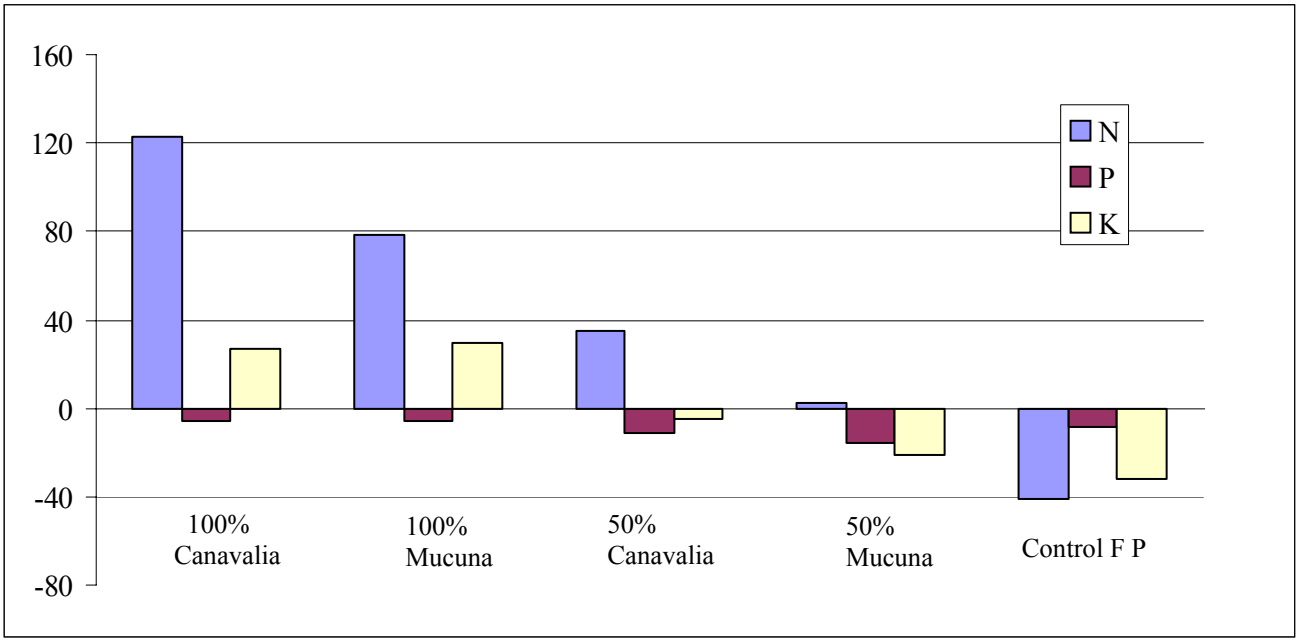


Figure 1: Macro-nutrient balance for maize grain and stover production following incorporation of 50% and 100% of the above-ground biomass of Mucuna and Canavalia legume cover crops

*Submitted to Experimental Agriculture*

# Farmer participatory evaluation of legume cover crop and biomass transfer technologies for soil fertility improvement using farmer criteria, preference ranking and logit regression analysis

Nyende, P. and Delve, R. J
Tropical Soil Biology and Fertility Institute of International Centre for Tropical Agriculture, PO Box 6247, Kampala, Uganda

## Summary
Six species, *Canavalia ensiformis*, *Crotalaria grahamiana*, *Dolichos lablab*, *Mucuna pruriens*, *Tephrosia vogellii* and *Tithonia diversifolia* were evaluated as potential species for soil fertility replenishment in on-farm adaptive trials, farm visits and field days in Tororo District, eastern Uganda. Farmers used multiple criteria for assessing and selecting potential species that fitted within their production systems and production objectives. Farmers also adapted the technologies to allow for local opportunities and constraints. A preference ranking and logit regression analysis of probabilities of acceptance of the species conducted in 19 farmer groups showed that Tithonia had high, Mucuna and Crotalaria intermediate and Lablab and Tephrosia low probabilities of being accepted or adopted. The evaluations showed that whilst technologies need to be adapted, a single use technology had little chance of large-scale adoption. This paper highlights adaptations/innovations by farmers and opportunities for participatory action research targeting farmers' production objectives.

## Introduction
In the recent past the image of agricultural and environmental crises in sub-Saharan Africa (SSA) has become increasingly common. Soil erosion and soil fertility loss are considered to be undermining the productive capacity of the agricultural systems (Giller *et al*., 1997; Sanchez *et al*., 1997; Smaling *et al.*, 1997). Within this environment smallholder farmers use a wide range of agro-ecological management techniques, resource management practices and production strategies specific to their environment to minimise risk, cope with change and shocks and to manage the environment (ecological, social, economic etc) they operate within. These can include, for example, agricultural intensification, expanded market-orientation, increased capital and labour investment. Alternatively, farmers have been found to exploit their resource base where constraints are too high, the returns to investment are too low (even negative, as when staple commodity prices plummet during bumper harvests), or environmental conditions too erratically variable for secure investment.

Since 1998, a number of collaborating partners working in Tororo district through an adaptive research project, the Integrated Soil Productivity Initiative Through Research and Education (INSPIRE) have been evaluating a range of soil fertility management options with farmers. The collaborators in the INSPIRE initiative which began with the main objective of introducing, developing, on-farm testing and disseminating improved soil fertility management technologies to address the alarming soil productivity problems in Tororo district include, Africa 2000 Network (A2N), Appropriate Technology (Uganda), International Centre for Tropical Agriculture (CIAT), Tororo district Departments of Agriculture and Extension, Farmer group representatives, Food Security and Marketing (FOSEM) project, International Centre for Research in Agroforestry (ICRAF), National Agricultural Research Organization (NARO), Makerere University, Tropical Soil Biology and Fertility Programme (TSBF), and Uganda National Farmers Association (UNFA).

During the participatory diagnostic stage of the project, use of legume cover crops and biomass transfer species to improve soil fertility were identified as potential technologies due to their cost effectiveness, appropriateness, simplicity, and multi-purpose nature in meeting the needs of resource poor farmers. In smallholder farming systems of the tropics and sub-tropics, increasing use is being made of legume cover crops (LCCs) and biomass transfer (BT) species as sources of nutrients, particularly nitrogen, for crop growth (Dreschel, *et al.*, 1996; Rommelse, 2001; Buresh and Niang, 1997). This is in

part due to the increasing cost and variable availability of inorganic fertilizers at the village level. Less than 5% of the farmers in eastern Uganda use mineral fertilizers and this is usually on an irregular basis (Mirro *et al*., 2002). In addition, traditional natural fallow is no longer practiced due to the decreasing farm sizes and the availability of animal manure is limited by decreased cattle numbers (Mirro *et al*., 2002).

Six species, *Canavalia ensiformis*, *Crotalaria grahamiana*, *Dolichos lablab*, *Mucuna pruriens*, *Tephrosia vogellii* and *Tithonia diversifolia* were first introduced in two sub-counties of Kisoko and Osukuru. Much work has been conducted on the biophysical performance of these legume cover crop and biomass transfer technologies since 1998 in Tororo (Tumuhairwe, 2002a; Tumuhairwe 2002b; Delve and Jama, 2002b). Beyond agronomic evaluation it is essential to identify opportunities and constraints of each introduced technology, conduct assessments to understand farmers' actual use and management of the technologies, perceived benefits, farmers ideas and perceptions, innovations, and problems and solutions in the use of the technologies (Douthwaite *et al.*, 2002; Bellon, 2001). To address this, a farmer participatory evaluation of these technologies was therefore initiated in December 2001 and January 2002 (after seven seasons) with the main objective of providing a feedback on the performance of the technologies. This paper reports on the findings and analysis of participatory evaluations by 19 farmer groups, involving 234 individual farmers (92 male, 142 female), who had been evaluating through on-farm adaptive research the performance of legume cover crops (LCCs) and biomass transfer (BT) species for soil fertility improvement.

## Materials and methods

*Developing qualitative farmer criteria for preference ranking*

Farmer participatory evaluations were conducted using open questions, probing questions and preference matrix ranking. The farmers who participated in the evaluation exercise were purposively selected and belonged to a farmer group who had at least five seasons experience experimenting with LCCs and biomass transfer species. Focus group discussions were used to elicit farmer criteria (negative and positive) used in selection and preference ranking of LCCs and biomass transfer technologies.

*Quantitative analysis of ranking data*

From the preference rank list of the six species from each group, a frequency table was drawn up of the number of times each species was ranked in a certain position, where one is the most and six is the least preferred species. From this frequency table, the probability of a particular species being ranked in a certain position was calculated, where,

Probability = frequency / total number of observations …….(1)

A further calculation was done to produce the cumulative probability of each species, that is, the sum of the probability for that rank and the probabilities for all previous ranks. Further data analysis was done using a logit regression with a Chi-squared test (at 15% level significance) using the Logistic Preference Ranking Analysis Tool for evaluating technology options (Hernandez-Romero, 2000). The preference ranking logic regression allowed the statistical analysis of qualitative preference ranking data and allowed a further separation of species into those likely to be adopted or not.

*Innovations with the technologies*

During the focus group discussions and evaluation process, farmers were asked to list the innovations (i.e. what they did differently from the initial aim of the demonstration) for the different species and how this differed from what they had seen in the demonstration sites

## Results

*Farmer evaluation of options*

Farmers' evaluation of the LCCs and biomass transfer species revealed many positive and negative aspects for each species (Table 1). Some of the positive criteria were, improving soil fertility and providing

livestock fodder. More interesting from the research perspective were the negative aspects. For example, Mucuna and Canavalia were notably disliked because their seeds are not edible yet they looked very attractive to eat, and are produced in large numbers even in dry seasons. Mucuna was further disliked for its unsuitability for intercropping and because it can harbour snakes and wild cats if planted near the homesteads. The pest problem on *C. grahamiana* was cited as a serious set back as the caterpillars that eat the leaves and flowers scare the women and children. Tephrosia also was cited as having a pest problem that leads to flower abortion and hence poor seed formation. Lablab was reportedly having a problem of seed formation while Tithonia was feared to be a potential weed if not managed properly.

*Criteria for evaluating the LCCs and biomass transfer species*

Criteria for ranking the species' performance were developed and a summary of criteria is given in Table 2. Each group developed its own criteria for ranking, however the four most important criteria for all 19 groups were, yield increase of crop after fallow or intercrop, soil fertility increase, multiple uses of the LCC or BT species and ability to control weeds.

*Farmer preference ranking of the LCCs and BT species*

Based on the criteria developed with the farmers a ranking analysis tool was used to rank the six species. There was little variation among groups in the rank orders but the overall rank order from the most to the least preferred was Mucuna, Canavalia, Crotalaria, Tithonia, Tephrosia and Lablab (Table 3). Since farmers first experienced most of the LCCs and BT species in the course of the present study, the ranks assigned to some species are a preliminary hint to their adoption potential.

Distribution of probabilities of acceptance of LCCs and biomass transfer technologies

Table 4 shows the number of times a particular species is ranked in a certain position (acceptance frequencies). For example, Mucuna was ranked in position one seven times, five times in position two, zero times in position three, etc by all the 19 farmer groups. Plotting cumulative probability against the ranking position allows a graphical representation of the acceptance of a technology option (Figure 1). The analysis of cumulative probability versus ranking position showed that for the 19 groups, Mucuna, Crotalaria, Canavalia and Tithonia all had positive intercepts on the y-axis (probability of acceptance), i.e. high probability of being ranked highly by farmers and Tephrosia and Lablab had negative intercepts and are therefore likely to be rejected by the farmers and not adopted (Figure 1; Table 5).

A higher slope with a positive intercept on the y-axis means that the technology option has a high probability of being ranked highly by farmers, indicating that they have characteristics that meet farmers needs and therefore should be taken into account while promoting the species. In addition, they are more likely to be adopted. In contrast, a high slope with a negative intercept shows a likelihood of that technology option being ranked often in the last places of the ranking and hence is not liked by farmers.

*Statistical analysis of the logit regression*

Further analysis of the slope of the regression line and using a Wald chi-square test showed that Mucuna and Crotalaria have low slopes of 0.04 and 0.08 respectively, but with positive intercepts indicating intermediate probabilities of acceptance (Table 5). Canavalia and Tithonia with high slopes of 0.10 and with positive intercepts (differs statistically) have high probabilities of acceptance in accordance with the model used in this analysis. On the other hand Lablab and Tephrosia with high slopes but with negative intercepts indicate low probabilities of acceptance. The analysis of Canavalia was not significantly different ($P<0.15$) to zero (i.e. there is no difference between the use or no use of the species), indicating likelihood for non-acceptance by the farmers.

*Farmer innovations with the LCC and biomass transfer species*

Some farmers indicated that they had tried using the LCCs and biomass transfer species in a different way besides what the researchers had demonstrated during the trials. The ways in which the farmers adapted and adopted the technologies are shown in Table 6. Farmers also invented their own names for some species of the LCC and biomass transfer species they were using (Table 1). Canavalia was locally known

as ‘Yathipendi’ meaning ‘medicine for banana’ and another group that was dominated by old men identified it as ‘Akengu ka Angu’ meaning ‘trap for the Hyena’. Tephrosia was locally known as ‘Yathi fuuko’ (medicine for mole rat) or ‘Yathirechi’ (medicine for fish). *Tithonia diversifolia,* was locally referred to as ‘Mawuwa’ but with no particular meaning attached to the name. Mucuna and Crotalaria were known by their botanical names as obtained from the researchers. Farmers’ identification of the LCC and biomass transfer species by such names reveals several issues.

**Discussion**

*Farmer evaluation of options*

When faced with many options, framers face complex decisions. This study shows that farmer’ assessment of the LCCs and biomass transfer species revealed many positive and negative aspects for each species. The criteria used for selection and the farmers’ innovations revealed new research constraints and opportunities. For this farming system, highlighting potential new areas of research, for example, research into suitable niches for the best-bet species (Muhr *et al*., 2001) and/or identifying varieties that can be consumed by humans, e.g. dual-purpose grain legumes (Ecoregional Alliance, 2001) are important for enhancing the adoption of a technology. This study also confirms the labour constraint with use of LCCs and BT species for soil fertility improvement and therefore a serious constraint in the adoption of the technology (Obonyo, 2001; Tumuhairwe *et al.*, 2002b). Addressing these identified constraints will ensure that future research is relevant to the needs of the farmers and therefore have a higher chance of being adopted.

There was no doubt among the farmers that the LCCs technologies work and were better than the traditional practice as far as improving soil fertility was concerned. In terms of costs, it was reported that the use of LCCs and BT species offered a low input technology to the farmers, as most of them could not afford use of inorganic fertilizers especially on the low value crops like maize. Farmers however, observed that the use of LCCs and BT species required a substantial amount of land for production and for sole crop production which is left under fallow with no food crop being produced, high labour for clearing and ploughing in the vegetation, and patience in attaining the results.

The fact that food production is the key priority of the farmer means that they are very risk averse and need to produce a food crop every season, so investing present resources in the possibility of future increased production is not necessarily interesting to farmers. As an adaptive research farmer commented, ‘*Its better to have even one gorogoro tin of maize from a depleted field that was planted with maize than to be guaranteed no maize at all this season by planting a cover crop we can’t eat*’ (Ramisch, pers. Comm..). Despite these constraints, farmers conducting trials on legume cover crops for soil, water and nutrient management in Malawi expressed that through learning-by-doing and doing-by-learning, they learnt that there are some legume cover crops such as Mucuna, pigeon pea, tephrosia, soybeans ground nuts and common beans that improve soil fertility and at the same time be used as a green manure and/or food (Marra *et al*., 2002; Douthwaite *et al*., 2002). Recent experiences with farmers using simulation model discussions further provide evidence of the role risk, uncertainty and learning play in the process of adopting/adapting new technologies (Braun, 2001).

*Statistical analysis of the logit regression*

This study shows that farmers can make use of more than one LCC or BT technology depending on their production objectives and resource endowments. They can observe, compare and decide on alternatives, using criteria drawn from their own experiences. Findings from case studies in Malawi and Zimbabwe also indicate that a broad range of options rather than blanket recommendations (as offered by government extension services) can increase adoption and improve productivity and food security (Marra *et al*., 2002).

The logit preference ranking analysis tool used in this study helps to explain decisions on acceptance or rejection of the technology, based on the criteria and/or farmer group used to choose one technology rather than another. The tool further allows the statistical analysis of qualitative data and a detailed separation of technologies into those likely or unlikely to be accepted, something that is not possible through ranking alone. Information generated from this tool provides essential feedback to the

technology development process. This tool has been used to conduct participatory evaluations of cassava, potato, beans and maize varieties in Ecuador and Colombia (Hernandez-Romero, 2000).

*Implications of participatory evaluation on the research process*

In the process of technology change and innovation it is essential to understand not only the farmers perceptions but also those of all the stakeholders involved in the research process (Douthwaite *et al.*, 2002; Bellon, 2001). Therefore, the next stage in this adaptive research process involved the systematisation of information, detection of knowledge gaps, and the identification of potential research questions during follow-up community meetings attended by the farmers, extension agents, NGO and CIAT staff. During these meetings the results of the participatory evaluation were discussed and this led to the identification of new research questions that need to be addressed through strategic on-station research; adaptive research conducted by National partners and adaptive research conducted by farmers. The different partners then agreed on the way forward to address these issues:

Key farmers to conduct adaptive research on behalf of the community. These farmers will establish a range of experiments, and will be responsible for monitoring the experiments and reporting back to the whole community on the results.

Applied research questions to be addressed by National agricultural research partners, through an array of methods from on-station research to on-farm research.

Strategic research questions to be addressed by CIAT, TSBF, and other partner international research institutes through an array of methods from, strategic on-station research to on-farm research.

In this study, LCC and BT technologies that were introduced to farmers for soil fertility replenishment have been adapted and are being improved through participatory evaluations to include a much wider range of production objectives. The evaluations showed that whilst technologies need to be adapted, a single use technology had little chance of large-scale adoption. This has led to a major rethink by researchers and partners of the methodology and approach taken and the types of research conducted in the project.

## Conclusions

Whilst technologies exist that increase soil productivity and are profitable for farmers there are many other factors preventing them from adopting the technology. Fallowing the land for example, is not possible where small land sizes or high population densities exist and where seed supply for these legume cover crops is not good. In eastern Uganda, where the population pressure is much lower and where natural fallowing is still part of the farming system, the opportunities for improved fallowing or biomass transfer is much higher. Even so, issues of increased labour requirements for incorporation or collection of biomass are commonly cited by farmers during evaluations.

In this dynamic environment farmers assess the different management options available to them and adapt them to fit their own circumstances and production objectives. For example, growing Tithonia on-farm in available niches (around the field boundaries, for example) is one way of over-coming shortage of Tithonia and reducing the labour that would be needed if collecting the biomass from off-farm locations. Innovations in using these legume cover crop and biomass transfer species are very common. This work has identified many adaptations/innovations by farmers not just for increasing crop production but also for pest and weed control, consumption of the seeds and for livestock feeding.

The criteria used for species selection and the farmers' innovations provide essential feedback to the participatory action research approach as they reflect the opportunities and constraints of the production systems of the farmers and raise many new areas of research, opportunities of evaluation of new technologies and species and the better targeting of existing information.

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**Table 1. Farmers' assessment of the LCCs and BT species**

| LCC/shrub | Positive aspects | Negative aspects |
|---|---|---|
| *Mucuna pruriens*<br>Local name: none | Improves soil fertility<br>Suppress weeds effectively<br>Produce high biomass<br>Quick maturing | x Not edible<br>x Not good for intercropping (Climbs the crops)<br>x Requires high labour for clearing and incorporation<br>x Can harbour snakes and wild cats if planted near the home |
| *Canavalia ensiformis*<br><br>Local name: Yathipendi (medicine for banana) or Akengu ka angu (trap for the hyena) | Improves soil fertility<br>Has fodder value<br>Suppresses weeds<br>Easy to multiply (high seed production)<br>Good for intercropping | x Not edible |
| *Crotalaria grahamiana*:<br>Local name: none | Improve soil fertility<br>Suppress weeds | x Has pest problem – scaring caterpillars |
| Tephrosia vogellii<br><br>Local name: Yathi fuuko (medicine for mole rat) or Yathirechi (medicine for fish) | Improves soil fertility<br>Control mole rat | x Has pest problem that eats the pod, hence poor seed formation |
| Labalab<br>Local name: none | Improves soil fertility<br>Has fodder value<br>Suppresses weeds | X difficult to obtain seed |
| Tithonia diversifolia<br><br>Local name: Mawuwa | Improves soil fertility<br>Medicine for malaria & stomach aches<br>Has pesticidal properties<br>Fodder for goats | x It is a weed |

**Table 2. Criteria developed by farmers for ranking of the LCCs and biomass transfer species**

| Criteria | Justification of criterion |
|---|---|
| Yield increase of crop after fallow or intercrop | - Weight of grain, bunch, fruit etc |
| Crop vigour of crop after fallow or intercrop | - Health<br>- Greenness of leaves |
| Soil fertility increase | - Change of soil colour to dark<br>- Depth of soil increased<br>- Ease of ploughing<br>- Soil erosion control<br>- Moisture retention<br>- Time taken to cause significant fertility increase |
| Ease of germination, establishment & seed production of the LLC or shrub | - More seed produced in a short time & viable for a longer time.<br>- Small seed difficult to collect |
| Multiple uses of the LLC or shrub | - The number of other additional uses from the LCC or shrub e.g. firewood, medicine, fodder etc. |
| Suitability for intercropping | - Intercrop compatibility i.e. minimal competition of the LCC or shrub with the crop |
| Ability to control weeds | - Dense canopy formation which suppress undergrowth |
| Amount of biomass production | - Number of leaves<br>- Size of leaves<br>- Ground coverage<br>- Shorter maturity period |
| Labour requirement for clearing, uprooting, cutting and incorporation | - Ease of bush clearing, uprooting, cutting stems and leaves & then incorporation into the soil |

**Table 3. Overall raking of the LCCs and biomass transfer species by the groups**

| **Group name** | **Ranking of species** | | | | | |
|---|---|---|---|---|---|---|
| | **Mucuna** | **Canavalia** | **Lablab** | **Crotalaria** | **Tephrosia** | **Tithonia** |
| Manakori | 1 | 2 | 5 | 6 | 4 | 3 |
| Katamata | 2 | 3 | 4 | 1 | 6 | 5 |
| Umoja | 1 | 2 | 6 | 2 | 4 | 4 |
| Boke A | 1 | 2 | 5 | 3 | 5 | 4 |
| Boke B | 1 | 2 | 6 | 3 | 5 | 4 |
| Aputiri | 2 | 5 | 4 | 3 | 6 | 1 |
| Amorio | 2 | 3 | 5 | 6 | 4 | 1 |
| Osukuru post test club | 2 | 4 | 6 | 1 | 3 | 5 |
| Anyari Nglechom | 5 | 4 | 6 | 3 | 2 | 1 |
| Jachandi | 1 | 3 | 6 | 4 | 5 | 2 |
| Chemo Apecho | 2 | 3 | 5 | 1 | 6 | 4 |
| Chandere | 1 | 2 | 6 | 3 | 4 | 4 |
| Tekere | 1 | 2 | 4 | 3 | 6 | 5 |
| Geno | 4 | 5 | 3 | 2 | 6 | 1 |
| Abongit Chymeromo | 1 | 2 | 6 | 3 | 5 | 4 |
| Theketheke | 1 | 3 | 5 | 4 | 6 | 2 |
| Mari | 1 | 3 | 6 | 4 | 5 | 2 |
| Temokinyieko | 1 | 2 | 6 | 3 | 5 | 4 |
| Ichi Awati | 1 | 3 | 6 | 2 | 5 | 4 |
| Total | 31 | 55 | 100 | 57 | 92 | 60 |
| Rank order | 1 | 2 | 6 | 3 | 5 | 4 |
| 1 = most preferred species 6 = least preferred species | | | | | | |

**Table 4. Distribution of acceptance frequencies**

| Species | Ranking order | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Total |
| Mucuna | 7 | 5 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 14 |
| Canavalia | 0 | 5 | 4 | 1 | 1 | 2 | 0 | 0 | 0 | 0 | 13 |
| Lablab | 0 | 0 | 1 | 2 | 3 | 2 | 3 | 2 | 1 | 0 | 14 |
| Crotalaria | 3 | 2 | 5 | 0 | 2 | 1 | 1 | 0 | 0 | 0 | 14 |
| Tephrosia | 0 | 1 | 0 | 1 | 4 | 5 | 2 | 1 | 0 | 0 | 14 |
| Tithonia | 4 | 0 | 1 | 3 | 4 | 1 | 1 | 0 | 0 | 0 | 14 |
| Total | | | | | | | | | | | 134 |

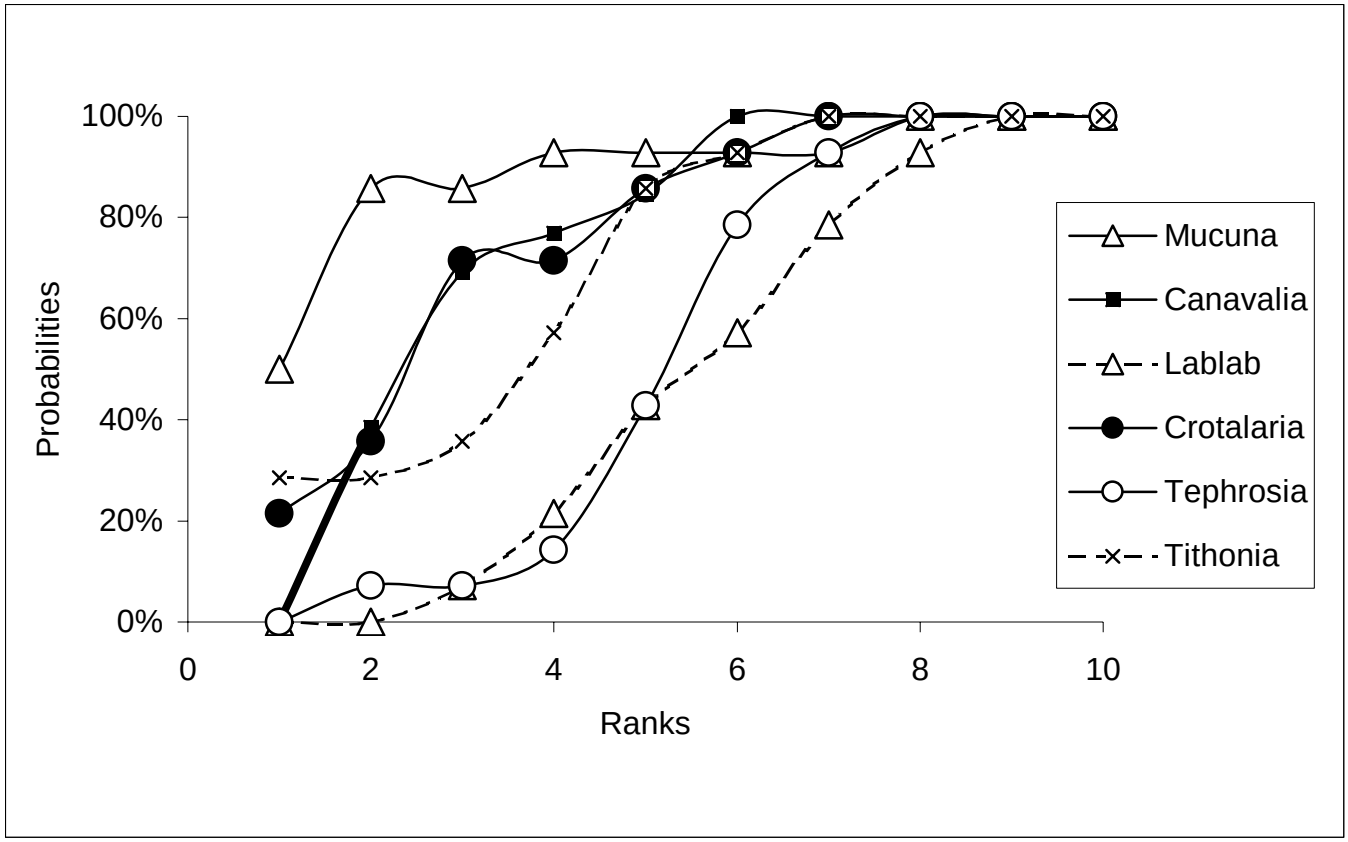
**Table 5. Statistical analysis of the logistic regression**

| Technology | Estimated parameter b (intercept) | Parameters m (slope) | Standard error (SEb) | Wald Chi-Square | Chi Square | Significance (P<0.15) |
|---|---|---|---|---|---|---|
| Mucuna | 0.69 | 0.04 | 0.07 | 10.08 | 0.00 | ** Differs statistically |
| Canavalia | 0.25 | 0.10 | 0.13 | 1.96 | 0.16 | Does no differ |
| Lablab | -0.24 | 0.13 | 0.06 | 4.20 | 0.04 | ** Differs statistically |
| Crotalaria | 0.31 | 0.08 | 0.09 | 3.46 | 0.06 | ** Differs statistically |
| Tephrosia | -0.22 | 0.14 | 0.10 | 2.24 | 0.13 | ** Differs statistically |
| Tithonia | 0.20 | 0.10 | 0.09 | 2.24 | 0.13 | ** Differs statistically |

**Table 6. Farmer innovations with the legume cover crop technologies**

| LCC/BT species | Research recommended management and use | Modification in management and use |
|---|---|---|
| Crotalaria | Intercrop with maize or as a one season fallow crop.<br>When mature, uproot and mulch in maize, beans, sorghum, millet, cotton, etc.<br>Thresh pods to get seed.<br>Mulch | Boundary planting around the homesteads<br>Intercrop with beans to control nematodes and other bean diseases.<br>Seed put together with bean seed during storage controls bean storage pests |
| Mucuna | Use it as a one season fallow crop, uproot at planting and mulch in the following crop<br><br>Use as cover crop in banana plantations | Attempts to cook it and eat the seed as sauce<br>Efforts to crash seed to make animal feed<br>Good feed for goats, cattle and rabbits |
| Canavalia | Canavalia intercropped with coffee, maize and bananas | Used to scare off hyenas in the olden days (and monkeys these days) |
| Lablab | Grow for two seasons as a fallow crop, uproot at planting and mulch in the following crop.<br>Use as a fodder crop and as cover crop in banana plantations<br>Livestock feed | Seed and the leafy vegetation edible (i.e. used as sauce) |
| Tephrosia | Plant around field for trapping the mole rat<br>Plant as a sole crop | Leaves are crashed, poured into rivers and streams to catch fish<br>Doubt on its effectiveness in controlling the mole rat |
| Tithonia | Boundary planting, biomass<br>Transfer | Leaves used for treatment of stomach ailments and fevers<br>Planting from cuttings rather than from seed |

**Figure 1: Comparison of acceptance of technologies**



*Draft paper*

**Evaluation of cowpea and Lablab dual-purpose legumes**

R. Delve and P. Nyende
TSBF-CIAT, PO Box 6247, Kampala, Uganda

**Rationale:** The criteria used for legume cover crop (LCC) species selection and the farmers' innovations with these LCC species in the participatory action research of INSPIRE in Tororo district revealed new constraints and opportunities of the farming system. Farmers' assessment of the LCCs revealed many positive and negative aspects for each species, but of major concern was on Mucuna and Canavalia which were disliked because their seeds are not edible yet they looked very attractive to eat, and are produced in large numbers, even in dry seasons. Despite the strong caution not to eat the seeds, a few farmers attempted to cook and eat seeds from these LCC seeds. A research agenda that address this new challenge of proving dual-purpose legumes was introduced in 2002. Two species cowpea and lablab were evaluated as dual-purpose legumes to address farmers' prioritized need for food, fodder and soil fertility improvement

Evaluation of dual purpose cowpea: Cowpea International Trial 101
Fifteen elite lines of cowpea identified and developed by the Grain Improvement Program of IITA, Nigeria, were introduced with two main objectives of the trials:

1. To evaluate the performance and farmer evaluations of these lines in view of selecting the most promising as regards to improving soil fertility and provision of food and fodder.
2. To provide grain legumes improvement programs with regional evaluation data and to select lines for further testing

**Methodology**: 15 cowpea lines (including a local check) were tested on-station at the Distinct Agricultural Training and Information Centre in Tororo, eastern Uganda. Crop management, trial layout and data collection was strictly followed based on recommendations from the Grain Improvement Program of the IITA. In addition, a farmer evaluation of the varieties was also done at grain harvesting stage with the objective of evaluating the varieties for acceptability and seed multiplication. This was done on a farmer field day organized in collaboration with Africa 2000 Network and the DATIC management. In a participatory manner, 20 farmers from each of the two sub counties of Kisoko and Osukuru participated in an absolute evaluation of the 15 varieties.

**Results:** Before a field a valuation farmers were engaged in a discussion on several aspects of the cowpea crop. Farmers revealed that they grow only one variety of cowpea, locally known as 'Ngori'. This has either white or brown seeds. The following were listed as main ways in which the crop is utilized:

- Leaves (at 3-4 WAP) are boiled and eaten as sauce (vegetable) with other foods
- Seeds are roasted and eaten as snack e.g. with tea
- Seeds are boiled and made into samosas using baking flour
- A meal composed of cowpea serves as a food reserve during travels and is eaten while travelling as keeps long in the stomach
- Cowpea is used in exchange for labour if there is no cash available at hand
- Cowpea is also known to improve soil fertility

Cowpea is mainly planted during the short rain season because it does not tolerate too much rain. Farmers traditionally broadcast cowpea and ensure larger spacing compared to that recommended by the Grain Improvement Program of IITA (20cm x 50cm). Leaves are picked at 2-3 weeks after planting and used as vegetables. Also at this time thinning is done and leaves and/or whole stems are used in sauce preparation. Pruning encourages more branches to sprout and more flowers to develop and hence more

yields. Young and tender leaves are continuously picked during the entire growing period for sauce. In Tororo, there are several grain legume food crops grown but the major ones in order of importance are cowpea, groundnuts, common bean, simsim, soyabean and green gram. Cowpea was ranked first because it fetches more income than other grains grown in the area.

**Farmers' criteria used to evaluate the cowpea varieties**

The following criteria was consensually agreed upon and enlisted by the farmers and used to conduct an absolute evaluation:

- Multiple utilization (e.g. as vegetable sauce, Sumbusa)
- Pest and disease tolerance
- Improve soil fertility
- Good taste and satisfaction obtained when eaten (i.e. ability to stay in the stomach for long)
- Grain yield obtained (i.e. many grain filled pods)
- Marketability of the grain seed (i.e. big seed, uniform colour)

This present season the farmers are further evaluating the five most promising varieties. In addition, two more varieties breed by Makerere University are being evaluated alongside these. Evaluations will be done at two stages, at 2-3 WAP (for vegetable attributes) and at harvest maturity for grain and biomass yield.

The evaluation was done by men and women separately to cater for gender differences.

***Table 1. Women's ranking of cowpea lines***

| Farmer ranking | Replicate No. | | | |
|---|---|---|---|---|
| | REP 1 | REP 2 | REP 3 | REP 4 |
| 1 | IT95K-238-3 | IT98K-205-8 | Local check | IT95K-238-3 |
| 2 | Local check | IT95K-238-3 | IT98K-205-8 | Local check |
| 3 | IT94K-437-1 | IT97K-499-38 | IT94K-437-1 | IT98K-205-8 |
| 4 | IT98K-279-3 | IT94K-437-1 | IT95K-238-3 | 1T98-279-3 |
| 5 | IT98K-205-8 | Local check | 1T98D-1399 | IT98K-1382 |
| 6 | IT98K-1382 | IT97K-350-4-1 | IT98K-279-3 | IT98K-1382 |
| 7 | IT95K-463-6 | IT98K-463-6 | IT98K-1312 | IT97K-499-34 |
| 8 | IT97K-350-4-1 | IT97K-1068-7 | IT97K-566-6 | IT98K-131-2 |
| 9 | IT97K-1068-7 | IT97K-449-38 | IT97K-350-4-1 | IT97-556-4 |
| 10 | IT97K-499-38 | IT97K-350-4-1 | IT94K-440-3 | IT97K-1068-7 |
| 11 | IT97K-499-39 | IT98K-131-2 | IT97-499-8 | IT94K-440-3 |
| 12 | IT94K-440-3 | IT97K-1069-7 | IT94K-440-3 | IT98K-463-6 |
| 13 | IT98K-131-2 | IT94K-440-3 | IT94K-437-1 | IT94K-440-3 |
| 14 | IT97K-556-4 | IT98K-1382 | IT98K-463-6 | IT97K-350-4-1 |
| 15 | IT98D-1399 | IT98D-1399 | IT98K-1382 | IT98D-1399 |

***Table 2. Men's ranking of cowpea lines***

| Farmer ranking | Replicate No. | | | |
|---|---|---|---|---|
| | REP1 | REP 2 | REP 3 | REP 4 |
| 1 | Local check | IT98K-205-8 | Local check | Local check |
| 2 | IT98K-205-8 | IT97K-499-38 | IT95K-238-3 | IT95K-238-3 |
| 3 | IT98K-279-3 | IT94K-437-1 | IT94K-437-1 | IT98K-205-8 |
| 4 | IT98D-1399 | IT95K-238-3 | IT98K-279-3 | IT98K-278-3 |
| 5 | IT97K-1068-7 | Local check | IT98K-205-8 | IT97K-1068-7 |
| 6 | IT95K-238-3-3 | IT94K-440-3 | IT98K-1382 | IT97K-279-3 |
| 7 | IT97K-499-38 | IT97K-350-4-1 | IT97K 350-4-1 | IT98K 1382 |
| 8 | IT94K-437-1 | IT97K-556-4 | IT98D-1399 | IT97K 556-4 |
| 9 | IT94K-446-3 | IT98K-279-3 | IT97K-1068-7 | IT97K-350-4-1 |
| 10 | | IT97-1068-7 | IT97K-1068-7 | IT98D-1399 |
| 11 | IT97K-350-4-1 | IT97K-499-39 | IT97K-499-39 | IT97K-499-39 |
| 12 | IT98K-1382 | IT98K-463-6 | IT97K-556-4 | IT94K-437-1 |
| 13 | IT97K-499-39 | IT98K-1382 | IT94K-440-3 | IT98K-131-2 |
| 14 | IT97K-556-4 | IT98K-131-2 | IT98K-131-2 | IT94K-440-3 |
| 15 | IT98K-463-6 | IT98D-1399 | IT98K-463-6 | IT98K-463-6 |

The central objective in conducting a genderized evaluation of the cowpea lines was to make proactive efforts to ensure that women participate and benefit from the technology and capture their innovations. It was anticipated that women face different constraints from men and have different incentives to invest in or adopt cow pea varieties. Based on the evaluation results and field observations, men gave higher score to the local variety compared to the women. However, with regard to the new varieties under evaluation, there wasn't much difference in preference between women and men as reflected also in the evaluation criteria. Furthermore, based on the criteria enlisted by the farmers, the following varieties look promising: IT98K-238-3-3, IT98K-279-3, IT98K-205-8, IT98K-279-3, IT95K-238-3.

*Evaluation of dual-purpose lablab: Accessions from CSIRO-Australia*

One of the major problems identified by farmers during participatory research was the lack of seed production from Lablab species due to late flowering and flower abortion, that was severely inhibiting adoption of an otherwise preferred dual-purpose legume option. Thirty-three lines from CSIRO that had early flowering characteristics were introduced with two main objectives of the trials:

1. To evaluate the performance of these lines in view of selecting the most promising as regards to improving soil fertility and provision of food
2. To provide grain legumes improvement program with an opportunity to select lines for further testing and use, either directly as varieties or as source of breeding materials.

**Methodology**: In the 2002b season an on-station evaluation was established at Kawanda Agricultural Research Institute, Kampala, Uganda to evaluate the different accessions for a range of phenotypic characteristics and biomass production. Results from this work are not presently available

*African Crop Science Journal (submitted)*

**Mineral nitrogen contribution of Crotalaria grahamiana and Mucuna pruriens short-term fallows in eastern Uganda**

Tumuhairwe, J.B[1]., B. Jama[2*], and R. Delve[3], M.C. Rwakaikara-Silver[1]
[1]Makerere University, Department of Soil Science, P. O. Box 7062, Kampala, Uganda
[2]International Centre for Research in Agroforestry, P. O. Box 30677, Nairobi, Kenya.
[3]Tropical Soil Biology and Fertility (TSBF) and International Centre for Tropical Agriculture (CIAT), P. O. Box 6247, Kampala, Uganda

**Abstract:**
Nitrogen (N) is one of the major limiting nutrients to crop production in Uganda and is depleted at faster rates that replaced. Consequently, yields at farm level are less than 30% of the expected potential. Paradoxically, the majority subsistence farmers are poor to afford use of mineral fertilisers but improved fallow have been reported economically feasible in such conditions. Therefore, a study was initiated in Tororo district, eastern Uganda (i) to determine mineral N contribution of *C. grahamiana* and *M. pruriens* short-duration fallows compared with farmers' practices of natural fallow, compost manuring and continuous cropping, (ii) sampling period that closely related to maize grain yield was also determined and also (iii) whether improved fallow provided adequate mineral N for optimum grain yield compared to farmers' practices. It was noted that improved fallows increased mineral N at Dina's site during fallowing (at 0 week sampling), and in the first and fifth week after incorporating their biomass than farmers' practices. For instance, at harvesting fallows (0 week sampling), *C. grahamiana* and *M. pruriens* had 12.68 and 12.97 mg $Kg^{-1}$ N compared to 6.79 and 7.79 mg $kg^{-1}$ N from following natural fallow and continuous cropping respectively. However, no significant increase was realised at Geoffrey's site at any of the sampling dates attributed to low biomass yield and incorporated. *C. grahamiana* increased grain yield by 29.3% (Dina's site) and 56.6% (Geoffrey's site) and *M. pruriens* by 36.0% (Dina's site) and 27.2% (Geoffrey's site) compared to natural fallow with -11.9% (Dina's site) and 17.4% (Geoffrey's site) then compost manure -9.6% (Dina's site and 0% (Geoffrey's site) in relation to continuous cropping as a bench mark. Supplementing the land use systems LUS (*C. grahamiana*, *M. pruriens*, natural fallows, compost manure and continuous cropping) with inorganic N fertiliser as urea significantly increased grain yield in all except *C. grahamiana* at both sites. There were two peaks on mineral N. The first and major peak occurred in the third week dominated by $NO_3^-$-N and the minor one in the tenth week with $NH_4^+$-N prominent consistent at both sites. Mineral N in the fifth week after incorporating biomass was most closely related to grain yield followed by sampling at planting (0 week).

The second Masters thesis (Comparison of the effects of *Mucuna pruriens, lablab purpureus, canavalia ensiformis* and *crotalaria grahamiana* on soil productivity in Tororo district eastern Uganda) was submitted in September 2002, the abstract form this thesis is reproduced here.

*Masters thesis submitted in September 2002*

**The effect of green manures, Mucuna, Lablab, Canavalia and Crotalaria on soil fertility and productivity in Tororo District, Uganda.**

Matthew Kuule
Makerere University, Kampala, Uganda

**Abstract**
There is much concern over the declining crop yields over much of sub-Saharan Africa, and has largely been blamed on declining soil fertility, since increasing population has rendered traditional shifting cultivation and long-term fallowing, less practical. Strategies such as mineral fertilizer application, use of manure (compost and animal) and green manuring have been shown to sustain and/or increase soil productivity. Mineral fertilizers restore lost or limited soil nutrients fast, but are expensive for most farmers and do not improve soil organic matter. Similarly, compost and animal manure use is limited by the quality of the composted and/or feed material as well as the labour requirements for their preparation and application to farm fields. Legume cover crops, which are produced on the field with the crops and later incorporated into the soil to provide plant nutrients upon decomposition, could be a viable option for soil productivity improvement, especially in smallholder low-input agriculture systems. Whereas the technology has been widely adopted in the tropics, it is still low in Uganda, probably due to lack of awareness and performance data. This study was therefore planned to demonstrate the value of legume cover crops on soil productivity improvement and to determine and compare the economic viability of four legume species (*Mucuna pruriens, Crotalaria grahamiana, Lablab purpureus* and *Canavalia ensiformis*) in order to give sound recommendation for wider adoption of the technology. To be of relevance to farmers, six on-farm trials (each farmer as a replicate) were set up in two sub-counties Kisoko and Osukuru, and another on-station trial at the District Agricultural Training Centre (DATIC) with four replicates, in Tororo District, eastern Uganda. In August 2000, maize (cv. Longe1) was established on five-5 x 5 m plots and at first weeding stage (4WAP), the four legume cover species were each planted between maize rows in all the plots except the control (maize monocrop). After harvesting maize in December 2000, the cover crops continued to accumulate biomass for two more months, and in February 2001, the above ground biomass of the cover crops and of weeds was harvested, fresh weight taken, sampled for drymatter determination and incorporated into the soil during land preparation for the long rain season in March 2001. Production costs that were different for different treatments were estimated and recorded during the experiment. Maize yields were also recorded to allow computation of the returns from legume cover crops using marginal rate of return of non dominated treatments, as a basis for recommending the cover crop species to farmers. Results indicated significant ($p<0.05$) maize yield increases for Crotalaria and Lablab treatment of 96.4% and 69.6 % respectively on farmers' fields in the second season (after legume biomass incorporation) and non-significant yield response to all legume cover crops on-station in both seasons, were obtained. The significant maize yield response to Crotalaria and Lablab on-farm and not on-station was probably due better synchrony of nutrients released from their biomass on an initially poorer soil at the on-farm compared the relatively better soil on-station. The analysis of costs and benefits revealed favourable marginal rates of return to Crotalaria, Canavalia and Mucuna of 246, 120 and 30.4% respectively and were all recommended for adoption with more emphasis on Crotalaria.

*Draft paper to be submitted to Journal of Agricultural Economics or African Crop Science Journal*

**Financial benefits of Crotalaria grahamiana and Mucuna pruriens short-duration fallow in eastern Uganda**

*Tumuhairwe, J.B[1]., B. Jama[2*], and R. Delve[3], M.C. Rwakaikara-Silver[1]*
[1]Makerere University, Department of Soil Science, P. O. Box 7062, Kampala, Uganda
[2]International Centre for Research in Agroforestry, P. O. Box 30677, Nairobi, Kenya
[3]Tropical Soil Biology and Fertility (TSBF) and International Centre for Tropical Agriculture (CIAT), P. O. Box 6247, Kampala, Uganda

**Abstract**
*Crotalaria grahamiana* and *Mucuna pruriens* improved fallows are gaining popularity among smallholder farmers in Uganda to address soil fertility decline. The technology supplies nutrients and increases crop yields but its economic viability is uncertain in eastern Uganda. Therefore, two researcher-managed experiments were established in Tororo District, eastern Uganda to determine the financial benefits of the *C. grahamiana* and *M. pruriens* improved fallow compared to farmers' practices of natural fallow, compost manure and continuous cropping. Higher returns to land were obtained from improved fallow compared to farmers' practices. *C. grahamiana* realised US$267.4 (Dina's site) and $ 283.2 (Geoffrey's site), and *M. pruriens* had $284.1 (Dina's site) and $248.7 (Geoffrey's site) compared to natural fallow $223.3 (Dina's site) and $274.3 (Geoffrey's site), compost manure $70.9 (Dina's site and 114.2 (Geoffrey's site) and continuous cropping $314.2 (Dina's site) and $314.2 (Geoffrey's site) per hectare. Improved fallows saved on labour compared with continuous cropping and compost manure except for natural vegetation fallow. Higher returns to labour were obtained through use of improved fallow than compost manure and continuous cropping. Returns to labour of $0.54 day$^{-1}$ were obtained for compost manure (at Dina's site), which is less that the wage rate at $0.57 day$^{-1}$ indicating a loss in labour invested.

The second Masters thesis (An assessment of the profitability and acceptance of alternative soil improvement practices in Tororo district, Uganda) was submitted in September 2002, the abstract form of this thesis is reproduced here.

Agricultural production in Eastern Uganda is declining due to increasing population pressure on the land. A resultant feature is the dependence of soils on external inputs to attain acceptable crop yields. Resource-poor smallholder farmers, who form the majority of the farmer population in this area, can typically ill-afford recommended levels of inorganic fertilizer use to replenish lost nutrients. Alternative options to expensive and often unavailable inorganic fertilizer use for this small scale farmer population include the integrated use of inorganic fertilizer and organic inputs such as legume cover crops and biomass production shrub and tree technologies. These technologies were incorporated into the farming systems in Eastern Uganda, Tororo district, in 1998 through farmer groups. An economic evaluation of 10 researcher-designed-farmer managed maize trials using *Mucuna pruriens* and *Canavalia ensiformis* fallow and *Tithonia diversifolia* biomass land use systems were conducted. The profitability was determined using gross margins, after which modelling produced the optimal land use system. A survey of 108 respondents was also conducted to determine the acceptance and farmer-perception of 8 previously exposed shrub and tree species. The economic evaluation favoured the use of Integrated Nutrient Management of soil amendments. The 100% incorporation of Mucuna produced the highest benefits of 185,641/= ha$^{-1}$ as opposed to the net benefit of 134,901/= that would be produced in the optimal solution from 0.6 ha using 191 labour days. The application of 0.91t ha$^{-1}$ + N biomass system would produce the highest benefits of 445,744/= ha$^{-1}$ with an optimal net benefit solution of 342,080/= on 0.8ha using 263 labour days. The survey results showed that in the sample size, the acceptance rate was 53 percent. The age and area under shrub were significantly different (0.01) across accepters and non-accepters. The cultivated area (0.1) and employment activities (0.05), institutional support such as belonging to groups and number of extension visits significantly also differed. Alternative uses of shrubs and trees, use of

other complimenting inputs and perceptions of the soil fertility were highly significant across acceptor category. Farming experience and use of farmyard manure were not significant. *Sesbania sesban,* and *Mucuna pruriens* were found to be the most popular shrubs (36.69%, and 20.6% respectively) and problematic (36.22%, and 25.20% respectively). Popular uses were weed suppressant uses (17.5%) and fuel wood production (23%) for 7 out of 8 shrubs. Major reported problems were the increased labour demands, (21.5%), pest and vermin association (25.3%), and access to planting material and seed (26.7%). Further economic studies that will determine the optimal levels at which the incorporation of livestock management systems into the cropping systems using integrated nutrient management options are recommended. Farmer designed-farmer managed trials would establish preferred farmer management practices to ensure sustainability of these land use systems.

*Synthesis paper presented at regional workshop*

# Impacts of land management options in western Kenya and eastern Uganda

**Delve[1], R. J. and Ramisch[2], J. J.**
[1] Tropical Soil Biology and Fertility Institute of International Centre of Tropical Agriculture (TSBF-CIAT), PO Box 6247, Kampala, Uganda; email: r.delve@cgiar.org
[2] TSBF-CIAT, PO Box 30592, Nairobi, Kenya, email: j.ramisch@cgiar.org

## Introduction

Over the last 10 years the image of agricultural and environmental crises in sub-Saharan Africa (SSA) has become increasingly common. Soil erosion and soil fertility loss are considered to be undermining the productive capacity of the agricultural systems (Giller *et al*., 1997; Sanchez et al., 1997; Smaling *et al*., 1997). These problems have been ascribed to many different causes, social, economic, biological and physical. Many authors have also highlighted concern over the increasing land degradation in the highlands of East Africa (e.g. Hilhorst and Muchena, 2000; Farley, 1995; Getahun, 1991) where increases in agricultural production in recent decades have been achieved through intensification of existing agricultural practices and through expanding the cultivated areas of land, especially in fragile environments. Soil degradation, soil erosion and loss of soil fertility have been widely quoted as resulting from these intensive and extensive agricultural production systems.

Blaming smallholder farmers for this degradation is over simplistic in the least. Furthermore, tropical agricultural production systems are characterized by dynamic features, resilience and many examples of modified production practices to cope with and adjust to changes (Brookfield and Padoch, 1995; Farley, 1995; Goldman, 1995). Smallholder farmers use a wide range of resource management practices and production strategies specific to their agro-ecology to minimise risk, cope with change and shocks and to manage the environment (ecological, social, economic etc) they operate within. These can include, for example, agricultural intensification, expanded market-orientation, increased capital and labour investment. Alternatively, farmers have been found to exploit their resource base where constraints are too high, the returns to investment are too low (even negative, as when staple commodity prices plummet during bumper harvests), or environmental conditions too erratically variable for secure investment. Where purchased inputs or labour are scarce, mining the soil's nutrient capital resource can appear to smallholders as good economics and an acceptable cost of agricultural production.

This paper uses evidence from two sites in eastern Uganda and western Kenya to investigate land management, land use changes, and the policy environment within which smallholders have to operate, and assess their impacts on smallholder farmers' production strategies. Both sides of the border have similar agro-ecosystems and cropping systems, with eastern Uganda through to western Kenya occupying a gradient with changing soil types, from the alfisols in Uganda to humic nitisols in western Kenya, increasing agricultural production and also increasing population densities from east to west. This has resulted in a range of land use systems to manage this gradient.

## Land management technologies

Ugandan and Kenyan national research institutions (in collaboration with international agricultural research centres) have developed an array of technologies that can effectively address local production problems, for example, improved banana and maize varieties for various agro-ecological zones, as well as, legumes and cover crops that improve soil fertility and provide fodder. Many of these technologies have, however, not been disseminated adequately to farmers and have, therefore, little impact at the farm level. The need for improved dissemination of knowledge to farmers has been identified by many studies (e.g. Onesimus *et al*., 1999). To do this, it is increasingly being recognised that the best approach is one in which farmers, the local administration, and the community participate actively.

Examples of technologies developed in the region by collaborative research between farmers and scientists include:

*Phosphorus replenishment*. Phosphorus is a major limiting nutrient to much of the region's crop production due to low soil P availability and many soils' high P-fixing capacity, especially in western Kenya. The socio-economics of smallholder production limit the feasibility of using fertilisers, but combining organic residues with locally available, low-cost rock P, can improve P availability to crops. As well, research on a P-fixing Nitisol in western Kenya has shown that soil P replenishment using seasonal additions of small rates of P fertilisers could be attractive to some small-scale farming systems (Nziguheba, 2001). Seasonal additions of 25 kg P $ha^{-1}$ increased maize yield with gradual replenishment of soil P. Smaller rates of 10 kg P $ha^{-1}$ contributed to soil P depletion, while large seasonal applications of 150 kg P $ha^{-1}$ resulted in low efficiency of applied fertilisers.

- *Legume cover crops*. In regions where natural fallowing is still practiced (as in Eastern Uganda), green manure species like *Mucuna pruriens* and *Canavalia ensiformis* increases the following maize yields (Delve and Jama, 2002a). In addition, the significant increases in associated maize stover production increased options available to farmers, such as using it for livestock feed or bedding, soil erosion control, compost making, or mulching the banana crop. Delve and Jama (2002a) also found that incorporating 50% or 100% of the *in-situ* produced biomass did not result in significantly different increases in maize grain and stover yield. This would allow farmers to use 50% for incorporation and the remaining 50% for livestock feed, sale to other farmers, or to produce hay for dry season feed. Increasing the resource management options and therefore the production options of the farming enterprise is critical where land sizes and the area available for non-food crop production are small, and where cash is not readily available to buy inputs for crop and livestock production.
- *Biomass transfer.* In both western Kenya and eastern Uganda application of high quality local materials, such as *Tithonia diversifolia*, has shown good potential to increase productivity. Work in western Kenya, supplying a constant rate of 15 kg P $ha^{-1}$ through combinations of Tithonia leaves low-quality maize stover and triple super-phosphate (TSP), showed that maize yields increased between 18-24% as the share of P contributed by Tithonia in the residue–fertiliser mix was increased above 36%. The results indicate that a high quality organic input can be more profitable than using inorganic P, and comparable to or more effective than inorganic P in increasing P availability in the soil. Work in Uganda combining Tithonia with fertilisers also obtained the greatest benefits by maximising the proportion of Tithonia in the mixture (Delve and Jama, 2002b).

Whilst technologies exist that increase soil productivity and are profitable for farmers there are many factors limiting technology adoption. The fact that food production is the key priority of the farmer means that they are very risk averse and need to produce a food crop every season. Even where land is not apparently scarce, investing present resources in the possibility of future increased production is not necessarily attractive to farmers. As a research farmer in Kenya commented, '*Its better to have even one gorogoro tin of maize [from a depleted field that was planted with maize] than to be guaranteed no maize at all this season by planting a cover crop we can't eat*'. Issues of increased labour requirements for incorporation or collection of biomass are also commonly cited by farmers during evaluations of the organic technologies. In western Kenya there are even examples of teachers using 'free' labour of children coming to school to harvest Tithonia for use on school plots.

The implicit assumption of most agricultural research is that farmers' current resource management decisions are not the optimal ones, and that providing them with 'better information' would lead them to better choices. However, without understanding farmers' priorities and constraints the rationality of their current decisions will also be misunderstood. Similarly, by ignoring farmers' existing knowledge (or not accurately locating the gaps in that knowledge) the impacts of improved land management technologies will be minimal. Agricultural knowledge, access to new sources of information, and control of resources can vary considerably within a given community, especially across axes of difference such as gender or age. Technologies that are designed collaboratively by researchers, extensionists, and farmers are more likely to correctly target the socio-economic and agro-ecological

niches where they will be most relevant.

**Adaptations by farmers**

Innovations in using these soil fertility management technologies are very common. A recent survey identified many adaptations/innovations by farmers using cover crop and biomass transfer species not just for increasing crop production but also for pest and weed control, consumption of the seeds and for livestock feeding (Nyende and Delve, 2002). Farmers assess the different management options available to them, and adapt them to fit their own circumstances and production objectives. Growing Tithonia on-farm in available niches (around the field boundaries, for example) is one way of overcoming shortage of Tithonia and reducing the labour that would be needed if collecting the biomass from off-farm locations. For other farmers, the rapid decomposition of Tithonia makes it 'more like a fertiliser' (i.e. immediate effect, with little residual benefit) and therefore less attractive than farmyard manure (compost of animal, household, and crop wastes) which 'builds the soil' for the long term.

Recognition that innovation comes from multiple sources means that technology development must involve potential users from very early in the design process. To support this, extension must be more intimately linked with research to ensure that nascent technologies take fuller account of farmers' existing knowledge, practices, and priorities. 'Dissemination' would be of prototypes fully intended for modification or rejection by farmers and not of 'finished' products. However, by treating technology itself as politically neutral – i.e.: without knowing who benefits from existing practices, or who will likely benefit from changes – policy recommendations relating to soil fertility management will remain too vague to truly assist policy-makers, or be delivered through inappropriate channels to sectors unable to make use of them.

**Implications of the policy environment on land management**

While some of the constraints to crop production and examples of options available for alleviating soil productivity problems have been discussed at the farm level, many of the constraints facing farmers come from external forces, such as the (mis-) functioning of input and output markets, which can only be affected by modification of the 'policy environment'. For example, the bumper harvest reported in Kenya and Uganda in the 2001 short-rain season led to sale prices of maize that were often below production costs. In such situations, farmers face the prospective of losing money if they sell their maize to generate cash, but there is also no incentive for them to invest in their agricultural enterprises given the policy environment they operate within. Clearly, innovations need to address food security and livelihood sustainability, not just increased production as a good in its own right. Policy interventions that would rationalise input and output markets, and buffer smallholders from their volatility, should have as their goal a) increasing farmers' opportunities to innovate, and b) making investments back into agriculture attractive. One way in which such support could be given to smallholders would be by increasing investment in linking research, development, and extension with farm communities. In Kenya, the collapse of the formal extension network over the last five years has led to a shift towards farmer extension and farmer-to-farmer training through for example, farmer field schools. This increased reliance on information diffusion through social networks requires a better understanding of the role of social capital in innovation. In contrast, in Uganda, a newly privatised extension service is being piloted in test districts across the country, where parish level farmer forums feed through sub-county and counties to the district, which then contracts extension providers to provide the demanded services. This demand-led process has the potential to allow smallholder farmers increased access to markets, agricultural inputs and extension services and to improve access to information and technologies through the contracting of private sector service providers. This in turn will lead towards a more market orientated smallholder production sector.

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**Contending with Complexity: The Role of Evaluation in successful INRM**

Boru Douthwaite[1], Robert Delve[2], Javier Ekboir[3] and Steve Twomlow[4]
[1] Adoption and Impact Specialist, IITA, Ibadan, Nigeria
[2] Soil Fertility Management, TSBF Institute of CIAT, Kampala, Uganda
[3] Economist, CIMMYT, Mexico
[4] Global Theme Leader Water, Soil and Agrobiodiversity for Ecosystem Health, ICRISAT, Bulawayo, Zimbabwe.

**Abstract**
In contrast to reductionist approaches, Integrated Natural Resource Management (INRM) takes a holistic perspective that sees technology change as a complex social process, in which networks of agents that include, among other members, farmers, researchers, input suppliers, NGOs, extension agents and other government agencies generate and diffuse technologies. The technologies, networks and individual agents coevolve in response to emerging technical, social and economic challenges and opportunities. These changes affect adoption rates and who benefits and loses. More importantly, early identification of the forces that shape the evolution path of the technology and the network is essential for successful introduction and adoption of a new technology. Hence, it follows that rural development is an immensely complex process, with a high degree of non-linearity. Current 'best practice' economic evaluation methods commonly used in the CGIAR system, which attempt to establish a linear link between a project's outputs and regional or economy-wide impacts, struggle in this complexity. Indeed, such economic Impact Assessment (IA) is only valid if: 1) the causal link dominates from start of research to the measurement of impact; 2) there are no other factors affecting adoption and impact; 3) chance has no influence; and 4) inputs and impacts can be measured to an acceptable degree of accuracy. In practice replacement plant breeding is one of the very few CGIAR activities where these assumptions are likely to hold. A second shortcoming of economic IA is that it focuses largely on *ex-ante* and/or *ex-post* IA, but has little to offer in the area of monitoring and evaluation (M&E), despite M&E being identified as important in ensuring research projects actually achieve impact.

In this paper we review three case studies of M&E being conducted by three CGIAR centres in Africa. The case studies are: 1) Farmer participatory evaluation of legume cover crop and biomass transfer technologies for soil fertility improvement in eastern Uganda; 2) Impact pathway evaluation of integrated *Striga* control in Northern Nigeria; and 3) monitoring and evaluation of the dissemination of crop management options in Zimbabwe and Malawi. Although carried out independently, all three case studies focus on identifying the contributions of individual agents (e.g., farmers, researchers or input suppliers) to the adaptation and adoption of innovations, and the agents' motivations and perceptions that mould them. In each case study we examine the project, the creation of organisational capabilities and the changes that result from this understanding and conclude that participatory M&E has a vital role to play in helping projects respond early to farmers' evolving opportunities and needs. Finally, we argue that *ex-post* impact assessment should be based on the understanding of innovation processes developed during the M&E which shows which role each stakeholder played and why it made a difference, but without attempting to attribute a value to that contribution.

## Introduction

*The shortcomings of traditional economic impact assessment (IA)*

Folklore in the CGIAR system tells of a golden period in the 1970s when the only financial constraint was the capacity to spend the money wisely. Back then, donors believed that "if a group of competent scientists were based in a developing country, were provided with excellent facilities, and were isolated from political pressure for several years, they were bound to generate useful new technologies" (Horton and Prain, 1989, p. 302). Those days have long gone. Not surprisingly donors started to perceive that

isolation made CGIAR centres unresponsive to the needs of farmers and agro-industries, and started to demand evidence of priorities set jointly with the intended beneficiaries of the research, research impacts and the efficiency of research investments. In response to this pressure CGIAR centres invested much effort in the 1980s and 1990s in developing impact assessment methods (Ekboir, 2002). Much of this work was driven by the dominant social science approach in the CGIAR system, which remains grounded in traditional agricultural economics (Horton, 1997). These approaches rely on establishing a mechanical causal relationship between the costs and benefits of research.[4] 'Best practice' economic impact assessment is represented by the book *Science under Scarcity* (Alston et al., 1995), which is dismissive of other, less linear approaches as being "unlikely to yield any meaningful indications of the economic effects of research. … Therefore, they are not useful for informing allocation decisions." (p.501-2).

We contend that the predominance of traditional economic IA methods in the CGIAR system, often to the exclusion of a whole gamut of evaluation approaches developed in the field of evaluation, does not help solve donors' legitimate concerns about research relevance and impact. This is for two main reasons. Firstly, economic IA methods focus largely on ex-ante IA and then *ex-post* IA, but have little to offer in the area of monitoring and evaluation (M&E), despite M&E being identified as being important in helping research projects actually achieve impact. Secondly, economic IA, based as it is on linear models that link research inputs to outputs, is only valid if: 1) the causal link dominates from start of research to the measurement of impact; 2) there are no other factors affecting adoption and impact; 3) chance has no influence; and 4) inputs and impacts can be measured to an acceptable degree of accuracy (Ekboir 2002). In practice these assumptions can hold, as Table 5 shows, only for research activities developing 'minor' technological changes intended for use in 'simple' systems. Breeding of new plant varieties for irrigated areas that are already growing improved varieties of that particular crop, is one of the very few CGIAR research activities that would qualify. New varieties are simple to use because they are not new technologies but rather minor improvements of existing techniques along well known technological trajectories. Hence, the need for user modification and innovation, and therefore the unpredictability and non-linearity that this brings to IA, is limited. But since market and policy changes can affect adoption decisions in unforeseen ways, even relatively simple cases like the one described, are becoming increasingly complex due to globalisation and deregulation of agricultural markets.

**Table 5: A diagram showing a two by two matrix of system versus technology complexity, examples of the research activities that fit in each matrix square, and where economic IA methods can and cannot work**

| Knowledge complexity of technology developed | Complexity of system into which technology is introduced | |
|---|---|---|
| | *Simple* | *Complex* |
| *Complex* "hard-to-employ" | Natural resource management in simple systems | Natural resource management in complex systems |
| *Simple* "easy-to-employ" | Plant breeding for irrigated systems | Participatory varietal selection in rain-fed systems |

Key:

Where linear innovation approach and conventional impact assessment could eventually work

Where complexity requires close research and user interaction and assumptions underpinning economic impact assessment breakdown

[4] Where mechanical is used in the sense of mechanism: a system with well defined and stable interrelations among variables that uniquely define the system's response to a change in one of the exogenous variables.

Box 1 gives a case study of a 6-fold increase in grain production in MERCOSUR[5] that was the result of the interaction of three technologies with social innovations and explains why impacts cannot be attributed to research outputs alone. The case study also shows that ex-ante impact assessment prioritised the wrong research area, illustrating the point that ex-ante impact assessment can only recognise technological trends once they have begun to emerge. Hence, institutions can only establish research programs in relatively known fields. If new trends are to emerge, researchers must be allowed to explore less known areas of research.

Box 1: A case study of impact where traditional economic IA does not work (from Ekboir, 2002)
In the 40 years between 1961 and 2001 production of maize, sorghum, sunflower, soybeans and wheat in MERCOSUR increased from 23 million tonnes to 152 million tonnes. The increase came about by farmers adopting three interdependent technologies: the introduction of soybeans in late 1960s, zero tillage and improved germplasm. Soybean production led to an intensification of agriculture, which caused serious soil degradation. A number of technical solutions were proposed to solve the problem, including zero tillage and terracing. At the time, researchers identified terracing as the more promising option, and as a result soil conservation projects neglected work on zero tillage. Nevertheless, by 1985 viable zero tillage systems had been developed by a network of agents, including agrochemical companies, a few public sector researchers, farmers and agricultural machinery manufacturers. In the late 1980s researchers and farmers, with support from Monsanto, created associations to promote zero tillage. Adoption, however, remained low until the early 1990s because the herbicide glyphosate (a key component of the package) was expensive. Then, a change in corporate policies helped bring about a fall in price from US$ 40 per litre to US$ 10 per litre. The new relative prices combined with a very effective diffusion policy organized by the association caused adoption to explode (Ekboir, 2001). Zero tillage reduced production costs, reversed soil erosion and allowed an expansion of agriculture into previously marginal lands. Without zero tillage, grain production would have had to be abandoned in many areas.

The impact of these technologies cannot be separated. Without zero tillage, the impact of improved germplasm would have been very small, as zero tillage was necessary to stop soil erosion and improve water management. At the same time, new and improved germplasm increased the profitability of zero tillage, fostering adoption. But adoption only exploded when a key input produced by a private firm became affordable.

Economic IA assumes a mechanical link between research outputs and the benefits, and then attempts to separately attribute impact to the different components of the package. However, this is not possible in cases like this characterized by multiple interactions and feedback loops among several physical and social components and agents. Hence, traditional economic IA is not able to evaluate the research that contributed to the impact, because, for example, without the reduction in the price of glyphosate the impact would have been small. But the price reduction was completely unrelated to plant breeding or development of zero tillage.

In addition to the failure of ex post economic IA, ex ante impact assessment also failed by wrongly prioritising terracing as the most viable technical solution to soil degradation. As a result resources were siphoned off that might have otherwise hastened the adoption of zero tillage. Only after terracing proved to be unsustainable was zero tillage recognised as the best option.

*Evaluation that can deal with complexity*
Complex adaptive systems are characterized by three features: several interactions among agents and processes, strong feedback loops and intrinsic randomness. Because of these three features, these systems are essentially unpredictable in the long run, even though limited predictability is possible in the short run. Although outcomes cannot be predicted, key factors that influence the probability of success of agricultural innovation processes have been identified. These are the emergence of strong and flexible networks, the adoption of participatory research and diffusion methods where farmers play a key role,

[5] MERCOSUR is an imperfect customs union formed in 1995 by Argentina, Brazil, Paraguay and Uruguay.

flexible evaluation and monitoring routines in public research institutions and access to internationally generated information (Ekboir and Parellada 2002). Effective monitoring and evaluation routines of these factors that result in rapid corrective measures can greatly increase the chances of large impacts.

In addition to traditional IA, the CGIAR system needs innovative M&E approaches that aid a continuous redesign of on-going research projects (including 'learning by doing', 'learning by learning', mapping of innovation networks, creation of organizational capabilities and adaptive management). The importance of M&E to good, adaptive, project management is recognised as key to successful Integrated Natural Resource Management (Sayer and Campbell, 2001). Furthermore, donors at the February 2002 CGIAR Impact Assessment Conference urged centres to focus more on M&E that contributes to institutional learning and change, and less on *ex-post* IA of successes for publicity purposes. The following are three cases studies of recent and on-going M&E exercises to show the types of knowledge that this work can produce, and how it can feed back into the research and priority setting process. We then follow with a discussion of how inclusion of M&E can build the foundation for more plausible *ex-post* IA and be used as an essential tool in priority setting.

### *Case Studies of M&E being carried out by CGIAR Centres*

*Conceptual map of the innovation process*

All three case studies described in this section implicitly assume the conceptual map of the technology development and adoption process shown in Figure 1, and therefore the case studies are described with reference to the model. The model recognises four phases in the innovation process:

**Development Phase**— Innovators (e.g., researchers, farmers, input suppliers or other agents working together or in isolation) are permanently searching for new technological or economic alternatives to achieve their objectives (which may include improved livelihoods for farmers or professional recognition for researchers). Problem diagnosis with the intended target group(s) is part of this process. When an alternative is identified, the innovators develop 'best bet' integrated solutions.

**Start-Up Phase**—The network of early developers take these 'best bet' options and demonstrate them to individual and/or a network of farmers, in the hope that farmers will see that at least some aspects hold out a 'plausible promise' of being benefit to them, sufficient to motivate at least a few to contribute their own time and land in experimenting.

**Adaptation Phase**—Experimenting farmers and other agents work together to adapt and refine the 'plausible promise' into something better; something that is seen to work and make sense to the wider community;

**Expansion Phase**—Adoption levels expand as the community begins to adopt their locally-constructed solution(s). This might be an integrated package and/or a single component of the 'best bet' options originally introduced.

While necessary in all phases, M&E is particularly important in the adaptation phase to help ensure the innovations and farmer adaptations can be captured and incorporated into the research process.

Implicit to this conceptual map is the premise that once developed, a complex technology that is widely adopted in a pilot site, will scale-out to other, similar, communities through multi-actor interactions. However, scaling-out can be accelerated by a properly designed extension approach that speeds up both the knowledge spread and the experiential learning that is necessary to construct the technology in communities elsewhere.

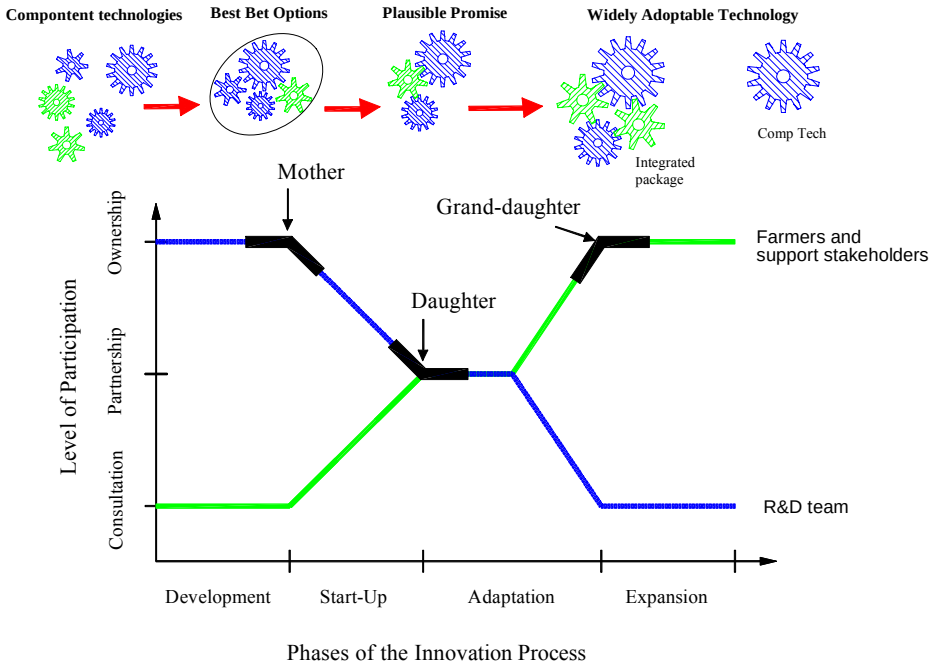



**Figure 1:** Conceptual map of the development and adoption process adopted in the case studies

***TSBF-CIAT: Farmer participatory evaluation of legume cover crop and biomass transfer technologies for soil fertility improvement in eastern Uganda***

**Introduction**

In late 1998, the Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture (TSBF-CIAT) introduced legume cover crop (LCC) and shrub species, proven to improve soil fertility, into two sub-counties of Tororo District, in eastern Uganda. These legume species were: *Canavalia ensiformis; Crotalaria grahamiana*; *Dolichos lablab; Mucuna pruriens; Tephrosia vogellii;* and *Tithonia diversifolia*. TSBF-CIAT began by setting up several on-farm trials, together with 40 participating farmers. The purpose of these trials was to validate and demonstrate the effectiveness of the LCCs and shrubs as, for example, cover crops to control weeds, or to improve soil fertility, by, in some cases, biomass transfer (BT) from one field to another. These activities were backstopped by project field officers, as well as, by the district extension services of the government. To reach more farmers a range of approaches were implemented, extension agents were trained on the use and management of the technology, innovative farmers were identified in each sub-county and trained, farmer-to-farmer extension formed an important component of the program. Many study and exchange tours were organized to enhance farmer-to-farmer learning and adoption of the technologies promoted. By the end of 2001 over 2000 farmers had established their own evaluation trials as a result of extension visits and farmer-trainer visits and from exchange visits to demonstrations sites.

*Materials and methods*

TSBF-CIAT conducted a farmer participatory evaluation of the LCC and BT species after seven seasons in December 2001 and January 2002 with 21 farmer groups, representing 234 farmers (92 male, 142 female). The farmer groups were purposively selected on the basis of having several seasons' experience with the legumes and their management. Group discussions and key informant interviews were then held to:

- Establish farmers' assessment of the legume species for soil fertility improvement;
- Identify farmer innovations with respect to the use and management of the legumes;
- Identify farmers' evaluation criteria when comparing between legumes;
- Conduct a matrix ranking based on these criteria.

*Results and discussion*

Farmers identified a number of positive and negative characteristics of each legume (**Table 6**). Some of the positive aspects correspond to innovations made by farmers during their trials (**Table 7**). Generally, the innovations show that farmers are seeking to increase the benefits of the technologies by finding alternative and dual-purpose uses for the legumes, other than for soil fertility or weed suppression. These include attempting to: eat the seed and leaves in sauce (*Lablab*, *Mucuna*), to control crop pests and diseases (*Crotalaria, Canavalia, Tephrosia*), catch fish (*Tephrosia*) and curing human ailments (*Tithonia*). Other innovations, for example, border planting, are designed to reduce the cropland taken by the legumes. An indication that farmers had learnt to value the legumes was that some groups gave them local names. One group called *Canavalia* 'Yathipendi' meaning 'medicine for banana' while another group, that was dominated by old men, identified it as 'Akengu ka Angu' meaning 'trap for the Hyena'. Tephrosia was locally known as 'Yathi fuuko' (medicine for mole rat) or 'Yathirechi' (medicine for fish). *Tithonia diversifolia,* was locally referred to as 'Mawuwa' but with no particular meaning attached to the name. It should be noted, that in some cases farmers knew the species before TSBF-CIAT established the trials but were not aware of their potential uses and that some of the names, innovations and discoveries occurred outside the learning cycles that took place as a result of the project trials.

**Table 6: Farmers' assessment of the legume species**

| LCC/shrub | Positive aspects | Negative aspects |
|---|---|---|
| *Mucuna*<br>Local name: none | Improves soil fertility<br>Suppress weeds effectively<br>Produce high biomass<br>Quick maturing | Not edible<br>Not good for intercropping (Climbs the crops)<br>Requires high labour for clearing and incorporation<br>Can harbour snakes and wild cats if planted near the home |
| *Canavalia*<br>Local name: Yathipendi (medicine for banana) or Akengu ka angu (trap for the hyena) | Improves soil fertility<br>Has fodder value<br>Suppresses weeds<br>Easy to multiply (high seed production)<br>Good for intercropping | Not edible |
| *Crotalaria*<br>Local name: none | Improve soil fertility<br>Suppress weeds | Has pest problem – scarring caterpillars |
| *Tephrosia*<br>Local name: Yathi fuuko (medicine for mole rat) or Yathirechi (medicine for fish) | Improves soil fertility<br>Control mole rat | Has pest that eats the pod, hence poor seed formation |
| *Lablab*<br>Local name: none | Improves soil fertility<br>Has fodder value<br>Suppresses weeds | Difficult to obtain seed |
| *Tithonia*<br>Local name: Mawuwa | Improves soil fertility<br>Malaria & stomach ache medicine<br>Has pesticidal properties<br>Fodder for goats | It is a weed |

**Table 7: Farmer modifications and innovations to management and use of legume species**

| Legume species | Modification to management and use |
|---|---|
| *Mucuna* | Attempts to cook it and eat the seed in sauce |
| | Efforts to crush seed to make animal feed |
| | Good feed for goats, cattle and rabbits |
| *Canavalia* | Used to scare-off hyenas in the olden days, and monkeys these days |
| *Crotalaria* | Boundary planting around the homesteads instead of researcher-recommended intercropping with maize or planting as one season fallow crop |
| | Intercrop with beans to control nematodes and other bean diseases. |
| | Seed put together with bean seed during storage to control bean storage pests |
| *Lablab* | Seed and the leafy vegetation eaten in sauce |
| *Tephrosia* | Leaves are crashed, poured into rivers and streams to catch fish |
| | Doubt on its effectiveness in controlling the mole rat |
| *Tithonia* | Leaves used for treatment of stomach ailments and fevers |

Farmers were also asked to make explicit the criteria they used when evaluating the legumes

Table **8**) and the overall farmer ranking, developed using a ranking analysis tool with the 21 groups, is shown in Table 9. The rank order from the most to the least preferred was *Mucuna, Tithonia, Canavalia, Crotalaria, Lablab* and *Tephrosia*.

**Table 8: Criteria used by farmers in ranking LCC and shrub species**

| Criteria | Reason of criterion |
|---|---|
| Yield increase of crop after fallow or intercrop | Weight of grain, bunch, fruit etc |
| Crop vigour of crop after fallow or intercrop | Health |
| | Greenness of leaves |
| Soil fertility increase | Change of soil colour to dark |
| | Depth of soil increased |
| | Ease of ploughing |
| | Soil erosion control |
| | Moisture retention |
| | Time taken to cause significant fertility increase |
| Ease of germination, establishment & seed production of the LLC or shrub | More seed produced in a short time & viable for a longer time. |
| | Small seed difficult to collect |
| Multiple uses of the LLC or shrub | The number of other additional uses from the LCC or shrub e.g. firewood, medicine, fodder etc. |
| Suitability for intercropping | Intercrop compatibility i.e. minimal competition of the LCC or shrub with the crop |
| Ability to control weeds | Dense canopy formation which suppress undergrowth |
| Amount of biomass production | Number of leaves |
| | Size of leaves |
| | Ground coverage |
| | Shorter maturity period |
| Labour requirement for clearing, uprooting, cutting and incorporation | Ease of bush clearing, uprooting, cutting stems and leaves & then incorporation into the soil |

**Table 9: Overall matrix ranking of the LCCs and biomass transfer (BT) species based on the criteria (from 21 farmer groups)**

| Criteria for ranking | LCC and shrub species | | | | | |
|---|---|---|---|---|---|---|
| | *Mucuna* | *Canavalia* | *Crotalaria* | *Tithonia* | *Tephrosia* | *Lablab* |
| Yield increase in crop | 2 | 4 | 3 | 2 | 5 | 4 |
| Crop vigour of crop | 1 | 4 | 2 | 2 | 5 | 5 |
| Soil fertility increase | 2 | 4 | 4 | 2 | 5 | 5 |
| Ease of establishment | 2 | 3 | 5 | 2 | 6 | 5 |
| Multiple uses | 5 | 5 | 5 | 4 | 4 | 4 |
| Suitability for intercropping | 4 | 2 | 2 | 3 | 3 | 5 |
| Ability to control weeds | 1 | 4 | 3 | 3 | 6 | 4 |
| Amount of biomass production | 2 | 4 | 4 | 2 | 5 | 5 |
| Labour requirement | 3 | 1 | 3 | 4 | 4 | 4 |
| TOTAL | 22 | 31 | 32 | 24 | 43 | 41 |
| RANK | 1 | 3 | 4 | 2 | 6 | 5 |

For the 21 groups a cumulative probability was plotted against the ranking order given by each group (Figure 2). The area under the lines for the different LCC and BT species is directly related to its ranked popularity. For example nearly all the groups rated *Mucuna* either first or second, giving a large area under the *Mucuna* line, while most farmers rated *Tephrosia* either fifth or sixth giving a much smaller area under the Tephrosia line. What Figure 2 shows is that *Mucuna* is clearly the most popular, *Lablab* and *Tephrosia* are almost universally unpopular and have a low probability of being accepted in any village, while *Crotalaria*, *Canavalia* and *Tithonia* are moderately popular with little to distinguish between them. This analysis has been confirmed using a logic regression analysis (Nyende and Delve 2002).

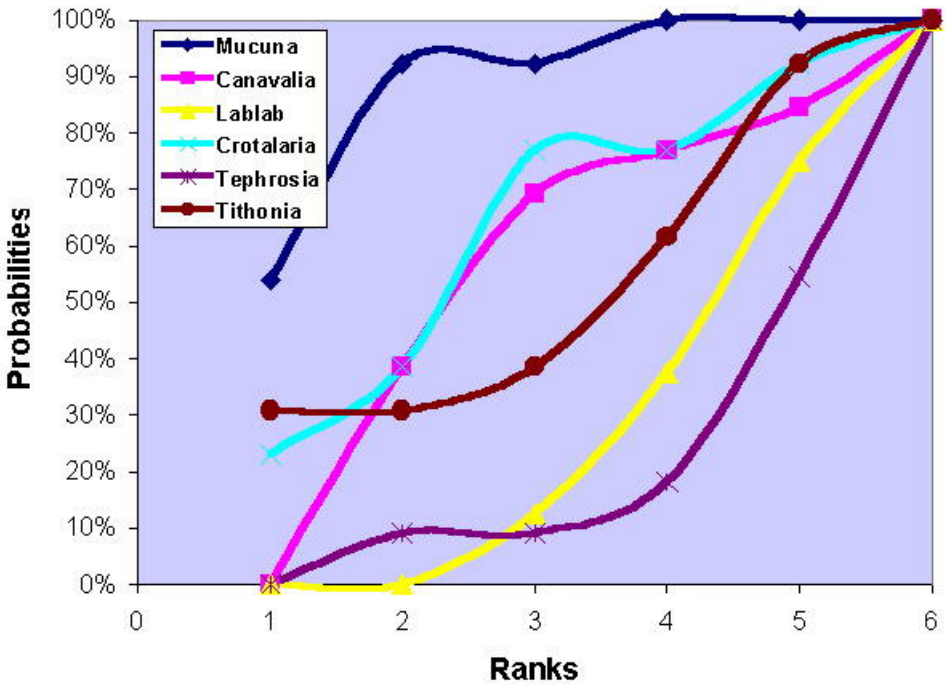



**Figure 2:** Comparison of the acceptability of LCC and BT species by plotting cumulative probability against the ranking given by the different groups

Discussions with farmers during the group assessments and ranking exercises, as well as open and probing questions, gave insights into the constraints to farmer adoption. Fallowing the land is not possible where small land sizes or high population densities exist and where seed supply for these legume cover crops is not good. In eastern Uganda, where the population pressure is much lower and where natural fallowing is still part of the farming system, the opportunities for improved fallowing or biomass transfer is much larger. Even so, farmers commonly cite difficulties in finding the labour required for collecting or incorporating biomass. Also, many farmers are very reluctant to use land and effort without producing a crop, even if future benefit justifies the investment. This is because most farmers' main priority is food production, and they are very risk adverse. As an adaptive research farmer commented, '*Its better to have even one gorogoro tin of maize [from a depleted field that was planted with maize] than to be guaranteed no maize at all this season by planting a cover crop we can't eat*' (Ramisch, pers. Comm.).

The next stage in this adaptive research process involved the systematisation of information from the M&E, detection of knowledge gaps, and the identification of potential research questions during follow-up community meetings attended by the farmers, extension agents, NGO and CIAT staff. During these meetings the results of the participatory evaluation were discussed and this led to the identification of new research questions that needed to be addressed. For example, *Lablab* was identified as a very promising multi-purpose legume but the variety the community had was not producing seed. As a result new photoperiod insensitive and early flowering germplasm from Australia and Africa is now under-going on-station evaluation.

After identifying new research questions the different partners then agreed on how to address the issues. They did this by:

- Identifying key farmers to conduct adaptive research on behalf of the community. These farmers will establish a range of experiments, and will be responsible for monitoring the experiments and reporting back to the whole community on the results.
- Applied research questions to be addressed by National agricultural research partners, through an array of methods from on-station research to on-farm research.
- Strategic research questions to be addressed by CIAT, TSBF, and other partner international research institutes through an array of methods from, strategic on-station research to on-farm research.

**Conclusions**

The most important outputs of the M&E process was the identification of the criteria used for species selection and the farmers' innovations. Both provided essential feedback to the participatory action research approach as they reflect the opportunities and constraints of the production systems of the farmers and raise many new areas of research, opportunities of evaluation of new technologies and species, and the better targeting of existing information. The M&E has shown that farmers adapted technologies introduced primarily for soil fertility replenishment in an attempt to fulfil a much wider range of production objectives, leading to the conclusion that a single-use technology had little chance of large-scale adoption. This has resulted in a major rethink by researchers and partners of the methodology and approach taken and the types of research conducted in the project.

### *IITA: Impact Pathway Evaluation of Integrated Striga Control (ISC) in Northern Nigeria*

***Introduction***

*Striga hermonthica* is a parasitic weed that attaches itself to the roots of cereals (e.g. maize, sorghum, millet and rice), diverting essential nutrients and leaving the host stunted and yielding little or no grain. The weed is the severest biological constraint to cereal production in sub-Saharan Africa, infesting almost

21 million hectares of land causing millions of dollars of damage (Sauerborn, 1991). Farmers world-wide call it 'witch' weed, because it does most of its damage before it emerges from the soil.

Research at IITA and elsewhere is showing that *Striga* control is possible using an integrated approach that attacks *Striga* from several sides at the same time. A key component of this Integrated Striga Control (ISC) approach is the use of a legume crop (e.g., soybean, cowpea, groundnut) that induces a high proportion of *Striga* seeds to germinate, which then die because they cannot parasitize legumes. This is called 'trap cropping'. To be effective, legume trap crops must be planted much more closely than farmers usually plant their legumes, and should be used together with *Striga*-resistant cereals, seed cleaning to remove *Striga* seed, crop rotation, weeding of the *Striga* plants before they set seed, and improved soil fertility.

Since 1999, a research project at IITA has been working in four villages in Northern Nigeria using participatory research approaches to develop locally-adapted integrated Striga control (ISC). The villages where chosen on the basis of having severe *Striga* problems. Two group meetings were held, first to carry out a problem consensus to rank *Striga* in relation to other problems, and then to design experiments to evaluate the options for *Striga* control. The R&D team has provided training to improve farmers' understanding of *Striga*. The work began with 19 participating farmers (Schulz et al. in press).

**Materials and methods**

M&E has been built into the project from early on, based on the project impact pathway shown in Figure 3. The impact pathway describes how the project expects the output—validation and adaptation of ISC options in farmers' fields—might lead ultimately to the project goal of improved livelihoods for the 100 million people in Africa that are affected by *Striga*. The shaded boxes are the intermediate outcomes that the project is monitoring. The unshaded boxes will be evaluated in the *ex post* impact assessment some time after the end of the project.

The project is using two published approaches to monitor and evaluate the delivery of the intermediate outcomes shown in Figure 3. The first is the 'Follow the Technology' (FTT) approach (Douthwaite et al. 2001; Douthwaite 2002) that sees technological change in general, and early adoption in particular, as an evolutionary process in which stakeholders generate novelties (i.e., make modifications; innovate), select those that appear to work and promulgate the results. The Follow the Technology approach involves, as the name suggests, following new technologies and knowledge as they are adopted. The FTT approach focuses on identifying modifications, selection decisions (i.e., whether farmers decide to adopt a modification), and promulgation processes. Key to the direction and nature of an evolutionary process is the environment, hence the FTT approach pays particular attention to seeking explanations for novelties generated, selection decisions made and the nature of promulgation paths to understand the socio-economic and cultural factors affecting farmers' learning and decision making processes. By paying particular attention to who is, and is not, modifying and adopting, as well as identifying conflicts arising from adoption, the FTT approach is able to identify negative as well as positive consequences.

The project will use the Sustainable Livelihoods Framework (SLA) (Scoones, 1998), summarised in **Figure 4**, to guide an evaluation of whether adoption of ISC is having any impact on peoples' livelihoods. This will be done by constructing case studies of individual households, purposively selected to be representative of poor, medium and rich households in the four villages.

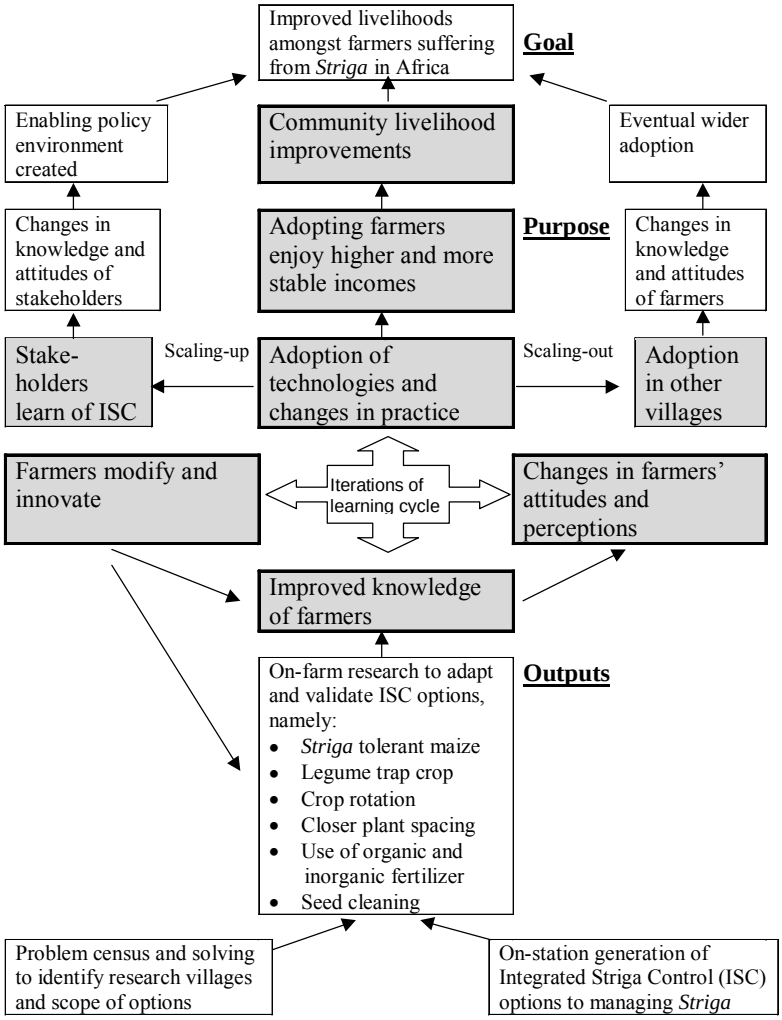



**Figure 3:** Impact pathway for an Integrated *Striga* Control (ISC) Project in Northern Nigeria

From October 2001 to January 2002 a survey was carried out to identify farmers who had adopted at least one component of ISC from the participating farmers. A total of 245 expansion farmers were identified in this way. The positions of the 44 participating farmers' experimental plots and the subsequent 'expansion' plots were then marked using a hand-held GPS and plotted using the geographic information systems (GIS) program ArcView (ESRI, 1999). A data sheet was completed to record what was planted in the fields, and modifications made to the recommended package shown in Figure 3. From February to June 2002 an in-depth survey was then carried out of a random sample of 149 of the participating and expansion farmers. The survey sought explanations for farmers' adoption and modification decisions, his or her understanding of ISC, and to find out where the farmer received the technologies from, and who he or she has passed them on to. The questionnaire specifically asked whether farmers passed on any of the agronomic recommendations, e.g., close legume spacing, in addition to distributing seed. In this way the FTT approach monitors and evaluates changes to five of the boxes shown in Figure 3, that is, changes in farmer knowledge and perceptions; modifications; adoption; and the spread from the pilot villages elsewhere (scaling-out).

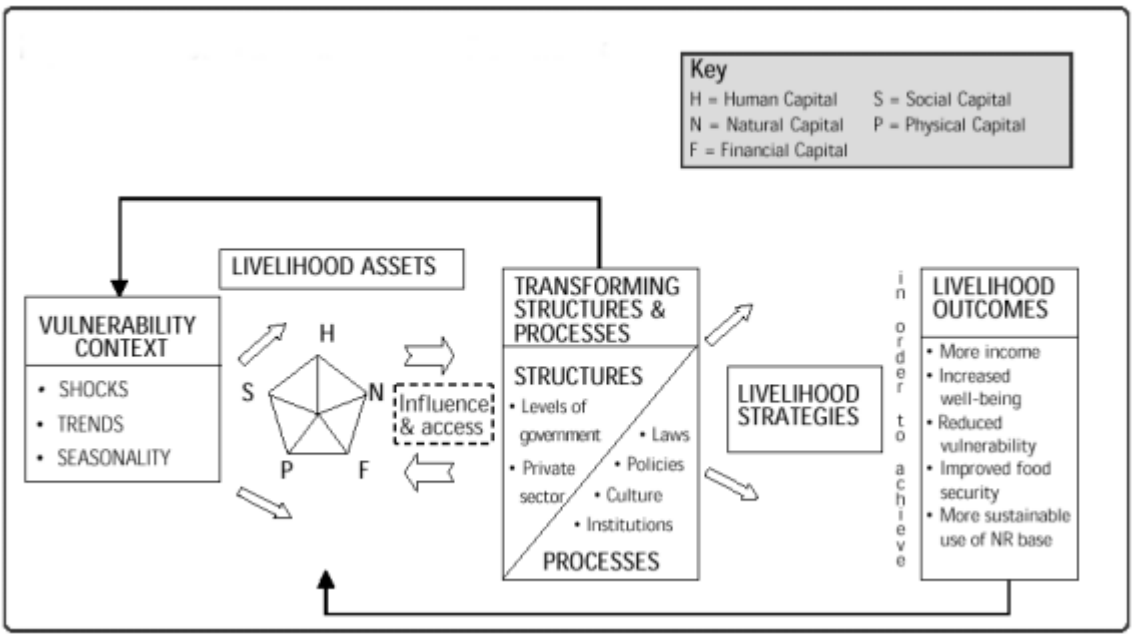



**Figure 4:** The Sustainable Livelihoods Framework

**Findings and Discussion**

**Table 10** shows that over half of the farmers had made at least one modification to researcher-recommended management when they adopted aspects of ISC. Most of these were to reject the researcher-recommended sole-cropping and closer plant spacing, in particular for soybean. The latter was largely because recommended soybean row spacing was 35cm, while in most farmers' fields row spacing was fixed by the local animal-driven plough at 70cm. One farmer, however, came up with the innovative approach of planting two rows per ridge, shown in
. It shows that the farmer has understood the principle of suicidal germination and the need for higher soybean root density. The project has subsequently adopted this practice because it reduces the cost of establishing legume trap crops.

**Table 10: Modifications made to researcher-recommended Integrated Striga Control (ISC) package**

| Modification | f |
|---|---|
| No modification | 75 |
| Planting widely spaced single rows of cereal in soybean (Gicci) perpendicular to the ridges | 37 |
| Wider row spacing | 15 |
| Strip cropping (e.g. 2 rows cereal, 4 rows legume) | 11 |
| Intercropping (e.g. maize, sorghum and groundnut in same field) | 6 |
| Relay cropping (e.g., cowpea planted into established maize field) | 4 |
| Planting two rows of soybean on 1 ridge | 1 |

n=149

Farmers' rejection of sole cropping has negative implications for *Striga* control because mixed cropping with cereals (gicci, strip, intercropping and relay) is a concern to the project because it means that Striga will grow and flower each year in the field thus replenishing the seed bank. The reasons farmers gave for continuing with mixed cropping is that it reduces risk, and gives a higher overall yield. Both reasons are valid, although the second is only true with low fertilizer use that necessitates wide cereal plant spacing, leaving room for a legume in-between. However, researcher-managed trials have shown that a sole-crop legume followed in rotation with close-spaced sole-crop maize with moderate fertiliser application rates gives better *Striga* control and much higher yields than farmers' practice, and is more profitable (Schulz et al. In press). In an effort to bring farmers' and researchers' perceptions and understanding closer together the project is planning to carry out a participatory budgeting exercise at the end of the 2002-cropping season to help farmers more clearly see the economic benefits of sole-cropping and legume-cereal rotations, and for researchers to better understand the benefits of mixed cropping. This would not have happened without the data from the monitoring and evaluation.

**Figure 5:** Farmer in Northern Nigeria who is experimenting with planting soybean on either side of the row so as to increase soybean planting density

Figure **6** is an example of maps drawn for each of the four villages where the experimental plots were first set up, showing the spread of the ISC crop varieties, and one of the management recommendations—the close planting of legume trap crops. Other maps are possible showing the adoption of the other components of ISC. However, what these particular maps show is firstly the majority of farmers are adopting closer spacing of legumes, showing that knowledge about how to use the trap crops is spreading as well as the seed. Secondly, the maps show that the adoption pattern is different in different villages. In Kaya village, for example, adoption is clustered around the participating farmers and their fields, while in Mahuta, aspects of ISC have moved up to 40km. The project is now planning to develop a ISC extension approach built on fostering these indigenous scaling-out mechanisms. Again, without M&E the project would not be following this path.

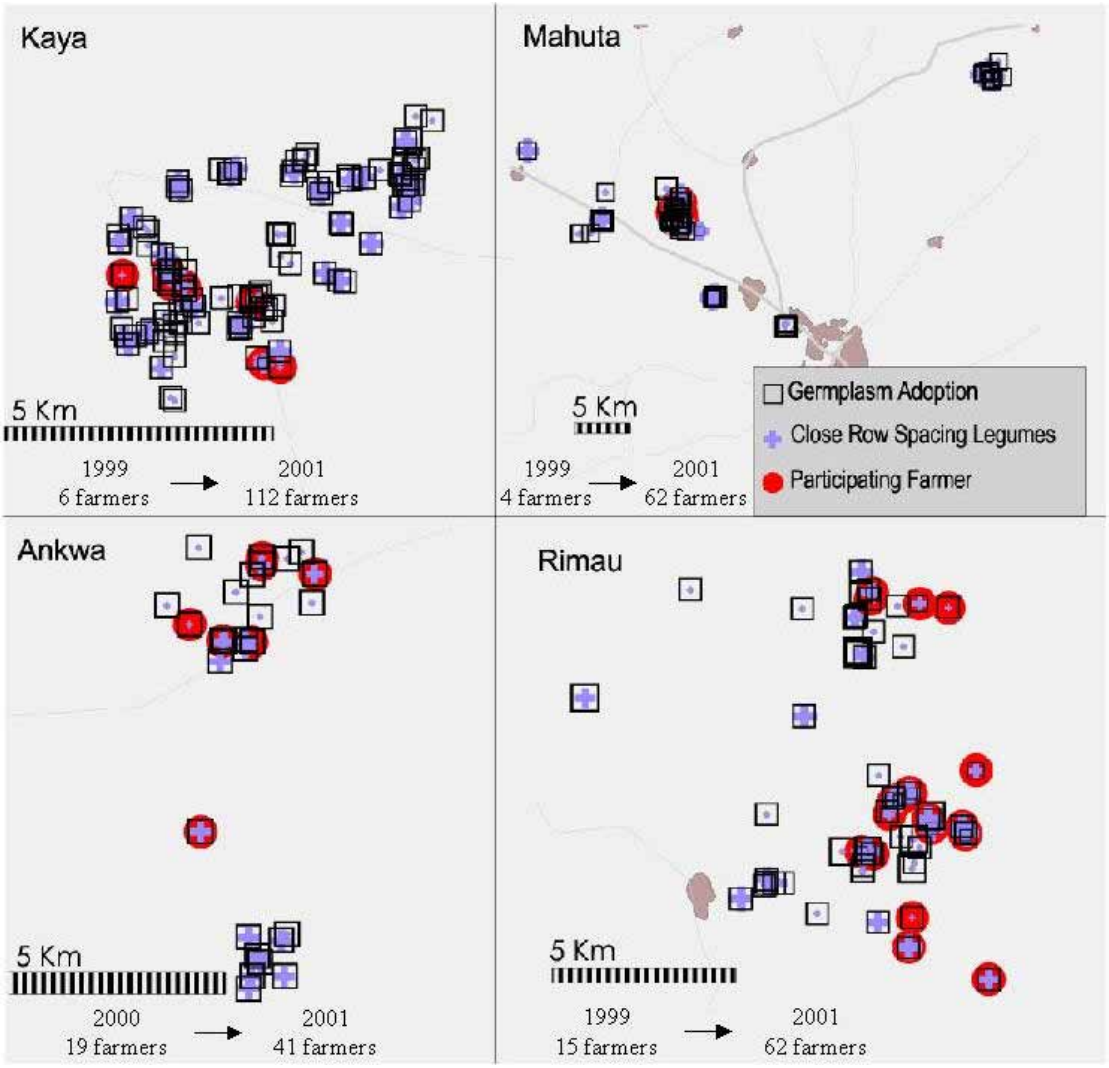



**Figure 6:** Adoption and spread of integrated *Striga* control technologies in four villages in Northern Nigeria. Each point represents one farmer's field. Two or more legends superimposed on one point mean that the farmer adopted two or more technologies

**Conclusions**

M&E has helped give the ISC project a much clearer impact focus through the process of defining the project's impact pathway. The M&E findings have redirected research efforts in a number of ways, including through the incorporation of farmer innovations in the recommended basket of options; the decision to carry out a partial budgeting exercise to bring farmers' and researchers' perceptions of the pros and cons of mixed versus sole cropping closer together; and by providing the understanding of adoption processes necessary to develop an effective ISC dissemination approach.

***More practical crop management options for potential dissemination to women-headed households in Malawi and Zimbabwe - A Case Study by ICRISAT-Zimbabwe***

**Introduction**

In 1998, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and its partners in Malawi and Zimbabwe began a comparison of different Farmer Participatory Research (FPR) approaches being used by various organizations in Malawi and Zimbabwe. A key objective was to compare the effectiveness of different methodologies in the development and testing of soil management technologies for resource-poor farmers, particularly women farmers. A second objective was to investigate the contribution that crop systems simulation modelling could make to FPR. To accomplish the objectives the project tested FPR methods at each of six case study sites, three each in Malawi and Zimbabwe. The various methods involved varying degrees of farmer participation: traditional research-led, researcher-led with farmer input, and farmer-led with research input.

The project tested four hypotheses:

- The provision of a broad range of soil water and nutrient management options is better than blanket fertiliser recommendations currently offered by government extension services, which are 3 to 8 times higher than the rates that farmers usually apply;
- Recommending less inorganic fertilizer and more manure and legumes to women farmers would increase their adoption rates, and thus improve productivity and food security.
- Uptake of technologies would vary with the wealth of the household and gender of the household head.
- Adoption would follow a cycle starting with a low rate of inorganic fertilizers and manure and increase through learning-by-doing and learning-by-using.

**Materials and Methods**

At start-up the project invested heavily in training activities with research and development staff from the different partner institutions to introduce the various concepts of the participatory research process and simulation modelling. However, the short duration of the project meant that much of the problem identification and selection of best bets occurred prior to the training. The 'best bet' technology options were selected in part through an exercise in systems analysis conducted in September, 1999, based on crop simulation modelling and resource-constrained scenarios that incorporated realistic levels of farmer resources. Socio-economic data and the judgement of agronomists and economists were used to devise resource-constrained scenarios (e.g., trade-offs for allocation of labour and resources among different farm management components: timely planting and weeding, fertilizer and manure). Simulation was then used to evaluate different scenarios, with the goal of maximizing return from the whole farm while limiting risk. The best bet options chosen included a range of legume intensified systems (Chamango, 2002; Twomlow et al., 2002), moderate inorganic fertilizer use alone or in combination with extra weeding (Dimes et al., 2002), and manure (Murwira and Kudya, In press).

Throughout the projects life various formal and informal workshops were held in both Malawi and Zimbabwe to introduce various concepts of the participatory research process and simulation modelling to researchers, extensionists and farmers. On-farm experimentation with the best bet options was then conducted over the 1999/2000 and 2000/2001 growing season at the six case study sites. Each case study village had a research-led, farmer-input trial and either a farmer-led, research-input and/or a research-led, traditional trial. The choice and implementation of the best bet options and the FPR approaches varied depending on the experiences of the local team.

To fully understand the household labour implications and farmer perceptions of the different technologies being tested at the six field sites field days were held on a seasonal basis and farmers perceptions of each technology were solicited using a range of participatory tools, such as matrix ranking. These field days were followed up by a series of focus group discussions between March and May 2001,

with participating farmer groups in both countries (Rusike and Twomlow, unpublished field notes; Ncube and Twomlow, 2001). At each of these meetings the farmers were asked to describe their cropping calendar in relation to local soil taxonomies, the labour resources used for each task, and local input and output prices, the technologies they had been evaluating, and what, if anything they had adopted or adapted (see

). This information was then used to construct a final adoption survey from which partial budgets for each technology were determined, from which net benefit curves and a marginal rates of return analyses were calculated to identify what financial benefits might accrue for a rural household and the potential risks of the different technologies. Based on this information a whole farm mathematical programming model was constructed to determine profitability of the improved soil water and fertility management options relative to other investment options given the household resource constraints and preferences for risk, and thus identify constraints to adoption. The model was set up to maximize net revenue of the whole farm subject to resource constraints. The model captured risk as the minimum quantity of staple food grain (1 ton of maize, sorghum or millet grain per 6 family members) that the household needs to produce to meet its food requirements for the year. The model was then run for different resource categories of farmers using the gender of household head as the proxy indicator.

**Figure 7:** Malawian collaborator describing the field trials she has hosted over the last two seasons

**Results and Discussion**

The FPR trials indicated significant yield increases result from use of best-bet options compared to farmers' practice, including small quantities of fertilizers linked to weeding, legume rotations and intercrops and anaerobically-composted manure.

Marginal rate of returns analysis showed that best bet technologies offered significant benefits to farmers and had returns which exceeded 100%, which is usually assumed to be the minimum required for smallholders to widely adopt this type of agricultural technology (see
**Table 11** and
**Table 12** for example marginal rate of return analyses for legume best bet trials in Malawi and Nitrogen by Weeding Trials in Zimbabwe). However, farmers' evaluation of technologies, using matrix ranking exercise during field days, showed that they may still not adopt the technologies despite their competitive marginal rates of returns shown in
Table **11** because of resource constraints, access to input and output markets, risk and food security (Table 14).

**Table 11: Marginal returns analysis of undominated treatments tested in legume trials, Malawi, 1997/98-1999/2000**

| Chisepo | | Mangochi | | Dedza | |
|---|---|---|---|---|---|
| **Treatment** | **Return (%)** | **Treatment** | **Return (%)** | **Treatment** | **Return (%)** |
| Unfertilized maize | n.a. | Unfertilized maize | n.a. | **Unfertilized maize** | n.a. |
| *Mucuna*-maize | 1562 | *Mucuna*-maize | 675 | *Mucuna*-maize | 135 |
| Maize-Tephrosia | Dominated | Maize-*Tephrosia* | Dominated | Bean-maize | 1743[a] |
| Maize+pigeon pea | Dominated | Maize+pp unfertilized | Dominated | Maize/*Tephrosia* | 101[b] |
| Groundnut+pp | Dominated | Groundnut + pp | 44 | Maize+legume unfertilized | Dominated |
| Maize+fertilizer | 60[a] | Maize+fertilizer | Dominated | Maize+fertilizer | Dominated |
| Maize+pp+ fertilizer | 152[a] | Maize+pp+ fertilizer | Dominated | Maize+legume+ fertilizer | Dominated |

| | |
|---|---|
| n.a. | Not applicable because it is the control treatment |
| Dominated | Treatment marginal rate of return worse than control |
| a. | If rule out *Mucuna*-maize system |
| b | If rule out *Mucuna*-maize and bean-maize systems |

**Table 12: Marginal returns analysis of undominated treatments tested in fertilizer by weeding trials, Zimbabwe, 1997/98-1999/2000**

| Treatment | Marginal rate of return (%) |
|---|---|
| 0 kg/ha Nitrogen-1-weeding | n.a. |
| 18 kg/ha Nitrogen-1-weeding | 218 |
| 18 kg/ha Nitrogen-2-weeding | 380 |
| 35 kg/ha Nitrogen-1-weeding | 471 |

**Table 13: Comparison of acceptability of technology options tested in the trials, Malawi, 1997/98-2000/2001**

| Best Bet Option | Agronomic[1] Acceptability | Economic[2] Acceptability | Farmer [3] Acceptability |
|---|---|---|---|
| Unfertilized maize | 5 | 6 | 5 |
| Maize + area specific fertilizer | 2 | 4 | 7 |
| Maize+pigeon pea | 3 | 2 | 2 |
| Maize+pigeon pea+area specific fertilizer | 1 | 3 | 6 |
| Groundnut+pigeon pea | 6 | 5 | 3 |
| Maize+*Tephrosia* | 4 | 7 | 4 |
| *Mucuna*-maize rotation | 7 | 1 | 1 |

1 - Agronomic acceptability in terms of yield performance
2 - Economic acceptability in terms of marginal rates of return analyses
3- Farmer acceptability based on seasonal matrix ranking exercises.

Nevertheless, the 2000/2001 end-of-season survey of farmers who hosted trials and non-host farmers in neighbouring villages showed that farmers are adapting and adopting some technologies from the trial plots to their main fields (Table 14). The crop management practices being adopted/adapted by farmers in both Malawi and Zimbabwe are summarised in Table 11.

**Table 14: Percentage of farmers reporting taking practices from trial plots to their main fields, 2000/2001**

| Taken practices from research to fields | Malawi | | Zimbabwe | |
|---|---|---|---|---|
| | Host | Non-host | Host | Non-host |
| Yes | 64.7 | 19.8 | 76.7 | 47.3 |
| No | 35.3 | 80.2 | 23.3 | 52.7 |

Malawi: n=227 (158 male, 69 female)
Zimbabwe: n=194 (138 male, 56 female)

**Table 15: Farming practices taken up by farmers onto main fields from soil fertility research to their main fields, Malawi and Zimbabwe, 2000/2001**

| Crop management practices taken by farmers into main fields | % uptake Malawi (N=227) | Zimbabwe (N=194) |
|---|---|---|
| Groundnut varieties and groundnut rotation and intercrops | 19 | 6.8 |
| Maize-pigeon pea rotation and intercrop | 16.7 | 0[1] |
| Maize-soybean rotation and intercrops | 13.7 | 0 |
| Maize-*Mucuna* rotation and intercrop | 9.1 | 0.5 |
| Incorporating crop residues | 9.1 | 0.5 |
| Spacing, planting methods | 6.8 | 8.6 |
| Maize hybrids | 6.6 | 5 |
| Maize-*Tephrosia* rotation and intercrop | 6.1 | 0 |
| Crop rotation | 6.1 | 6.8 |
| Compost manure | 3 | 0.5 |
| Early planting, top dressing with inorganic N, early weeding, many weedings, zero tillage, fermented cow dung | 1.6 | 9.6 |
| Kraal manure | 1.5 | 2.3 |
| New sorghum and pearl millet varieties | 0[1] | 17.3 |
| Heaped covered manure | 0 | 9.9 |
| Dead level contours, infiltration pits | 0 | 7.7 |
| Seed priming | 0 | 7.7 |
| Pit manure | 0 | 7.2 |
| Modified tied ridges | 0 | 5.4 |
| Maize, sorghum and pearl millet-cowpea rotations and intercrops | 0 | 4.1 |

[1]A zero responses indicate that the farmers had not been exposed to the crop management practice.

The adoption of maize-legume systems by households in both countries is influenced by access to input markets for seed and output markets to earn cash through commercial grain sale. In both countries the use of inorganic fertilizer is constrained by a combination of high fertilizer prices, and blanket recommendations that do not take account of households perceptions of risk and liquidity, as few households earn enough income from their crop sales to enable them to invest such large cash inputs. The small doses of fertilizer, 10 to 20 kg of N $ha^{-1}$ that the project tested with farmers appears to be at an investment level that households are willing and able to risk. However, information is lacking on fertilizer application rates that farmers currently use, how they can best use the small quantities of fertilizer they have, and on manure-fertilizer combinations, and integrating inorganic and organic fertility amendments.

Table 15 shows that in both Malawi and Zimbabwe the most popular technologies were improved germplasm with accompanying management practices. However, the table also shows that farmers in Zimbabwe were much more willing to expand investments in a range of improved soil, water and nutrient management practices than in Malawi, where pre-plant ridges are the norm, rather than the exception. Other findings from the research showed, however, that adoption of soil, water and nutrient management practices should be accompanied by improvements in basic crop management practices such as variety selection, tillage, planting method, spacing, timing of planting and weeding in order for the investment in improved soil fertility management to provide acceptable payoffs.

In Malawi, it would appear from our survey data that proportionately more female-headed households have changed their crop management practices as a result of the projects activities. Female-headed households are adopting new maize varieties; groundnut, soybeans and *Tephrosia* intercrops; and modifying their plant populations to reflect those used in the trials (Table 10). In contrast, male-headed households were emphasising pigeon pea and *Mucuna* rotations, incorporation of plant residues, kraal and compost manures, and early planting and small quantities of fertilizer. These difference have been attributed to the fact that female-headed households tend to have greater land, labour and cash constraints, and as a consequence are more food deficit than male-headed households (Freeman, 2002).

**Table 16: Practices taken up by farmers onto main fields by gender of household head, Malawi 2000/2001**

| Practice | Status of household heads | | |
|---|---|---|---|
| | Male-Headed (n=158) | Female-Headed (n=69) | All (N=227) |
| New maize varieties | 5.2 | 14.3 | 7.6 |
| Groundnut rotation and intercrops | 17.5 | 22.9 | 19 |
| Soybean rotation and intercrops | 12.3 | 17.1 | 13.7 |
| *Tephrosia* rotation and intercrops | 5.1 | 8.6 | 6.1 |
| Pigeon pea rotation and intercrops | 17.5 | 11.4 | 15.9 |
| Mucuna rotation and intercrops | 11.3 | 2.9 | 9.1 |
| Incorporating crop residues | 10.3 | 5.7 | 9.1 |
| Crop rotations | 7.2 | 2.9 | 6.1 |
| Intercrops | 0 | 2.9 | 0.8 |
| Spacing, plant population | 6.2 | 8.6 | 6.8 |
| Early plant, small fertilizers | 2 | 0 | 1.6 |
| Kraal/compost manure | 5.2 | 2.9 | 4.5 |

Focus group discussions held in both countries (Rusike and Twomlow, unpublished field notes, 2002; Ncube and Twomlow, 2001) showed that farmers' perceptions of soil fertility management vary widely, depending on the resources available to the individual household. In Zimbabwe, *de facto* female-headed households with access to cash appeared to be adopting new cereal varieties, seed priming, pit-composted manure and small quantities of inorganic fertilizer, manure and weeding combinations (Table 11). In contrast, the poorer resourced *de jure* female-headed households were adopting heap-covered composted manure, dead level contours, modified-tied ridges and reduced tillage because they have more severe capital and labour constraints. Male-headed households with access to labour and draught animals but not cash favoured legume rotations, small doses of fertilizer and water harvesting, especially infiltration pits that are labour-intensive.

**Table 17: Practices taken up by farmers onto main fields by gender of household head, Zimbabwe, 2000/2001**

| | *% uptake* | | | |
|---|---|---|---|---|
| Practice | Male-Headed (n=138) | *De facto* Female (n= 42) | *De jure* Female (n= 14) | All N=194) |
| New cereal varieties | 31.5 | 37.8 | 16.6 | 32.3 |
| Legumes rotations/intercrops | 20.8 | 10.2 | 13.3 | 18.7 |
| Seed priming, planting methods, spacing | 16.1 | 20.5 | 16.6 | 16.8 |
| Small fertilizer/weeding/manure | 8.6 | 13.8 | 0 | 7.7 |
| Treated manure | 16.7 | 30.9 | 26.7 | 19.9 |
| Water harvesting | 14.8 | 0 | 20 | 13.6 |
| Reduced tillage/compost | 0.6 | 0 | 6.6 | 1.4 |

Solutions from the whole farm mathematical programming model suggest that for male, *de facto* and *de jure* headed households that the most attractive technologies are:
Legume-rotations and treated manures for male-headed households with access to draft animals, labour and land;
Small quantities of inorganic fertilizer, treated manure and manure-fertilizer technologies for *de facto* female-head households with an off-farm cash income;
Legume intercrops in the female-headed households, typically *de jure*, who have the most severe resource constraints.

The model outputs disagreed with the working hypotheses based on expert opinion, and show that the wealthiest households, irrespective of gender, with lowest opportunity cost of working capital, will allocate more land and money to inorganic fertilizers than the more marginalised groups. These marginalised groups typically have less working capital and a higher opportunity cost. Therefore, better-resourced households will invest in high input technologies such as small quantities of fertilizer and treated manure. In contrast, the poorer resourced households will invest in low input technologies such as legume-cereal intercrops, as their opportunity cost of labour is very high and they are better off selling labour to wealthier households.

**Conclusions and Lessons Learned**

Overall, three major lessons have been learned about the differential adoption and targeting of alternative soil water and nutrient management to differently resourced households:

1. Small quantities of fertilizer and manure-fertilizer combinations have a high payoff and supplying inorganic fertilizers in small packs reduces the liquidity constraint and enhances returns to investment in chemical fertilizers.
2. Input and output markets drive legume intensification.
3. Legume intensification needs to target poor households for food for home consumption and wealthier households for cash income through producing marketable surpluses.

Another conclusion is that a pure farmer-led approach may not always be appropriate where researchers have spent time understanding the farming system and the externalities that impact upon it, simulation playing an important part in this understanding. A major advantage of linking FPR and simulation modeling was the co-learning that took place between the researchers and the farmers about the impacts of climatic risk and resource endowments, and how they influence household's investment choices. In fact, if Integrated Natural Resource Management (INRM) research is about better communication and more effective interaction on the part of researchers with managers (about system management), then linking simulation modeling and participatory research should be viewed as an integral part of applied INRM in smallholder farming systems. The results also indicated that when there are no clear procedures

to directly target women farmers, and gender issues are not sufficiently integrated into the research process they tend to be under-represented.

## Synthesis and Conclusions

*M&E to aid impact facilitation*

The case studies show clearly that rural technology change, brought about by the generation and diffusion of new technologies, is an evolutionary and highly complex process. An evolutionary process is one in which novelties are generated, selections of beneficial novelties are made and these improvements are retained and promulgated (Douthwaite et al. 2002). The Uganda and Nigeria case studies show that farmers were actively modifying the technologies in ways that improved their 'fitness' or adoptability. In Uganda farmers sought alternative uses for the LCC and BT technologies that would increase the return on their investment in labour and land. In Nigeria, farmers sought to find compromises between the 'best bet' agronomic practice and what fitted their own systems. Some of these innovations have been incorporated in the recommended package for Integrated *Striga* Control. The Zimbabwe and Malawi case study showed how important these compromises are because farmers do not select technologies purely on agronomic or economic performance, which is often the basis by which researchers select their 'best-bets' for their trials (see Figure 1). Instead farmers chose to adopt based on a number of factors that is dependent on the resources available to that household, perceptions of risk and the gender of the household head. The Uganda case study showed that preferences for technologies changes from location to location. Hence, identifying farmer adaptations through M&E is an important source of incremental improvements to a technology and future research areas, as well as providing good insights into farmers' perceptions and motivations.

The case studies show that M&E also has a crucial role to play in identifying differences in perceptions between researchers and farmers, and between individual farmers in their responses to new ideas and technologies. In all three case studies it was impossible for researchers to know beforehand how different farmers would react to the new technologies. However, the M&E carried out gave this information and has allowed the projects to adjust accordingly, thus making widespread adoption and impact more likely. For example, the M&E exercise helped ICRISAT and its partners to see that *de jure* women-headed households can generally only adopt the lowest input technology, which was the legume-cereal intercrops because they did not have the cash to buy inorganic fertilizer, or the labour to make and spread compost. In Nigeria, M&E findings showed that many farmers were adopting improved germplasm but not the concepts of sole cropping and crop rotation, preferring instead to continue with their own mixed cropping practices. In response the project will carry out participatory partial budgeting to examine together with farmer the advantages and disadvantages of sole versus mixed cropping.

The three case studies largely confirm the conceptual map of the development and adoption process adopted in the case studies shown in Figure 1. All the case studies found that there is a role for researchers to take the lead in introducing 'best bets'. Those 'best-bets' are more likely to adopted and adapted by farmers when researchers have spent time understanding local farming systems, and, in the case of Zimbabwe and Malawi used simulation modelling to evaluate different options with farmers. Purely farmer-led participatory technology development is less likely to bring new ideas into to community because researchers have a deeper knowledge and understanding of new technical options, while farmers are concerned with their current problems and have little human and financial resources to search for and adapt novel solutions. However, whatever the source of innovation, once adoption begins, M&E has a role to play in facilitating the close interaction between farmers and researchers required to co-develop new technologies to make them more widely adoptable.

The Zimbabwe/Malawi and Nigerian case studies looked at farmer to farmer spread of new technologies and ideas, in other words the selection and promulgation functions of the evolutionary innovation process. Whether farmers recommend a new technology to others, and who they recommend to, are the most important indicators of whether a technology is likely to scale-out, where it will go, and how fast. The Nigerian case study is using a GIS-based approach to map the adoption/adaptation,

selection and promulgation process and is developing an extension approach that complements existing promulgation channels.

*M&E as a basis for Priority Setting and ex post Impact Assessment*

Thomas Kuby has developed an impact model, shown in Figure 8, based on experience at GTZ (Kuby, 2000). The model shows projects carrying out their own M&E, similar to ways in which M&E has been carried out in the three case studies, to the point of assessing whether the project has delivered intended benefits, or unintended benefits and negative consequences. Assigning this role to the project comes from years of project experience that has shown that: "as a rule, self-evaluation is more critical and better value for money than external monitoring – and that it makes a much greater contribution to learning, both in the projects and in the whole organisation"[6] (Kuby, 2000 p. 4). This learning helps make impact more likely, as well as contributing to priority setting in the organisation.

*Priority Setting*

Formal and static routines are not adequate for research priority setting due to the essential unpredictability of complex systems. Since many outcomes cannot be forecast, expected impacts cannot guide priority setting. Even though particular outcomes cannot be predicted, it is possible to identify factors that will, with high probability, affect the chances of success or failure. More flexible approaches (such as adaptive management) require strong M&E to identify as early as possible unintended (both positive and negative) consequences so that appropriate responses can be implemented. M&E also has a role to play to ensure that all stakeholders understand the processes that generated the outcomes.

In addition to contributing to organisational learning, M&E can help all partners, from farmers to donors, to learn from the research to adoption process. The three case studies presented here showed that farmer adoption and subsequent innovation and adaptation are invaluable indicators of the likely adoptability of the introduced options. Early identification of farmer adoption / non adoption and modification allows the research process to be adapted and allows the setting of new priority areas for research. Without this flexibility in the approach, 'best bet' options demonstrated on-farm are unlikely to undergo the necessary co-development necessary to be more widely adopted.

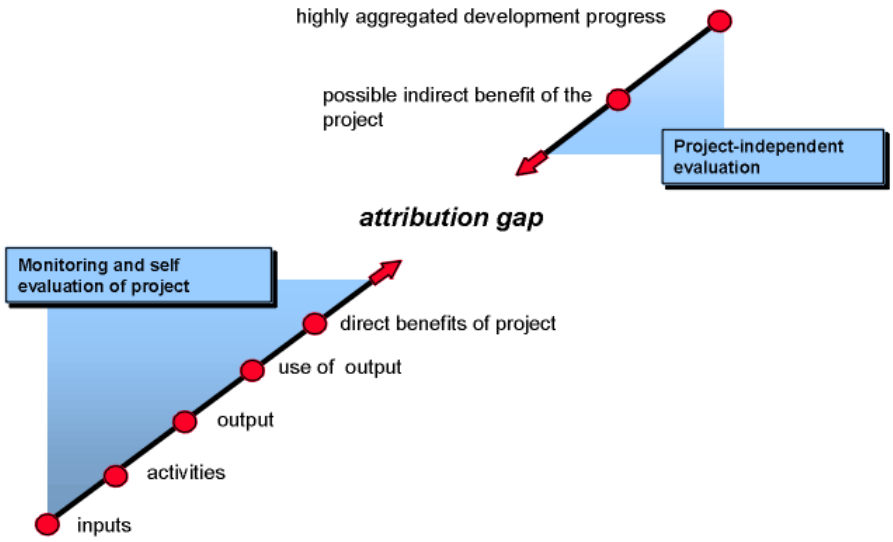
***Ex post* impact assessment**

The Kuby model shows an attribution gap between a project's direct benefits and wider, more highly aggregated impacts, for example poverty alleviation, that might result from these benefits. Hence the model agrees with our earlier discussion of why attribution of impact is nearly always impossible because of the interconnected nature of causes and effects.

The causes and effects that lead from a project's direct benefits to broader impacts result from two linked processes that are known as scaling-out and scaling-up. Scaling-out is a horizontal spread of an innovation from farmer to farmer, community to community, within the same stakeholder groups. Scaling-up is an institutional expansion from grassroots organizations to policy makers, donors, development institutions, and other stakeholders key to building an enabling environment for change. Both are linked because as a change spreads further geographically the greater the chances of influencing those at higher levels, and likewise, as one goes to higher institutional levels then the greater the chances for horizontal spread.

[6] Kuby, T. 2000. Turning attention towards results: how GTZ is building its impact evaluation capacity. Internal GTZ document. Eschborn, Germany.

**Figure 8: Kuby's impact model (Kuby, 2000)**




The three case studies help show why an attribution gap exists. The case studies demonstrate that even to achieve direct benefits, the projects have been working with a wide range of agents, including farmers, NGOs, extension workers and national research institutes in an iterative and adaptive process. Attributing impact even at this stage to individual agents is impossible. Scaling-out and scaling-up will require a broadening of the process and more agents to become involved, particularly those at a higher scale (e.g., state and national level).

Even though attributing impact to individual stakeholders may be impossible, this does not mean ex post impact assessment should not be carried out. *Ex-post* IA is important for organisational learning and change, and the adaptive management of complex systems. Also *ex-post* IA remains necessary to help donors demonstrate to their constituency that the money they have given out has contributed to development. Hence, rather than attempt to quantify impact using 'heroic' assumptions, *ex-post* impact assessment should focus on establishing what development changes have taken place, and whether the project as a whole made a contribution. In other words, more than concentrating the efforts in a few impact indicators (e.g., rate of return or output growth) of dubious meaning, IA should focus on a) the processes of knowledge generation and diffusion, b) the creation of organizational capabilities, i.e., the collective ability to develop appropriate solutions to identified problems and c) the emergence and evolution of innovation networks.

The GTZ-led donor Workgroup on Assessing the Impact of Agricultural Research in Development recently published a set of requirements for plausible impact assessment (Bauer et al., 2002) that are consistent with this view of ex post impact assessment. The donor workgroup say that plausible impact assessment should:

- Identify the source of impact being assessed;
- Clearly state the impact model used by the impact assessor;
- Identify the 'theory of action' (i.e., the impact pathway) of the project being assessed;
- Discuss the objectives and limitations of the impact assessment;
- Specify and test impact hypotheses;
- Consider alternative causes of impact;
- Consult a range of informed opinions.

The workgroup does not say that impact should be attributed or quantified.

The Nigerian case study shows how M&E based on an impact pathway can form the foundation of a plausible *ex post* impact assessment by making explicit the source of impact (the project's direct outputs), the impact model, the impact pathway and the impact hypotheses. The impact pathway evolves during the duration of the project as M&E identifies incipient scaling out and up processes including processes of knowledge generation and diffusion, the emergence and evolution of innovation networks, and the creation of organisational capabilities. Hence, the description of the impact pathway at the end of the project would be an invaluable starting point to *ex-post* impact assessment some years after. Indeed, without process M&E, plausible *ex-post* IA of INRM projects, based as it needs to be on a convincing explanation of process, will be extremely difficult.

Institutionalising M&E in CG Centres

The M&E approaches described in the three case studies are relatively new and are not yet well institutionalised in their respective CGIAR Centres. Whether they are or not will depend on three factors:

- Being able to demonstrate to fellow researchers that the benefits of M&E are worth the cost;
- Having the capacity to carry out effective M&E;
- Support for M&E from senior management.

Of course, all three are linked. If CGIAR scientists can come to see M&E as something useful and not threatening then support from senior management is likely to follow, together with additional capacity to carry out the work. Experience shows that self-monitoring is less threatening and more useful than external M&E, which suggests that individual projects within Centres should be responsible for M&E, but with backstopping from an M&E unit.

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# Organic resource management in sub-Saharan Africa: validation of a residue quality-driven decision support system

Bernard Vanlauwe[1], Cheryl A Palm[1], Herbert K Murwira[1] and Roel Merckx[2]
[1]Tropical Soil Biology and Fertility Programme, UN Gigiri, PO Box 30592, Nairobi, Kenya
[2]Laboratory of Soil Fertility and Soil Biology, Faculty of Agricultural and Applied Biological Sciences, Kasteelpark Arenberg 20, 3001 Heverlee, Belgium

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## Abstract
A conceptual Decision Support System (DSS) for organic N management was developed based on information on residue quality – N-mineralization relationships. The current paper aims at validating the DSS using data obtained in sub-Saharan Africa on biomass transfer systems with maize. The percentage fertilizer equivalency (%FE) values of the organic resources increased linearly with their N content above a minimum of 2.3% N. For resources with high polyphenol contents, the slope of the regression decreased and the critical N content increased to 2.8%. For manures, no clear relationship between their %FE and quality was observed. Medium quality materials are to be applied together with mineral N. Several cases are discussed in which added benefits as a result of positive interactions between medium quality organic resources and mineral N were generated. Finally, thought is given on the information needed to turn the DSS from a concept into a useful soil management tool.

## 2. Introduction
For ages, agricultural production depended on organic resources for soil fertility replenishment, either by including long-term fallow periods, as was, e.g., the case in sub-Saharan Africa (SSA), or by application of vast amounts of manures or other organic resources, e.g. sods of peat in northern Belgium (Dudal, 2001). The use of fertilizers started in western Europe only at the end of the 19$^{th}$ century in response to a higher demand for food. Other continents followed at a later stage, but even up to the mid-1960s, fertilizer use in SSA was restricted to export crops such as groundnut, cotton, coffee, tobacco, or oil palm (Dudal, 2001).

During the 'Green Revolution' in the 1960s in Asia and Latin America organic resources were not considered essential in boosting agricultural production. In this context, Sanchez (1976) stated that when mechanization is feasible and fertilizers are available at reasonable cost, there is no reason to consider the maintenance of soil organic matter (SOM) as a major management goal. However, application of the 'Green Revolution' strategy in SSA resulted only in minor achievements because of a variety of reasons (IITA, 1992). This, together with environmental degradation resulting from the massive applications of fertilizers and pesticides and the abolition of the fertilizer subsidies in SSA, imposed by structural adjustment programs led to a renewed interest in organic resources in the early 1980s (Table 1). This interest has only grown stronger in recent years driven by the development of an Integrated Soil Fertility Management (ISFM) strategy for soil fertility replenishment of which the combined application of organic resources and mineral inputs forms the technical backbone. In this context, Sanchez (1994) revised his earlier statement by formulating the Second Paradigm for tropical soil fertility research: 'Rely more on biological processes by adapting germplasm to adverse soil conditions, enhancing soil biological activity and optimizing nutrient cycling to minimize external inputs and maximize the efficiency of their use'.

Since the early 1980s, progress in developing organic resource management related knowledge has been substantial, driven by the hypotheses formulated by Swift et al. (1979) and Swift (1984, 1985, 1986), culminating in an International Symposium in 1995 (Table 1). As a result of the Symposium,

efforts were made to consolidate information on residue quality – N dynamics relationships resulting in an Organic Resource Database (ORD). The ORD contains information on organic resource quality parameters and N mineralization dynamics from almost 300 species found in tropical agroecosystems (Palm et al., 2001). A careful analysis of the information in the ORD has led to the development of a Decision Support System (DSS) for organic matter (OM) management (Fig. 1) (Palm et al., 2001). The DSS makes recommendations for appropriate use of organic materials, based on their N, polyphenol, and lignin contents resulting in four classes of organic resources (Palm et al., 2001). For instance, high quality organic resources with a N content > 2.5%, a lignin content of < 15% and a polyphenol content of < 4% are recommended to be applied directly to the soil as these are expected to release a substantial part of their N in the short term (Fig. 1). Medium quality organic residues having < 2.5% N and < 15% lignin, or > 2.5%N and a polyphenol content > 4%, on the other hand, are recommended to be applied together with fertilizer N or high quality organic resources. Lastly, low quality organic resources with a low N and high lignin content are recommended to be surface applied as such residues would result in the most substantial mulch effects. The combined application of organic resources and mineral N is hypothesized to yield added benefits in terms of extra yield or improved soil fertility compared with the sum of the responses in the treatments with sole application of organic resources and mineral N. A *Direct* and *Indirect Hypothesis* which could form the basis for the occurrence of such benefits has been formulated by Vanlauwe et al. (2001). The *Direct Hypothesis* was formulated as: *Temporary immobilization of applied fertilizer N may improve the synchrony between the supply of and demand for N and reduce losses to the environment*. The *Indirect Hypothesis* was formulated for N supplied as fertilizer as: *Any organic matter-related improvement in soil conditions affecting plant growth (except N) may lead to better plant growth and consequently enhanced efficiency of the applied N*. Both hypotheses, when proven, lead to an enhancement in N use efficiency, processes following the *Direct Hypothesis* through improvement of the N supply and processes following the *Indirect Hypothesis* through an increase in the demand for N. Obviously, mechanisms supporting both hypotheses may occur simultaneously.
The objectives of the current paper are (i) to validate the concepts proposed in the DSS with field data, including plant materials and animal manure as organic resources; (ii) to explore the occurrence of added benefits when applying organic resources in combination with mineral N, and (iii) to reflect on the activities required to develop the DSS into a practical recommendation tool.

## 3. Experimental Approaches

### *3.1. Experiments in West, East and southern Africa studying the N supply potential of organic resources*

A greenhouse trial was carried out in Ibadan, southwestern Nigeria, aiming at quantifying immediate and residual relationships between organic resource quality and maize N uptake (Vanlauwe et al., unpublished data). A range of organic materials containing between 0.14 and 3.53% N was applied in pots with a Nitisol from Southern Benin Republic at an equivalent rate of 90 kg N $ha^{-1}$ and maize was grown for 7 weeks. After harvesting the first crop, a second crop was grown for another 7 weeks without fresh residue application. Total N uptake by the maize in the shoots and roots was measured at each harvest.
In East and southern Africa, a set of field experiments was set up to determine the fertilizer equivalency values of organic resources (Murwira et al., 2001). Each trial contained a set of locally available sources of plant materials or cattle manure. The organic resources were applied on the field in a randomised complete block design which included a number of plots aimed at determining the response to fertilizer N using maize as a test crop. Based on the response curve and the yield increases in the organic resource treatments, fertilizer equivalency values were calculated and converted to percentage fertilizer equivalency values (%FE) taking into account the N application rates of the organic materials.

In West Africa, a multilocational set of field experiments also using maize as a test crop was established using various inputs of plant materials – and cattle manure in a single case – and the %FE was calculated using the similar approach as indicated above (Vanlauwe et al., 2002). In both sets of trials, P

and K were applied in non-limiting quantities to ensure that N was the sole nutrient limiting maize production.

*3.2. Evaluation and quantification of added benefits in experiments with simultaneous application of organic resources and mineral N in West, East and southern Africa*

Several trials were established in the various sub-regions aiming at quantifying potential added benefits in treatments with combined applications of organic resources and mineral N (Table 2). All cropping systems considered were organic resource transfer or biomass transfer systems using maize as a test crop. Added benefits were mathematically evaluated using the equation:

$$AB = Y_{comb} - (Y_{fert} - Y_{con}) - (Y_{OM} - Y_{con}) - Y_{con} \quad (1)$$

where *AB* signifies *Added Benefits* and $Y_{con}$, $Y_{fert}$, $Y_{OM}$, *and* $Y_{comb}$ mean grain yields in the control treatment, in the treatments with sole application of fertilizer and organic matter, and in the treatment receiving both inputs, respectively (Vanlauwe et al., 2001). In equation 1, the yields are adjusted for similar amounts of organic resources and mineral N applied in the combined as in the sole treatments, following information obtained through the N response curve or if the latter is absent assuming linear responses to applied organic and mineral N.

## 4. Evidence from field trials in West, East and southern Africa

*4.1. Agronomic evaluation of organic resources of varying quality as source of N*

The greenhouse trial data clearly show a significant positive relationship between the organic resource N content and the total maize N uptake of the first crop (Fig. 2). Low quality materials such as maize stover or sawdust immobilized N resulting in less N uptake compared to the unamended control. For the second crop, however, the relationship was negative, indicating that the medium to low quality materials provide more N to a second growing maize crop compared to the high quality materials (Fig. 2). Even in the treatment with maize stover, no further immobilization of N was observed. Only the sawdust treatment kept the N immobilized beyond the second crop. These data show that while organic resources with a high amount of available N can immediately stimulate crop growth, while for medium to low quality materials, residual N supplies are greater. More cropping cycles would be needed to judge whether the cumulative yields are similar for the high and low N organic resources. Cadisch et al. (1998), on the other hand, observed no compensation in initial N release from low quality, high polyphenol containing prunings at later harvests compared to high quality materials and attributed this to the stability of polyphenol-N complexes. The data also indicate that for materials with a N content below 1%, additional N should be applied either as fertilizer or as high quality organic matter to overcome the negative impacts caused by N immobilization.

Data from the field experiments in West, East and southern Africa show that the percentage fertilizer equivalencies (%FE) values for organic materials with a low polyphenol content (< 4%) and a N content > 2.3% were positively related to their N content (Fig. 3). The critical level of N for increasing crop yield was 2.3%, confirming the initial value hypothesized by Palm et al. (2001). Organic matter with a high polyphenol content (> 4%) still led to positive %FE values, but the increase with increased N content was less and the N content needed to improve maize yield was 2.8 rather than 2.3% (Fig. 3). Polyphenol – N interactions seem to delay the immediate availability of N as concluded by others from data obtained under controlled laboratory or greenhouse conditions (Palm and Sanchez, 1991, Oglesby and Fownes, 1992). Data obtained with *Calliandra calothyrsus* residues did not show a consistent trend. While in all cases their polyphenol content was high, data from certain sites did not show any reduction in %FE. This may be related to the specific rainfall patterns, as high rainfall immediately after applying the *Calliandra* residues may remove a substantial part of the polyphenols through leaching. While from the

current data polyphenols appeared to be under certain conditions important modifiers guiding initial N release from organic materials, the lignin content was not observed to improve on the derived equations. This does, however, not exclude their importance in medium to long term N dynamics, as shown in the greenhouse experiment (Fig. 1) and discussed below.

Some organic resources led to N fertilizer equivalency values exceeding 100%, especially in the case of *Tithonia diversifolia* (Fig. 3). This is likely caused by a better synchrony between the supply of and demand for N derived from *Tithonia* residues than for immediately available fertilizer-derived N. Mineral N inputs are readily available and as such prone to leaching and/or gaseous losses, even if split applied.

Manure does not show a consistent trend across sites (Fig. 3). Very low N containing cattle manure was observed to decrease crop yield but fertilizer equivalency values of manure containing between 0.7 and 2.4% N were almost similar and equal to about 35%. N content alone could not satisfactorily explain the observed responses to manure application indicating that other indicators are necessary for quantitative evaluation of manure. This may be related to changes in quality and partial stabilization of the organic resources while passing through the rumen or while storing pending application on the field. Nzuma and Murwira (2000) showed considerable differences in manure quality when stored in a pit or heap. Manure may require other indicators for assessing its quality, likely based on nutrient and biochemical components the soluble fraction rather than on the overall material.

*4.2. Occurrence and quantification of added benefits*

Organic resources with a N content below 2.5% would need to be applied in combination with additional mineral N to substantially increase crop yields (Fig. 3). Significant added benefits in treatments with combined application of organic resources and mineral N do occur in various experiments although the mechanisms governing these benefits are not always clearly understood. In the experiment in Zimbabwe with various mixtures of cattle manure and ammonium nitrate, added benefits ranging between 663 and 1188 kg maize grains $ha^{-1}$ were observed by Nhamo (2001), as calculated using equation 1 (Fig. 4). The author related this to the supply of cations, contained in the manure, which may have alleviated constraints to crop growth caused by the low cation content (CEC varied between 1.2 and 2.5 $cmol_c\ kg^{-1}$ with an average of 1.7 $cmol_c\ kg^{-1}$) of the very sandy sites (clay content varied between 2 and 10% with an average of 4%). Although temporary immobilization of fertilizer N by decomposing manure can not be excluded, this may be less likely as the C/N content of the used manure was below 10, assuming that this would be a suitable indicator for assessing N dynamics of manure. In a trial in central Kenya, Okalebo et al. (2002) similary observed added benefits of 684 kg grains $ha^{-1}$ in 1998 when mixing low quality wheat straw and soybean trash with urea for an acidic Ferralsol (pH-water of 4.9) (Fig. 5). After application of the organic residues, the pH-water increased to 5.4, on average, while pH in the control soils remained unchanged. Rainfall in 1997 was low and not well distributed leading to absence of major responses to applied N.

Mucheru et al. (2002) observed added benefits ranging from – 250 to + 550 kg maize grains $ha^{-1}$ during the short rainy season of 2000 (Fig. 6). Values for the long rainy season, which experienced lack of rainfall after germination, were not different from 0. These benefits varied substantially for the different organic resources used. The high amount of K in the *Tithonia* residues may have caused the substantial added benefits in the combined *Tithonia*-N fertilizer treatment, as earlier observed by Sanchez and Jama (2001). Besides supplying K, Tithonia residues have been shown to ameliorate soil aggregation, reduce P sorption sites, reduce P-metal complexes and Al-toxicity (Cong, 2000). Causes for the added benefits created in the cattle manure treatment are not clear.

While in the above experiments, added benefits were observed only for certain organic resources, in the Sekou experiment, in which organic resources with a N content varying between 2.4 and 4.7% were used, similar added benefits were observed for all organic resources (Fig. 7). As the site experienced drought stress during maize grain filling, Vanlauwe et al. (2002) attributed the added benefits to improved soil water conditions in the mixed treatments, caused by the surface or sub-surface placement of the organic resources, compared to the treatment with sole application of fertilizer. Alleviation of moisture

stress may have improved the N use efficiency of the applied fertilizer. In formerly discussed trials with organic resources, no alleviation of moisture stress was observed (Figs. 5 and 6) but in these trials, organic resources were incorporated. During seasons with shortage of rain, this residue management practice has been shown not to substantially alter soil moisture conditions vis-à-vis surface or subsurface placement (Minhas and Gill, 1985, Sembiring et al., 1995). No soil water data were taken, so the above would need to be evidenced.

## 5. Looking ahead

The final product of all above work should be a tool to assist farmers on how to optimally manage their scarcely available organic resources and costly mineral fertilizers, preferably adapted to their biophysical environment and targeted yields for specific crops. Although this seems like an impossible task, generation of the following information would signify substantial progress: (i) generation of a more detailed understanding of the mechanisms creating added benefits, (ii) assessment of the influence of intrinsic soil properties (e.g., texture and clay mineralogy, water holding capacity), and climate conditions (e.g., risk of rain shortage) on the latter, (iii) quantification of the residual effects of organic resources of varying quality, applied sole or in combination with fertilizer, on crop yield, and (iv) evaluation of the immediate and residual responses of other crops besides maize to applied organic resources and fertilizer.

The mechanistic basis for added benefits created through positive interactions between OM and mineral N is broad and has not been clearly understood yet. Although in the above case studies, likely reasons behind the added benefits could be put forward, little or no evidence was gathered to substantiate these. Trials which explicitly quantify some of the changes in soil properties as affected by OM application are needed. Such trials would also include treatments in which the hypothesized constraint to crop growth is alleviated using external inputs containing only the agent addressing this constraint. Although it may be an illusion to aim at understanding all interactions between organic resources and fertilizer under all conditions, under certain specific conditions, clear organic resource-related improvements in soil fertility status could be identified. For instance, the use of high P containing manure or compost on low P soil could lead to an improved use efficiency of N fertilizer and consequently added benefits. When looking at legume-cereal rotations, the mechanisms potentially creating added benefits may even be more diverse relative to the ones discussed in biomass transfer systems in this paper. Many rotational effects are often explained in terms of changes in pest and disease spectra during legume growth (Akhtar, 2000) or in terms of legume rhizosphere processes (Vanlauwe et al., 2000).

Organic resources are known to show some residual effects. Optimal nutrient management strategies need to take into account these effects. In the long term, an improved soil organic matter status may equally lead to enhance N fertilizer use efficiencies, although quantifying the latter may prove very difficult. Vanlauwe et al. (unpublished data), e.g., showed a negative relationship between the proportion of maize N derived from urea and the soil total N content, presumably caused by a higher supply of native soil N in soils with a higher total N content.

Most of the data presented in this paper, and similarly in other work dealing with soil fertility management, were obtained in maize-based cropping systems. It is likely, however, that farmers would prefer to use their often scarcely available organic resources on crops which yield more income. In this context, it has been observed that farmers in western Kenya would rather apply high quality *Tithonia* residues to kale (*Brassica oleracea*) rather than maize (Jama, personal communication). This would not necessitate to initiate a vast amount of trials using other crops than maize, but to consider the nutrient uptake patterns of those other crops and use the information obtained for maize to test specific hypotheses related to the potential effects of organic resources and fertilizer on other crops.

After having obtained relevant information as described above, two extra steps may be required to complete the development of a user-friendly decision aid: (i) all above information needs to be synthesized in a quantitative framework and (ii) that framework needs to be translated in a format accessible to the end-users. The quantitative framework could look as presented in Fig. 8 for a situation where all interactions between organic matter and fertilizer happen through N immobilization reactions,

thus supporting the *Direct Hypothesis*. Temporary immobilization of fertilizer N by medium to low quality resources may reduce the potential for losses of fertilizer N materials and consequently less fertilizer N may be required to reach the same amount of available N (the 'added benefits' situation in Fig. 8). If the immobilization lasts beyond a growing season, on the other hand, additional fertilizer N may be required to reach the same amount of available N (the 'immobilization' situation in Fig. 8). The current concept may be adapted to initial soil fertility status by including a background soil N supply and to different crops. In case the mechanisms creating added benefits following the *Indirect Hypothesis* are known, the concept could also be adapted to these conditions. The final format of the decision aid should take into account the realities on the field. Some of these realities, among others, are: (i) large scale soil analyses are not feasible, so local soil quality indicators need to be included in decision aids as farmers use those to appreciate existing soil fertility gradients within a farm; (ii) conditions within farms vary as does the availability of organic resources and fertilizer, therefore rules of thumb rather than detailed quantitative recommendations would be more useful to convey the message to farmers; (iii) farmers decision making processes involve more than just soil and crop management; and (iv) access to computers, software and even electricity is limited necessitating hard copy-based products.

## 6. Conclusions

Although the data obtained largely support the concepts outlined in the DSS for organic N management, the reality on the field is such that the availability of high quality, fertilizer-like organic materials is very limited. Therefore, the arms dealing with medium to low quality organic resources are likely to be most relevant for real cropping systems. Such organic resources are recommended to be applied in combination with mineral fertilizer, and when doing so, added benefits do occur, although their mechanistic basis if most of the time not clearly understood. The relevance of such potential added benefits needs to be assessed for various biophysical environments and crops. In conditions where it is difficult to assess these potential benefits, assuming additive effects is usually good enough as a first approach as negative interactions are not commonly observed. Finally, generation of the needed knowledge will by itself not change the way farmers are managing their organic and mineral resources. This knowledge needs to be condensed in tools adapted to the clients targeted.

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**Table 1: A brief summary of the science of tropical organic resource management.**

| Period | Scientific progress | Reference |
|---|---|---|
| < 1970s | Organic matter as a 'blob' | Palm, personal communication |
| 1979 | Organisms - Physical environment – Quality framework for organic matter decomposition | Swift et al., 1979 |
| 1984-1986 | Development of the 'synchrony' research theme within the Tropical Soil Biology and Fertility programme | Swift, 1984; Swift, 1985; Swift, 1986 |
| 1990s | Various experiments addressing the 'synchrony' hypothesis | Various |
| 1995 | International Symposium on 'Plant Litter Quality and Decomposition' | Cadisch and Giller, 1997 |
| 2000 | Development of the 'Organic Resource Database' and the Decision Support System for organic N management | Palm et al., 2001 |
| > 2001 | Quantification of the Decision Support System for organic N management | Future publications |

**Table 2: Treatment structures and year/season of implementation of the various experiments on organic-mineral interactions in West, East, and southern Africa. An appreciation of the rainfall received during the experiments is also given.**

| Site - country (reference) | Organic resources used (%N) | Mineral N used | Organic resources application rates | Mineral N application rates | Year – season[a] | Rainfall |
|---|---|---|---|---|---|---|
| Sekou - Benin (Vanlauwe et al., 2002) | *Leucaena leucocephala* (4.7%), *Azadirachta indica* (2.4%), *Senna siamea* (3.0%) | Urea | 90 kg N $ha^{-1}$ in sole; 45 kg N $ha^{-1}$ in combined treatments | N response curve (0, 22.5, 45, 67.5, 90 kg N $ha^{-1}$); 45 kg N $ha^{-1}$ in combined treatments | 1997 – 1 | Drought stress during flowering |
| Meru - Kenya (Mucheru et al., 2002) | *Leucaena leucocephala* (3.8%), *Calliandra calothyrsus* (3.3%), *Tithonia diversifolia* (3.0%), Cattle manure (1.4%) | Compound fertilizer (23:23:0) | 60 kg N $ha^{-1}$ in sole; 30 kg N $ha^{-1}$ in combined treatments | 60 kg N $ha^{-1}$ in sole; 30 kg N $ha^{-1}$ in combined treatments | 2000 – 1 | Low rainfall during first 20 days |
| | | | | | 2000 – 2 | Normal |
| Eldoret - Kenya (Okalebo et al., 2002) | Wheat straw (0.7%), Soybean trash (1.1%) | Urea | 2 ton dry matter $ha^{-1}$ | 80 kg N $ha^{-1}$ in sole; 20, 40, 80, and 100 kg N $ha^{-1}$ in combined treatments | 1997 | Low rainfall and poor distribution |
| | | | | | 1998 | Normal |
| Various - Zimbabwe (Nhamo, 2001) | Cattle manure (2.6%) | Ammonium nitrate | 25, 50, 75, and 100 kg N $ha^{-1}$ | Complement organic resource application rates to reach 100 kg N $ha^{-1}$ | 1997/98 | Normal |
| | | | | | 1998/99 | Normal |

[a] Only given when more than 1 season per year occurs.

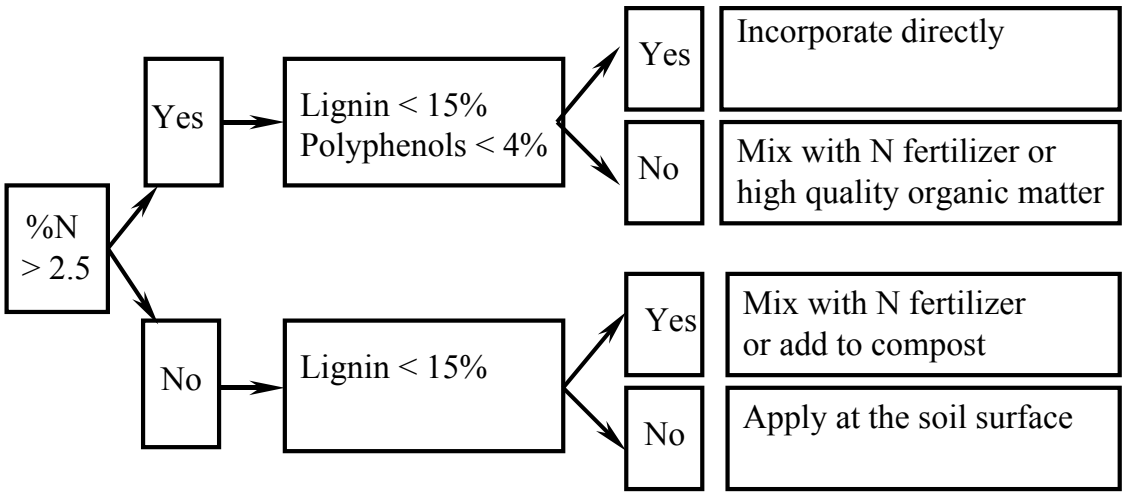


**Fig. 1: The Decision Support System for organic N management, leading to 4 classes of organic resources (adapted from Palm et al., 2001).**

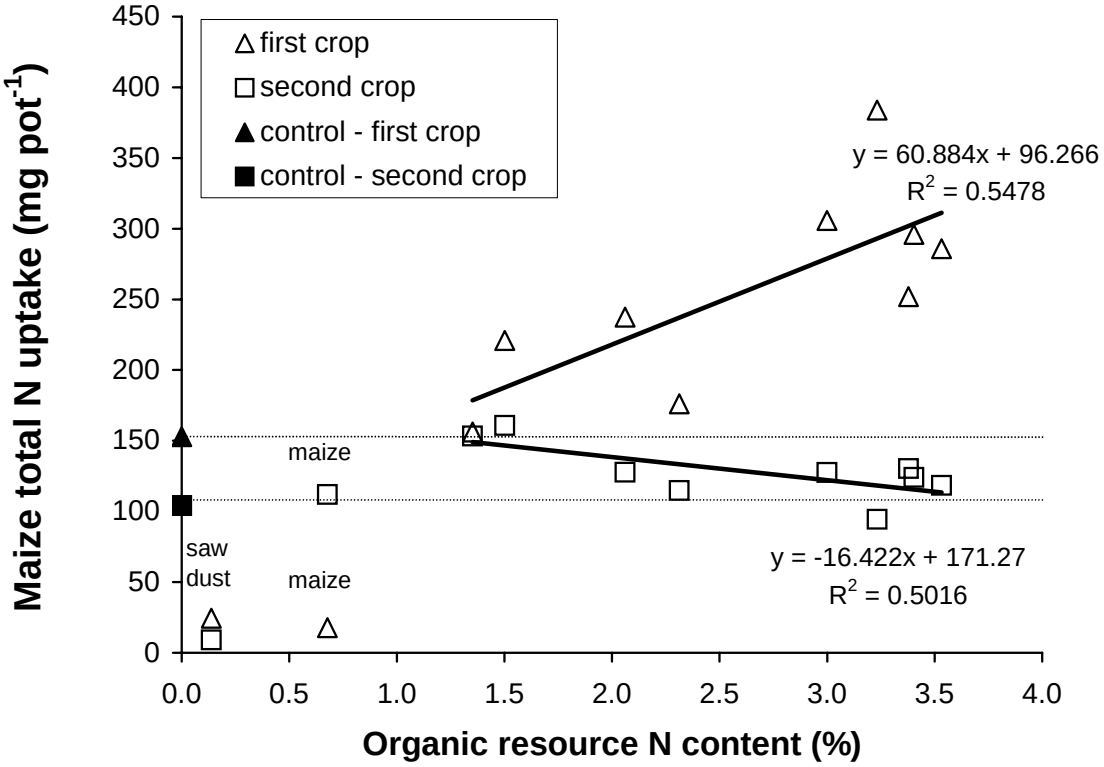


**Fig. 2: Relationship between the N content of a wide range of organic resources and the total (shoot + root) N uptake by maize in a greenhouse pot trial. The regression equations were calculated for all residues excluding maize and sawdust. The dashed lines give the maize total N uptake in the control soils**.

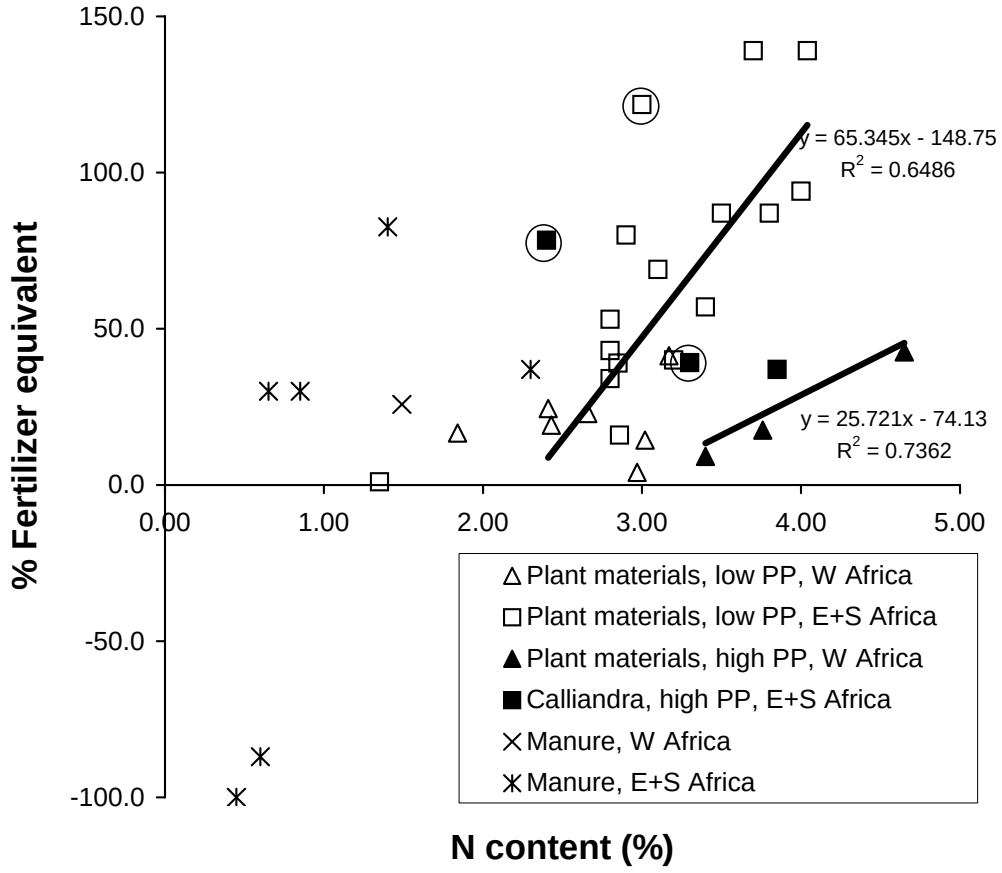


**Fig. 3: Relationship between the N fertilizer equivalent and the N content of plant residues and manure for a series of sites in West (W), East and Southern (E+S) Africa. The linear regression equations were calculated separately for the plant materials with low and high polyphenol (PP) content. Encircled values were excluded from the regression analysis. Source: Vanlauwe et al. (2002), Murwira et al. (2001), Kimetu et al. (2002), Mucheru et al. (2002).**

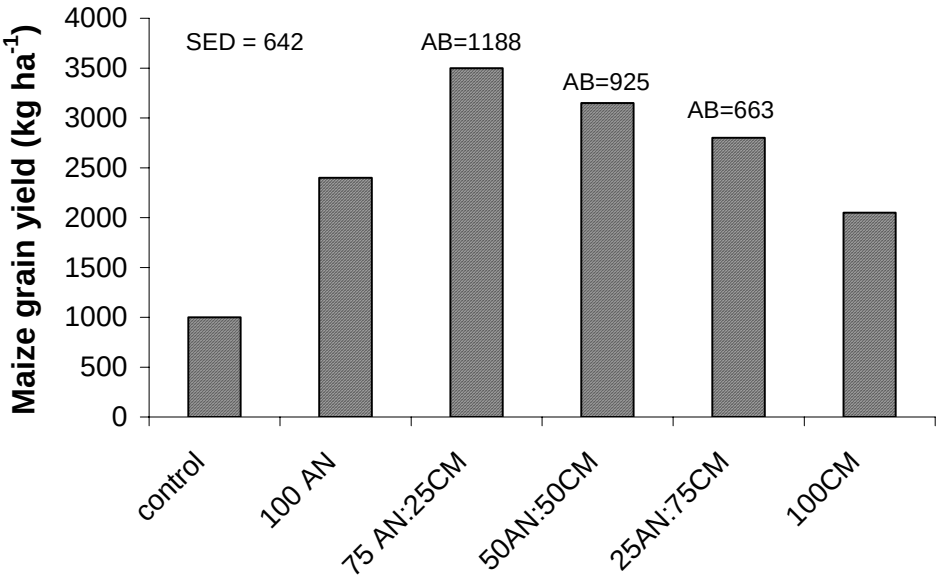


**Fig. 4: Maize grain yield as affected by inputs of various combinations of cattle manure (CM) and ammonium nitrate (AN) for a series of on-farm trials (14 trials) in Zimbabwe. Data are averaged over all sites and two seasons. The added benefits (AB) (in kg maize grain ha$^{-1}$) have been calculated following equation 1. 'SED' means 'Standard Error of the Difference'. Adapted from Nhamo (2001).**

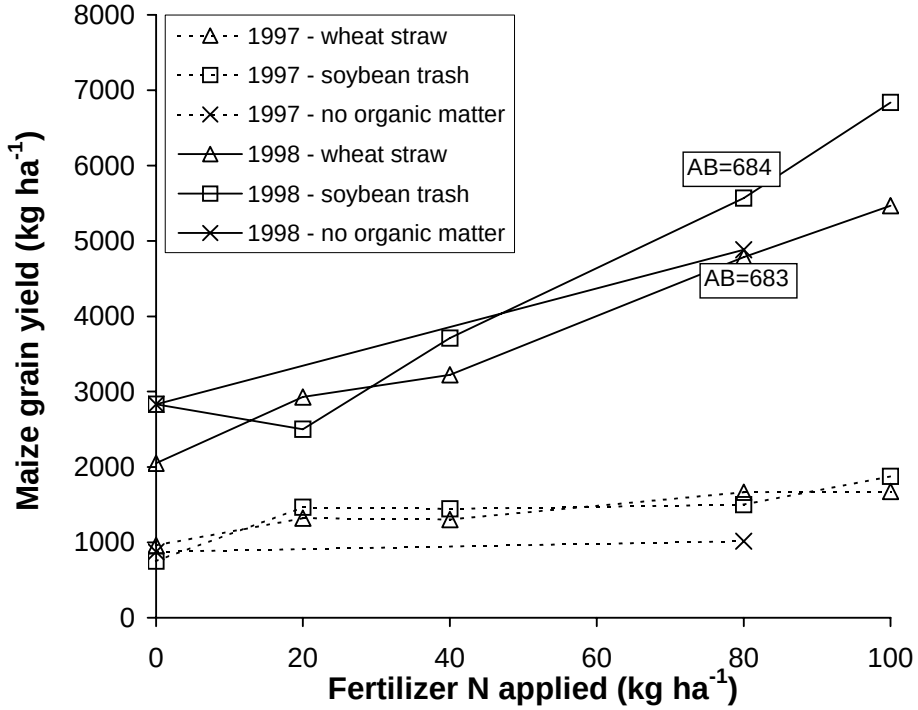


**Fig. 5: Maize grain yield in 1997 and 1998 as affected by the application of low quality organic resources supplemented with various rates of urea for a site in central Kenya. The added benefits (AB) (in kg maize grain ha$^{-1}$) have been calculated following equation 1. Adapted from Okalebo et al. (2002).**

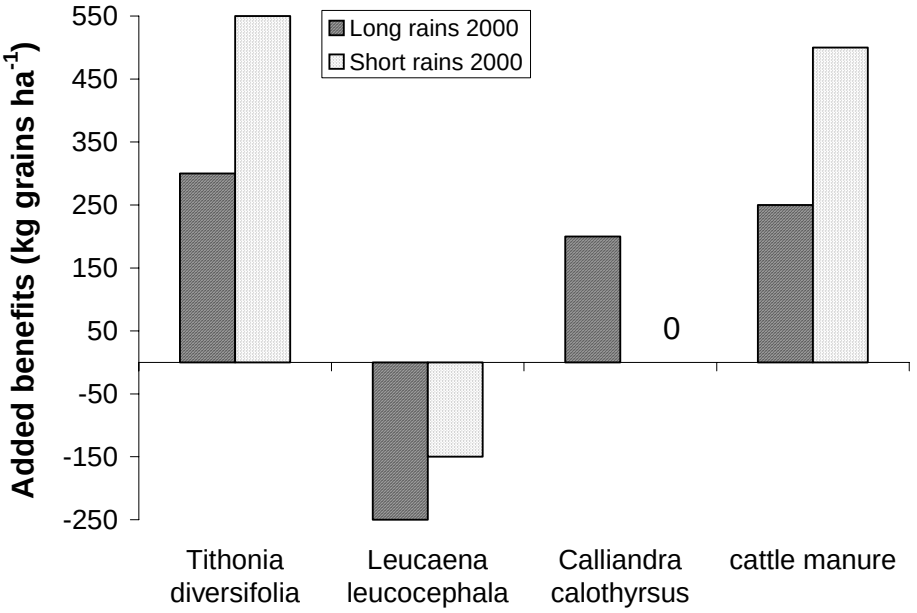


**Fig. 6: Added benefits (in kg maize grain ha$^{-1}$) as affected by organic resource for 2 seasons on a site in central Kenya. The added benefits have been calculated following equation 1. Adapted from Mucheru et al. (2002).**

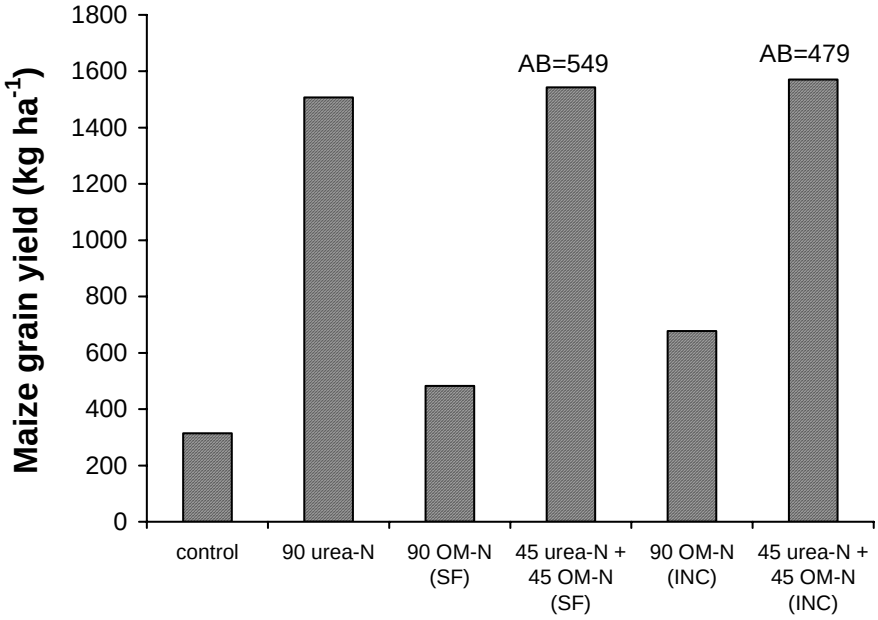


**Fig. 7: Maize grain yields in Sekou as affected by the application of urea, organic materials, or the combination of both. 'SF', 'INC', and 'OM' mean 'surface-applied', 'incorporated', and 'organic matter', respectively. Numerical values for treatments are expressed as kg N ha$^{-1}$. The added benefits (AB) (in kg maize grain ha$^{-1}$) have been calculated following equation 1. Adapted from Vanlauwe et al. (2002).**

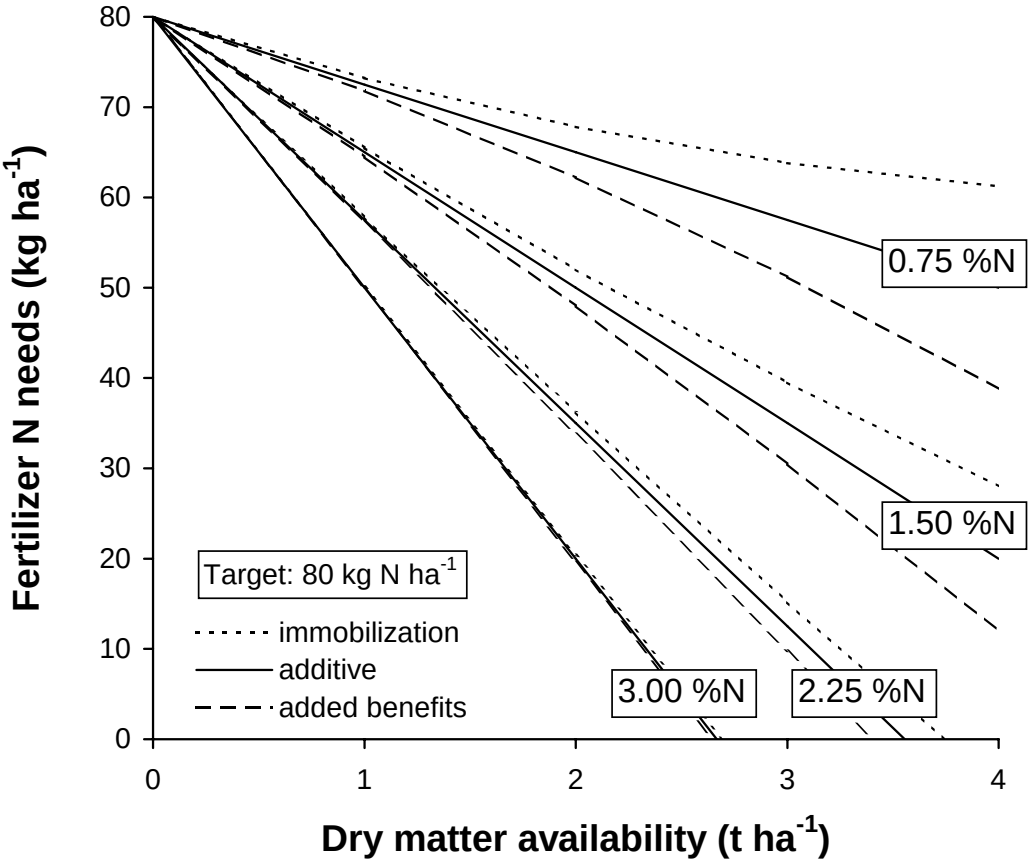


**Fig. 8: Conceptual model for recommending the amount of N fertilizer needed for a specific targeted crop yield when a certain amount of organic matter with a certain quality is available. The model assumes that direct interactions between organic matter and fertilizer will be more substantial as the quality of the organic matter decreases. Depending on the duration of the immobilization, less (in case of temporary immobilization with reduced losses of fertilizer N) or more (in case of prolonged immobilization, e.g., with sawdust – Fig. 2) N fertilizer may be required to reach the same target (here hypothetically set at 80 kg N ha$^{-1}$).**

***Submitted to Agriculture and Human Values***

**Using decision guides on manure use to bridge the gap between researchers and farmers.**

Herbert K. Murwira*, Killian Mutiro and Pauline P. Chivenge
Tropical Soil Biology and Fertility Program (TSBF Zimbabwe), c/o Faculty of Agriculture, University of Zimbabwe, P.O.Box MP228, Mt Pleasant, Harare, Zimbabwe
*Corresponding author's E-mail: hmurwira@zambezi.net

**Abstract**
A lot of work has been done to assess the value of manure as a plant nutrient source, characterize its quality, and on ways of improving its effectiveness through better storage or integrated use with inorganic fertilizers. While the knowledge gained on manure use has been immense; the information has hardly been translated into a useable form for farmers and extension. There are no effective messages that research and extension has passed on to farmers. There is a growing need to develop communication strategies that could effectively link farm practice with research results and ultimately bring about a positive change in the way farmers manage resources available to them. This paper presents some decision guides developed for manure use based on both researchers' understanding and farmer perceptions. The decision guides have been field tested and developed further following discussions held with farmers. The usefulness of the decision guides as communication tools to enhance uptake of soil fertility management options is discussed.

*Key words: manure, decision guides, farmer perceptions*

**Introduction**
Much work has been done on understanding the effects of manure on crop response, and on manure quality and how quality can be improved by better methods of composting and beneficiation with inorganic fertilizers especially rock P (Mugwira and Murwira, 1997). Several workers have reported the beneficial effects of combining manure with inorganic fertilizers (Murwira, 1993; Mubonderi, 1999; Nhamo et. al., 2001, Munguri ,1996 ). Use of combinations can help synchronise nutrient supply and crop uptake, improve on-farm nutrient cycling, reduce environmental pollution (N and P) and be used to manage mineralisation-immobilisation processes. Placement studies have also shown that broadcasting manure was less effective than banding and station placement (Munguri, 1996).

Recommendations on rates of manure application for field crops are varied but difficult to compare across sites because nutrient content data is often not cited (Mugwira and Murwira, 1997). It is however difficult to come up with prescriptive guidelines on use of manure as the quality varies considerably from farmer to farmer because of they way it is managed and stored prior to application in the fields (Murwira et al, 2001). Our challenge is to translate the scientific understanding we have into farm practice taking into consideration quality and quantity of manure available, short- and long-term effects, economic factors, environmental factors, farmer perceptions and limiting nutrients. This requires sharing with farmers the scientific principles of using manure and the development of communication strategies that could bring about a positive change in the way farmers manage resources available to them. Understanding farmer decision making is a key to this process and we advocated in this study an approach that entails the development and use of decision guides to bridge the gap between researchers and farmers.

It has been argued that farmers make decisions on fertilizer and organic resource use in a decomposed fashion using relative comparisons of singular alternatives rather than holistic assessments of utility (Schoemaker, 1982). In other words the decision to use a specific type of input, its utility, is based on asking oneself a series of questions that lead a choice. The decision making process can thus be described as a decision tree which is a sequence of discreet decision criteria, all of which have to be passed along a path to a particular outcome or choice (Gladwin, 1989). The biggest assumption behind the use of decision guides is that the decision-makers themselves are the experts on how they make the

decisions they take. Therefore it is crucial to elicit from the decision-makers themselves their decision criteria which can then be presented in the form of a decision tree.

Early decision trees attempted to use socio-economic variables such as labour availability, cash income, livestock ownership etc to arrive at 'recommended actions' for different socio-economic scenarios. Using a reductionist logic based on binary oppositions (e.g. livestock owners Vs non-livestock owners, female headed Vs male headed households, labour-rich Vs labor-poor farmers etc), it was assumed that an analyst could determine the series of decisions which farmers should make when choosing between technological options. The main criticism is that such decision trees can never sufficiently mimic the much more diverse and dynamic realities under which different individual farmers operate. For example, it is not always possible to conclude that a livestock owner should behave differently from a non-livestock owner because the latter may use a number of local arrangements and networks to gain access to cattle or cattle resources. Similarly a 'resource poor' farmer may suddenly find himself or herself with sufficient inorganic fertilisers accruing from different possible sources. In such situations, individuals do not stop and say, 'since I am classified as a resource-poor farmer in a decision tree, I will manage my fertiliser in this way'. The bottom-line is that the binary permutations constructed by analysts in the form of decision trees cannot capture the flow and flux of everyday life, which determine farmer decision making and choices. Also it is necessary to make a distinction between describing what farmers do and offering them options e.g. what can you do if you have livestock or if you have livestock you can do the following.

Other types of decision trees have binary categories that are constructed on the basis of relatively stable bio-physical variables such as N content, lignin content etc (Palm et. al, 1997). These variables are not amenable to direct manipulation by individual farmers, nor are they subject to sudden socio-economic upheavals such as credit availability, access to markets and so on. Having said so, it is important to recognize that farmers' decisions are based on a judgement between options that relate to the whole range of economic, cultural and biological parameters (Swift et. al, 1994). Categories are also less fixed than may be apparent (Palm et. al., 2001) because of modifiers which for example, polyphenols, may affect nutrient release.

Given the apparent weakness in the two approaches discussed above, there exists a strong argument for the integration of socio-economic variables in natural resource management decision trees. In this case, the challenges are there but not insurmountable. The first challenge is that these decision trees should not be seen as recipes for action but as sets of options which farmers can validate and 'ground truth' to suit their own individual circumstances. This requires a joint learning process between researchers and farmers. The immediate challenge is to determine the most suitable ways in which this joint learning can take place in terms of what tools and platforms to use. There is an urgent need to test a range of practical tools to communicate scientific principles to farmers through use of 'farmer friendly decision trees'. This study is an attempt to derive decision guides for manure use. The objective of formulating the decision guides were two fold:

1. to document how farmers use the available manure and,
2. to use the decision guide as a tool to identify opportunities in manure management and enhancement of soil fertility.

**Materials and methods**

The study was an attempt to come up with a framework for developing manure decision guides based on both research and farmer perceptions and understanding. The starting point for the study pivoted around the key question of what type of guide should be developed and the target clientele. Would there be separate guides for research and extension and one for farmers? For which nutrients and for what crops? An even more important question was how do we integrate what farmers are doing into research recommendations? Are research recommendations and farmer perception compatible? In this regard it was important to establish farmers' characterization of quality- especially the range of manure qualities found.

A draft guide was synthesized from available research information by the authors to design a single framework representing the essential elements required in providing researchers and extension with a tool for manure management. The framework was further distilled through peer review after which it was field-tested with a group of 50 farmers in Mfiri village, Shurugwi District, Zimbabwe. Testing of the

decision guide was carried out to identify gaps and weaknesses in its thought flow (presentation) and content. The decision guide was presented to farmers and the field testing of the guide took three forms:

1. eliciting information to improve the guide in group discussions,
2. eliciting information on decision criteria used by farmers when using manure (focus group discussions to develop a farmer guide), and,
3. Personal interviews to get information on specific household management practices.

In order to incorporate farmer perceptions into the design of the guide, focus discussions to find out current manure use practices were held with discussions centered on manure quantities available, quality, curing methods, methods of application and supplementation. Household interviews were conducted with four farm families that were randomly picked from the large group of almost 50 farmers. The sample size was small, but nevertheless targeted at bringing out the diversity in individual practice and the elements that farmers consider being important for inclusion in a decision guide. These personal interviews provided an opportunity to explore further the issues that came up from the large group discussions.

After the meetings with farmers, the results of the field testing of the guide were evaluated and changes incorporated into the research and extension guide. A second framework was developed based on the discussions held with farmers. A spidogram or web analysis was used as a tool for eliciting and summarizing information on the management framework used by farmers. The web analysis allowed participants to draw out the complex, inter-linked relationships among effects, causes or factors during decision making.

**Results**

The challenge in developing research and extension guides is making sure that they are technically precise. Scientific insights into mineral release and fertilizer equivalence require that for such a guide to be useful, it must differentiate the use of different quality manures and the conditions that lead to those differences in quality. It came out clearly in the study that other useful categorizations in the research guide could be based on socio-economic variables such as livestock ownership (numbers owned and access to manure) as well as biophysical factors like use and type of residues in kraals, type of feed, quantity, storage and chemical characteristics which influences manure quality. An interesting result of the survey was farmers have their own indicators of quality and these include presence of moulds, colour, compactness, lumpiness, and texture. These indicators are qualitative but are useful to incorporate in a technical guide.

Rates of application of manure are very variable even for the same farmer. There are seasonal variations of rate based on previous crop performance, quantities of manure available and manure rotations/cycles within a field. The frequency of manure application ranged from two to four years depending on the number of livestock hence quantity of manure a farmer had, and the residual effects of previously applied manure (Table 1). An interesting point that came from the discussions with farmers was that all available manure was used irrespective of quality but that use practice could be dependent on quality. From the personal interviews it was clear from some farmers that poor quality manure was most often broadcast whereas high quality manure was banded. Fields considered as breadbaskets are targeted for manure application. Some farmers use high rates of application if quality was poor and where fertilizer is available they supplement with large rates of nitrogenous fertilizer. Rate of fertilizer supplementation depends on crop performance and available income to purchase inorganic fertilizer.

Using the above information from farmers and from secondary data combined with scientific understanding of nutrient management, a research and extension guide was developed (Fig.1). The guide has two major components; the first (in the upper box) focussing on manure production and storage and their impact on quality, and the second emphasizing management of different quality manure. The guide is not crop specific but there is implicit recognition that farmers in Zimbabwe where the guide is initially targeted give priority to maize and vegetables. The management systems that the guide attempts to address are complex and depend on individual decision making and the soil type at any particular location and other household labor limitations.

**Decision-making and manure use: the farmer's view**

The results presented in this section were from discussions with a focus group involved in analyzing decision criteria. Decision-making by the farmers was analyzed through a spidogram approach culminating in the development of a farmer derived decision framework (Fig.2). One farmer presented the guide to the larger group of farmers after which it was further refined. The salient features of the farmer decision guide were that:

1. Farmers have a range of options that they use for soil fertility improvement as shown in the upper sections (A) of the diagram in Fig 2.
2. Farmers value quantity as being more important than quality of manure. This could be an indication that farmers are primarily more interested in the amount of resources they have and the extent to which they can be spread around over the farm. This seems rational as the larger the quantity, albeit of poor quality manure, the more nutrients they will be adding to the soil. There are also other secondary benefits of organic matter addition such as increase in water holding capacity, increased nutrient use efficiencies etc. As a result, farmers have developed several strategies to improve the quantity of manure obtained from their kraals (Fig.2, B). These include adding anthill soil, crop residues, leaf litter etc. From the discussions there appeared to be a strong realization by farmers that management affects quality. Farmers however do not deliberately manage or manipulate quality of manure to target it to a specific crop even though they might have preferences of which crop to apply higher quality manure (Fig 2, C and D). Residues are added primarily to increase quantity though they may have a secondary effect on manure quality. There is a limit to which residues can be added to the kraal, however.
3. Farmers are vague on rates, which maybe a reflection of a lack of consensus within a large group but also of wide differences between households. However they have guides on how to target manure application.
4. The quantity of manure that is pit stored is likely to remain small as some farmers feel that they have limited labor available.

**Discussion**

The farmer framework is much more comprehensive than the research and extension guide and probably fits more within their environment. Concerns were raised that the farmer guide is more likely to vary from area to area. A useful decision guide should be generic allowing for modifications to be made as circumstance change. The farmer guide was useful as a training tool to let farmers be more aware of the need to manage quality as well rather than quantity of manure alone. There was broad consensus that the research extension guide should be technically precise.

There is a big gap that needs to be filled on farmer quality characterization. It will be necessary to more thoroughly ascertain the range of manure qualities that are identifiable by farmers, and how the identifiable indicators differ with region, and whether those indicators are socially differentiated. A pertinent question for research is whether there is a clear color pattern associated with stage of decomposition? If so then this opens up the potential to use color charts as indicators of quality and hence of how a particular manure could be managed. There is need to look at farmer indicators and how they relate to laboratory indices. Farmer quality indices might need to be considered in combination and not individually.

The farmer-developed manure guide still looks complex despite the fact that it was presented by a farmer to a larger audience of farmers. Opportunities for the further simplifying it should be identified. There is no doubt that farmers were excited by the manure decision guide hence it would be worthwhile to expand the range of decision guides that could be developed for the many options that farmers have for soil fertility improvement (Fig.2). Whilst a singular decision tree for a particular option forms the best way of exploring the way it is managed and how its management can be improved, farmers are most often managing combinations of different resources. The challenge therefore remains of how to integrate use of different decision trees for optimal management of multiple resources. For example, how do legumes fit within intervening years of the manure cycle etc. Similarly, a range of platforms and learning spaces

suitable for different categories of farmers should also be identified and tested (these could range from nutrient test strips to village labs and pot experiments).

**Conclusions**

A lot of issues have been raised above. Critical among those issues is to continue testing the decision guides and ensure that they are robust and applicable (but not necessarily) to a wide range of environments without losing the context of farmer circumstances. The question of validation should be left to farmers while the main role of the scientist should be that of facilitating this process of validation. Validating decision trees should not be viewed more in terms of going out in the field to prove a scientific point, but rather in terms of enabling farmers to test our scientific models.

In order for farmers to validate decision trees, they must understand the basic scientific principles from which scientists derived them, and this can only be done through a process of researcher farmer dialogue and mutual learning. By the same token the joint learning process should also enable scientists to refine and adjust their scientific models by closely observing how and why different farmers are making their choices.

**Acknowledgements**

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**Table 1. Diversity in manure management and fertilizer use strategies for different farmers in Shurugwi District, Zimbabwe.**

| | Manure Management and Use | | | Mineral Fertilizer Use | |
|---|---|---|---|---|---|
| | Rate of Application | Method of application | Manure Application Rotations | Type of Fertilizer | Rate of application |
| Farmer 1 | 4t/ha<br><br>17t/ha | Broadcasted<br><br>Banded | 2 year rotation maize-g/nut-maize | AN applied | Uses Coca – Cola bottle top for pit stored manure<br>And cup number 2.5 for heap stored manure |
| Farmer 2 | 21t/ha- first season<br>16t/ha – second season | Broadcasted | 3 year rotation maize-maize-g/nut | No mineral fertilizer for pit stored manure<br>Used to apply AN when using heap stored manure | Could not give rate of application of AN when heap stored manure was used |
| Farmer 3 | 3t/ha banded and an additional 4t/ha broadcasted | Banding and broadcasting | 3 year rotation maize-maize-g/nuts | No ammonium nitrate applied | Seems application of AN is targeted or done only when crop deserves it |
| Farmer 4 | Banded at 2 cm depth in ridge | Banding | 2 year rotation maize-g/nuts-maize | No ammonium nitrate applied | Seems application of AN is targeted or done only when crop deserves it |

***Note: Application rates were converted from scotch carts to tonnes per hectare and each scotch cart can carry approximately 400kg of manure.***

**Fig.1.Researcher developed manure decision guide**

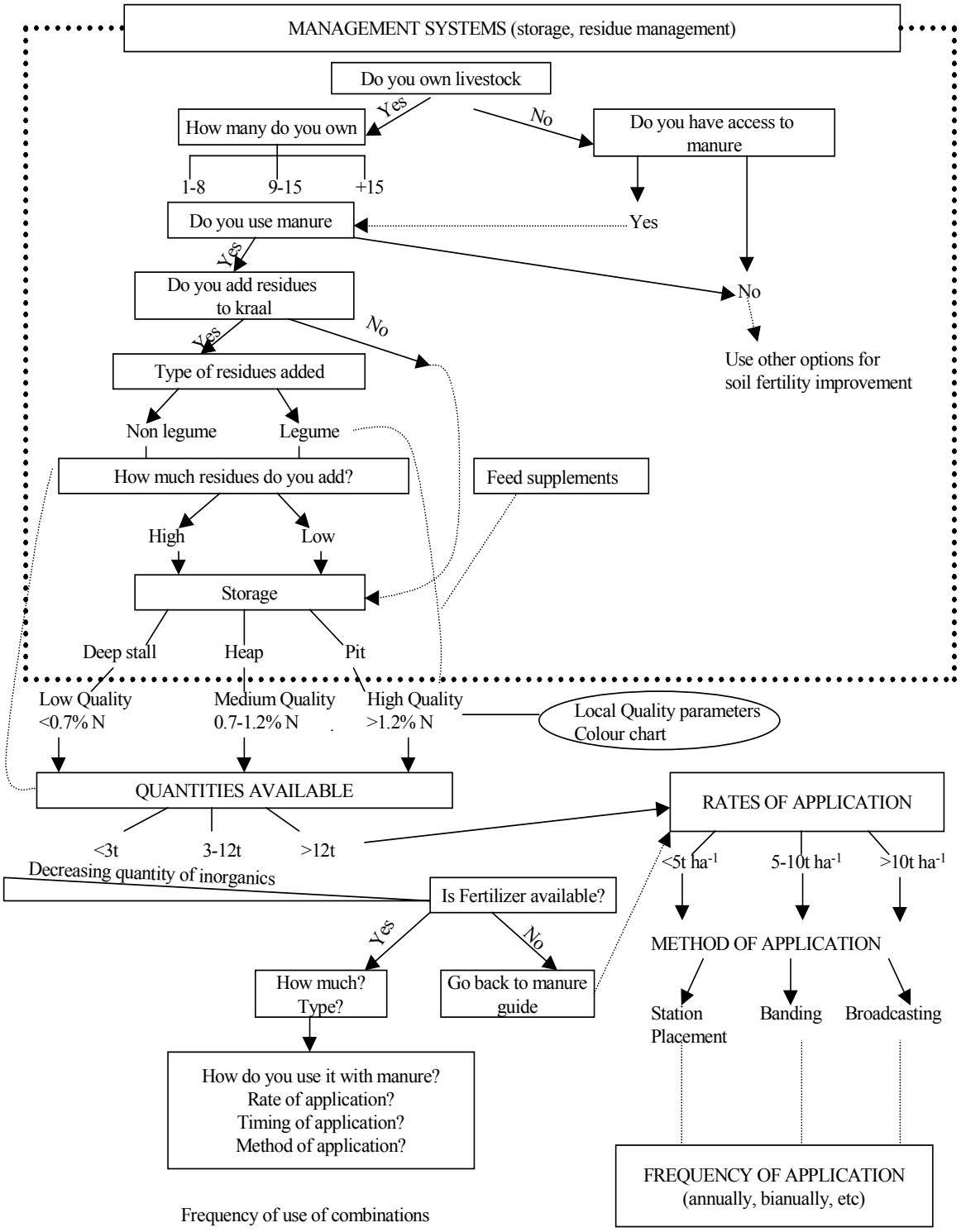
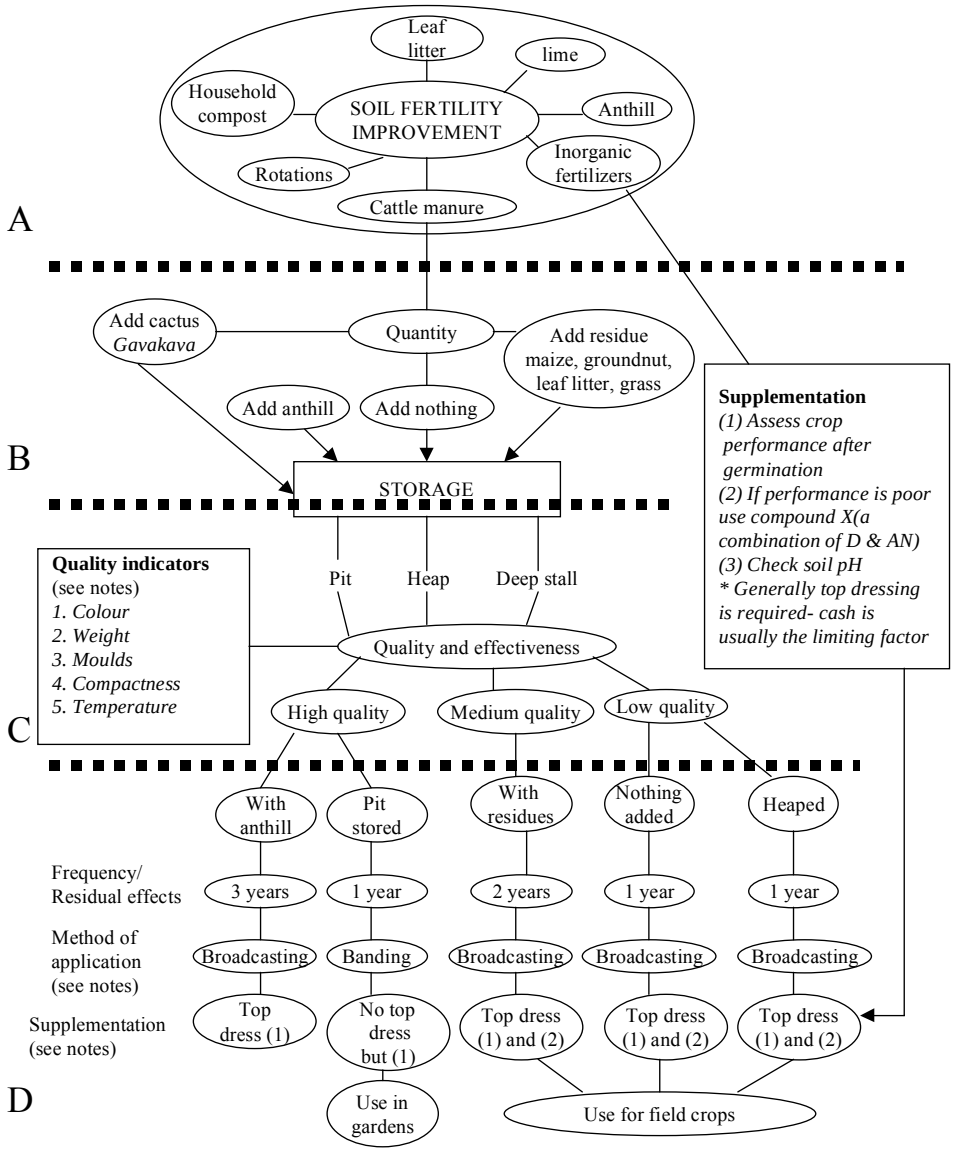


**Fig.2. Farmer manure decision guide developed using a spidogram analysis**




**Notes on rates of manure application**

- It depends on the quantities of manure available
- Rotations of manure application depend on the plot/farm size
- Manure is usually targeted for high potential fields (for food security)

**Considerations**

- Soil type
- Presence of witch weed-striga

Low rates or no manure applied to low potential fields

*Draft*

**Efficacy of soil organic matter fractionation methods for soils of different texture under similar management.**

Pauline P. Chivenge[1*], Herbert K. Murwira[1] and Ken E. Giller[2]
[1]Tropical Soil Biology and Fertility (TSBF), P O Box MP 228, Mt Pleasant, Harare, Zimbabwe.
[2]Soil Science and Agricultural Engineering Department, Faculty of Agriculture, University of Zimbabwe, PO Box MP 167, Mt Pleasant, Harare

**Abstract**
High soil dispersion is essential for the effectiveness of physical soil organic matter fractionation methods based on fraction size and/or density. A study was conducted to test the use of two dispersing agents, sodium resin bags and sodium hexametaphosphate for organic matter fractionation in two soils, a sand and a red clay soil. Two concentrations of sodium hexametaphosphate, 0.5% and 2% were used, and for the 2% concentration another treatment of pre-soaking versus not soaking was added.

Complete dispersion was achieved with all the dispersing agents used for the sandy soil. For the red clay soil none of the dispersing agents used achieved complete dispersion. Compared with the sodium hexametaphosphate, sodium resin bags resulted in a three-fold decrease in the amounts of coarse organic matter fractions for both the sand and the red clay soils. The use of resin bags resulted in a decrease in the amount of organic C in the coarse sand (212-2000 μm) and the medium sand (53-212 μm) fractions. There were however no differences in the amounts of the mineral fractions obtained by using the two dispersing agents for the two soil types.

Increasing the concentration of sodium hexametaphosphate did not result in an increase in soil dispersion for both the sand and red clay soils. There were no differences in the amounts of organic and mineral fractions obtained using the two concentrations for both the sand and red clay soils. Pre-soaking the soil resulted in an increase in soil dispersion reflected by a decrease in the amount of coarse sand and medium sand mineral fractions for the red clay soil. There were no effects on soil dispersion caused by soaking on the sandy soil. There were however no differences in the amounts of coarse and medium sand organic matter fractions obtained before and after soaking the soil. We concluded that using 0.5% sodium hexametaphosphate after soaking the soil was the most appropriate dispersing agent to use for achieving high soil dispersion without altering the soil organic matter distribution in the various size fractions for the red clay and the sandy soils.

***Key words:*** *soil organic matter, soil organic matter fractions, soil dispersion, and dispersing agent*

**Introduction**
Soil organic matter (SOM) plays an important role in determining the fertility and productivity of soils and hence the need to understand more clearly the factors that control SOM dynamics as affected by land use management practices. The association of organic matter with particular constituents of the mineral soil may be important in regulating the mineralization and storage of SOM. Pools of organic matter with different stabilities provide a spectrum of nutrient availability that have different rates of release and are susceptible to different kinds of disturbance (Woomer et al., 1994). The ability to quantitatively estimate SOM fractions is important for understanding SOM dynamics in agricultural systems.

Several chemical and physical methods have been developed to separate SOM fractions. Chemical separation methods yield fractions that are not closely related to functions of SOM (Blair *et al*., 1997) to soil processes such as aggregation and organic matter mineralization (Stevenson and Elliot, 1989; Feller and Beare, 1997). These methods give information on the kind of organic matter present that may vary in age and N content (Duxbury *et al*., 1989). Chemical fractions (humic and fulvic acids) generally have a low turnover rate and are therefore not necessarily implicated in the short-term processes commonly studied in cultivated soils (Feller and Beare, 1997). Physical fractionation yields functional

SOM pools which differ in composition and biological function as they give information on where the organic matter is located (Elliot and Cambardella, 1991).

The effectiveness of soil dispersion with minimum alteration of associated organic matter, is crucial for physical fractionation. Limited dispersion of soil may result in the recovery of the most easily dispersed part of the fraction, or the recovered fraction may consist of an unknown mixture of primary particles and microaggregates of the same size but belonging to different size classes (Sanchez *et al*. 1989). Soil disruption is more rapid and complete with sandy soils than with heavy textured soils (Stevenson and Elliot, 1989). Soil dispersion can be achieved by sonication or shaking. Sonication can achieve high dispersion but it results in the breakdown of organic matter into finer particles (Feller and Beare, 1997) and produces heat, which might alter organic matter composition (Stevenson and Elliot, 1989). Shaking reduces organic matter redistribution. It can be done in water with or without glass beads, or after chemical pre-treatment of soil with sodium saturated chemicals.

The work reported in this paper is part of a broader study to determine the effects of tillage on SOM dynamics in a long-term experiment. The experiment was carried out at two sites in Zimbabwe, on a sandy soil (Udic Kandiustalf- USDA) at Domboshawa and on a red clayey soil (Rhodic Paleustalf- USDA) at the Institute of Agricultural Engineering (IAE) in Hatcliffe Harare. Before following the dynamics of SOM in these soils initial studies were conducted to test and establish methods for the fractionation of SOM. The methods tested are based on similar principles (physical- particle size separations) but use different dispersing agents. The degree of dispersion of aggregates was used as the criterion for choosing one method.

The objectives of this experiment were to assess the effectiveness of soil dispersion for two soil types (a sand and a red clay soil) under different tillage treatments by a) using sodium resin bags and sodium hexametaphosphate, b) two concentrations of sodium hexametaphosphate (HMP) 0.5 % and 2%, and c) pre-soaking the soil before shaking. It was hypothesized that a) higher dispersion would be achieved with the use of sodium resin bags than with sodium hexametaphosphate, b) increasing the concentration of sodium hexametaphoshate would increase the degree of dispersion, and c) pre-soaking the soil before shaking would increase soil dispersion.

**Materials and Methods**

The tillage experiments that were established in 1988/89 season at Domboshawa and Institute of Agricultural Engineering (IAE), Harare were used for this study. There were five tillage treatments, mulch ripping, conventional tillage, tied ridging and clean ripping. Soil samples were collected in October 1998 and passed through a 2 mm sieve.

Soil dispersion was done in sodium hexametaphosphate at two concentrations, 0.5% and 2%, and sodium resin bags, which were regenerated in 3M trisodium citrate. For soil dispersed in 2% sodium hexametaphosphate one set of samples was soaked in water overnight before shaking while for the other set there was no soaking. Fractionation was carried out by sieving the soil through two sieves to get the following size fractions, size fractions 212-2000 μm, 53-212 μm and 0-53 μm. The 53-212 μm size fraction of soil shaken in sodium resin bags was shaken for 1hr in resin beads to allow for further disruption of aggregates. The fractions were viewed under a binocular microscope to check for purity of the fractions and degree of dispersion of aggregates.

The 212-2000 μm and 53-212 μm organic matter fractions were analysed for organic carbon using a Leco Carbon Analyser. Organic C in the 0-53 μm fraction was not analysed for organic C.

T-tests for paired observations using Genstat 5 Release 4.1 were done to test for differences in using the different dispersing agents.

**Results**

**The effects of texture on soil dispersion**

For the red clayey soil none of the dispersing treatments achieved complete dispersion. This was observed under a binocular microscope, by the presence of micro-aggregates in the mineral fractions and mineral

particles coating the organic matter fractions. For the sandy soil, however, complete dispersion of aggregates was achieved with all the dispersing agents used. The mineral fractions did not show the presence of micro-aggregates while the organic matter fractions were not coated with mineral fractions.

**The effectiveness of dispersing agents**

Sodium resin bags and sodium hexametaphosphate were effective in achieving complete soil dispersion in the sandy soil. There were no significant differences in the amount of fractions separated using the different dispersing agents except for the coarse organic matter fractions separated using the resin bags. There was a reduction in the amount of coarse sand organic matter fraction separated using resin bags compared with sodium hexametaphosphate (Table 1).

For the clayey soil none of the dispersing treatments used achieved complete dispersion. The use of resin bags increased dispersion of aggregates but reduced the amount of coarse organic matter recovered compared to sodium hexametaphosphate (Table 1). There was a slight but not significant decrease in the coarse mineral fraction and an increase in the intermediate mineral and mixed fractions obtained with the resin bags compared with sodium hexametaphosphate. There were significant differences in amounts of fractions dispersed in 2% hexametaphosphate and resin bags. Sodium hexametaphosphate gave higher amounts of the coarser fractions than resin bags (Table 1).

Increasing the concentration of sodium hexametaphosphate from 0.5 to 2% did not result in an increase in soil dispersion for the red clayey soil. There were no significant differences in the mass of the organic matter and mineral fractions obtained using the two concentrations.

**Effects of dispersing agents on organic C distribution**

The reduced amount of organic matter after using resin bags might have been a result of purer fractions being obtained. To see if the reduction in the amount of organic matter was a result of an increase in purity of the organic matter fractions, the fractions were analysed for organic C. The use of resin bags resulted in the reduced amount of organic C in the coarse organic matter fractions than sodium hexametaphospahte (Table 2).

**Effects of soaking**

For the red clay soil pre-soaking gave lower amounts of the mineral fraction with fewer aggregates than without soaking for separations done in 2% sodium hexametaphosphate (Table 3). Soaking did not however result in differences in the coarse organic matter fractions. Soaking did not result in differences in the masses of fractions obtained for the sandy soil.

**Effects of tillage treatments on the effectiveness of dispersion**

The effectiveness of aggregate dispersion was not affected by the different tillage treatments. The response of the different tillage treatments was the same across all the dispersing agents used.

For the red clay soil conventional tillage and clean ripping had similar amounts of coarse and medium sand organic matter fractions although clean ripping had higher amounts of total organic C than conventional tillage (Table 4). In the fine sand fraction clean ripping had higher amounts of organic matter than conventional tillage. Mulch ripping had higher total organic C, coarse and medium sand fraction organic matter contents than clean ripping (Table 4). Tied ridging had the highest total organic C (20.4 mg C $g^{-1}$ soil) and sand fractions organic matter contents in the red clay soil (Table 4).

Bare fallow showed the highest decline in soil organic matter content as indicated by the lowest total organic C content (2.2 mg C $g^{-1}$ soil) and smaller amounts of organic matter in all the organic matter fractions separated (Table 5). Conventional tillage had low total organic C content and low amounts of organic matter sand size fractions. Mulch ripping had higher total organic C amounts of sand size fractions than clean ripping (Table 5). Tied ridging had similar total organic C and amounts of organic matter in the sand fractions with clean ripping (Table 5). Hand hoeing had lower total organic C content and organic matter in the sand fractions than mulch ripping except for the fine sand fraction where there were no treatment differences (Table 5).

## Discussion

### Effects of texture on soil dispersion

There was no complete dispersion for the red clayey soil probably due to the high clay content (>40%) which results in the formation of strong bonds between mineral and organic particles to form micro- and macro-aggregates. Clay particles have high surface area and tend to form strong mineral-mineral and ogano-mineral interactions that require high force to disrupt. In the sandy soil there was complete dispersion due to the presence of weak aggregates that require minimal force to disrupt. Elliot and Stevenson (1989) also found that disruption was more rapid and complete with sandy soils than with heavy textured ones. Sandy soils tend to have weak structure due to high sand content, which has low surface area, no charge and no hydrogen bonding for formation of aggregates (REF).

### Effectiveness of dispersing agents

Resin bags and sodium hexametaphosphate were effective in dispersing the sandy soil as complete dispersion was achieved. Both dispersing agents were however not effective in dispersing the red clayey soil. This was probably due to the strong interactions in the micro-aggregates such that there might be need for stronger forces to break down the aggregates.

Although the use of resin bags led to an increase in the dispersion of aggregates, it also led to a significant decrease in the amount of organic matter recovered. The use of resin bags could have caused further breakdown of the coarse organic matter or solubilisation of the organic matter. The material used to make the resin bags has a mesh size of about 150 μm such that some material may have been entrapped inside the bags and was difficult to wash out resulting in erroneous results and reducing the effectiveness of the regeneration of the resin bags.

There was no increase in dispersion caused by increasing the concentration of the hexametaphosphate from 0.5 to 2%. More effective dispersion might be achieved at higher concentrations of the salt, but hexametaphophate does not readily dissolve making it difficult to make higher concentrations. Sodium hexametaphosphate is likely to result in salt interacts with the fractions during mineralization making it unsuitable to use if incubation studies are to follow.

### Effects of dispersing agent on organic C

The use of resin bags resulted in smaller amount of organic C in the coarse organic matter fractions and redistribution into finer fractions. The redistribution of organic matter among size fractions complicates efforts to selectively isolate organic matter fractions from specific sources in the soil confusing interpretation of results. The finer fractions were not analyzed in this preliminary test. Complete dispersion was not achieved for the clay soil such that the mineral fraction contained some micro-aggregates and a significant amount of organic C is found within micro-aggregates (Stevenson and Elliot, 1989).

### Effect of soaking on improving soil dispersion

Soaking the soil before shaking led to an increase in the dispersion of aggregates (Table 2). Soaking did not affect the coarse organic matter fraction as it is not found in close association with the soil and hence is easy to disperse. There was a decrease in the amount of the coarse mineral fraction after soaking the soil as more aggregates were disrupted and the bonds in the aggregates weakened. The larger amounts of the mineral fractions in dispersion without soaking was due to the inclusion of aggregates, many aggregate classes have the same size range as sand (0.05-2mm). Increased dispersion after soaking led to an increase in the amount of the fraction less than 53um as the finer fractions that make up the aggregates were dispersed.

### Effects of tillage treatments on the effectiveness of dispersion

The lack of differences in the sand size fractions organic matter contents between conventional tillage and clean ripping (Table 4) for the red clay soil could have been because no organic residues were added to the soil for both treatments. Clean ripping had higher organic matter contents in the finer fractions than

conventional tillage probably due to aggregate disruption that occurs under conventional tillage causing higher organic matter decomposition. Mulch ripping had higher organic matter contents in the coarse and medium sand fractions than clean ripping because of organic residues that are added to the soil. Tied ridging had the highest amounts of organic matter probably because there was minimum tillage involved. The ridges were established at the onset of the experiment in 1988/89 season with opening of holes for planting such that there was minimum disruption of aggregates.

For the sandy soil bare fallow had lowest amounts of organic matter most probably because there were no organic residues added to the soil. The treatment involved annual ploughing without planting anything to the soil causing soil organic matter loss through runoff and erosion. Mulch ripping had the highest amounts of organic matter unlike the red clay where tied ridging had the highest amounts of organic matter. This was probably because of additions of organic residues under mulch ripping. The clay content of the sand was very low (<6%) such that there was no organic matter stabilisation between and within soil aggregates and the finer soil particles.

**Conclusion**

Of the methods tested using 0.5% sodium hexametaphosphate after soaking the soil would be the most suitable dispersing agent to use for getting high dispersion without altering organic matter distribution in the various size fractions for the red clayey soil and the sandy soil. This was so because increasing the concentration of sodium hexametaphosphate did not increase soil dispersion for the red clayey soil. Soaking the soil on the other hand resulted in an increase in disruption of aggregates by decreasing the mass of the mineral fraction by about 30%. Using resin bags resulted in low recoveries of the amount of organic C and mass of organic matter fractions compared with sodium hexametaphosphate and hence its selection.

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**Table 1. A comparison of soil organic matter size fractions obtained using two dispersing agents, 2% sodium hexametaphosphate and resin bags**

| Treatment | Weight of size fraction (g/g soil) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 212-2000 µm OM | | 212-2000µm Mineral | | 53-212 µm OM | | 53-212 µm Mineral | | 0-53 µm Mixed | |
| | HMP | Resin | HMP | Resin | HMP | Resin | HMP | Resin | HMP | Resin |
| Red Clayey | | | | | | | | | | |
| Mulch | 0.004 | 0.001 | 0.041 | 0.041 | 0.025 | 0.008 | 0.032 | 0.050 | 0.897 | 0.910 |
| Conventional | 0.003 | 0.001 | 0.038 | 0.034 | 0.019 | 0.005 | 0.041 | 0.062 | 0.895 | 0.897 |
| Tied | 0.006 | 0.003 | 0.035 | 0.036 | 0.023 | 0.012 | 0.052 | 0.054 | 0.888 | 0.896 |
| Clean | 0.003 | 0.001 | 0.039 | 0.039 | 0.018 | 0.007 | 0.046 | 0.070 | 0.882 | 0.884 |
| t statistic | 12.5 | | 1.2 | | 7.9 | | -5.1 | | -3.5 | |
| Sandy | | | | | | | | | | |
| Mulch | 0.004 | 0.001 | 0.594 | 0.476 | 0.004 | 0.005 | 0.222 | 0.260 | 0.176 | 0.258 |
| Conventional | 0.002 | 0.001 | 0.647 | 0.462 | 0.002 | 0.001 | 0.213 | 0.262 | 0.138 | 0.174 |
| Tied | 0.004 | 0.001 | 0.616 | 0.547 | 0.002 | 0.002 | 0.204 | 0.238 | 0.172 | 0.212 |
| Clean | 0.003 | 0.001 | 0.591 | 0.457 | 0.002 | 0.002 | 0.249 | 0.276 | 0.155 | 0.262 |
| t statistic | 5.4 | | 10.4 | | -2.6 | | -12.3 | | -5.9 | |

**Table 2 A comparison of carbon content in organic matter size fractions obtained after using sodium hexametaphosphate (HMP) and resin bags as dispersing agents**

| Tillage treatment/ Soil type | Total C mg C $g^{-1}$ soil | >212 µm OM mg C $g^{-1}$ soil | | 53-212 µm OM mg C $g^{-1}$ soil | |
|---|---|---|---|---|---|
| Red clay | | HMP | Resin | HMP | Resin |
| Mulch | 17.2 | 1.066 | 0.423 | 4.90 | 2.808 |
| Conventional | 14.9 | 1.023 | 0.484 | 4.418 | 1.857 |
| Tied | 20.4 | 2.319 | 0.959 | 5.016 | 2.517 |
| Clean | 16.8 | 1.065 | 0.480 | 4.201 | 1.761 |
| Sandy soil | | | | | |
| Mulch | 6.8 | 0.846 | 0.465 | 1.347 | 0.844 |
| Conventional | 4.2 | 0.376 | 0.216 | 0.362 | 0.281 |
| Tied | 4.8 | 1.032 | 0.470 | 0.397 | 0.563 |
| Clean | 4.6 | 0.941 | 0.444 | 0.651 | 0.454 |

**Table 3 A comparison of soil organic matter size fractions obtained using 2% sodium hexametaphosphate before soaking and after soaking**

| | Weight of size fraction (g $g^{-1}$ soil) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Treatment | >212 μm OM | | >212 μm Mineral | | 53-212 μm OM | | 53-212 μm Mineral | | <53 μm Mixed | |
| | Unsoaked | Presoaked | Unsoaked | Presoaked | Unsoaked | Presoaked | Unsoaked | Presoaked | Unsoaked | Presoaked |
| Red Clayey | | | | | | | | | | |
| Mulch | 0.006 | 0.004 | 0.059 | 0.041 | 0.024 | 0.025 | 0.055 | 0.032 | 0.857 | 0.897 |
| Conventional | 0.003 | 0.003 | 0.050 | 0.038 | 0.16 | 0.019 | 0.065 | 0.041 | 0.855 | 0.895 |
| Tied | 0.007 | 0.006 | 0.055 | 0.035 | 0.023 | 0.032 | 0.076 | 0.052 | 0.841 | 0.888 |
| Clean | 0.004 | 0.004 | 0.058 | 0.039 | 0.014 | 0.018 | 0.067 | 0.046 | 0.858 | 0.882 |
| t statistic | 1.9 | | 14.4 | | -0.7 | | 0.0 | | -11.4 | |
| Sandy | | | | | | | | | | |
| Mulch | 0.005 | 0.005 | 0.594 | 0.573 | 0.004 | 0.003 | 0.258 | 0.232 | 0.134 | 0.176 |
| Conventional | 0.002 | 0.002 | 0.647 | 0.634 | 0.002 | 0.001 | 0.236 | 0.219 | 0.180 | 0.138 |
| Tied | 0.004 | 0.004 | 0.619 | 0.616 | 0.001 | 0.001 | 0.246 | 0.224 | 0.152 | 0.172 |
| Clean | 0.004 | 0.003 | 0.591 | 0.586 | 0.003 | 0.002 | 0.256 | 0.240 | 0.129 | 0.155 |
| t statistic | 1.8 | | 2.3 | | 2.8 | | 4.6 | | -0.9 | |

**Table 4 A comparison of tillage effects on the amount of organic matter in a red clay soil from the Institute of Agricultural Engineering, Harare**

| Tillage treatment | Soil organic matter mg $g^{-1}$ soil | Weight of organic matter fraction (mg $g^{-1}$ soil ) | | |
|---|---|---|---|---|
| | | 212-2000 μm Coarse sand | 53-212 μm Medium sand | 20-53 μm Fine sand |
| Conventional tillage | 14.9 | 2.65 | 3.64 | 5.46 |
| Clean ripping | 16.8 | 2.69 | 5.24 | 8.98 |
| Mulch ripping | 17.2 | 3.48 | 6.34 | 10.18 |
| Tied ridging | 20.4 | 6.08 | 12.28 | 11.36 |
| Weedy fallow | 27.9 | 22.46 | 19.72 | 17.76 |
| SED | | 0.278 | 1.204 | 1.091 |

*NB Fractions less than 20 μm (silt and clay) are not shown in the table because organic matter was not separated from the mineral particles.*

**Table 5 A comparison of tillage effects on the amount of organic matter in the sandy soil From Domboshawa Training Centre**

| Tillage practice | Soil organic matter mg $g^{-1}$ soil | Weight of organic matter fraction (mg $g^{-1}$ soil) | | |
|---|---|---|---|---|
| | | 212-2000 μm Coarse sand | 53-212 μm Medium sand | 20-53 μm Fine sand |
| Bare fallow | 2.2 | 0.32 | 0.60 | 0.58 |
| Conventional tillage | 4.2 | 1.54 | 1.48 | 1.70 |
| Clean ripping | 4.6 | 2.96 | 2.26 | 2.56 |
| Tied ridging | 4.8 | 3.78 | 1.54 | 2.12 |
| Hand hoeing | 6.0 | 3.40 | 2.10 | 3.08 |
| Mulch ripping | 6.8 | 4.68 | 4.26 | 3.16 |
| Weedy fallow | 11.3 | 3.34 | 18.26 | 4.98 |
| SED | | 0.552 | 0.331 | 0.552 |

*NB Fractions less than 20 μm (silt and clay) are not shown in the table because organic matter was not separated from the mineral particles.*

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# Nitrogen mineralisation from aerobically and anaerobically treated cattle manures

J.K. Nzuma[1] and H. K. Murwira[2]
[1]Crop Nutrition Section, Chemistry & Soil Research Institute, Box CY 550 Causeway, Harare, Zimbabwe.
[2]T.S.B.F. Department of Soil Science, University of Zimbabwe, Box MP228, Mt Pleasant, Harare, Zimbabwe.

## Summary
Short-term mineralisation-immobilisation turnover of N after amending soil with aerobic and anaerobic manures treated in April and July with or without straw was studied during a 77-day incubation period using the leaching tube method. The dynamics of N mineralisation were described by first order kinetics with high rate constants for anaerobic manures without straw treated in July. The decomposition of aerobic manures in soil followed a slow linear immobilisation pattern suggesting asynchrony of nutrient release and plant uptake. The course of N turnover for anaerobic manures suggested two phases, an initial exponential immobilisation phase followed by a slow linear re-mineralisation phase. It was concluded that in spite of the initial immobilisation period that occurred with anaerobic manures, the re-mineralisation that took place indicated that manure-N might be synchronised with crop demand in the short term.

## Introduction
Different storage conditions influence both carbon and nitrogen turnover of the manures after application to soil. During aerobic composting organic materials of high stability are formed and the inorganic N can be low. Anaerobic decomposition can lead to the production of low-molecular compounds such as volatile fatty acids and high ammonium-N contents have been reported (Thomsen, 2000). The addition of anaerobically decomposed manure to soil has been found to immobilise N due to the presence of easily decomposable C sources as observed in the work of Bernal and Kirchmann, (1992), Flowers and Arnold (1983) and Sims, (1986), with pig slurry and Murwira, (1993) with cattle manure. The dynamics of C or N mineralisation of organic manures in soils have been described by first-order reaction kinetics (Chae and Tabatabai, 1986 or a set of first-order reactions (Gale and Gilmour, (1986).

In the present paper, we report the results of a study on N release patterns from aerobic and anaerobic manures treated in April and July with or without straw after application to a sandy soil The aim of the investigation was to establish possible differences in short-term N turnover rates in aerobic and anaerobic manures applied to soil and implications to the cropping system..

## Materials and methods

### Manures and soil used
Manures used in the study were obtained from four storage treatments namely pit manure (anaerobically decomposed) with or without straw; heap manure (aerobically composted) with or without straw. The manures had been composted in April 1999 and replicated in July 1999. Samples of manure were collected in October1999 and air dried then ground to pass a 2-mm sieve, analysed for organic C (Nelson and Sommers, 1982) total N using the Kjeldahl procedure (Bremner and Mulvaney, 1982).The chemical composition of these manures is presented in Table 1.

The experimental soil was collected from a site in Murewa. The soil was a deeply weathered and leached loamy sand with 4% clay, 4% silt, 92% sand and a pH of 4.5 ($CaCl_2$) classified as a Haplic Lixisol (FAO), Nyamapfene, (1991). The soil was air dried and allowed to pass through a 2mm sieve and analysed for organic C using the Walkely and Black Method (Nelson and Sommers, 1992) and total N using the Kjeldahl procedure (Bremner and Mulvaney, 1982).

**Incubation procedure**

The aerobic leaching tube mineralisation method (modified from Stanford and Smith, 1972) was used in this study. This method was employed to reduce the number of tubes that would be required if the static method was to be used. An added advantage of the leaching tube method is that it mimics the field situation where N is constantly removed from the soil crop system through crop uptake and leaching. The tubes can also be used over a long period without experiencing problems of accumulation of N and other toxic products of decomposition (Bremner, 1965; Stanford and Smith, 1972). One disadvantage of the leaching tube is that, it removes the soluble carbon, which drives the mineralisation process.

The leaching tubes consisted of a plastic transparent cylinder (200ml by volume) with a hole (0.5mm diameter) at the bottom. A narrow glass tubing (10cm long) was inserted at the base through the hole to allow drainage and secured with plasticine at the base. A glass wool 3cm thick was placed at the base of the tube to prevent movement of soil-manure particles from draining out of the tube.

Ten grams of acid washed sand was added on top of the glass wool before adding soil-manure mixture to ensure even distribution of suction. A further 10g of acid washed sand was added at the top of the soil-manure mixture to avoid movement of particles upon pouring leaching solution.

To reduce moisture loss, a pierced aluminum foil was placed on top of the tube covering it loosely. A mass of 100g of soil was placed in each glass jar. This was mixed homogeneously with 8 different manures applied at quantities equivalent to 60 kg N/ha and transferred into leaching tubes. A set of control tubes with 100g of soil only was added. All treatments were replicated 4 times. Moisture content was adjusted to 70% of water holding capacity (WHC) and the tubes were incubated in a constant temperature room at 25$^{o}$C.

**Sampling**

The tubes were leached at day 0 to remove background mineral N. They were then leached on day 3, 7 and every week thereafter for a period of 11 weeks. The tubes were leached with 100ml of a leaching solution in two 50ml aliquots and the leachates collected in conical flasks. The leaching solution contained 1mM $CaCl_2$, 1mM $MgSO_4$, 0.1 mM $KH_2PO_4$ and 0.9 mM KCI. At each leaching date, moisture content was adjusted to 70% of WHC.

Concentrations of mineral N ($NH_4$-N plus $NO_3$-N) in the leachates were measured immediately after sampling using micro Kjedhal N method. The mineralisation of manure nitrogen was determined by subtraction of the amount of inorganic nitrogen mineralized in the soil (control) from total inorganic N amounts mineralized in the soil-manure mixture.

**Statistic analysis**

Cumulative data on N mineralisation were fitted to a first order kinetic function using Genstat 5 procedures. Analysis of variance procedure using Mstat 1988 was used to measure the significance of net mineralisation during the incubation period.

**Results**

**Chemical composition of manures**

The chemical composition of manures is presented in Tables 1. Anaerobic manures were always high in total N concentrations. A greater proportion of the total N in these manures was present as inorganic N in the form of $NH_4$-N. Highest concentrations were observed for JP- manures. The C/N ratio for anaerobic manures was high, between 14 and 19 compared with 8 – 13 for aerobic manures.

**Net N mineralisation**

Net N mineralisation from manures (without soil) Fig. The course of mineralisation/immobilisation significantly differed ($P<0.05$) according to the different storage treatments applied to the manure samples prior to incubation. In general, there was also a significant month * straw interaction and straw *

storage method interaction (P<0.05). Straw effect was significant (P<0.05) and amplified in anaerobic manures in July.

Anaerobic manures resulted in shorter periods of rapid initial immobilisation phase lasting between 4 and 5weeks Fig .1. In general, the immobilisation period was increased in manures with straw. Aerobically treated manures resulted in immobilisation, which lasted 7 weeks after incubation for manures with and without straw (Fig 1).

In terms of net N mineralisation, anaerobic manures had significantly higher net N mineralisation at 11 weeks after incubation than aerobic manures (P<0.05). July anaerobic manures were found to have significantly higher net N mineralisation than April manures. A release of 48 and 58 ug$N^{-1}$g soil of mineralisable N was observed from anaerobic manures with and without straw in July at 11 weeks. April anaerobic manures with and without straw released 25 and 30*u*g N $g^{-1}$ soil of mineralisable N at 11 weeks. Anaerobic manures achieved a net N mineralisation of less than 20*u*g N $g^{-1}$ soil for manures from this farm (Fig 1).

**Cumulative N mineralisation**

The cumulative N curves of aerobic and anaerobic manures were fitted to a first-order kinetic function with the rate constants describing the release of mineral N (Fig 2).

Mineralisation was expressed as a percentage of the amount of total manure-N added. After 77 days of incubation, N mineralised showed the following pattern:

JP- (30.65%) > JP+ (25.59%) > AP- (22.75%) > AP+ (22. 60%) > JH- = JH+ =AH- = AH+ (0.00%).

The order of percentages of total N that was mineralised over 77 days of incubation followed that of the rate constants for the slow re-mineralisation phase High coefficients of determination were found (R2 = 0.939 -0.990). (Table 2).

In general, all aerobic manures followed a linear course for either nitrogen immobilisation or mineralisation which, lasted over the whole experimental period of 77 days. The rate constants were low for aerobic manures as shown in Table 2. The decomposition of anaerobic manures was characterised by two different phases, a rapid exponential initial immobilisation phase followed by a slow linear re-mineralisation phase.

The rate constants for the slow re-mineralisation phase exhibited the following pattern:

JP- (0.068 N $day^{-1}$) > JP+ (0.058 N $day^{-1}$) > AP- = AP+ (0.05 N $day^{-1}$) > JH- (0.038 N $day^{-1}$) > JH+ (0.028 N $day^{-1}$) > AH-= AH+ >0.00 N $day^{-1}$).

**Discussion**

**Immobilisation phase**

Initial immobilisation effects by anaerobic pretreated manures were observed in this study. The reason appeared to be three-fold; the high C/N ratio greater than 15 found in anaerobic manures which was similar to that reported by Bernal and Kirchmann, (1992) and Castellanos and Pratt, (1981). Secondly, high microbial activity, which causes a shift in microbial population from predominantly anaerobic bacteria resulting in a flush of readily available carbon and consequently more C utilisation for microbial proliferation (Thomsen and OsIen, 2000). Thirdly, the presence of energy-rich easily degradable C compounds by microorganisms such as volatile fatty acids (Spoelstra, 1979) (though not measured in this study), when a shift into aerobic conditions occurred. The work of Paul and Beauchamp, (1989) showed that volatile fatty acids in slurry can be oxidized within 4 days after amending soil with anaerobic manure together with a parallel immobilisation of $NH_4$-N. Earlier findings reported by Sims (1986) and Flowers and Arnold, (1983) found that up to 40% of $NH_4$-N in anaerobic manures can be immobilised.

The present data on prolonged periods of N immobilisation in soil with aerobic manures can be attributed to the stability of the organic materials in these manures. This is because easily decomposable organic compounds are respired during aerobic composting phase (Sana and Soliva, 1987). For example, water soluble and easily hydrolysable sugars are reduced during composting. Immobilisation of N was also possible with aerobic manures because a greater proportion of N was organically bound

These results imply that the application of aerobic manures to soil could induce N deficiency during rapid crop growth leading to depressed yields (Murwira and Kirchmann, 1993; Nyamangara et al., 1999; Paul and Beauchamp, 1994). These workers found N release from aerobic manures to be asynchronous with maize crop N requirements. The results from this study have also been demonstrated in the work of Thomsen, (2000), Hadas and Portnoy, (1994) and Hadas et al., (1996). Their findings showed low N mineralisation rates for composted manures as reported in this study.

**Re- mineralisation phase**

In spite of the initial immobilistion, which occurred in soil with anaerobic manures, re-mineralisation of the inorganic N, occurred with these manures achieving highest rate constants with July stored manures and subsequently more inorganic N was released than similar manures stored in April. These differences can be attributed to a decrease in mineralisation rates with length of storage as shown by Bernal et al., (1998) and more readily decomposable organic forms were converted to stable forms with prolonged duration of storage (Castellanos and Pratt, 1981; Chaney, Drinkwater and Pettygrove, 1992; Kirchmann, 1985). The re-mineralisation of N that occurred with anaerobic manures during the fifth and sixth weeks after incubation is in agreement with the work reported by Murwira and Kirchmann, (1993).

The results in this study contradict findings reported by Thomsen and Oslen, (2000) in which soils with anaerobic manures showed net immobilisation only after 266 days of incubation. Because of high microbial proliferation that occurs after application of anaerobic manures, these workers suggested that it might be more difficult to synchronise N release from anaerobic manures with crop N demand. However, in the present study, re-mineralisation of the inorganic N occurred close to the rapid crop growth stage between the fourth and sixth weeks after incubation. This implies that the release of N from these manures can be synchronised with crop N requirements.

Because of slow mineralisation rates found in soil after application of aerobic manures, crop yield potentials in the short term can be adversely affected. This might imply that aerobic manures are only beneficial to the crop in the subsequent years after application. (Tanner and Mugwira, 1984; Paul and Beauchamp, 1994).

**Conclusion**

Results showed significant variations in the decomposition of manures from different storage conditions. Differences in the rate constants between the manures reflected initial short term variations in the inorganic-N content of the readily decomposable fractions. Anaerobic manures with their high initial $NH_4$-N contents were found to have highest rate constants than aerobic manures.

The decomposition of anaerobic manures in soil almost always resulted in temporal initial immobilization. The immobilisation period was lengthened in manures with straw and by the age of manure owing to duration of storage. In spite of the initial immobilisation of the inorganic N that occurred in soil with these manures, re-mineralisation occurred close to the rapid crop growth stage reflecting that these manures may be synchronised with crop N requirements in the short term.

Little or no N was mineralised from aerobic manures. The implications are that these manures could be an inefficient source of fertiliser N for the crop. Though N released by these manures may be asynchronous with maize crop N requirements in the short term, the proportion of the N that still remains in organic bound form could be available for transformation in the residual years.

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Table 1. Some selected chemical properties of manures (N=3)

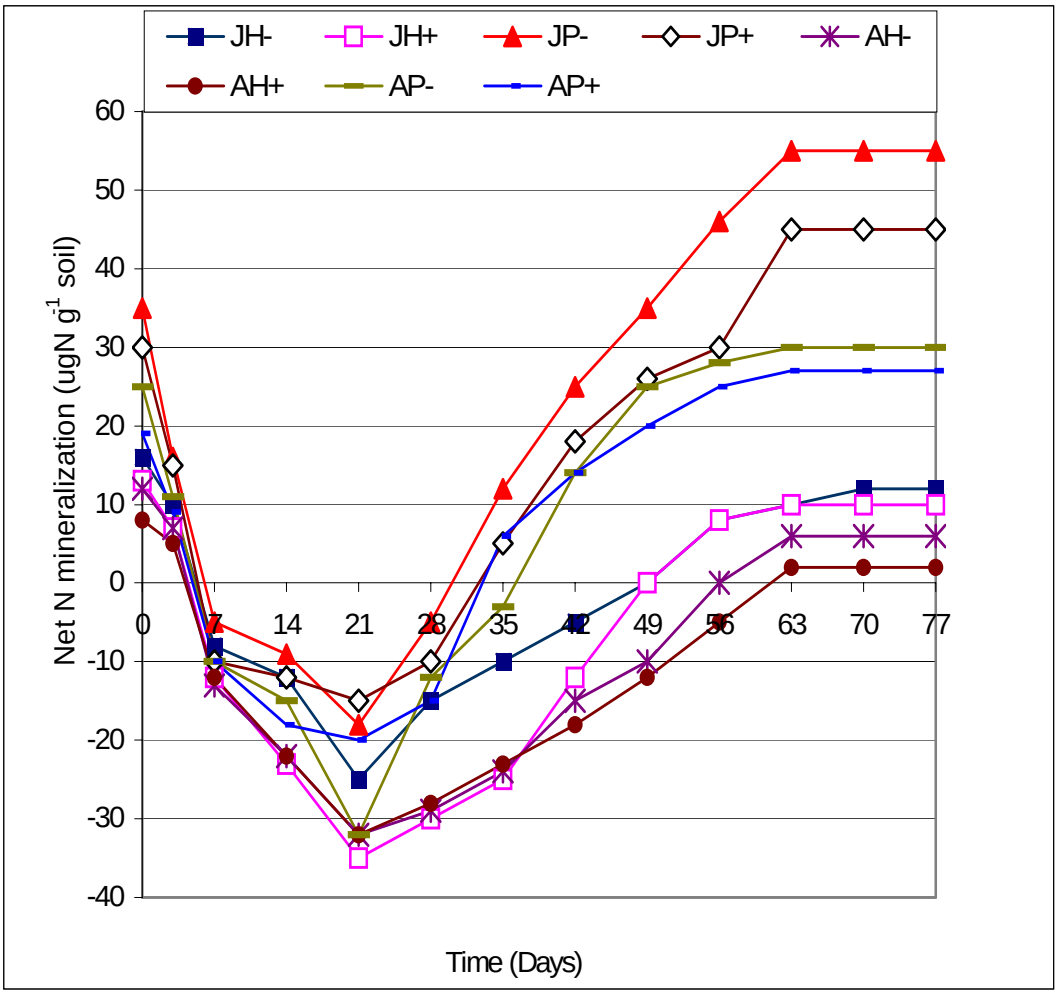
| **Storage Treatment** | **Lignin (%)** | **Nitrogen (%)** | **Carbon (%)** | **$NH_4$-N (mg/kg)** | **C/N ratio** |
|---|---|---|---|---|---|
| JH- | 1.32 | 1.00 | 9 | 560 | 9 |
| JH+ | 5.31 | 0.90 | 7.8 | 400 | 8.6 |
| JP- | 6.41 | 1.86 | 25.5 | 285 | 14 |
| JP+ | 10.92 | 1.48 | 27.8 | 255 | 18.9 |
| AH- | 0.41 | 0.70 | 7.2 | 335 | 10.2 |
| AH+ | 1.68 | 0.62 | 7.8 | 320 | 12.5 |
| AP- | 14.59 | 1.22 | 18.6 | 230 | 15.2 |
| AP+ | 8.37 | 1.14 | 19 | 202 | 16.6 |

J = July storage + = with straw H = heap manure (aerobic)
A =April storage - = without straw P = pit manure (anaerobic)

**Table 2. N mineralisation/immobilisation kinetics in aerobic and anaerobic cattle manures mixed with soil; data obtained with a first order kinetic function**.

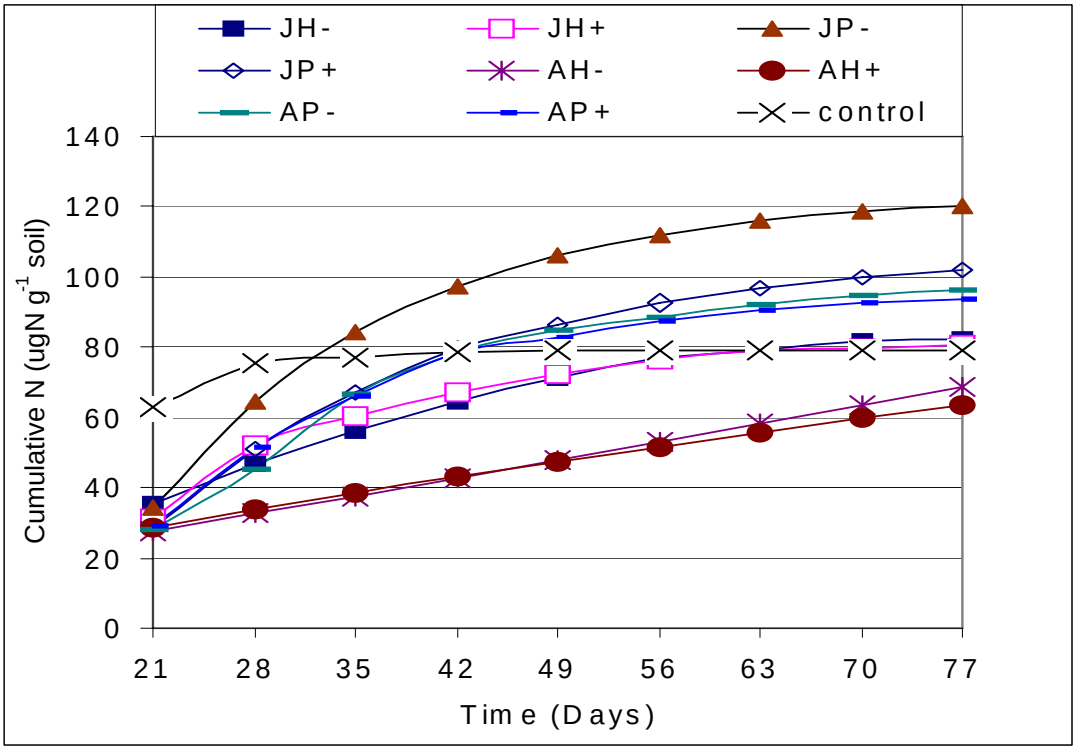
| Manure storage treatment | Course of N turnover | N min. (%) | Rate constant (day $^{-1}$) | $R^2$ |
|---|---|---|---|---|
| JH- | Linear immobilization | - | 0.038 | 0.969 |
| JH+ | Linear immobilization | - | 0.028 | 0.945 |
| JP- | Exponential; Imm; linear min. | 30.65 | 0.068 | 0.990 |
| JP+ | Exponential; Imm; linear min. | 25.59 | 0.058 | 0.984 |
| AH- | Linear immobilisation | - | 0.000 | 0.939 |
| AH+ | Linear immobilisation | - | 0.000 | 0.942 |
| AP- | Exponential; Imm; linear min. | 22.75 | 0.050 | 0.984 |
| AP+ | Exponential; Imm; linear min. | 22.60 | 0.050 | 0.972 |

J = July storage + = with straw H = heap manure (aerobic)
A =April storage - = without straw P = pit manure (anaerobic)
Imm = immobilisation min. = mineralisation




**J = July storage+ = with straw** **H = heap manure (aerobic)**
**A =April storage - = without straw** **P = pit manure (anaerobic)**

**Figure 1**. Net N mineralisation/immobilisation of aerobic and anaerobic manures (n=3)
Data presented excludes soil.




**J = July storage (aerobic)** **+ = with straw** **H = heap manure**

**A =April storage (anaerobic)** **- = without straw** **P = pit manure**

**Figure 2.** Cumulative N mineralisation of aerobic and anaerobic manu. Lines represent the curve-fitting result, symbols are experimental data.

*Draft*

**Influence of tillage management practices on organic carbon distribution in particle size fractions of a chromic luvisol and an areni-gleyic luvisol in Zimbabwe**

P. P. Chivenge[1*], H. K. Murwira[1] and K. E. Giller[2]
[1]TSBF-CIAT, Box MP228, Mt. Pleasant, Harare, Zimbabwe.
[2]Professor-Plant Production Systems, Department of Plant Sciences, Wagenigen University, P. O. Box 430, 6700 AK Wagenigen, The Netherlands

**Abstract**
Long-term tillage effects on soil organic matter dynamics were evaluated for a Chromic Luvisol (red clay soil) and Areni-Gleyic Luvisol (sandy soil) in Zimbabwe. The soils had been under conventional tillage, mulch ripping, clean ripping and tied ridging for at least nine years. Clay soil had about three times more soil organic matter than the sandy soil because of better physical protection of organic matter. Conventional tillage caused the highest organic C decline of 47% and 61% for the red clay and sandy soils, respectively. The highest organic C content of 0.68% in the sandy soil was under mulch ripping whilst for the red clay soil tied ridging had the highest content of 2.04%. These values were, however low, when compared with the weedy fallow which was 1.13% and 2.79% total organic C soil for the sandy and red clay soils, respectively. This indicates preservation and lower losses of organic matter in the weedy fallow. Conventional tillage reduced organic C in the coarse fractions by up to 78% and 84% for the red clay and sandy soils, respectively. Clay size fractions were the most stable fractions because of physical protection from microbial attack and this was shown by their small responses to tillage. Most of the organic matter was associated with the finer fractions for the red clay soil while for the sandy soil the greater proportion of the organic matter was associated with the sand fractions.

**Introduction**
Conventional tillage mixes the surface soil horizon diluting the superficial organic layer and resulting in faster decomposition of organic matter compared with minimum tillage management practices. Conservation tillage results in higher organic matter contents due to reduced contact of added organic matter with the soil, reduced exposure of new soil surfaces and decreased soil erosion (Dalal, Henderson and Glasby, 1991). Cultivation disrupts aggregate-protected organic matter, that is, the heavier fractions thereby increasing its mineralization associated with greater short-term nutrient availability and loss from the soil (Hassink, 1995). Soil disturbance from tillage is a major cause of organic matter depletion and reduction in the number and stability of soil aggregates (Six *et al*., 2000). Soil organic C storage was 25% greater in the no tillage treatment than the conventional tillage (mouldboard ploughing) after nine years of continuous cultivation (Yang and Wander, 1999).

Removal of crop residues from the fields is known to enhance soil organic matter decline especially when coupled with conventional tillage (Yang and Wander, 1999). In most communal areas of Zimbabwe, crop residues are removed from the fields for use as animal feed, resulting in small inputs of organic matter. Practising conservation tillage and proper residue management can substantially increase long-term soil organic matter and crop production (Smith and Elliot, 1990). Leaving residues on the surface can increase crop productivity by conserving moisture and reducing soil erosion.

Conservation tillage practices can reduce soil organic matter loss compared with conventional tillage practices depending on the clay content of the soil (Janzen et al., 1998). There is more rapid SOM loss in coarse textured soils, characteristically found in the greater parts of the communal areas of Zimbabwe (Grant, 1981), where decomposition is enhanced by lack of physical protection of organic matter (Hassink, 1995). In fine textured soils, clay and silt sized particles with high surface activity may physically protect SOM from decomposition due to isolation within and between micro-aggregates (Franzluebbers et al., 1996). As a result clay soils tend to have higher SOM contents than sandy soils.

The objective of this study was to assess tillage effects on SOM content and SOM fractions on two different soil textures. It was hypothesised that minimum tillage practices would promote SOM build-up, especially the physically protected organic matter, compared with conventional tillage systems.

**Materials and Methods**

This experiment was done on the tillage experiments that were established in the 1988/89 season at the Institute of Agricultural Engineering (IAE) in Harare (17°45' S; 31°10'E) and Domboshawa Training Centre (DTC) (17°35' S; 31°10'E) approximately 40 km NE of Harare. The IAE site is on red clay soil derived from gabbro parent material and is classified as Rhodic Paleustalf (USDA), Chromic Luvisol (FAO) and Harare 5E.2 (Zimbabwe). The DTC site is on a sandy soil derived from granitic parent material classified as Udic Kandiustalf (USDA), Areni-Gleyic Luvisol (FAO) and Harare 6G.3 (Zimbabwe). The clay mineralogy for both locations is predominantly kaolinite. Both sites are found in Natural Region II (annual rainfall 800-1000 mm) with most of the rain falling between November and March.

The tillage treatments at the sites were as follows:

1. **Mulch Ripping**- rip-between-row into residues (tine into residues)
2. **Clean Ripping**- rip-between-row without residues (tine into bare soil)
3. **Conventional tillage**- annual ox ploughing (single furrow mouldboard plough and spike harrow)
4. **No-till tied ridging**- permanent crop ridges at 1 in 100 grades
5. **Hand hoeing**- digging out plant holes with a hand hoe without residues
6. **Bare fallow**- annual tractor disc plough and disc harrow, no crops are grown

At these sites there were annual fertiliser additions of 350 kg compound D (8% N, 14% $P_2O_5$, 7% K) and 250 kg ammonium nitrate (34.5% N) per hectare. The total amounts of nutrients added were 114 kg N, 50 kg $P_2O_5$ (22 kg P) and 25 kg K per hectare. Maize was planted as the test crop.

Soil samples were collected in October 1998 and passed through a 2 mm sieve. Fifty grams soil was shaken overnight in 200 ml of 2% sodium hexametaphosphate after soaking the soil overnight for 16 hours. Soil was wet sieved through a series of sieves to separate 212-2000 μm, 53-212 μm, 20-53 μm fractions followed by separation of organic and mineral fractions in each size fraction by swirling and floating of the organic matter in water. The 0-5 and 5-20 μm fractions were separated by the sedimentation method but were not separated for organic and mineral fractions. Carbon in the organic matter fractions and the mixed fractions was analysed using a Leco Carbon Analyser.

Statistical analysis was done using GENSTAT 5 for analysis of variance (ANOVA).

**Results**

**Texture effects on organic matter content and distribution in size fractions**

When comparing within tillage treatments, total organic C contents were higher in the red clay than the sandy soil (Tables 1 and 2). Total organic C was almost three times higher for the red clayey soil than the sandy soil for all the treatments. The weedy fallow had the highest total organic C contents for both the red clay and the sandy soil with the red clay soil having higher C contents (27.9 mg C $g^{-1}$ soil) than the sandy soil (11.3 mg C $g^{-1}$ soil) (Tables 1 and 2). Of the tillage treatments, tied ridging had the highest total organic C content with 20.4 mg C $g^{-1}$ soil for the red clayey soil while for the sandy soil mulch ripping had the highest organic C content of 6.8 mg C $g^{-1}$ soil. For both soils organic C content was lowest in the conventional tillage treatment with the red clay having 14.9 mg C $g^{-1}$ soil and 4.2 mg C $g^{-1}$ soil for the sandy soil.

Coarse sand organic matter content (212-2000 μm) was higher in the red clayey soil than the sandy soil for the conventional and tied ridging treatments where organic matter content was almost twice as high in the former than in the latter (Tables 1 and 2). Coarse organic matter content was similar in the

red clay and the sandy soil for the other treatments. Organic matter content for the medium sand (53-212 μm) fraction was almost twice as high in the red clay soil than in the sandy soil except in the tied ridging treatment where organic matter was more than seven times as high in the clay soil than in the sandy soil. For the fine sand (20-53 μm) fraction, organic matter content was almost three times as high for the red clay soil than for the sandy soil. As the fraction size decreased the difference between the amount of organic matter in the sand and the clay soil increased with more organic matter being found in the clay soil.

Most of the organic matter was associated with the finer fractions for the red clay whilst for the sandy soil the greater proportion of the organic matter was associated with the coarse mineral (sand) particles. As the particle size decreased there was an increase in the amount of organic matter in the red clay soil whereas there was no difference in the amount of organic matter in the particle size fractions for the sandy soil (Tables 1 and 2).

**Tillage effects on soil organic matter contents of the size fractions**

For the red clayey soil clean ripping and conventional tillage had similar amounts of coarse and medium sand organic matter fractions although clean ripping had higher organic C content than conventional tillage (Table 1). In the fine sand fraction clean ripping had higher amounts of organic matter (10.1 mg $g^{-1}$ soil) than conventional tillage (8.0 mg $g^{-1}$ soil). Mulch ripping had higher total C, coarse and medium organic matter contents than clean ripping (Table 1). The fine sand associated organic matter content of conventional tillage was not significantly less than that of clean ripping. Of the tillage treatments, tied ridging had the highest organic C content and amount of sand organic matter fractions in the red clayey soil (Table 1).

Bare fallow resulted in the highest decline in soil organic matter content as indicated by the lowest total organic C content (2.2 mg C $g^{-1}$ soil) and smaller amounts of organic matter in each of the size fractions (Table 2). Conventional tillage had low total organic C contents and low amounts of organic matter in the size fractions in the sandy soil. Mulch ripping had higher total organic C content and amounts of organic matter in the coarse- and medium-sand fractions than clean ripping (Table 2). However the amount of organic matter in the fine sand fraction was not significantly larger for the mulch ripping treatment compared with the clean ripping treatment. Total organic C and amounts of organic matter in the sand fractions for tied ridging were not significantly different from the clean ripping treatment except for the medium sand fraction where clean ripping (2.2 mg $g^{-1}$ soil) had higher amounts of organic matter than tied ridging (1.5 mg $g^{-1}$ soil) (Table 2). Hand hoeing had lower total organic C content and organic matter in the sand fractions than mulch ripping except for the fine sand fraction where there were no significant differences (Table 2).

For both soils the highest decline in organic matter under the different tillage treatments was in the coarse sand organic matter fraction when compared with the weedy fallow (Tables 1 and 2). With decrease in the organic matter size fraction there was a decrease in the magnitude of the difference in the amounts of the organic matter fractions under different tillage treatments when compared with the weedy fallow.

**Tillage effects on organic C distribution in soil organic matter size fractions**

Cultivation of soil at the IAE site led to a decrease in total organic C and organic C in the organic matter size fractions. All tillage treatments led to a decrease in organic C distributed in the size fractions when compared with the reference point, the weedy fallow. The coarse sand organic matter fraction (212-2000 μm) showed the highest decline in organic C after cultivation from 4.47 mg $g^{-1}$ soil for the weedy fallow to as low as 0.97 mg C $g^{-1}$ soil for conventional tillage (Table 3). The 0-5 μm fraction showed the lowest decline in organic C under all the tillage treatments. This was shown by the small margin of difference of organic C in the 0-5 μm size fractions under the tillage treatments compared with the weedy fallow. The smallest decline in organic C was under tied ridging in the 0-5 μm organic matter size fraction where

there was no significant difference between organic C in the weedy fallow (23.5 mg C $g^{-1}$ soil) and tied ridging (18.8 mg C $g^{-1}$ soil).

Conventional tillage showed the highest decline in organic C in all the size fractions compared with the other tillage treatments and the weedy fallow. Tied ridging showed the least decline in organic C in all the organic matter size fractions (Table 3) as indicated by the high organic C in the organic matter size fractions compared with the other tillage treatments. Clean ripping had higher organic C contents in the organic matter size fractions except for the coarse sand organic matter fraction compared with conventional tillage but less than mulch ripping (Table 3).

At the Domboshawa site the bare fallow showed the highest decline in organic C in all the organic matter size fractions. This was more pronounced in the sand organic matter fractions where bare fallow had 0.05 mg C $g^{-1}$ soil compared with 2.85 mg C $g^{-1}$ soil for the weedy fallow (Table 4). In the clay size fraction bare fallow had 1.64 mg C $g^{-1}$ soil while the weedy fallow had 4.37 mg C $g^{-1}$ soil. Mulch ripping treatment had higher organic C contents in the organic matter size fractions than tied ridging. Mulch ripping had higher organic C (0.92 mg C $g^{-1}$ soil) than hand hoeing (0.63 mg C $g^{-1}$ soil) in the sand fractions (20-2000 μm) but had lower organic C contents in the finer fractions.

There was a differential treatment effect on total soil organic C and organic C in the organic matter size fractions caused by tillage for the two soils. Tied ridging had the highest organic C and C in the size fractions for the red clay soil (Table 3) and mulch ripping had the highest total organic C and C in the size fractions for the sandy soil (Table 4).

When organic C in the organic matter size fractions for both soils was totalled, recoveries of total organic C were not 100%. Higher organic C recoveries were obtained for the sandy soil than for the red clay soil. Organic C recoveries averaged 85% for the red clay soil (Table 3) and 95% for the sandy soil (Table 4).

## Discussion

### Effects of texture on organic matter content and distribution in size fractions

Total organic C was higher in the clay soil than in the sandy soil most likely due to lack of physical protection of organic matter from microbial attack in the sandy than in the clay soil, as well as larger residue inputs from roots due to greater productivity (Hassink, 1995; Hassink, 1996). The high clay content (~60% in the plough layer) in the clayey soil promotes formation of micro- and macro-aggregates which might physically protect soil organic matter from microbial decomposition and hence promote organic matter accumulation. This is unlike the sandy soil which has a low clay content (~5% in the plough layer) such that there is minimum aggregation and hence little organic matter accumulation. Hassink et al. (1997) observed a close relationship between silt and clay content, and organic C content of soil, with sandy soils having lower organic C in whole soil and fractions than clay soils.

The difference of organic matter contents of the coarse sand fractions for the red clay and the sandy soil was small but the differences increased as the fraction size decreased. Organic matter in the finer fractions is protected from microbial decomposition and hence the increase in the margin of the difference in organic matter content as the fraction size decreases for the red clay soil compared with the sandy soil, mainly due to the higher proportion of finer fractions in the clay soil. As a result of this much of the organic matter in the clayey soil tends to be associated with the finer particles.

### Tillage effects on soil organic matter fractions and organic C in the organic matter fractions

Bare fallow involves ploughing of plots every year without planting anything and this enhances soil erosion resulting in soil organic matter loss. Ploughing the soil enhances organic matter decomposition by disrupting aggregate protected organic matter. This could have resulted in lower soil organic C and N when compared with the other tillage treatments. This supports the findings of Cambardella and Elliot (1994) who found that bare fallow soil had significantly less total organic C and N than mulch tillage and no-till soils. Cambardella and Elliot (1992) demonstrated that loss of coarse organic matter under a bare fallow treatment amounted to 70% of that of native grass over a period of twenty years.

For the red clayey soil clean ripping and conventional tillage had similar organic matter contents in the coarse and medium sand fractions probably because no residues were added to the soil in both treatments and hence they received similar and small amounts of organic inputs. In the fine sand, however, clean ripping had higher organic matter contents than conventional tillage probably due to reduced tillage for the clean ripping treatment such that there was reduced disruption of the soil resulting in reduced organic matter decline compared with conventional tillage. The higher coarse sand organic matter content in the mulch ripping treatment (34.8 mg $g^{-1}$ soil) compared with 26.8 mg $g^{-1}$ soil in the clean ripping treatment was probably because of organic residues that are added on the surface for the mulch treatment (Table 1). Total soil organic C and organic matter in the finer fractions was not significantly different for the two treatments probably because both treatments involve minimum tillage such that organic matter in the finer fractions is not affected by tillage. The two treatments are similar in terms of tillage intensity hence organic matter in the finer fractions was similar. Since much of the organic matter for the clay soil is associated with the finer fractions the difference in total organic C content of the two treatments was not significantly different. Tied ridging involves planting of maize on permanent ridges where tillage is reduced to opening of planting holes such that there is minimum soil disruption and hence greater organic matter accumulation.

Conventional tillage had low total organic C contents and organic C in the SOM fractions than conservation tillage practices mainly because of the high tillage intensity which enhance organic matter loss from the soil (Hassink, 1995) and small organic matter additions to the soil (Yang and Wander, 1999). Dalal et al. (1991) observed that in the top soil layers the interactive effects of zero tillage and returning of residues resulted in high organic C contents when compared with conventional tillage and zero tillage with residue burning. Work done by Arshad et al. (1990) showed that organic C and total N were 26% greater following 10 years of zero tillage compared with conventional tillage in the upper 7.5 cm of a silt loamy soil.

Lower organic matter contents for conventional tillage when compared with the conservation tillage treatments were most likely a result of aggregate formation and turnover processes. Conservation tillage practices allow for slow macroaggregate turnover resulting in the formation of fine particulate organic matter and the subsequent encapsulation of the fine particulate organic matter by mineral particle and microbial by-products to form stable microaggregates (Six et al., 2000). In contrast the turnover of macroaggregates in conventional tillage is fast, providing less opportunity for the formation of crop derived fine particulate organic matter and stable microaggregates (Six et al., 2000).

Mulch ripping had higher total organic C content (6.8 mg C $g^{-1}$ soil) and organic matter in the coarse- (46.8 mg $g^{-1}$ soil) and medium (42.6 mg $g^{-1}$ soil) sand fractions than clean ripping for the sandy soil (Table 2). This was possibly due to the addition of organic residues under the mulch ripping treatment, which resulted in higher organic matter in the coarse- and medium sand fractions than clean ripping. This could have resulted in higher total organic matter under mulch ripping than clean ripping because much of the organic matter in the sandy soil is associated with sand particles and hence the larger sand size fraction organic matter with mulch ripping resulted in higher total organic matter content. Hand hoeing involves reduced tillage and hence had high organic matter contents although it was lower than mulch ripping.

There was a decrease in organic C in the organic matter fractions and total soil organic C for all the tillage treatments on the two soils compared with the weedy fallow (Tables 3 and 4). This was maybe because cultivation disrupts aggregate protected organic matter and enhances its decomposition. The largest decline of organic C in the organic matter fractions was in the sand fractions under conventional tillage, 4.47 mg C $g^{-1}$ soil for the weedy fallow compared with 0.97 mg C $g^{-1}$ soil for conventional tillage on the red clay soil (Table 3) and 2.85 mg C $g^{-1}$ soil for the weedy fallow compared with 0.05 mg C $g^{-1}$ soil for conventional tillage on the sandy soil (Table 4). This was probably because of the absence of the annual litter additions under conventional tillage compared with the weedy fallow. Conventional tillage also involves intensive cultivation of the soil promoting soil organic matter decomposition and subsequent loss from the system. For all the tillage treatments, however, the largest organic C decline occurred in the coarse organic matter fractions probably as a result of physical disintegration of soil

aggregates associated with SOM decomposition and mineralization (Tiessen and Stewart, 1983). Tied ridging showed the least decline in organic C in the 0-5 μm fraction probably due to minimum tillage practised under tied ridging resulting in minimal disruption of aggregates.

These results confirm the findings of Cadisch et al. (1996) and Barrios, Buresh and Sprent (1996b), that coarse organic matter (light fraction) is an early indicator of changes in soil fertility and is the fraction most affected by cropping systems. Chan (1997); Hassink et al. (1997) also observed that the light fraction is lost more rapidly than other fractions. Under forest conditions, the light fraction was shown to be a strong short-term sink of N incorporating more than 50% of added N while the heavy (fine) fraction incorporated less than 5% after an 18 hour incubation (Compton and Boone, 2002). Work done by Lehmann et al. (1998), however, showed that short-term addition of Senna and Gliricidia leaves resulted in an increase in C and N in the silt and clay fractions.

Bare fallow involves annual ploughing without planting anything without any input additions. This induces soil erosion which is associated with soil organic matter loss showing a large decline in organic C in all the organic matter fractions in the bare fallow treatment compared with the weedy fallow and other treatments (Table 4). Unlike for the red clayey soil, mulch ripping had higher organic C in all the organic matter fractions than tied ridging probably due to low clay content such that there is little physical protection of organic matter for the sandy soil.

Results from this study indicate that there were higher soil organic matter losses under conventional tillage when compared with the other tillage treatments for both soils. This was maybe caused by the differing degrees of disruption of soil aggregates under the different management practices. Beare et al. (1994a) showed that after 13 years of conventional and no-tillage management resulted in 18% greater standing stock of soil organic C in the plough layer of no-tillage soil than conventional tillage soil. Beare et al. (1994b) also showed that the largest water stable aggregates were more abundant in the surface samples of no-till soil and that these aggregates were more stable and contained higher concentrations of C and N than did water stable aggregates under conventional tillage.

**Tillage effects on maize yield and surface runoff**

Soil organic matter results were supported by maize yields and runoff loss results that were observed in the same experiment. Conservation tillage practices had higher maize yields and lower runoff losses than conventional tillage although there were seasonal variations. The variations were mainly a result of differences in the rainy seasons with some seasons being wet while some seasons were dry (Figs 1 and 2).

In most seasons tied ridging gave higher grain yields for both soils because of the moisture benefits associated with tied ridging (Nehanda, 2000). The improvement in water use efficiency caused by tied ridging, which also had high organic matter contents could have possibly resulted in an increase in nutrient use efficiency resulting in higher yields. The higher maize yields under tied ridging were most likely associated with high root biomass additions to the soil and hence the high soil organic matter contents. In drier years conventional tillage gave higher yields because of less vigorous growth associated with crops under conventional tillage such that their moisture demands were lower. When however averaged across season, conventional tillage had the lowest maize yields. These results imply that conventional tillage causes faster soil degradation with increased soil organic matter decline, nutrient loss and susceptibility of soil to erosion, faster soil fertility decline and lower crop yields in the long run (Doran et al., 1987; Franzlubbers and Arshad, 1996; Feller and Beare, 1997). Higher grain yields were obtained for the red clay soil than the sandy soil due to the high water and nutrient holding capacity of the clay soil.

Conventional tillage resulted in higher surface runoff for both soils because tillage loosens soil making it prone to rain drop impact and detachment (Figs 3 and 4).

Conventional tillage had double surface runoff compared with the other tillage treatments while the other treatments had minimum surface runoff. The bare fallow treatment for sandy soil had the highest surface runoff losses because of the lack of a crop to cover the soil and protect the soil from being washed away from the soil surface. Surface runoff for the two soils was not different perhaps because the two sites receive similar rainfall. These results are similar to total C and organic C in the SOM fractions,

where low organic C contents were observed under the bare fallow treatment and with high runoff losses, some of the organic could have been lost through erosion.

**Conclusion**

At the IAE site conventional tillage led to a high decline in total organic C content (14.9 mg C $g^{-1}$ soil) and organic C in the organic matter fractions compared with tied ridging (27.9 mg C $g^{-1}$ soil) that promoted organic matter accumulation. For the sandy soil there was higher total organic C and organic C in the organic matter fractions under the mulch ripping treatment while conventional tillage led to higher organic C degradation. This means that tied ridging conserves organic C for the red clayey soil while mulch ripping conserves organic C in the sandy soil compared with the other tillage treatments tested. Higher organic matter loss was observed for the sandy soil with up to 61% organic C decline following conversion from the weedy fallow to conventional tillage. This was much higher compared with 47% organic C decline under the same conversion for the clayey soil. This means that sandy soils degrade faster than clayey soils under the same management practices because they have lower capacity to protect soil organic matter. Higher crop yields on the red clay soil also resulted in higher organic matter additions to the soil through root biomass compared with the sandy soil.

Cultivation when compared to the weedy fallow results in the faster turnover and decline of organic matter especially in the coarse fractions. Conventional tillage resulted in faster losses of coarse organic matter than conservation tillage practices as there are no organic inputs and in the finer fractions because it does not allow for the formation of stable microaggregates.

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Figures 1 – 4 missing

**Table 1 A comparison of tillage effects on organic matter in a red clay soil from the Institute of Agricultural Engineering, Harare**

| Tillage treatment | Total organic C mg $g^{-1}$ soil | Weight of organic matter fractions (mg $g^{-1}$ soil) | | |
|---|---|---|---|---|
| | | 212-2000 µm Coarse sand | 53-212 µm Medium sand | 20-53 µm Fine sand |
| Conventional tillage | 14.9 | 2.7 | 3.6 | 8.0 |
| Clean ripping | 16.8 | 2.6 | 5.2 | 10.1 |
| Mulch ripping | 17.2 | 3.4 | 6.3 | 10.2 |
| Tied ridging | 20.4 | 6.1 | 12.7 | 11.4 |
| Weedy fallow | 27.9 | 22.5 | 19.7 | 17.8 |
| SED | 0.6 | 0.278 | 1.204 | 1.091 |

(NB Fractions less than 20 µm (silt and clay) are not shown in the table because organic matter was not separated from the mineral particles.)

**Table 2 A comparison of tillage effects on organic matter in the sandy soil from Domboshawa Training Centre**

| Tillage treatment | Total organic C mg $g^{-1}$ soil | Weight of organic matter fractions (mg $g^{-1}$ soil) | | |
|---|---|---|---|---|
| | | 212-2000 µm Coarse sand | 53-212 µm Medium sand | 20-53 µm Fine sand |
| Bare fallow | 2.2 | 0.23 | 0.6 | 0.6 |
| Conventional tillage | 4.2 | 1.7 | 1.5 | 1.7 |
| Clean ripping | 4.6 | 2.9 | 2.2 | 2.6 |
| Tied ridging | 4.8 | 3.1 | 1.5 | 2.1 |
| Hand hoeing | 6.0 | 3.4 | 2.1 | 3.1 |
| Mulch ripping | 6.8 | 4.7 | 4.3 | 3.6 |
| Weedy fallow | 11.3 | 10.5 | 8.6 | 6.9 |
| SED | 1.1 | 0.552 | 0.331 | 0.525 |

(NB Fractions less than 20 µm (silt and clay) are not shown in the table because organic matter was not separated from the mineral particles.)

Table 3 Tillage effects on organic carbon distribution in soil organic matter size fractions of a red clay soil in Harare

| Tillage treatment | Organic C in SOM size fractions (mg C $g^{-1}$ soil) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 212-2000 µm coarse sand | 53-212 µm Medium sand | 20-53 µm Fine sand | 5-20 µm Silt | 0-5 µm Clay | Sum | Total measured | % Recovery |
| Conventional tillage | 0.97 | 0.95 | 0.84 | 1.69 | 8.1 | 12.6 | 14.9 | 84.6 |
| Clean ripping | 1.05 | 1.21 | 0.96 | 1.90 | 8.7 | 13.8 | 16.8 | 82.1 |
| Mulch ripping | 1.04 | 1.34 | 1.00 | 2.09 | 9.0 | 14.5 | 17.2 | 84.3 |
| Tied ridging | 1.93 | 1.64 | 1.47 | 2.66 | 10.1 | 17.8 | 20.4 | 87.3 |
| Weedy fallow | 4.47 | 3.57 | 1.90 | 3.15 | 10.4 | 23.5 | 27.9 | 84.2 |
| SED | 0.167 | 0.187 | 0.091 | 0.118 | 0.242 | | 0.6 | |

NB n=3 except for the weedy fallow where n=1

**Table 4 Tillage effects on organic carbon distribution in soil organic matter size fractions of a sandy soil at Domboshawa Training Centre**

| Tillage treatment | Organic C in SOM size fractions (mg C $g^{-1}$ soil) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 212-2000 µm coarse sand | 53-212 µm Medium sand | 20-53 µm Fine sand | 5-20 µm Silt | 0-5 µm Clay | Sum | Total measured | % Recovery |
| Bare fallow | 0.05 | 0.07 | 0.10 | 0.14 | 1.64 | 2.0 | 2.2 | 90.9 |
| Conventional tillage | 0.47 | 0.35 | 0.24 | 0.24 | 2.7 | 4.0 | 4.2 | 95.2 |
| Clean ripping | 0.53 | 0.37 | 0.33 | 0.34 | 3.0 | 4.5 | 4.6 | 97.8 |
| Tied ridging | 0.66 | 0.37 | 0.39 | 0.30 | 3.0 | 4.7 | 4.8 | 97.9 |
| Hand hoeing | 0.63 | 0.40 | 0.48 | 0.43 | 3.66 | 5.6 | 6.0 | 93.3 |
| Mulch ripping | 0.92 | 0.87 | 0.60 | 0.40 | 3.89 | 6.7 | 6.8 | 98.5 |
| Weedy fallow | 2.85 | 1.97 | 0.99 | 0.65 | 4.37 | 10.4 | 11.3 | 92.0 |
| SED | 0.183 | 0.112 | 0.075 | 0.131 | 0.657 | | 1.1 | |

NB n=3 except for the weedy fallow where n=1

*Draft*

***Towards Addressing Land Degradation in Ethiopian Highlands: Opportunities and Challenges***

Tilahun Amede
TSBF-CIAT, AHI, Ethiopia

**Introduction**

Land resource degradation is one of the major threats to food security and natural resource base in Ethiopia. Hundreds of years of exploitve traditional land use, aggravated by high human and livestock population density have led to the extraction of the natural capital, which caused the farming of uncultivable sloppy lands and overexploitation of slowly renewable resources. The outcome is that half of the highlands are eroded, of which 15% are so seriously degraded that it will be difficult to reverse them to be agriculturally productive in the near future. In the mountainous highlands, there is a direct link between land-based resources and rural livelihoods. Decline in soil fertility as a result of land degradation decreases crop/livestock productivity and hence household income. Depleted soils commonly reduce payoffs to agricultural investments, as they rarely respond to external inputs, such as mineral fertilizers, and hence reduce the efficiency and return of fertilizer use. Degraded soils have also very poor water holding capacity partly because of low soil organic matter content that in turn reduce the fertilizer use efficiency. There have been various attempts to reduce land degradation in Ethiopia since the 1970s, through national campaigns on construction of terraces, project afforstation programmes and policy interventions. The objective of this paper is to review the various research/development experiences on integrated soil fertility management and synthesize the positive experiences augumented by the experiences of the African highlands initiative on integrated land management in Ethiopian Highlands. The paper will also suggest an outline that could be used by farmers, researchers and policy makers to reverse the alarming trend of land degradation in the mountainous highlands.

This work has consulted the available literature on land degradation and soil fertility management in Ethiopian highlands. While TSBF-CIAT/AHI has been working closely with the Ethiopian Agricultural Research Organisation (EARO) and the Buro of Agriculture, and conducting participatory research in two benchmark sites of the Ethiopian highlands on INRM issues, it became apparent that land degradation is the most fundamental threat for the Ethiopian Agriculture. Based on the systems intensification work that we have been conducting in the two benchmark sites of African highlands initiative, Areka and Ginchi, augmented by secondary data on relevant themes, the following approach was suggested to address land degradation in the country.

***Root Causes of Land Degradation in the mountainous highlands***

There are multiple factors that cause land degradation at short and long terms in the region. In Sub Saharan Africa, the major bio-physical agents of land degradation are water erosion, wind erosion and chemical degradation that affected soil loss by 47, 36 and 12%, respectively. Given the mountainous and sloppy landscapes, the major environmental factor that causes considerable soil and nutrient loss within a short period of time is water erosion followed by wind erosion. Most of the Wollo and Shewa highlands became erosion-prone due to high rainfall intensity accompanied by very steeply farmlands. Recent surveys showed that erosion effect is severe in high rainfall areas predominantly covered by nitisols and vertisols. In about 40% of the highlands, the erosion effect was so severe that active erosion was transformed to passive erosion, and hence there are rarely visible signs of sheet or rill erosion, but gullies and land slides. The hazards of erosion in the region was accelerated by socio-economic factors, namely absence of land ownership rights that discourage long term investments, population pressure, lack of alternative income generating options, and weak social capital that failed to protect communal grazing lands, up-slope forest covers and water resources.

Although the degree of soil erosion is highly related to the interaction of Wischmeier factors, the

type of land use and management may have played an important role in the Ethiopian highlands. The contribution of different management factors towards land degradation in Africa is estimated to be 49%, 24%, 14%, 13% and 2% for overgrazing, agricultural activities, deforestation, overexploitation and industrial activities (Vanlauwe et al, 2002). The livestock sector is a very important component of the system both as an economic buffer in times of crop failure and economic crisis and as a supportive enterprise for crop production. There is a considerable concern, however, that the number of animals per household in Ethiopian highlands is much higher than the carrying capacity of land resources. Overgrazing due to very high livestock population density in the Amhara region is expected to contribute most to land degradation. For instance, the total annual feed available in the highlands is estimated to be about 9.1 million tones of biomass while the demand is about 21 million tones, double that of the carrying capacity of the land (Betru, 2002). Another very important factor that aggravated land degradation in the Ethiopian highlands is deforestation. The forest cover went down from 40% at the beginning of this century to less than 3% at present, due to ever-growing demand for wood products and very low commitment in planting trees mainly because of the prevailing nationalization of private woodlots in the 1970s and 1980s. Besides, a very high consumption of wood for fuel and housing, wood products, mainly charcoal, became a major cash generating activities in the country in recent years. Deforestation and overgrazing accelerated land degradation in many ways. Firstly a land without vegetative cover is easily susceptible to erosion, both wind and water, and hence causes a considerable nutrient movement. Secondly, a large amount of litter that could have contributed for maintaining soil organic matter and nutrient status is considerably reduced. Thirdly deforestation in the highlands caused lack of fuel wood, and hence farmers use manure and crop residue as cooking fuel, which otherwise could have been used for soil fertility replenishment.

Over-mining of land resources with out returning the basic nutrients to the soil is also an important factor that contributed most for soil fertility decline in the region. For instance, barley is the single dominant crop in the upper highlands of Wollo. The system has very low crop diversity with legume component of less than 3%. The system receives external inputs very rarely with a fertilizer rate of less than 5 kg/ha (Quinones et al., 1997), and the practice of applying this limited amount of mineral fertilizer is a recent practice. Data from the region on the amount of nutrients returned to the soil in comparison to the nutrients lost through removal of crop harvest showed that only 18, 60 and 7 % of nitrogen, phosphorus and potassium is returned to the soil, respectively (Sanchez et al., 1997). Hence there is an over mining of nutrients from the same rhizosphere for years and years.

Another cause of land degradation is lack of early awareness about land degradation by farmers, which is partly associated with the rural poverty. McDonagh, et al., (2001) reported that when farmers were asked to describe their indicators of soil erosion they stated gully/rill formation, exposed underground rocks, land slides, wash away of crops, shallowing of soils and siltation of the soil. Similarly farmers indicators of soil fertility decline include stunted crops, yellowing of crops, weed infestation, and change of soil color to red or grey. These are soil traits that appear in a much later stage of soil degradation, after the soil organic matter and nutrients of the soil are removed. If farmers respond to soil erosion at this stage, the probability of reversing the fertility status to its earlier value would be difficult.

### *Towards Integrated Soil Fertility Management*

Application of small amounts of mineral fertilizer alone, as it has been practiced on the 0.5 ha demonstration plots by FAO and the ministry of Agriculture for years, did not improve crop productivity much. The failure of this mono-technology approach calls for an integrated nutrient management that suits local biophysical, social and economic realities. Integrated nutrient management technologies can be nutrient saving, such as in controlling erosion and recycling of crop residues, manure and other biomass, or nutrient adding, such as in applying mineral fertilizers and importing feed stuffs for livestock (Smaling and Braun, 1996).

The traditional field operation in the Ethiopian highlands, which could be characterized by multiple tillage, cereal-dominated cropping and very few perennial components in the system, is very

erosive for soils and nutrients. Continual farming in the high lands with out considering conservation measures caused severe land degradation. FAO study in Zimbabwe showed that each hectare of well-managed maize growing land lost 10 tones of soil. Depleted soils commonly reduce payoffs to agricultural investments for various reasons. Degraded soils rarely respond to external inputs, such as mineral fertilizers, and hence reduce the efficiency and return of fertilizer use. Degraded soils have also very poor water holding capacity partly because of low soil organic matter content that in turn reduce the fertilizer use efficiency. Results from the dry regions of Niger, Sadore, showed that application of fertilizer increased the millet yield by 71% and also improved the water use efficiency by 70% (Bationo et al., 1993). Hence improved soil fertility enhances the water use efficiency of crops in drought prone areas. Low soil organic matter accompanied by low soil water content may also reduce the bio-chemical activity of the soil that may affect the above and below ground biodiversity of the system. Degraded soils have also low vegetative cover that may accelerate further soil loss and runoff.

The effect of soil fertility decline goes beyond nutrient and water losses. There are conviencing results showing that the incidence of some pests and disease is strongly associated with decline in soil fertility. Results from the Amhara and Tigrai region showed that the effect of the notorious parasitic weed, striga, on maize and sorghum was severe in nutrient depleted soil (Esilaba, et al, 2001). It was possible to decrease the population & the incidence of striga significantly by improving the fertility status of the soil through application of organic fertilizers. Similarly the incidence of root rots in beans, stem maggots in beans, take all in barely and wheat is associated with decline in soil fertility (Marschner, 1995). The positive effect of application of organic and inorganic fertilizer on the resistance of the host crop is mainly through improving the vigorosity of the plant at the early phonological stages.

Amede et al., (2001) outlined the need for a combination of measures to reverse the trend of soil fertility decline in the African highlands as presented in the following section.

*1. Community-based soil and water conservation measures*

There are about 40 different types of indigenous soil and water conservation practices in different parts of the Ethiopian highlands, ranging from narrow ditches on slopping fields in Wollo highlands to the most advanced & integrated conservation measures in Konso, Southern Ethiopia. However, those indigenous practices are location specific and variable in their effectiveness, and call for closer understanding before any attempt is done for scaling-up. However, there is a consensus among actors that any attempt to protect land resources and improve productivity in the sloppy highlands should integrate system-compatible soil conservation measures. Research conducted in Andit tid and Gununo showed that increasing the vegetation cover of the soil could decreases soil loss and runoff significantly (SCRP, 1996). In Andit tid, the amount of soil loss due to water erosion was 230 t/ha/year under hacked plots. However, it was possible to reduce the soil loss to 30 t/ha or less under crop covers or fallow grasslands (SCRP, 1996). When a cropland covered by crops or grasslands is compared to a frequently hacked farmland, run-off was reduced by about 90 and 100 % and soil loss by 68%, respectively. Hence soil nutrient loss and runoff could be minimized through increasing the frequency of crop cover, especially by those crops with mulching habits and higher leaf area indexs. Moreover, results from SCRP showed that perennial crops like enset and fruit trees or annuals with mulching and runner habits could reduce erosion effects significantly. Recent simulation modules in Northern Ethiopia showed that crop lands allocated for cereal crops like teff were very prone to erosion (Woldu, 2002), and the authors proposed that growing small seeded cereals, like teff, in sloppy farmlands should be discouraged.

There has been an attempt to control soil erosion and rehabilitate degraded lands through construction of farmland terraces in the Ethiopian Highlands starting from the early 1970s. The program was facilitated through the food-for-work scheme of the World Food Program, as a response to the frequent droughts of the 70s and 80s in Ethiopia. The program attempted to construct terraces on about 4 millions of hectares of farm land. In early 1990s, the annual physical construction of farmland terraces reached over 220,000 ha (Lakew, et al, 2000). However, as the campaign was trying to address the problem with out the full participation of the rural community, except selling labor, the farmers

considered the activity as an external imposition and hence failed to develop sense of ownership. The consequence being that farmers failed to maintain the terraces and, in some case, farmers have destroyed the terraces for getting another round of payment. When farmers were asked to list the reasons for rejecting soil and water conservation technologies they listed five major driving forces (Amede, 2002, unpublished) namely high labor cost, decreased farm size due to terraces, its inconvenience during farm operations especially for U-turn of oxen plough, and inefficiency of the terraces to stop erosion as they were only physical structures without any biological component and technical follow-ups. By considering those farmers criteria and by adopting participatory planning and implementation approaches farmers have adopted and disseminated soil conservation technologies in one the African Highlands Initiative benchmark sites, Areka (Amede et al, 2001). The major driving force for the adoption of the technology was its integration with high value crops (e.g. bananas, hops) and fast growing drought resistant feeds (e.g. Elephant grass, pigeon pea) grown on the soil bunds. The sustainable integration soil & water conservation technologies also depend heavily on the effectiveness of by-laws that limit free grazing and free movement of animals especially during the dry spells. This requires the empowerment of the local and regional policies so as to facilitate the integration of natural resource management technologies to practices of local communities. Moreover, effective landscape management, in terms of controlling soil erosion, is possible only when there is a community collective action. Unless the landscape is treated as a single unit and involves all potential stakeholders, any individual intervention could provoke social conflicts. For instance, construction of soil conservation bunds and deforestation of forests at the upper slope of the Lushoto highlands, Tanzania, decreased the amount of water flew to the valley bottoms, and affected the vegetable production and income of other farmers.

*2. Integrated Soil Fertility Management options*

Building the organic matter of the soil and the nutrient stock in short period of time requires a systems approach. These include the combination of judicious use of mineral fertilizers, improved integration of crops and livestock, improved organic residue management through composting and application of farmyard manure, deliberate crop rotations, short term fallowing, cereal-legume intercropping and integration of green manures. Because of the inconsistent use of mineral fertilizers and the very limited returns of crop residues to the soil, most of the internal N cycling in small holder systems results from mineralization of soil organic N. Such process may contribute most of the N for the annual crops until the labile soil organic fraction (N-capital) are depleted (Sanchez et al., 1997).

Apart from the occasional application of small amounts of mineral fertilisers, all other organic resources form the principal means of increasing soil nutrient stocks and hence soil fertility restorers in small-scale farms. If these approaches are used in combination and appropriately, they could reverse the trend and consequently increase crop yields and, thereby alleviate food insecurity. However, the continued low yields are an indication of insufficient inputs and/or inappropriate use of these technologies. The majority of the small-scale farmers are still aggravating the soil/plant nutrient deficit through improper land management and over-mining of the nutrient pool. However, there is still an opportunity to replenish the soil nutrient pool using integrated approaches depending on the degree of soil degradation, the production system and the type of nutrient in deficit.

One potential source of organic fertilizer is farmyard manure. There is a large number of livestock in the Amhara region that could produce a considerable amount of manure to be used for soil fertility replenishment. However, there is a strong competition for manure use between soil fertility and its use as a cooking fuel. Recent survey in the upper central highlands of Ethiopia showed that more than 80% of the manure is used as a source of fuel. Only farmers with access to fuel wood could apply manure in their home steads. Experiences from Zimbabwe showed that most manures had very low nutrient content, N fertlizer equivalency values of less than 30%, sometimes with high initial quality that did not explain the quality of the manure at times of use (Murwira et al., 2002). This could be explained by the fact that most manures were not composed of pure dung but rather a mixture of dung and crop residues from the stall. Besides the quality the quantity of manure produced on-farm is limited. Sandford (1989) indicated that to produce sufficient manure for sustainable production of 1-3 tonnes/ha of maize it

requires 10-40 ha of dry season grazing land and 3 to 10 of wet season Range land, which is beyond the capacity of Ethiopian farmers. Moreover, the potential of manure to sustain soil fertility status and productivity of crops is affected by the number and composition of animals, size and quality of the feed resources and manure management. Wet season manure has a higher nutrient content than dry season manure, and pit manure has a better quality than pilled manure. Similarly, Powell (1986) indicated that dry season manure had N-content of 6 g/kg compared with 18.9 g/kg for early rainy season manure when the feed quality is high.

Another potential organic source is crop residue. Returning crop residue to the soil, especially of legume origin, could replenish soil nutrients, like nitrogen. However, there is strong tradeoff for use of crop residue between soil fertility, animal feed and cooking fuel. In the upper Ethiopian highlands crop residues are used as a major source for dry season feed and supplementary for wet season feed. Hence little is remaining as a crop aftermath to the soil. Although legumes are known to add nitrogen & improve soil fertility, the frequency of legumes in the crop sequence in the upper highlands is less than 10%, which implies that the probability of growing legume on the same land is only once in ten years. The most reliable option to replenish soil fertility is, therefore, promoting integration of multipurpose legumes into the farming systems. Those legumes, especially those refereed as legume cover crops, could produce up to 10 ton/ha dry matter within four months, and are also fixing up to 120 kg N per season (Giller, 2002). Those high quality legumes adapted to the Ethiopian highlands include tephrosia, mucuna, crotalaria, canavalia, and vetch (Amede & Kirkby, 2002). However, despite a significant after effect of LCCs on the preceeding maize yield (up to 500% yield gain over the local management) farmers were reluctant to adopt the legume technology because of trade-off effects for food, feed and soil fertility purposes (Amede, unpublished data, 2002). In an attempt to understand factors affecting integration of soil improving legumes in to the farming systems of southern Ethiopia, Amede & Kirkby (2002) identified the most important socio-economic criteria of farmers namely, land productivity, farm size, land ownership, access to market and need for livestock feed. By considering the decision-making criteria of farmers on which legumes to integrate into their temporal & spatial niches of the system, it was possible to integrate the technology to about 10% of the partner farmers in southern Ethiopia.

Organic resources may provide multiple benefits through improving the structure of the soil, soil water holding capacity, biological activity of the soil and extended nutrient release, but it could be unwise to expect the organics to fulfil the plant demand for all basic nutrients. Most organic fertilizers contain very small quantities of some nutrients (e.g. P and Zn) to cover the full demand of the crop, and hence mineral fertiliser should supplement it. Combined application of organic fertilizers with small amount of mineral fertilizers was found to be promising route to improve the efficiency of mineral fertilizers in small holder farms. For instance, Nziguheba et al., (2002) indicated that organic resources enhanced the availability of P by a variety of mechanisms, including blocking of P-sorption sites and prevention of P fixation by stimulation of the microbial P uptake. Long term trials conducted in Kenya on organic and mineral fertiliser interaction also showed that maize grain yield was consistently higher for 20 years in plots fertilised with mineral NP combined with farmyard manure than plots with sole mineral NP or farmyard manure (S.M Nandwa, KARI, unpublished data 1997). Although most farmers are convinced of using farm-based organic fertilisers, they are challenged by questions like which organic residue is good for soil fertility, how to identify the quality of organic resource, how much to apply, when to apply, and what should be the ratio of organics to mineral fertilisers. This calls for development of decision support guides to support farmers' decision on resource allocation and management. Scientists from Tropical Soils Biology and Fertility Institute of CIAT developed decision guide to identify the quality of organic fertilisers based on the polyphenol, lignin and nutrient content as potential indicators (Palm et al., 1997). As those parameters demand laboratory facilities and intensive knowledge, Giller (2000) simplified the guide by translating it to local knowledge as highly astrigent test (high polyphenol content), fibrous leaves and stems (high lignin content) and green leaf colour (high N content) to make the guides usable to farmers.

In general, there is an increasing trend of mineral fertilizer use in the Ethiopian highlands over the past decades, and fertilizer imports into the country have increased from 47000 tonnes N & P in 1993 to

137 000 tones in 1996 (Quinones et al., 1997). It was mainly as a result of a strong campaign of Sasakawa-Global 2000 in collaboration with the Buro of Agriculture. However, there is a declining trend in fertilisers use in 2001/2002 due to increasing cost of fertilizers, lack of credit opportunities to resource poor farmers and low income return due to market problems.

*3. Systems Approach to INRM*

Sustainable rural development and natural resource management in the region demands an investment in and improvement of the natural capital, human capital and social capital. As the natural capital in the region had multiple problems that needs multiple solutions, there is a strong need for holistic approach to deliver options for clients of various socio-economic categories.

Given the complexity of the problem of land degradation, and its link to social, economical and policy dimensions, it requires a comprehensive approach that combines local and scientific knowledge through community participation, capacity building of the local actors through farmers participatory research and enhanced farmer innovation. This approach requires the full involvement of stakeholder at different levels to facilitate and integrate social, biophysical and policy components towards an improved natural resource management and sustainable livelihoods (Stroud, 2001). Watershed management as a unit of planning and change imposes the need for increased attention to issues of resource conservation and collective action by the community. The issues of land degradation may include afforstation of hillsides, water rehabilitation and/or harvesting and soil stabilization, soil fertility amendment through organic and mineral fertilizers and increasing vegetation cover by systematic use of the existing land and water resources. This could be achieved by working closely with communities and policy implementers in identifying and implementing possible solutions to address land degradation and other common landscape problems, like grazing land improvement, gully stabilization and by monitoring and documenting the processes for wider dissemination and coverage.

Some of the watershed conservation related solutions should be tried and implemented on specific test locations using farmers' own contribution and the INRM team's technical supervision. However, a wider application of these solutions to larger areas may require attracting additional funding investments from the district, donors or other NGOs in the area. The local village communities may also effect changes in the norms and rules governing the use of natural resources in their vicinity. Traditional rules and local by-laws (e.g. written and unwritten and called "afarsata" or awatcheyache) regarding the use and sharing of resources exist in most villages and these need to be identified and studied with a view to effect reform or renew their emphasis in the community. Integration of Agroforestry technologies in the farming systems of the Ethiopian highlands failed because of absence of national and/or local policies /by-laws that prohibit free grazing and movement of animals in the dry season. Experiences from the 1980s campaign of 'Green Campaign' in Ethiopia also showed that it is almost impossible to address the issue of land degradation without the full involvement and commitment of the local community. The local by-laws in resource arrangement and use should be facilitated and supported, as the rules and regulations at the local level could be implemented effectively through elders and respected members of the community with tolerance and respect. There may be a church and/or witchcraft dimensions to these, and there may be changes over time that might help to understand why people are doing what they are doing. In addition, the influence of national and regional policies on local resource management should be understood. These will form an important subject of community wide discussion and deliberation (Stroud, 2001). The current undertaking of soil and water conservation practices through voluntary participation campaign of the community in the northern Ethiopian Highlands is one positive step forward for initiating collective action.

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**Soil fertility management for sustainable land use in the West African Sudano-Sahelian zone.**

A Bationo[1], U. Mokwunye[2], P.L.G. Vlek[3], S. Koala[4] and B.I. Shapiro[5].
[1] A Bationo, T.S.B.F., P.O. Box 30592, Nairobi, Kenya
[2] United Nations University, University of Ghana, Legon, Ghana
[3] Zentrum fuer Entwicklungsforschung (ZEF University of Bonn), Center for Development Research, Friedrich-Wilhelm-Universitaet Bonn, Walter-Flex-Strasse 3, D-53113 Bonn, Germany
[4] ICRISAT, B.P. 12404, Niamey, Niger
[5] ICRISAT, B.P. 320, Bamako, Mali

**Introduction**

The Sudano-Sahelian zone of West Africa (SSZWA) is the home of the world poorest people, 90% of whom live in villages and gain their livelihood from subsistence agriculture. Per capita food production has declined significantly over the past three decades. According to FAO, total food production in Sahelian countries grew by an impressive 70% from 1961 to 1996, but it lagged behind the population which doubled, causing food production per capita to decline approximately by 30% over the same period (Bationo, 1996).

Low, erratic rainfall and high soil temperature, soil of poor native fertility, surface crusting and low water and nutrient holding capacity, and recurrent droughts are the main abiotic constraints to crop production in this environment.

The table on economic and human development characteristics of West African countries indicate that except for Senegal, Côte d'Ivoire, Mauritania and Ghana where the percentage of undernourished people is less than 19%, most countries have between 20 to 34% of undernourished people and countries like Niger have more than 35% of their population undernourished. Sahelian countries produce 80% of their total cereal production under very difficult conditions. The ability to obtain the remaining 20 percent of required food is limited by low income and underdeveloped marketing channels. Gross domestic product per capita, for example, ranged from US$177 in Chad to US$575 in Senegal and have stagnated in real terms over the past decade. From the United Nations Development Programme's Human Development index, which ranks countries in terms of life expectancy, education and income, Sahelian countries fall in the bottom 15 percent of the 174 countries ranked, the lowest being Niger.

In extensive agricultural systems, when crop yields decline to unacceptable levels, the land is left fallow to build up soil fertility, and new areas are then cultivated. Increasing population pressure has decreased the availability of land and resulted in reduced duration of fallow and increased the duration of cropping periods. Shifting cultivation is losing effectiveness and soil fertility is globally declining in many areas. The present farming systems are therefore unsustainable, low in productivity and destructive to the environment. Plant nutrient balances are negative (Stoorvogel and Smaling, 1990). The increasing need for cropland has prompted farmers to cultivate more and more marginal lands which are prone to erosion.

Agricultural output should expand by at least 4% annually by the year 2000 in order to ensure food security. Previous studies have clearly shown that the expansion of new farms cannot increase output by over 1% without accelerating environment degradation. Consequently, productivity of land currently under cultivation should increase by at least 3% per annum. Presently, over a quarter of West African sub-region's population of two hundred million inhabitants is threatened by food insecurity. Any program aimed at reverting the declining trend in agricultural productivity and preserving the environment for present and future generations in West Africa must begin with soil fertility restoration and maintenance (Bationo et al., 1996).

In this chapter, after a brief presentation of the crop production environment, we will present the state of the art of nitrogen, phosphorus and organic matter management for sustainable land use in the Sudano-Sahelian zone. Before presenting the new opportunities for future research for soil fertility

restoration in this zone, we will discuss the effect of different cropping systems on soil fertility and also the main research achievements of the on-farm evaluation of soil fertility restoration technologies.

**Crop production environments**

a) Climate

The rainfall in West Africa shows a significant north-south gradient because of the inter-seasonal movement of the intertropical convergence zone, north and south of the equator. The rainfall is low, variable and undependable. The north-south rainfall gradient is very steep. The further one goes from the Sahara margins, the greater is the rainfall by approximately 1 mm $km^{-1}$. The isohyets run parallel (Toupet 1965).

Sivakumar (1986) proposed a soil climatic zonation scheme for West Africa that is calculated from rainfall and potential evapo-transpiration. In this scheme a growing period of 60–100 days was used for defining the Sahelian zone. The geographical extent of the Sudanian zone has an average growing period of 100–150 days. The extent of the Sudano-Sahelian zone of West Africa (SSZWA) is represented by the Semi-Arid zone in Figure 1. The average annual rainfall of the cultivated zones varies from 300 to 900 mm and the ratio of annual rainfall to annual potential evapo-transpiration from 0.20 to 0.65. High soil temperature, sometimes exceeding 40$^{o}$C, can prevent crop establishment. Sand blasting and burial of the seedlings caused by wind erosion adds to this problem.

Time dependent variations in rainfall are quite common in the region with coefficient of variation of annual rainfall ranges between 15-30%, and rainfall in some years can be 50% below or above the long-term average. In instance, Nicholson (1981) showed that in 1950 rainfall all over West Africa was above normal, at some location even 250% above normal. However, in 1970 rainfall was below normal throughout the region.

It is well documented that precipitation determines the potential distribution of terrestrial vegetation and extended drought have initiated or exacerbated desertification. In the past 25 years, the SSZWA has experienced the most substantial decline in rainfall (Hulme and Kelly 1997; Hulme 1992; Nicholson and Palao 1993) and the downward trend is persistent since 1951 with more areas experiencing more higher rainfall variability. As a result of the decrease in rainfall there will be a decrease in the vegetation cover of the land and a reduction in the vegetation cover logically leads to reduce precipitation (Charney 1975; Cunnington and Rowntree 1986; Xue et al. 1990). The other non-climatic forces of desertification includes unsustainable agricultural practices, overgrazing and deforestation.

With the reduction of the vegetation cover, the soil is left bare and therefore directly exposed to wind and water vegetation. The effect of these changes on wind and water erosion are aggravated by the sandy nature of the soils of SSZWA, which are frequently poorly aggregated, offering little resistance to the erosive forces. The Global Assessment of Soil Degradation (GLASOD) project estimates that 65% of the African agricultural land 31% of permanent pasture land, and 19% of forest and woodland has already been degraded. Three hundred and thirty two million hectares of African drylands are subjected to soil degradation. This represents one third of the entire area of dryland soil degradation in the world.

Land degradation is one of the most serious threats to food production and soil lost through erosion is about 10 times greater than the rate of natural soil formation while deforestation is 30 times greater than of planned reforestation. Buerkert et al. (1996a) measured absolute soil lost of 190 t $ha^{-1}$ in one year on bare plots, as opposed to soil deposition of 270 t $ha^{-1}$ on plot with 2 t $ha^{-1}$ millet stover mulch. Sterk et al. (1996) reported a total loss of 45.9 t $ha^{-1}$ of soil during four consecutive storms. Buerkert et al. (1996b) reported that in unprotected plot up to 7 kg of available P and 180 kg $ha^{-1}$ of organic carbon are lost from the soil profile within one year. Wind erosion will decrease also the exchangeable base and increase soil acidification. Wind erosion constitutes one of the major causes of land degradation. This results from the low vegetation cover at the time when the most erosive winds are blowing in combination with sandy, easy erodable soils. Wind erosion induced damage includes direct damage to crops through sand blasting, burial of seedling under sand deposits, and loss of top soils (Fryar 1971, Ambust 1984, Fryar 1990. The loss of the top soil which can contain 10 times more nutrients than the sub-soil is particularly worrying,

since it potentially affects crop productivity on the long-term by removing the soil that is inherently rich in organic matter.

b) Soils

Entisols and Alfisols occupy most of the landscape in the SSZWA. Entisols are mainly composed of quartz sand, with low water and nutrient holding capacity. Alfisols have a clay accumulation horizon and a high base saturation because of lower rainfall and leaching but they have poor structural stability, poor water and nutrient holding capacity and lower organic matter than the ultisols and oxisols in the sub-humid areas.

The data in Table 1 shows physical and chemical properties of soils in the SSZWA. Most of the soils are sandy. One striking feature of these soils is their inherent low fertility which, is expressed in low levels of organic carbon (generally less than 0.3%), low total and available phosphorus and nitrogen and low effective cation exchange capacity (ECEC). The ECEC is attributed to low clay content and the kaolinitic mineralogy of the soils. Bationo and Mokwunye (1991) found that the ECEC is more related to the organic matter than to the clay content, indicating that a decrease in organic matter will decrease the ECEC and then the nutrient holding capacities of those soils. De Ridder and Van Keulen (1990) reported that a difference of 0.1% in organic carbon content results in a difference of 4.3 Cmol $kg^{-1}$ in ECEC.

Soil nutrient depletion is a major bottleneck to increased land productivity in the region and has largely contributed to poverty and food insecurity. Soil nutrient depletion occurs when nutrient inflows are less than outflows. Nutrient balances are negative for many cropping systems indicating that farmers are mining their soils. Table 2 shows the aggregated nutrient budgets for some West African countries. In Burkina Faso, current estimates indicate that in 1983, for a total of 6.7 million hectares of land cultivated, soil nutrient mining amounted to a total loss of 95000 tons of N, 28000 tons of $P_2O_5$ and 79000 tons of $K_2O$, equivalent to US$159 million of N, P and K fertilizers. In Mali, Van der Pol and Van der Geest (1993) reported that farmers extract, on average, 40% of their agricultural revenue from the soil mining. The significance of these figures is alarming when it is realized that productivity of these soils in their native state is already low because of low inherent levels of plant nutrients. The countries of the SSZWA consume less than 5 $kg.ha^{-1}$ of plant nutrients and in addition there is intense pressure on the governments to remove subsidies on fertilizers without alternative policies to sustain even the current low levels of use of plant nutrients.

The data in Table 3 indicates that continuous cultivation of the weakly buffered soils of northern Nigeria will result in a rapid decline of exchangeable cations and soil acidification in the Sudanian zone of Northern Nigeria. Soil calcium will decrease by 21% and pH by 4% after 50 years of continuous cultivation in farmers' fields.

Rains in West Africa frequently occurs in short and intense storms and pose special problems in term of soil conservation (Kowal and Kassam 1978). Charreau (1974) reported on rainfall intensities between 27 to 62 mm $h^{-1}$. In Northern Nigeria, Kowal (1970) reported rainfall intensities over 250 mm $h^{-1}$ for a short period. Hoogmoed reported a pick intensity of 300 mm $h^{-}$ in Niono, Mali and a pick of 386 mm $h^{-1}$ for Niamey, Niger (Hoomoed 1986). Land degradation due to water erosion is more severe in the Sudanian zone than in the Sahelian zone. On the bare, weakly crusted surface of the sandy Sahelian soil, infiltration rate of up to 100 mm $h^{-1}$ have been reported (ICRISAT 1985). For the Alfisols with indurate crust, infiltration rates of 10.8 mm $h^{-1}$ in Central Burkina Faso have been reported. As a result of the high rainfall intensities and low infiltration rates, runoff and soil loss are common in the region. The data in Table 5 indicate runoff and soil loss will depend on soil types and erodibility, land form and management system (Lal 1980). Whereas Sefa in Senegal with a slope of 1.2% on a bare soil a total runoff of 39.5% was recorded resulting in soil loss of 21 t $ha^{-1}$ $Yr^{-1}$, in Burkina Faso with a slope of 1.20% only 7.5% of runoff was recorded with soil loss of 6.4 t $yr^{-1}$ on pearl millet field.

**Management of Nitrogen, Phosphorus and Organic Matter**

A) Nitrogen

a) Introduction

For many years, several scientists in the Sudano-Sahelian zones initiated research to 1) assess the performance of the different sources of N fertilizers 2) to assess the efficiency of different methods of N placement 3) to calculate $^{15}N$ balances in order to determine N uptake and losses and 4) to determine efficiency of N under different management systems and the effect of the different soil and agro climatic factors on the performance of N fertilizers (Mughogho et al. (1986), Bationo et al. (1989), Christianson and Vlek (1991), Ganry et al. (1973), Gigou et al. (1984)).

Soil nitrogen is derived from air and dust, biological nitrogen fixation, organic sources, and fertilizers. About 98% of the soil nitrogen is stabilized in the organic matter. Thus the total nitrogen in the soil and the amount of nitrogen released for plant nutrients uptake will depend on organic matter content.

b) Efficiency of N fertilizers as affected by N sources, methods of placement and time of application

Christianson and Vlek (1991) used data from long-term experiment from the Sudano-Sahelian Zone to develop response function to N by pearl millet and sorghum and found that the optimum rate is 50 kg N/ha for sorghum and 30 kg N/ha for pearl millet. At these N rates the returns were 20 kg grain per kg N for sorghum and 9 kg grain per kg N for pearl millet.

The use of $^{15}N$ in order to calculate N balances and to determine fertilizers N uptake and losses provide an important tool for nitrogen management. Results with $^{15}N$ research in early years are reported in Mughogho et al. from which the following conclusion can be made.

1) Apparent uptake of fertilizer N exceeds measured uptake using $^{15}N$.
2) Uptake of $^{15}N$ labelled fertilizer and apparent recovery of unlabelled N decreases with increasing rates of application.
3) Loss of $^{15}N$ labelled fertilizer to the atmosphere and recovery of $^{15}N$ in the soil increases with increasing rates of fertilizer application.
4) Estimated losses of N are high regardless of N sources.

The urea and calcium ammonium nitrate (CAN) are the most common sources of nitrogen in the region. Trials were undertaken to evaluate these two sources of nitrogen with basal or split application, banded, broadcast or applied point placed as urea supergranule (USG) or CAN point placed. $^{15}N$ was applied in microplot in order to construct N balances and to determine N uptake and losses from the different sources of N, methods of application and timing of application.

From the data in table 5,6 and 7 the following conclusion can be made: 1) Fertilizer N recovery by plant was very low, averaging 25 – 30% over all years. 2) There is a higher loss of N with the point placement of urea (USG) (> 50%) and the mechanism of N loss is believed to have been ammonia volatilization. 3) For all years losses of N from CAN were less than from urea because one-half of the N in CAN is in the non-volatile nitrate form. 4) Although CAN has a lower N content than urea, it is attractive as an N source because of its low potential for N loss via volatilization, and its point placement will improve its spatial availability. The data in Figure 2 clearly indicates that CAN point placed outperformed urea point placed or broadcast and $^{15}N$ similar trials indicate that $^{15}N$ uptake by plants was almost three times higher from CAN than that of urea applied in the same manner (Table 7).

c) Efficiency of N fertilizers as affected by soil and crop management and rainfall

Mughogho et al. (1986) found significant relationships between crop yields and N recovery. N losses averaged 20% in the humid and sub-humid zones with maize and were significantly less than the average loss of 40% found over all treatments in the Sudano-Sahelian zone.

In the Sahelian zone, Bationo and Vlek (1998) reported nitrogen use efficiencies of 14% in plots without lime and phosphorus whereas this amount increased to 28% when P and lime were applied.

Rotation of cereals with legumes could be a way to increase N use efficiency. Bationo and Vlek 1998 reported a nitrogen use efficiency of 20% in the continuous cultivation of pearl millet but its value increased to 28% when pearl millet was rotated with cowpea.

Bationo et al. (1989) found a strong effect between planting density and response to N fertilizer. Christianson et al. (1990) developed a model on the effect of rainfall on N for pearl millet production in the Sahel and found that the response to N was affected by rainfall over a 45 days yield-sensitive period which coincides with the culms elongation and anthesis growth stages for millet (Figure 3).

(2) Phosphorus sources and management

a) Introduction

Among soil fertility factors, phosphorus deficiency is a major constraint to crop production in the Sudano-Sahelian zone. For many years, research has been undertaken to assess the extent of soil phosphorus deficiency, to estimate phosphorus requirement of major crops, and to evaluate the agronomic potential of various phosphate rock (PR) from local deposits (Goldsworthy, 1967; Pichot and Roche, 1972; Thibout et al. 1980; Bationo et al. 1987; Bationo et al. 1990; Hauck, 1966; Jones, 1973; Juo and Fox, 1977; Kang and Osiname, 1979; Boyer, 1954; Nalos et al. 1974; Juo and Kang, 1978; Mokwunye, 1979; Truong et al. 1978)

About 80% of the soils in sub-Saharan Africa are short of this critical nutrient element and without the use of phosphorus, other inputs and technologies are not effective. However, sub-Sahara Africa use 1.6 kg P/ha$^{-1}$ of cultivated land as compared to 7.9 and 14.9 respectively for Latin America and Asia. It is now accepted that the replenishment of soil capital phosphorus is not only a crop production issue, but an environmental issue and P application is essential for the conservation of the natural resource base.

Availability and total P levels of soil are very low in the SSZWA as compared to the other soils in West Africa (Bache and Rogers, 1970; Mokwunye, 1974; Jones and Wild, 1975; Juo and Fox, 1977). For the sandy Sahelian soils total P values can be as low as 40 mg P kg$^{-1}$ and the value of available P less than 2 mg P kg$^{-1}$. In a study of the fertility status of selected pearl millet producing soils of West Africa, Manu et al. 1991 found that the amount of total P in these soils ranged from 25 to 340% mg kg$^{-1}$ with a mean of 109% mg kg$^{-1}$. The low content of both total and available P parameters may be related to several factors including 1) Parent materials, which are mainly composed of eolian sands, contain low mineral reserves and lack primary minerals necessary for nutrient recharge. 2) A high proportion of total P in these soils is often in occluded form and is not available to crop (Charreau, 1974). 3) Low level of organic matter and the removal of crop residue from fields. Organic matter has a favourable effect on P dynamics of the soil; in addition to P release by mineralization, the competition of organic ligands for Fe and Al oxides surface can result in a decrease of P fixation of applied and native P.

The P sorption characteristics of different soil types has been investigated and as compared to the soils of the more humid regions, the soils of the SSZWA have very low capacity to fix P (Sanchez and Uehara, 1980; Udo and Ogunwale, 1972; Fox and Kamprah, 1970; Juo and Fox, 1977; Syers et al. 1971). For pearl millet producing soils, Manu et al. 1991 fitted the sorption data to Langmuir equation (Langmuir 1918) and P sorption maximum was determined using the method of Fox and Kamprath, 1970. From these representative sites in the Sudano-Sahelian zone the values of maximum P sorbed ranged from 27 mg kg$^{-1}$ to 253 mg kg-1 with a mean of 94 mg kg$^{-1}$.

Phosphorus deficiency is a major constraint to crop production and response to nitrogen is substantial only when both moisture and phosphorus are not limiting. Field trials were established to determine the relative importance of N, P and K fertilizers. The data in Table 8 indicates that from 1982 to 1986 the average control plot was 190 kg grain ha$^{-1}$. The sole addition of 30 kg P2O5/ha without N fertilizers increased the average yield to 714 kg ha$^{-1}$. The addition of only 60 kg N/ha did not increase the yield significantly over the control and the average grain yield obtained was 283 kg ha$^{-1}$. Those data clearly indicate that P is the most limiting factor in those sandy Sahelian soils and there is no significant response to N without correcting first for P deficiency. When P is applied the response to N can be substantial and

with the application of 120 kg N ha-1 a pearly millet grain yield of 1173 kg ha-1 was obtained as compared to 714 kg ha-1 when only P fertilizers were applied. For all the years the addition of potassium did not increase significantly the yield of both grain and total dry matter of pearl millet.

b) The use of alternative locally available phosphate rock

Despite the fact that deficiency of P is acute on the soils of West Africa, very little P fertilizers is used by local farmers, partially because of the high cost of the imported fertilizers. The use of locally available phosphate rock indigenous in the region could be an alternative to use of high cost imported P fertilizers. The effectiveness of phosphate rock (PR) depends on its chemical and mineralogical composition (Khasawneh and Doll (1978), Lehr and McClellan (1972), Chien and Hammond (1978). The most important feature of the empirical formula of francolite is the ability of carbonate ions to substitute for phosphate in the apatite latice. Smith and Lehr (1966) concluded from their studies that the level of isomorphic substitution of carbonate for phosphate within the latice of the apatite crystal influences the solubility of the apatite in the rock and therefore controls the amount of phosphorus that is released when PR is applied to soil. The most reactive PR are those having a molar $PO_4/CO_3$ ratio less than 5. West African PR's are not very reactive. Chien (1977) found that the solubility of PR in neutral ammonium citrate (NAC) was directly related to the level of carbonate substitution. Diamond (1979) proposed a classification of phosphate rock for direct application based on citrate solubility as >5.4% high; 3.2–4.5% medium and <2.7% low. Based on this classification only Tilemsi PR has a medium reactivity.

Environmental conditions, crop types, and management practices control the P supply and hence the effectiveness of a given PR in a given crop management environment, (Mokwunye, 1995). The ability of the soil to provide H+, soil with low P and Ca, soil moisture, the acidification of the rhizosphere, plants with high root density and high Ca uptake play an important role in P availability from PR (Kasawneh and Doll, 1978; Chien, 1977; Mokwunye, 1995; Hammond et al. 1986; Kirk and Nye, 1986; Hedley et al. 1982; Sale and Mokwunye, 1993; Föhse et al. 1988; Barrow, 1990; Hammond et al. 1989).

Bationo et al. (1987) have shown that direct application of PR indigenous to the region may be an economical alternative to the use of more expensive imported water-soluble P fertilizers for certain crops and soils. Bationo et al. 1987 while evaluating Parc-W and Tahoua PR indigenous to Niger found that PR is only 48% as effective as single superphosphate (SSP), whereas the effectiveness of the more reactive Tahoua rock was as high as 76% of SSP. Further studies by Bationo et al. (1990) showed that Tahoua PR is suitable for direct application, but Parc-W has less potential for direct application. The data from a long-term benchmark experiment show that SSP outperformed the other sources and its superiority to sulphur-free Triple Superphosphate (TSP) indicates that with continuous cultivation, sulphur deficiency develops. For both pearl millet grain and total dry matter yields, the relative agronomic effectiveness was almost similar for TSP as compared to the partially acidulated Parc W phosphate rock (PAPR) with 50% acidulation (PAPR50) indicating that partial acidification of Parc-W PR can significantly increase its effectiveness (Bationo et al 1996).

In trials conducted in the different agro-ecological zones of Niger it was found that Tahoua PR outperformed Kodjari PR (from Burkina Faso) (Figure 4). The results are in agreement with the fact that the molar $PO_4/CO_3$ ratio is 23 for Kodjari PR and 4.9 for Tahoua PR, and Tahoua PR has also a higher solubility in NAC.

Bationo et al. (1997) found that Tilemsi PR can result in net returns and value/cost ratios similar to recommended cotton or cereal complex imported fertilizers.

There is ample evidence that indicates that market differences exist between species and genotype for P uptake (Föhse et al. 1988; Caradus, 1980; Nielsen and Schjorring, 1983; Spencer et al. 1980). Bationo et al. 2001 found that the PUE among nine pearl millet varieties varied from 25 kg grain/kg P for variety ICMVIS 85333 to 77 kg grain/kg P for Haini-Kirei cultivar.

The data on Table 9 clearly shows that hill placement of small qualities of P fertilizers will have a higher phosphorus use efficiency (PUE) as compared to the broadcasting of 13 kg P/ha as recommended by the extension services. Whereas in 1995 the PUE was 47 with the broadcasting of 13 kg/P ha, a value

of 111 was obtained with the hill placement of 3 kg P/ha with the seed at sowing time. In on-farm researchers managed trials in the Sahelian zone, it was found that the efficiency of PR from Kodjari or Tahoua can be improved with the hill placement of 4 kg P/ha. Whereas the PUE of Kodjari PR applied alone was 14 it increased to 31 when additional P was hill placed at seedling time as 15-15-15 for pearl millet grain yield (Bationo, unpublished data).

In long-term soil management trials, application of nitrogen, crop residue and ridging and rotation of pearl millet with cowpea were evaluated to determine their effect on PUE. The results show that soil productivity of the sandy soils can dramatically increase with the adoption of improved crop and soil management technologies, whereas the absolute control recorded 33 kg $ha^{-1}$ of pearl millet grains, 1829 kg $ha^{-1}$ was obtained when phosphorus nitrogen and crop residue was applied to the ridged and fallowed leguminous cowpea upon the previous season. Results indicate for the grain yield that PUE increases from 46 with only P application to 133 when P is applied in combination with nitrogen, crop residue and the crop is planted on ridge in a rotation system (Table 10).

D. Organic matter management

a) Introduction

Maintaining soil organic matter is a key to sustainable land use management. Organic matter acts as source and sink for plant nutrients. Other important benefits resulting from the maintenance of organic matter is low-input agro-systems include retention and storage of nutrients, increasing buffering capacity in low activity clay soils, and increasing water holding capacity. Nye and Greenland (1960) estimated that the annual increase in nitrogen under forest fallow was 30 kg N $ha^{-1}$ in the soil and 60 kg N $ha^{-1}$ in the vegetation. For the savanna ecosystems, the annual increase was 10 kg N $ha^{-1}$ in the soil and 25 kg N $ha^{-1}$ in leaves and vegetation. Bationo et al. 1995 reported that continuous cultivation in the Sahelian zone has led to drastic reduction in organic matter and a subsequent soil acidification. Bationo and Mokwunye (1991) reported that in the Sudano-Sahelian zone, the effective cation exchange capacity (ECEC) is more related to organic matter than to clay, indicating that a decrease in organic matter will decrease the ECEC and subsequently the nutrient holding capacity of these soils. In a study to quantify the effects of changes in organic carbon on cation exchange capacity (CEC) De Ridder and Van Keulen (1990) found that a difference of 1 g kg-1 in organic carbon results in a difference of 4.3 mol $kg^{-1}$. In many cropping systems few if any agricultural residues are returned to the soil. This leads to decline soil organic matter, which frequently results in lower crop yields or soil productivity.

The concentration of organic carbon in the top soil is reported to average 12 mg $kg^{-1}$ for the forest zone, 7 mg $kg^{-1}$ for the Guinean zone, 4 mg kg-1 in the Sudanian zone and 2 mg $kg^{-1}$ for the Sahelian zone (Windmeijer and Andriesse (1993). The soils of the Sudano-Sahelian zone are inherently low in organic carbon. This is due to the low root growth of crops and natural vegetation but also the rapid turnover rates of organic materials with high soil temperature and microfauna, particularly termites. In a survey of millet producing soils, Manu et al. (1991) found an average soil Corg content of 7.6 g $kg^{-1}$ with a range from 0.8 to 29.4 g $kg^{-1}$. The data also showed that these Corg contents were highly correlated with total N (R = 0.97) which indicates that in the predominant agro-pastoral systems without the application of mineral N fertilizers, N nutrition of crops largely depend on the maintenance of soil Corg levels.

The importance of soil textural (clay and silt) properties for the Corg content of soil was stressed repeatedly as clay is an important component in the stabilization of organic molecules and mino-organisms (Amato and Ladd, 1992; Greenland and Nye, 1959; Feller et al. 1992). Thus Feller et al. (1992) reported that independently of climatic variations such as precipitation, temperature, and duration of the dry seasons Corg increased between 600 and 3000 mm annual rainfall with the clay and silt contents of low activity clay soils. Therefore small variations in topsoil texture at the field or watershed level could have large effects on Corg.

b) Effect of soil management practices on organic carbon contents

There is much evidence for rapid decline of Corg levels with continuous cultivation of crops in the SSZWA (Bationo et al. 1995). For the sandy soils, average annual losses in Corg often expressed by the K value (calculated as the percentage of organic carbon loss per year), may be as higher as 4.7%, whereas for the sandy loam soils, reported losses seem much lower, with an average of 2% (Pieri, 1989, Table 11). The data in Table 11 also clearly indicated that soil erosion can increase Corg losses from 2% to 6.3% and management practices such as crop rotation, following soil tillage, application of mineral fertilizers and mulching will have a significant effect on annual losses of Corg. The K-value in cotton cereal rotations were 2.8%, lower than the 2.8%, lower than the 2.8% in continuous cotton system. At Nioro-du-Rip in Senegal, soil tillage increased annual Corg losses from 3.8% to 5.2% and annual Corg losses declined from 5.2% without NPK to 3.9% with NPK application.

c) Effects of crop residues and manure on soil productivity

The Sahelian zone

In long-term crop residue and management trials, Bationo and Buerkert 2001 reported for the Sahelian zone a very significant effect between crop residue and mineral fertilizer (Figure 5). From this experiment started since 1984 Bationo et al. (1993) reported that the grain yield declined to 160 kg $ha^{-1}$ in unmulched and unfertilized plots. However, grain yield could be increased to 770 kg $ha^{-1}$ with a mulch of 2 t crop residue per hectare and 1030 kg $ha^{-1}$ with 13 kg P plus 30 kg N $ha^{-1}$. The combination of crop residue and mineral fertilizers resulted in grain yield of 1940 kg $ha^{-1}$. The application of 4 t of crop residue per hectare maintained soil organic carbon at the same level that in an adjacent fallow field in the top soil but continuous cultivation without mulching results in drastic reduction of Corg (Figure 6). In the Sudanian zone, all available reports show a much smaller or even negative effect of crop residue use as soil amendment (Bationo et al. 1995; Sedogo, 1993). In the Sahelian zone the application of crop residue increased soil pH, and exchangeable bases and decrease the capacity of the soil to fix phosphorus.

On the nutrient poor West African soil, manure, the second farm-available soil amendment can substantially enhance crop yields. For Niger, McIntire et al. (1992) reported grain yield increase between 15 and 86 kg for millet and between 14 and 27 kg for groundnut per ton of applied manure. Similar manure effects have been reported from other Sahelian countries. However, given the large variation in the nutrient concentration of the manure types applied comparisons between results from different experiments should be made with precaution. Powell et al. (1998) a very significant effect of manure and urine application on pearl millet in the Sahelian zone.

In the SSZWA crop residues use as surface mulch can plan an important role in the maintenance of Corg levels and productivity of the prevailing acid soils through the recycling of mineral nutrients, increased in fertilizer use efficiency and a decrease in soil erosion effect. However, organic material available for surface mulching are scarce given the low overall production levels of biomass and their multiple competitive use as fodder, construction material and cooking fuel (Lamers and Feil, 1993). The crop residue quantities found on-farm at the beginning of the rainy season ranged from 0 to 500 kg $ha^{-1}$. McIntire and Fussel (1986) reported that on farmers' fields in the Sahel average grain yields were 236 kg $ha^{-1}$ and mean crop residue yields barely reached 1300 kg $ha^{-1}$. Baidu–Forson (1995) reported on availability of 250 kg $ha^{-1}$ of crop residue at the onset of the rains. Powell et al. (1987) showed that 50% of the disappearance rates of millet stover could be attributed to livestock grazing.

Animal manure has a similar role as residue mulching for the maintenance of soil productivity but depending on rangeland productivity, it will require between 10 to 40 ha of dry season grazing land and 3 to 10 ha of rangeland of wet season grazing to maintain yields one one hectare of cropland (Fernandez-Rivera et al. 1995). The potential of manure to maintain soil Corg and sustain crop production is thus limited by the number of animals available and the size and quality of the rangeland.

At the farm level, the maintenance of Corg levels in the soils of the region will largely depend on an increase in C fixation by plants. Given the strong limitation of plant growth by the low availability of mineral nutrients, a yield-effective application of mineral fertilizers is crucial. It would not only allow

large increase in crop production and the amount of by-products but also to improve soil coverage by forage grass and weeds.

D) Relationships between cropping systems and fertility management

a) Introduction

The most common cropping system involves growing several crops in association as mixtures or intercrop. This practice provides the farmers with several options for returns from land and labor, often increases efficiency with scarce resources, and reduces dependence upon a single crop that is susceptible to environment and economic fluctuations. Steiner (1984) reported that traditional intercropping systems cover 75% of the cultivated land in the SSZWA. The principal reasons for farmers to intercrop are flexibility, profit and resource maximization, risk minimization, soil conservation and maintenance, weed control and nutritional advantages (Norman, 1974; Swinton et al. 1974; Fusel and Serafini, 1985).

Cowpea (Vigna unguiculata (L.) Walp) and groundnut (Arachis hypogea L.) are two of the predominant grain legumes in the SSZWA. Groundnut occupies 2.7 million hectares of arable land and cowpea 6 million hectares. The two legumes are important components of the mixed cropping systems of the resource-poor farmers. The most important cereals are sorghum and pearl millet and the two legumes are often intercropped with these cereals. While considerable information is available on fertilizer requirements for sole cropping of various crops, little is known on fertilizer requirement in intercropping.

In the mixed cropping systems, legume yields are very low due to low soil fertility, low planting densities and pest and decrease (Ntare,1989; Reddy et al. 1992). The yield of cowpea grain varies between 50 and 300 kg $ha^{-1}$ in farmers fields in marked contrast to yield over 2000 kg $ha^{-1}$ obtainable on research station and by large scale commercial enterprises in pure cropping. Rotation of cereals with legumes has been extensively studied in recent years. The use of rotational systems involving legumes for harvesting nitrogen fixation is gaining importance throughout the region because of economic and sustainability considerations. The beneficial effect of legumes on succeeding crops is normally exclusively attributed to the increased soil N fertility as a result of N-fixation. The amount of N2 fixed by leguminous crops can be quite high but some workers have demonstrated also that legumes can deplete soil nitrogen (Rupela and Saxena, 1987; Blumenthal et al. 1982; Tanaka et al. 1983). Most data reported on the quantity of N fixed by the legume crops in the SSZWA concerned the above ground part of the legume and very little is known on the nitrogen fixed by roots where much of the legume bio-mass is returned to the soil as green manure a positive N balance is to be expected. However, this may not be true for grain legumes and fodder. Where the bulk of above legume material is removed from the system. Nevertheless, many other positive effects of grain legumes such as the improvement of soil biological and physical properties and the ability of some legumes bounded phosphorus by roots exudates (Gardner et al. 1991; Arihara and Okwaki, 1989).

Other advantages of crop rotations include soil conservation (Stoop and Staveren, 1981) organic matter restoration (Spurgeon and Grimson, 1965) and pest and disease control (Sunnadurai, 1973).

In the mixed crop-livestock systems of the SSZWA, increasing legume component in the farming systems is important in order to increase the availability of fodder as source of livestock feed while increasing soil fertility.

b) Intercropping

Fussel and Serafini (1985) reported yield advantages from 10-100% in millet cowpea systems.

Yield stability has been proposed as a major advantage of intercropping (Wiley, 1979a, 1979b; Willey et al. 1985; Steiner, 1984) as farmers want to rely on management practices that increase yields, when this is possible, while improving the stability of the production in both good and poor rainfall years. Baker (1980) has compared relative stability of intercropping and cropping using stability analysis of Finlay and Wilkinson (1963) and found that in the groundnut/cereal systems in northern Nigeria, intercropping systems were found to be more stable. Ntare (1989) reported yield advantages of 20-70% depending on the different combinations of pearl millet and cowpea cultivars. Although traditional

intercropping cover over 75% of the cultivated area in the SSZWA, there is a scarcity of information on the efficiency of fertilizers under these systems. The number of days before planting the second crop will depend on the importance of the next rains after the first cereal crops have been planted. With a basal application of P fertilizers the cereal growth is rapid and can suppress completely the second crop if its planting occurs after three weeks after the cereal crops have been sown. In contrast if the legume crops is planted early it will compete more with the cereal crop for light, water and nutrients and can significantly reduce the yield of the cereal crop.

c) Relay and sequential cropping

In the Sudanian zone with longer growing season and higher rainfall there is greater opportunity than in the Sahelian zone to manipulate the systems with appropriate genotypes and management systems. Field trials have been conducted to examine the performance of the cultivars under relay and sequential systems and revealed the potential of these alternative systems over traditional sole or mixed cropping (ICRISAT, 1984 and 1987).

In Mali, by introducing short season sorghum cultivars in relay cropping with other short duration cowpea and groundnut cultivars, substantial yields of legumes and sorghum were obtained as compared to traditional systems (IER, 1990; Sogodogo and Shetty, 1991).

In the Sahelian zone (Sivakumar, 1986) analysed the data of the onset and ending of the rains and the length of the growing period. He found that an early onset of the rains offers the probability of a longer growing period while delayed onset results in a considerable short term growing season. The above analysis suggests that even for the Sahelian zone, cropping management factors using relay cropping can increase soil productivity with an early onset of the rains.

d) Crop rotation

Despite the recognised need to apply chemical fertilizers for high yields, the use of fertilizers in West Africa is limited by lack of capital, inefficient distribution systems, poor enabling policies and other socio-economic factors. Cheaper means of improving soil fertility and productivity are therefore necessary.

Cereals and legumes rotation effects on cereals yields have been reported by several scientists (Bationo et al. 1998; Klaij and Ntare, 1985; Stoop and Van Staven, 1981). Bationo and Ntare, 2000 data at Tara in the Sudanian zone clearly indicates that at all levels of nitrogen application the yield of pearl millet after cowpea outperformed the yield of millet in the continuous millet cultivation.

N has been used to quantify the amounts of nitrogen fixed by cowpea and groundnut under different soil fertility levels. The nitrogen derived from the air (NDFA) varies from 65 to 88% for cowpea whereas the values varied from 20 to 75% for groundnut. In the complete treatment where all nutrients were applied cowpea stover fixed up to 89 kg N $ha^{-1}$ whereas for same treatment groundnut fixed only 40 kg N $ha^{-1}$ in this Sahelian environment (Bationo and Vlek 1990). In order to determine $^{15}N$ recovery from different cropping systems, labelled nitrogen fertilizers were applied to microplots of pearl millet grown continuously, in rotation with cowpea, in rotation with groundnut, intercropped with cowpea, and intercropped with groundnut. The data indicates that nitrogen use efficiency increased from 20% in continuous pearl millet cultivation to 28% when pearl millet was rotated with cowpea (Bationo and Vlek, 1998). The same authors reported that in the Sudanian zone nitrogen derived from the soil increased from 39 kg N ha-1 in continuous pearl millet cultivation to 62 kg N/ha when pearl millet is rotated with groundnut. Those data clearly indicate that although all the above ground biomass of the legume will be used to feed livestock and not returned to the soil, rotation will increase not only the yields of succeeding cereal crop but also its nitrogen use efficiency.

Bayayoko et al. (2000) in studies of cereals legumes effects on cereal growth in the Sudano-Sahelian zone of West Africa reported that the rotation effect although significant in most of the cases varied with sites and years. At Sadore as an example, the millet rotated with cowpea yielded 1904 kg/ha whereas the continuous millet cultivation yielded 1557 kg ha-1. Bayoyoko et al. 2000 reported higher

levels of mineral N and native arbuscular mychorrhizae infection in the rotation systems as compared to the continuous cereal cultivation.

The different cropping systems have a significant effect on the soil organic carbon. The soil organic carbon levels was 0.22% in the continuous systems whereas it is increased to 0.27% in the rotation systems. As a result of this soil pH was higher in the rotation systems as compared to the continuous monoculture (Bationo, unpublished data).

**Farmers evaluation of soil fertility restoration technologies**

a) Introduction

A review of the state of the art of the agronomic research in soil fertility management showed that on-station research has developed a considerable amount of promising results but very few of these technologies have reached the small farmers. It is recognized that most of these technologies developed on-station are not always built on indigenous practices, local socio-economic realities, farmers priorities and perceptions. Most often no account has been taken of enabling policy environment and indigenous knowledge. Therefore on-farm research should involve farmers, researchers, extension agents, non-governmental agencies at the design, implementation and evaluation stages. In this way, the technologies generated have a better chance of adoption by the land users. Promising technologies were identified to be tested on-farm under farmers managed trials knowing that a particular farm management practice is often less effective in the hand of the farmer, than it is on-station. There is need for experimental farm input packages to be tested under farmer's conditions to allow the scientists to observe the transfer of technologies to the farmers field and to determine associated management practices to be adopted by farmers in order to ensure good economic returns.

The objectives of on-farm research activities is: 1) to assess farmers' perception of the different technologies proposed 2) to identify the farmers' management practices affecting the good performance of the different technologies 3) to evaluate the profitability of the different technologies tested 4) to identify the constraints to technology adoption and means to alleviate them and 5) to assess the impact of technology adoption.

b) Effects of soil fertility restoration technologies on land productivity from farmers managed trials in the SSZWA

In the Sahelian zone of Gobery in Western Niger, 20 farmers evaluated phosphorus and nitrogen fertilizers including partially acidulated phosphate rock (PAPR) from parc-W. The data in Table 12 indicate a strongly response to P with yield increase of 181% over control with the application of N and P. No significant difference was found between PAPR and SSP, nor was difference between broadcasting and hill placement of nitrogen. However, crop response to fertilizer use was strongly affected by the cropping density chosen by individual farmers (Bationo et al. 1992). Averaged over all fertilized treatments and all years, when farmers planted at less than 3500 pockets per hectare, yield was very low and no response was found to fertilizer use. However, each 1500 pocket/ha increases about 200 kg grain/ha.

Bationo and Baidu-Forson (1998) reported the agro-economic evaluation of farmers managed trials on the evaluation of water soluble fertilizers, phosphate rock and rotation of cereals with legumes. The net grains, over three years, resulting from partial budgeting analysis show that farmers could make net financial gains with only the application of P fertilizer. The use of N in addition to P significantly improved net grains. Water soluble single superphosphate generated higher net gains than Tahoua phosphate rock. As a result of the higher cowpea price and is beneficial effect on the improvement of soil fertility, the rotation systems involving cowpea were more profitable than continuous pearl millet cultivation.

Bationo et al. 1997 reported the economic evaluation data of Tilemsi phosphate rock by farmers in three agro-ecological zones of Mali. The agro-ecological zones were Tafla with an average rainfall of 600 mm, Sougoumba with 800 mm rainfall and Tinfounga with 1200 mm rainfall. The cropping systems

used were rotation of pearl millet with groundnut in Tafla, sorghum with cotton in Sougoumba and maize with cotton in Tinfounga. The data indicate that the different sources of fertilizers have a significant effect on crop yields and there was no difference between Tilemsi phosphate rock and the recommended imported water soluble fertilizers. However, the economic analysis of the data indicate that at some sites the imported recommended water soluble P fertilizers are more profitable than the use of Tilemsi phosphate rock.

Bationo et al. 1998 undertook an agro-economic evaluation of a set of soil fertility restoration technologies and concluded that hill placement of small quantities of P fertilizers at planting time had higher returns than broadcasting 13 kg P/ha.

From 1988 to 2000 farmers-managed trials in the Sahelian zone at Karabedji (~550 mm of rainfall per year) and in the Sudanian zone at Gaya (~800 mm of rainfall per year), over an average of about 2800 field plots showed the agronomic potential of fertilizers (Table 13). The hill placement of 4 kg P/ha almost doubled crop yield. Integrated use of hill placement of water soluble fertilizers in addition to Tahoua phosphate rock broadcast and soil amendment with crop residue application as mulch gave the highest crop yield (Figure 7). The returns over variable cost of fertilizers presented clearly demonstrate the economic importance of soil fertility restoration in the SSZWA.

**New research opportunities in the SSZWA**

a) New strategies for integrated nutrient management

In the past, integrated nutrient management concentrated mainly on the utilization of available organic and inorganic sources of plant nutrients in a judicious and efficient way. Integrated nutrient management is recently perceived much more broadly as the judicious manipulation of all soil nutrient inputs and outputs and internal flows.

Future research needs to adopt this new holistic approach to integrated nutrient management. For a given cropping system or watershed, this will require the establishment of the nutrient balances. Interventions to limit nutrient losses through erosion can be in some cases as important as research on increasing the efficiency of organic and inorganic plant nutrients for a sustainable land use. This new approach will enhance more carbon sequestration and increase more bio-mass production on the farms for domestic use and there will be more bio-man available for livestock feeds and for soil mulching.

b) Integration of socio-economic and policy research with the technical solution

In the past several technical solutions to the problem of land degradation in the SSZWA have been researched and tested, and may have shown the potential for addressing the problem in some places. Unfortunately a review of the state of the art indicated that very few of these technologies have been adopted by the resource poor farmers. Therefore future research should focus more on problems driven by socio-economic factors and enabling policy environment in order to enhance farmers' capacity to invest in soil fertility restoration. The adoption of the participatory approach will be essential. In this way, the technologies generated have a better chance of adoption by land users.

c) Combining rain water and nutrient management strategies to increase crop production and prevent land degradation

In the SSZWA high inter-annual variability and erratic rainfall distribution in space and time result in water-limiting conditions during the cropping season.

In areas with inadequate rainfall or in runoff-susceptible land, water conservation techniques and water harvesting techniques offer the potential to secure agricultural production and reduce the financial risks associated with the use of purchased fertilizers. Under the conditions of adequate water supply, the addition of organic and inorganic amendments is the single most effective means of increasing water use efficiency. Future research needs to focus on enhancing rainwater and nutrient use efficiencies and on capitalizing on their synergies for increasing crop production and preventing soil degradation.

d) Increasing the legume component for a better integration of crop-livestock production systems

The rotations of cereals with legumes have led to increased cereals yield at many locations in the SSZWA. Factors such as mineral nitrogen increase, enhancement of Vesicular-Azbuscular Mycorrhizal (VAM) for better P nutrition and a decrease in parasitic nematodes have been identified as mechanisms accelerating the enhanced yield of cereals in rotation with legumes. Most of the research quantify has focused on the quantification of the above-ground N fixed by different legumes cultivars, but very little is known on the below-ground N fixed.

There is need to increase the legume component in the mixed cropping systems for a better integration of crop-livestock. The increase of legume component in the present cropping system will not only improve the soil conditions for the succeeding cereal crop, but will provide good quality livestock feed, and the manure produced will be of better quality for soil amendment.

e) Exploiting genetic variation for nutrient use efficiency

Phosphorus is the most limiting plant nutrient for crop production in the SSZWA and there is ample evidence that indicates marked differences between crop genotypes for P uptake. A better understanding of the factors affecting P uptake such as the ability of plants to i) solubilize soil P through acidification of the rhizosphere and the release of chelating agents and phosphate enzymes ii) explore a large volume of soil and iii) absorb P from low P solution would help screening for the genotypes the best appropriate for nutrient use efficiency.

Another important future research opportunity is the selection of genotypes that can efficiently associate with Vesicular-Azbuscular Mycorrhizal (VAM) for better utilization of P applied as indigenous phosphate rock.

f) Use of decision support systems modelling, and GIS for the extrapolation of research findings

Farmers production systems vary with respect to rainfall, soil types and socio-economic circumstances and therefore they are complex. Dealing with such complexity only by empirical research will be expensive and inefficient. Use of models and GIS will facilitate the transfer of workable technologies to similar agro-ecological zones. The use of DSSAT, APSIM and GIS will facilitate extrapolation of findings to other agro-ecozones similar of the benchmark sites chosen for testing technologies and will be cost effective.

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**Table 1: Mean and standard deviation of physical and chemical properties of selected West African soils, 0-15 cm**

| Parameters | Mean | Standard deviation |
|---|---|---|
| pH $H_2O$ (2:1 water:soil) | 6.17 | 0.66 |
| pH KC1 (2:1 KC1:soil) | 5.05 | 0.77 |
| Clay (%) | 3.9 | 2.67 |
| Sand (%) | 88 | 8 |
| Organic matter (%) | 1.4 | 1.09 |
| Total nitrogen (mg $kg^{-1}$) | 446 | 455 |
| Exchangeable bases (cmol $kg^{-1}$) | | |
| Ca | 2.16 | 3.01 |
| Mg | 0.59 | 0.55 |
| K | 0.20 | 0.22 |
| Na | 0.04 | 0.01 |
| Exchangeable acidity (cmol $kg^{-1}$) | 0.24 | 0.80 |
| Effective cation exchange capacity (ECEC; | 3.43 | 3.801 |
| cmol $kg^{-1}$) | 88 | 17 |
| Base saturation (%) | 3 | 8 |

**Source: Bationo et al., 1996**

**Table 2: Nutrient losses for some West African countries**

| Country | Area (1000 ha) | Nutrient losses (1000 tons) | | |
|---|---|---|---|---|
| | | N | $P_2O_5$ | $K_2O$ |
| Benin | 2972 | 41.4 | 10.4 | 32.5 |
| Burkina Faso | 6691 | 95.4 | 27.8 | 78.8 |
| Ghana | 4505 | 137.1 | 32.3 | 90.5 |
| Mali | 8015 | 61.7 | 17.9 | 66.7 |
| Niger | 10985 | 176.1 | 55.3 | 146.6 |
| Nigeria | 32813 | 110.7 | 316.7 | 946.2 |

**Source: Stoorvogel and Smaling, 1990**

**Table 3: Percentage of soil fertility over 50 years in farmers' fields under continuous cultivation in the savanna zones of Nigeria**

| Zone | Exchangeable cations | | | pH |
|---|---|---|---|---|
| | Ca | Mg | K | |
| Sudan | 21 | 32.0 | 25.0 | 4.0 |
| Northern Guinea | 18.6 | 26.8 | 33.0 | 3.8 |
| Southern Guinea | 46.0 | 50.6 | 50.0 | 10.0 |

**Source: Adapted from Balasubramanian et al. (1984).**

**Table 4: Runoff and soil loss data for selected locations in west Africa**

| Country | Location | Mean annual rainfall (mm) | Slope % | Treatments | Annual runoff % | Soil loss (tons $ha^{-1}$ $year^{-1}$) |
|---|---|---|---|---|---|---|
| Benin | Boukombe | 875 | 3.7 | Millet conventional | 11.7 | 1 |
| Niger | Allokoto | 452 | 3 | Village | 16.3 | 8 |
| Nigeria | Samaru | 1062 | 0.3 | Sorghum, cotton | 25.2 | 3 |
| | Ibadan | 1197 | 15 | Bare soil | 41.9 | 229 |
| | | | | Bare soil | 13.5 | 40 |
| | | | | Maize-maize | 2.6 | 0 |
| | | | | Maize-cowpea | 1.7 | 4 |
| Senegal | Sefa | 1300 | 1.2 | Cowpea-maize | 39.5 | 21 |
| | | 1241 | 1.2 | Bare soil | 22.8 | 69 |
| | | 1113 | 1.2 | Groundnut | 34.1 | 83 |
| Burkina Faso | Ougadougou | 850 | 0.5 | Sorghum | 40.6 | 10.2 |
| | | | | Bare soil | 2.32 | 0.6 |
| | | | | Crop | 2.5 | 0.1 |
| Côte d' Ivoire | Bouake | 1200 | 0.3 | Forest | 15.3 | 18.3 |
| | Abidjan | 2100 | 7.0 | Bare soil | 38.0 | 108.2 |
| Mali | Niono | | 1.3 | Bare soil | 25.0 | NA |
| Niger | Sadore | 560 | | Millet | 1.5 | NA |
| | | | | Millet | 0.2 | NA |
| Sierra Leone | Mebai | 2000 | | Bare soil | 11 | NA |
| Sierra Leone | Mabai | 2000 | | Unfertilized maize | 8 | NA |

**Source: Bationo et al. (1996)**
Na=not available

**Table 5: Recovery of $^{15}N$ in the millet plant and soil at harvest, Sadore, Niger 1982**

| Treatment | Grain yield[a] (kg ha) | N recovery (%) | | | |
|---|---|---|---|---|---|
| | | Grain | Plant[b] | Soil | Loss |
| Check | 590 | - | - | - | - |
| CAN split band | 970 | 20.8 | 36.8 | 38.2 | 25.0 |
| Urea split band | 1.070 | 19.0 | 31.0 | 37.3 | 31.7 |
| Urea split broadcast | 1.070 | 17.0 | 31.3 | 41.0 | 27.7 |
| Urea basal broadcast | 1.010 | 16.9 | 26.7 | 41.6 | 31.7 |
| USG basal | 960 | 16.2 | 27.5 | 39.3 | 33.2 |
| USG split | 1.070 | 14.3 | 26.5 | 33.2 | 40.3 |
| LSD (0.01) | 167 | 4.6 | 6.0 | 6.0 | 9.8 |

a. Average yield for all N rates for each source
b. Sum of grain and stover $^{15}N$
CAN: Calcium ammonium nitrate
USG: Urea super granule

Sources: Christianson et al. 1990

**Table 6: Yield and recovery of $^{15}N$ in the millet plant and soil at harvest (1983-85), Sadore, Niger**

| Year | Treatment | Grain yield[a] (kg $ha^{-1}$) | Stover yield (kg $ha^{-1}$) | $^{15}N$ recovery (%) | | | |
|---|---|---|---|---|---|---|---|
| | | | | Grain | Plant[b] | Soil | Loss |
| 1983 | Check | 660 | - | - | - | - | - |
| | CAN split band | 940 | - | 13.0 | 28.8 | 34.2 | 37.0 |
| | Urea split band | 1.040 | - | 9.8 | 22.8 | 39.2 | 38.0 |
| | USG split | 990 | - | 8.0 | 22.0 | 25.3 | 52.7 |
| | LSD (0.01) | 110 | - | 1.6 | 3.2 | 3.4 | 2.2 |
| 1984 | Check | 460 | 1.570 | - | - | - | - |
| | CAN split band | 480 | 1.850 | 9.9 | 36.8 | 37.1 | 26.1 |
| | Urea split band | 470 | 1.930 | 5.5 | 20.0 | 40.1 | 39.9 |
| | USG split | 490 | 1.780 | 8.1 | 21.6 | 24.8 | 53.6 |
| | LSD (0.01) | 30 | 220 | 1.6 | 3.8 | 4.2 | 4.4 |
| 1985 | Check | 900 | 2.315 | - | - | - | - |
| | CAN split band | 1.320 | 2.910 | - | - | - | - |
| | Urea split band | 1.225 | 3.020 | - | - | - | - |
| | USG split | 1.350 | 3.000 | - | - | - | - |
| | LSD (0.05) | 175 | 386 | - | - | - | - |

$^{15}N$ was not used in 1985
[a]. Average yield for all N rates for each source
[b]. Sum of grain and stover $^{15}N$
CAN: Calcium ammonium nitrate
USG: Urea super granule

Sources: Christianson et al. 1990

**Table 7. Recovery $^{15}N$ fertilizer by millet applied at Sadore, Niger, 1985**

| N source | Application method | $^{15}N$ Recovery | | | |
|---|---|---|---|---|---|
| | | Grain | Stover | Soil | Total |
| | | (%) | | | |
| CAN | Point incorporated | 21.3 | 16.8 | 30.0 | 68.1 |
| CAN | Broadcast incorporated | 10.9 | 10.9 | 42.9 | 64.7 |
| Urea | Point incorporated | 5.0 | 6.5 | 22.0 | 33.5 |
| Urea | Broadcast incorporated | 8.9 | 6.8 | 33.2 | 48.9 |
| Urea | Point surface | 5.3 | 8.6 | 18.0 | 31.9 |
| SE | | 1.2 | 2.0 | 1.9 | 2.4 |

Sources: Christianson and Vlek, 1991
CAN: Calcium ammonium nitrate

**Table 8: Effect of N, P, and K on pearl millet grain and total dry matter (kg/ha) at Sadoré and Gobery (Niger)**

| **Treatments** | **1982** | | **1983** | | **1984** | | **1985** | **1986** | |
|---|---|---|---|---|---|---|---|---|---|
| | **Sadoré** | | **Sadoré** | **Gobery** | **Sadoré** | | **Sadoré** | **Sadoré** | |
| | Grain | TDM | Grain | Grain | Grain | TDM | Grain | Grain | TDM |
| N0P0K0 | 217 | 1595 | 146 | 264 | 173 | 1280 | 180 | 180 | 1300 |
| N0P30K30 | 849 | 2865 | 608 | 964 | 713 | 2299 | 440 | 710 | 2300 |
| N30P30K30 | 1119 | 3597 | 906 | 1211 | 892 | 3071 | 720 | 930 | 3000 |
| N60P30K30 | 1155 | 3278 | 758 | 1224 | 838 | 3159 | 900 | 880 | 3200 |
| N90P30K30 | 1244 | 3731 | 980 | 1323 | 859 | 3423 | 1320 | 900 | 3400 |
| N120P30K30 | 1147 | 4184 | 1069 | 1364 | 1059 | 3293 | 1400 | 1000 | 3300 |
| N60P0K30 | 274 | 2372 | 262 | 366 | 279 | 1434 | 290 | 230 | 1500 |
| N60P15K30 | 816 | 2639 | 614 | 1100 | 918 | 3089 | 710 | 920 | 3100 |
| N60P45K30 | 1135 | 3719 | 1073 | 1568 | 991 | 3481 | 1200 | 980 | 3500 |
| N60P30K0 | 1010 | 3213 | 908 | 1281 | 923 | 3377 | 920 | 910 | 3400 |
| S.E. | 107 | 349 | 120 | 232 | 140 | 320 | 162 | 250 | 400 |
| C.V(%). | 24 | 22 | 26 | 30 | 24 | 22 | 28 | 32 | 25 |

N.B. Nutrient applied are N, $P_2$05 and $K_2$0 kg/ha
TDM= Total dry matter

**Table 9: Effect of phosphorus placement on pearl millet total dry matter (TDM), grain yield, and phosphorus use efficiency (PUE), Niger, 1995-1996 cropping seasons**

| | 1995 | | | | 1996 | | | |
|---|---|---|---|---|---|---|---|---|
| | TDM | | Grain | | TDM | | Grain | |
| Treatments (Kg/ha$^{-1}$) | Yield (kg ha$^{-1}$) | PUE | Yield (kg ha$^{-1}$) | PUE | Yield (kg ha$^{-1}$) | PUE | Yield (kg ha$^{-1}$) | PUE |
| 0 | 1951 | | 532 | | 2413 | | 641 | |
| 13 (broadcast) | 4012 | 159 | 1138 | 47 | 4884 | 190 | 1240 | 46 |
| 3 (HP) | 3157 | 402 | 864 | 111 | 3216 | 268 | 846 | 68 |
| 5 (HP) | 3341 | 278 | 937 | 81 | 3847 | 287 | 996 | 71 |
| 7 (HP) | 3498 | 221 | 1018 | 69 | 4041 | 233 | 1074 | 62 |
| 13 (broadcast) + 3 (HP) | 4830 | 180 | 1382 | 53 | 5314 | 181 | 1279 | 40 |
| 13 (broadcast) + 5 (HP) | 4713 | 153 | 1425 | 50 | 5180 | 154 | 1295 | 36 |
| 13 (broadcast) + 7 (HP) | 4381 | 122 | 1287 | 38 | 4685 | 114 | 1131 | 35 |
| SE | 314 | | 92 | | 425 | | 89 | |

**HP Hill placed, TDM : Total dry matter; PUE = kg yield/kg P**
**Source: Muelhing-Versen et al 1997**

**Table 10: Effect of mineral fertilizers, crop residue (CR) and crop rotation on pearl millet yield wasts (kg/ha) and phosphorus use efficiency (PUE) Sadore, Niger, 1998 rainy season.**

| Treatment | Without CR, without N | | | | Without CR, with N | | | | With CR, without N | | | | With CR, with N | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TDM | | Grain | | TDM | | Grain | | TDM | | Grain | | TDM | | Grain | |
| | Yield | PUE | Yield | PUE | Yield | PUE | Yield | PUE | Yield | PUE | Yield | PUE | Yield | PUE | Yield | PUE |
| Control | 889 | | 33 | | 2037 | | 58 | | 995 | | 61 | | 1471 | | 98 | |
| 13 kg P/ha | 2704 | 140 | 633 | 46 | 4339 | 177 | 1030 | 75 | 4404 | 185 | 726 | 51 | 240 | 4594 | 1212 | 86 |
| 13 kg P/ha + ridge | 2675 | 137 | 448 | 32 | 4057 | 155 | 946 | 68 | 3685 | 210 | 785 | 56 | 4530 | 235 | 1146 | 81 |
| 13 kg P/ha + rotation | 5306 | 340 | 1255 | 94 | 6294 | 327 | 1441 | 106 | 5392 | 338 | 1475 | 109 | 6124 | 358 | 1675 | 121 |
| 13 kg P/ha + ridge + rotation | 5223 | 333 | 1391 | 104 | 5818 | 291 | 1581 | 117 | 6249 | 404 | 1702 | 126 | 7551 | 468 | 1829 | 133 |
| SE | 407 | | 407 | | 407 | | 407 | | 407 | | 407 | | 407 | | 407 | |

**CR Crop Residue; N Nitrogen; TDM Total Dry Matter; PUE (kg grain/kgP);**
TDM= Total dry matter

**Table 11: Annual loss rates of soil organic carbon measured at selected research stations in the SSWA**

| Place and Source | Dominant cultural succession | Observations | Clay + Silt (%) (0-0.2 m) | Annual loss rates of soil organic carbon (k) | |
|---|---|---|---|---|---|
| | | | | Number of years of measurement | k (%) |
| **Burkina Faso** | | With tillage | | | |
| Saria, INERA-IRAT | Sorghum monoculture | Without fertiliser | 12 | 10 | 1.5 |
| | Sorghum monoculture | Low fertilizser | 12 | 10 | 1.9 |
| | Sorghum monoculture | High fertiliser | 12 | 10 | 2.6 |
| | Sorghum monoculture | Crop residues | 12 | 10 | 2.2 |
| CFJA, INERA-IRCT | Cotton-cereals | Eroded watershed | 19 | 15 | 6.3 |
| **Senegal** | | With tillage | | | |
| Bambey, ISRA-IRAT | Millet-groundnut | Without fertiliser | 3 | 5 | 7.0 |
| | Millet-groundnut | With fertiliser | 3 | 5 | 4.3 |
| | Millet-groundnut | Fertiliser + straw | 3 | 5 | 6.0 |
| Bambey, ISRA-IRAT | Millet monoculture | with PK fertiliser + tillage | 4 | 3 | 4.6 |
| Nioro-du-Rip, IRAT-ISRA | Cereal-leguminous | F0T0 | 11 | 17 | 3.8 |
| | Cereal-leguminous | F0T2 | 11 | 17 | 5.2 |
| | Cereal-leguminous | F2T0 | 11 | 17 | 3.2 |
| | Cereal-leguminous | F2T2 | 11 | 17 | 3.9 |
| | Cereal-leguminous | F1T1 | 11 | 17 | 4.7 |
| **Chad** | | With tillage, high fertility soil | | | |
| Bebedjia, IRCT-IRA | Cotton monoculture | | 11 | 20 | 2.8 |
| | Cotton - cereals | | | 20 | 2.4 |
| | + 2 years fallow | | | 20 | 1.2 |
| | + 4 years fallow | | | 20 | 0.5 |

F0 = no fertiliser, F1 = 200 kg $ha^{-1}$ of NPK fertiliser, F2 = 400 kg $ha^{-1}$ of NPK fertiliser + Taiba phosphate rock, T0 = manual tillage, T1 = light tillage, T2 = heavy tillage.

*Source: Pieri, 1989*

**Table 12: Millet grain yields by treatment (mean of 3 years), Goberi, Niger**

| Treatment | Yield (kg $ha^{-1}$) |
|---|---|
| Control | 261 |
| SSP only | 586 |
| SSP + N hill placed | 700 |
| SSP + N broadcast | 751 |
| PAPR + N broadcast | 752 |
| $LSD_{0.05}$ | 84 |

**Source, Bationo et al., 1992**

**Table 13. Mean millet yield (kg $ha^{-1}$) as affected by fertilizer, phosphate rock and crop residue in Sudano-Sahelian zone, Niger, 1998-2000**

| *Treatment | Karabedji | Gaya |
|---|---|---|
| Farmer practice (FP) | 210 | 505 |
| P hill placement (HP) | 470 | 990 |
| HP + Phosphate rock (PR) | 580 | 1150 |
| HP+PR+Crop residue | 835 | 1320 |

*Hill placed (HP): P applied at 4 kg $ha^{-1}$ as 15-15-15.
Phosphate rock (PR): P broadcast and incorporated at 13 kg $ha^{-1}$ as Tahoua PR
Crop residue (CR): millet stover applied as mulch at 2 t $ha^{-1}$
**Average rainfall: 600 mm and 800 in Karabedji and Gaya**

Figure 1: Agro-ecological zones of West Africa

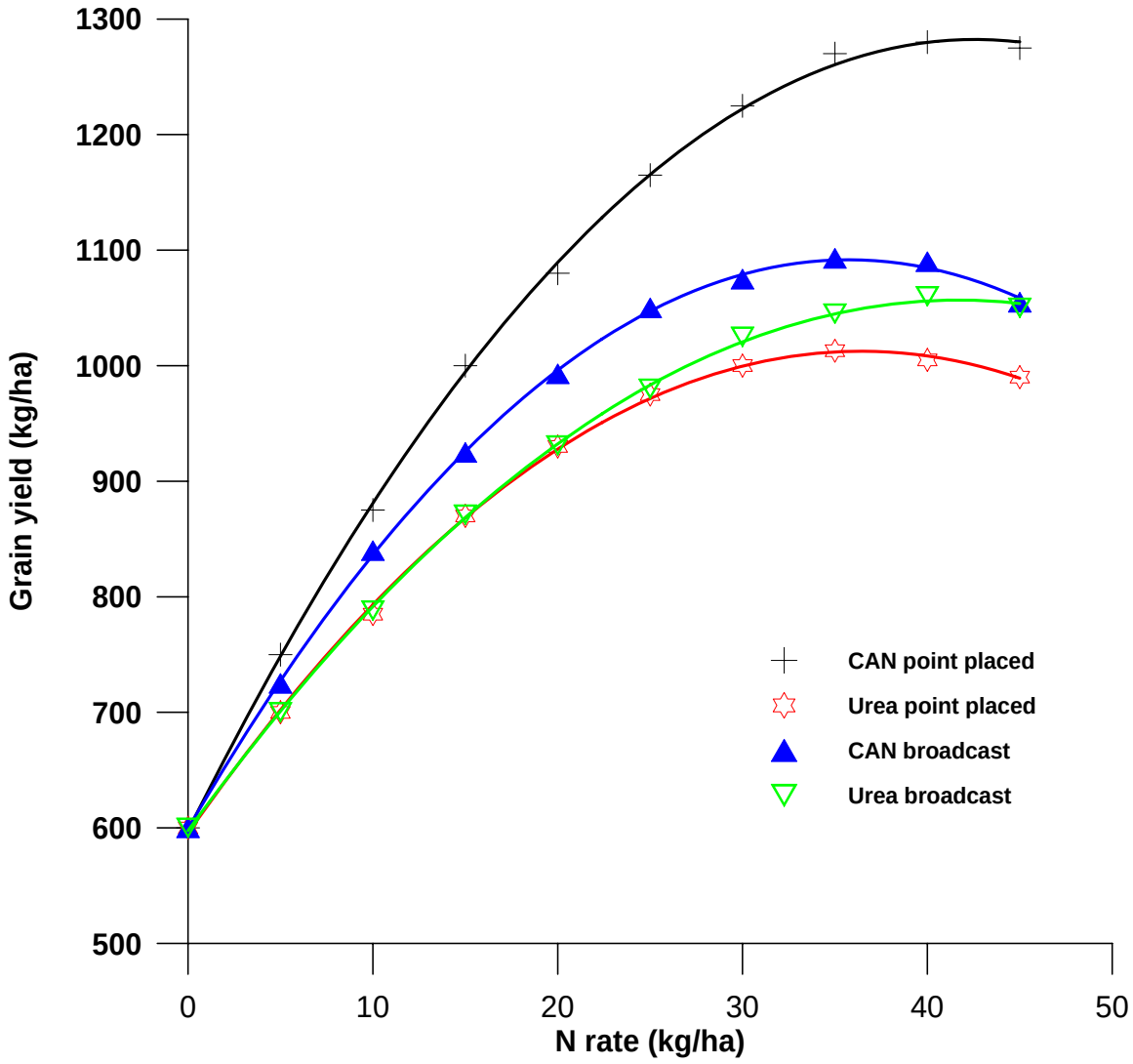


Figure 2: Effects of urea and calcium ammonium nitrate application on grain yield, Goberi, Niger, 1985
Source: Christianson and Vlek, 1991

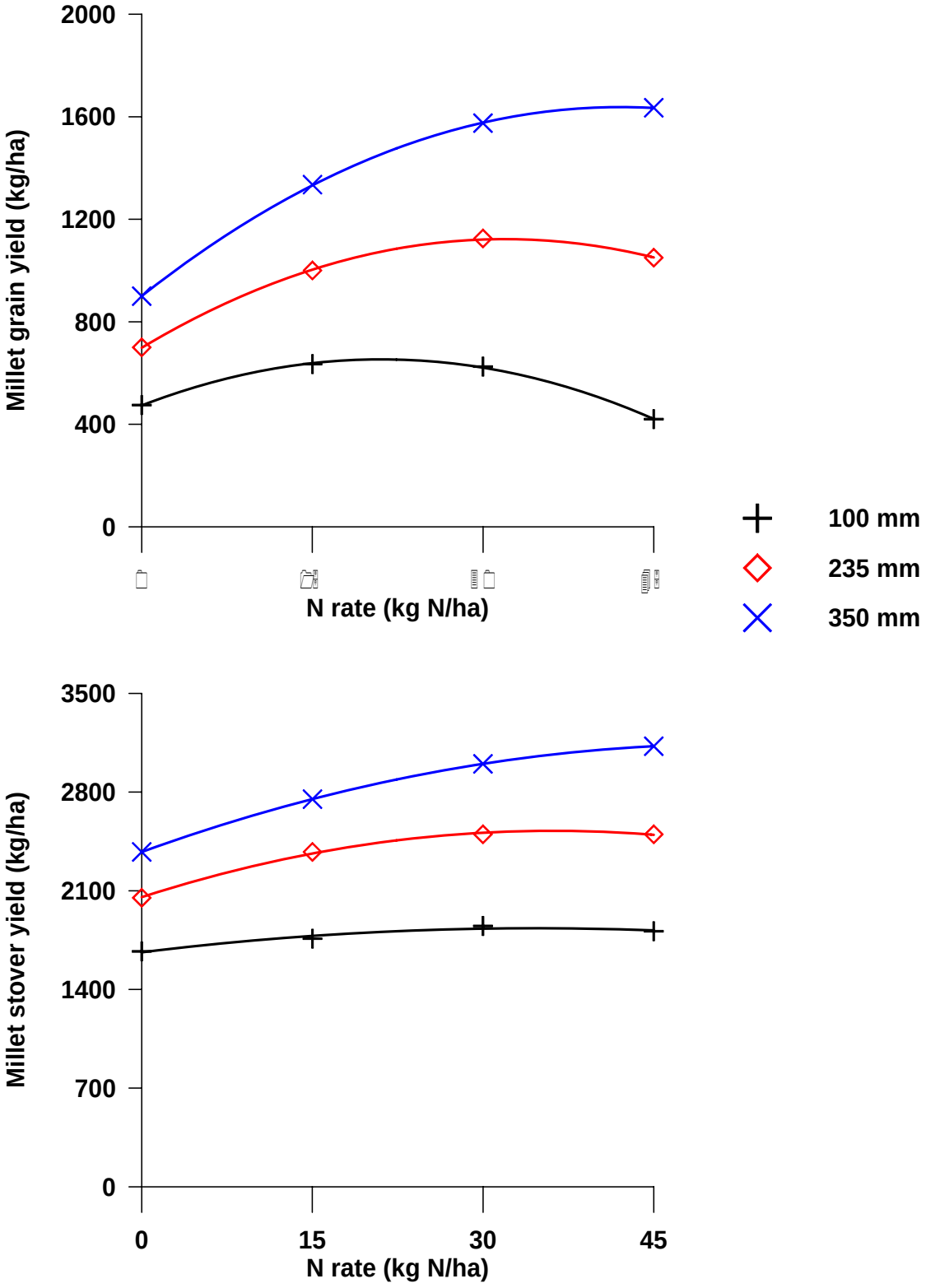


**Figure 3: Grain and stover yields affected by N rate and midseason rainfall. Sadore, Niger, 1982 to 1985**
**Source: Christianson et al., 1990**

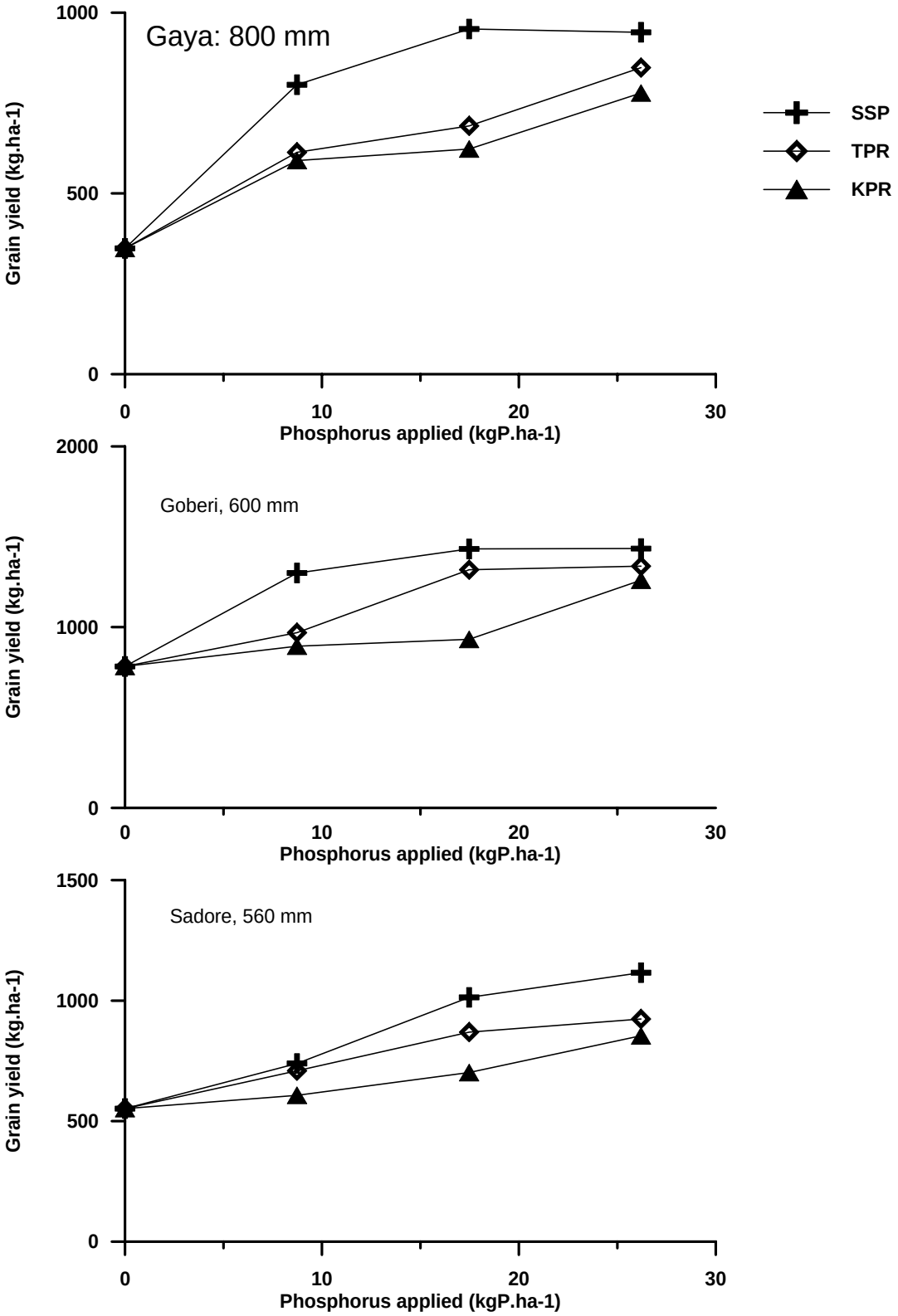


Figure 4: Relationship between P sources and rates on pearl millet grain yield in three agro-ecological zones of Niger, 1996 rainy season.

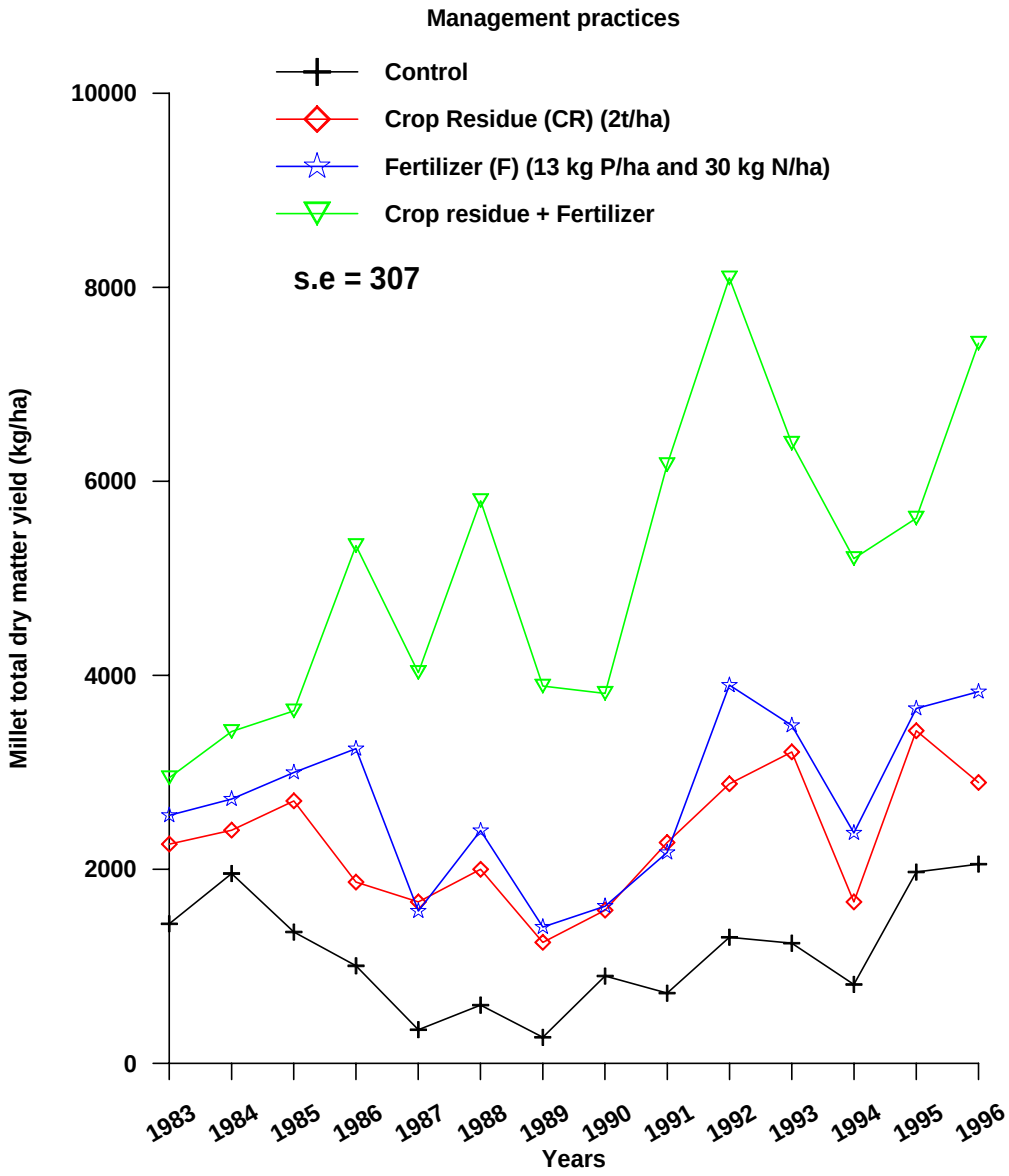


**Figure 5: Effect of different management practices on pearl millet total dry matter yield over years, Sadore, Niger.**

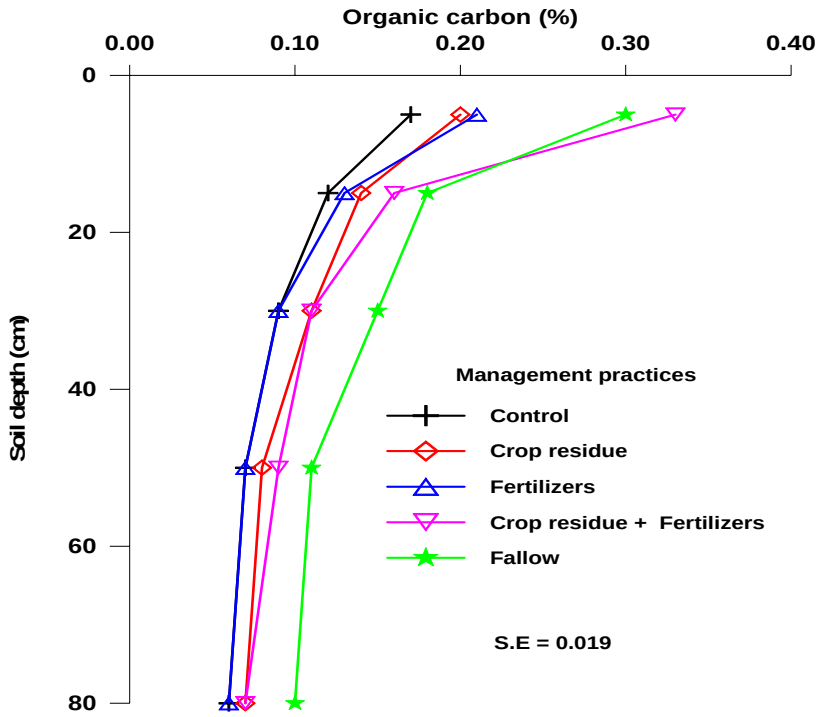


**Figure 6**: Effect of different management practices on soil organic carbon content after 14 years of cultivation, Sadore, rainy season 1997.

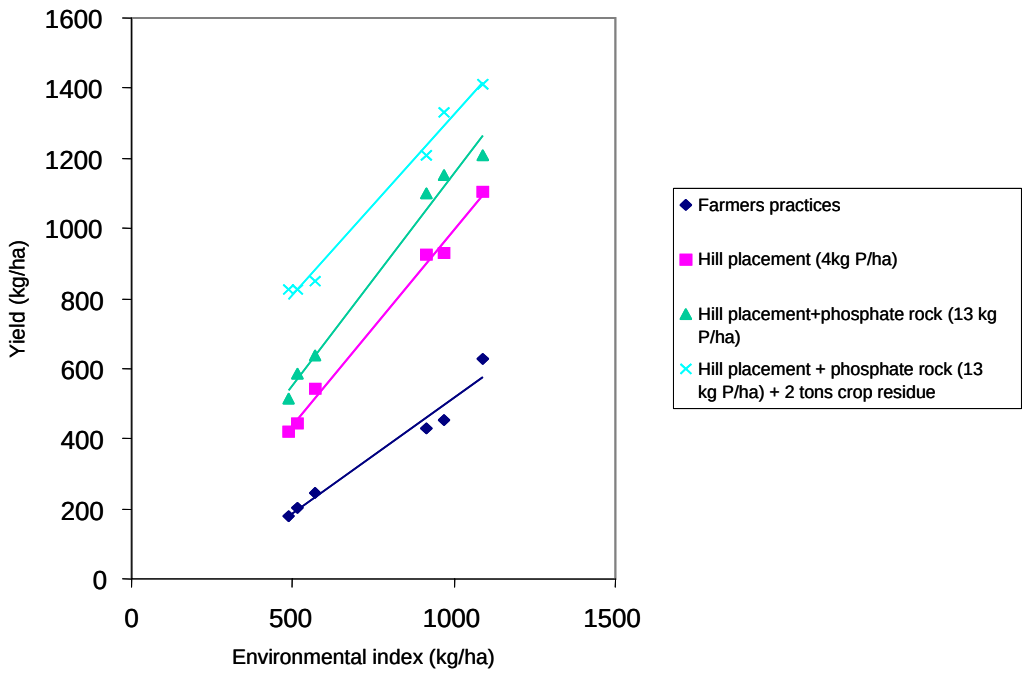


**Figure 7**: Relationship between environmental index and treatment yield of pearl millet in different agro-ecologiacl zones of Niger

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# Soil Fertility Management and Cowpea Production in the Semi-Arid Tropics of West Africa

Bationo[1], A., B.R. Ntare[2], S. Tarawali[3] and R. Tabo[2]
[1]IFDC/ICRISAT BP 12404 Niamey, Niger; [2]. ICRISAT Bamako, BP 320 Bamako, Mali[3.] ILRI/IITA, PMB 5320 Ibadan, Nigeria

## Abstract
Cowpea (*Vigna Unguiculata* L. Walp) is an important grain legume in West Africa as it is a major source of dietary protein for the people. It is usually grown as an intercrop with the major cereals, namely millet and sorghum. Despite its importance, its yields are very low due to several constraints including poor soil, insect pests and drought.

The soils in the Semi-Arid West Africa are inherently low in nitrogen and phosphorus. Soil, water and nutrients management practices are inadequate to sustain food production and to meet the food requirement of the fast growing population.

Research results show that proper management of organic amendments such as crop residues and manure, which are essential complement to mineral phosphorus fertilizers, can increase yields of cowpea and associated cereals more than three fold. Direct application of indigenous phosphate rocks can be an economical alternative to the use of imported, more expensive soluble phosphorus fertilizers for cowpea production in semi-arid tropics of West Africa. The agronomic effectiveness of indigenous phosphate rock is about 50% as compared to the imported single super-phosphate. Furthermore when the unreactive phosphate rocks are partially acidulated at 50%, their agronomic effectiveness can increase to more than 70%..

Studies on cereal-cowpea rotation revealed that yields of cereals succeeding cowpea can, in some cases, double as compared to continuous monoculture. In an efficient soil fertility management, cowpea can fix up to 88 kg N/ha and this results in an increase of nitrogen-use efficiency on the succeeding cereal crop from 20% in the continuous cereal monoculture to 28% when cereals are in rotation with cowpea. Furthermore, the use of soil nitrogen increased from 39 kg N/ha in the continuous cereal monoculture system to 62 kg N/ha in the rotation systems.

The increase of cowpea productivity and component in the cropping systems in this region will improve nutrition of people, increase the feed quantity and quality for livestock, and contribute to soil fertility maintenance. This should contribute to reduction in poverty and environmental degradation.

## I. Introduction
Per capita food production in the West African Semi-Arid Tropics (WASAT) has declined significantly over the past three decades and countries like Niger have more than 35% of their population undernourished. According to FAO, total food production in Sahelian countries grew by an impressive 70% from 1961 to 1996, but it lagged behind the population, which doubled causing food production per capita to decline approximately by 30% the same period. Low rainfall, infertile soils, and under-developed marketing channels markets are the main constraints preventing farmers to invest in productivity enhancing inputs. This situation has stemmed from increasing population pressure, and soil degradation in a particular drought-prone region where the soils are naturally infertile. The increasing need for cropland prompted the farmers to cultivate more and more marginal lands which are prone to erosion. Agricultural output should expand by at least 4% annually by the year 2000 in order to ensure food security. Previous studies have clearly shown that the expansion of new farms cannot increase output by over 1% without accelerating environmental degradation.

Consequently, the productivity of land currently under cultivation should increase by at least 3% per annum. As at now, over a quarter of West Africa Sub-region's population of two hundred million inhabitants is threatened by food insecurity. Any program aimed at reverting the declining trend in

agricultural productivity and preserving the environment for present and future generations in West Africa must begin with soil fertility restoration and maintenance.

Cowpea (*Vigna unguiculata* (L.) Walp) and groundnut (*Arachis Hypogea* L.) are two of the predominant grain legumes in the semi-arid tropics of West Africa. Groundnut occupies 2.7 million hectares of arable land and cowpea 6 million hectares. The two legumes are important components of the mixed cropping systems of resource poor farmers. The most important cereals are sorghum and pearl millet and legumes are often intercropped with these cereals (Steiner 1984).

The common cropping system involves growing several crops in association as mixtures or intercrop. This practices provide the farmers with several options for returns from land and labor, often increase efficiency with which scarce resources are used, and reduce dependence upon crop that is susceptible to environmental and economic fluctuations. While considerable information is available on fertilizer requirements for sole cropping of various crops, little is known on fertilizer requirement for inter-cropping. Steiner (1984) reported that traditional intercropping systems cover 75% of the cultivated area in the WASAT. The principal reason for farmers to intercrop are flexibility, profit resource maximization, risk minimization, soil conservation and maintenance, weed control and nutritional advantages (Norman 1974; Swinton et al. 1974; Shetty et al. 1995; Fussel and Serafini 1985).

Rotation of cereals with legumes has been extensively studied in recent years. Use of rotational systems involving legumes for harvesting nitrogen fixation is gaining importance throughout the region because of economic and sustainability considerations. The beneficial effect of legumes on succeeding crops is normally exclusively attributed to the increased soil N fertility as a result of $N_2$-fixation. The amount of $N_2$ fixed by leguminous crops can be quite high but some workers has demonstrated also that legumes can deplete soil nitrogen (Rupela and Saxena 1987; Blumenthal et al. 1982; Tanaka et al. 1983; Yoshida 1982; Ozaki 1969).

Most of the data reported on the quantity of N fixed by the legume crops in the WASAT concerned the above ground part of the legume and very little is known on the nitrogen fixed by the roots. Where much of the legume biomass is returned to the soil as green manure, a positive N balance is to be expected. However this may not be true for grain legumes and fodder crops, where the bulk of above legume material is removed from the systems. Nevertheless, many other positive effects of grain legumes such as the improvement of soil biological and physical properties (Hoshikawa 1990) and the ability of some legumes to solubilize occluded P and highly insoluble calcium bounded phosphorus by roots exudates (Gardner et al. 1991, Arihara and Ohwaki 1989). Other advantages of crop rotations include soil conservation (Stoop and Staveren 1981) organic matter restoration (Spurgeon and Grimson 1965) and pest and disease control (Curl 1963; Sunnadurai 1973).

Cowpea is often the only crop that survives severe drought in the WASAT. Cowpea grain contain about 22% protein, constitutes a major source of protein for resource poor people. It is estimated that cowpea supplies about 40% of the daily requirements to most of Nigeria population (Muleba et al. 1997).

In the mixed cropping systems, legumes yields are very low due to low soil fertility, low planting densities and pest and diseases (Ntare 1989; Reddy et al. 1992). The yield of cowpea grain varies between 50 kg $ha^{-1}$ and 300 kg $ha^{-1}$ in farmers fields in marked contrast to yield over 2000 kg $ha^{-1}$ obtainable on research stations and by large scale commercial enterprise in pure cropping. In the mixed farming systems of the WASAT, increasing legume component in the farming systems is important in order to increase the availability of fodder as source of livestock feed while increasing soil fertility.

In this paper, after a brief presentation of the cowpea production environment, we will discuss the effect of plant nutrient on cowpea production before reviewing the effect of cowpea cultivation on soil fertility maintenance and presenting the new opportunities for future research on soil fertility and cowpea production.

## II. Crop production environments

### a) Climate

Sivakumar (1986) proposed a soil climatic zonation scheme for West Africa that is calculated from rainfall and potential evapotranspiration. In this scheme, a growing period of 60 – 100 days was used for

defining the Sahelian zone. The geographical extent of the Sudanian zone has an average growing period of 100 – 150 days (**Figure 1**).

The rainfall in West Africa shows a significant north-south gradient because of the inter-seasonal movement of the intertropical convergence zone, north and south of the equator. The rainfall is low, variable and undependable. The rainfall gradient is very steep. The further one goes from the Sahara margin, the greater is the rainfall, approximately 1 mm $km^{-1}$. The isohyets run nearly parallel (Toupet 1965). Time dependent variations in rainfall are quite common in the region with coefficient of variation of annual rainfall ranges between 15-30%. The data in **Figure 2** clearly show the instability of the traditional mean figures for crop production as rainfall in some years can be 50% below or above the long-term average. Nicholson (1981) showed that in 1950, rainfall all over West Africa was above normal, at some location even 250% above normal. However, in 1970 rainfall was below normal throughout the region. As a result of rainfall variability, average yields of sorghum and pearl millet are unstable over years (**Figure 3**). The data in **Figure 4** give the annual rainfall values for a period of 40 years in the Douentza region of northwest Mali. From 1950 to 1990 median rainfall figures dropped from 650 mm/year to 350 mm/year.

It is well documented that precipitation determines the potential distribution of terrestrial vegetation and extended drought have initiated or exacerbated desertification. In the past 25 years, the WASAT has experienced the most substantial decline in rainfall (Hulme and Kelly 1997; Hulme 1992; Nicholson and Palao 1993) and the downward trend is persistent since 1951 with more areas experiencing more rainfall variability. As a result of the decrease in rainfall there will be a decrease in the vegetation cover of the land. Because evapotranspiration constitutes the only local input to the hydraulic cycle in the WASAT where there is no significant surface water, a reduction in the vegetation cover logically leads to reduce precipitation (Charney 1975). The reduction of vegetative cover will increase the albedo, which in turn, will lower surface temperature, decrease convection, cloud formation and precipitation. A further decrease in the rainfall will further decrease the vegetative cover (Cunnington and Rowntree 1986; Xue et al. 1990). However, Jackson and Idso 1974 disputed the importance of albedo. The non-climatic anthropogenic forces of desertification includes unsustainable agricultural practices, overgrazing and deforestation.

As already indicated, one important consequence in the reduction in rainfall is the reduction of vegetation cover. Consequently, the area of soil left bare and therefore directly exposed to wind and water erosion has considerably increased. The effect of these changes on wind and water erosion are aggravated by the sandy nature of the WASAT soils, which are frequently poorly aggregated, offering little resistance to the erosive forces. Buerkert et al. (1996a) measured absolute soil loss of 190 t $ha^{-1}$ in one year on bare plots, as opposed to soil deposition of 270 t $ha^{-1}$ on plot with 2 t $ha^{-1}$ millet stover mulch (**Figure 5**). Sterk et al. (1996) reported a total loss of 45.9 t $ha^{-1}$ of soil during four consecutive storms. Buerkert et al. (1996b) reported that in unprotected plots up to 7 kg of available p and 180 kg $ha^{-1}$ of organic carbon are lost from the soil profile within one year. Wind erosion will also decrease the exchangeable bases and increase soil acidification **(Table 1)**.

**b) Soils**

Entisols and Alfisols occupy most of the landscape for rainfed cropping in the WASAT. Entisols are mainly composed of quartz sand, with low water and nutrient holding capacity. The Alfisols have a clay accumulation horizon a high base saturation because of lower rainfall and leaching but they have poor structural stability, poor water and nutrient holding capacity and lower organic matter than the Utisols and Oxisols of the humid areas of the rainforest.

The data in **Table 2** show physical and chemical properties of soils from the WASAT. The soils have low organic carbon and total nitrogen content because of the low biomass production and a high rate of decomposition. One striking feature of these soils is their inherent low fertility which expressed in low level of organic carbon (generally less than 0.3%) total and available phosphorus and nitrogen and effective cation exchange capacity (ECEC). About 98% of the soil nitrogen is stabilized in organic matter. Thus the total nitrogen in the soil and the amount of nitrogen released for plant nutrients uptake will

depend on the organic matter level of the soil. Soil total organic carbon is highly correlated with the clay content of soil and as a result of the sandy nature of the soils in the WASAT, total nitrogen remain very low in most of the soils in the region. The importance of soil textural (clay and silt) properties for the organic carbon content was stressed repeatedly as clays are important component in the direct stabilization of organic molecules and micro-organisms (Amato and Ladd 1992; Greenland and Nye 1959; Feller et al., 1992). Thus Feller et al. (1992) reported that independently of climatic variations such as precipitation, temperature and duration of the dry season organic carbon content increased between 600 and 3000 mm annual rainfall soil organic carbon will increase with the clay and silt content of low activity clay soils. This is much evidence for a rapid decline of organic carbon levels with continuous cultivation in the sandy WASAT (Bationo et al. 1995). For the sandy soils, average annual losses in organic carbon expressed by K-value (calculated as the percentage of organic carbon per year), may be as high as 4.7%, whereas for sandy loam soils reported losses much lower, with average of 2% (Pieri 1989).

The low ECEC is attributed to low clay content and the kaolinitic mineralogy of the soils. Bationo and Mokwunye (1991) found that the ECEC is more related to the organic matter than the clay content, indicating that a decrease in organic matter will decrease the ECEC and then the nutrient holding capacities of those soils. De Ridder and Van Keulen (1990) reported that a difference of 1 g $kg^{-1}$ in organic carbon results in a difference of 4.3 mmol $kg^{-1}$ in ECEC.

Both total and available P levels are very low and P deficiency is the most limiting soil fertility factor for cowpea production. Apart from low P stocks, the low-activity nature of these soils results in a relatively low capacity to fix added P (Bationo et al. 1995). Phosphorus sorption maxima of the WASAT soil ranged from 27 to 405 mg P $kg^{-1}$ with a mean of 109 mg P $kg^{-1}$. The data in **Figure 6** indicate that low quantities of P are needed to be added in the soil to maintain 0.2 ppm P in the soil solution. For example, the sandy loam soil of Gaya with relatively high level of sesquioxydes 35 mg P/kg soil are needed to be added to the soil to maintain 0.2 ppm P in the soil whereas for the sandy Sahelian soil at Sadore only 10 mg P/kg soil is needed. Compared with the Utisols and Oxisols found in the humid tropical regions these soils can be considered to have relatively low P-fixing capacities, hence small additions of P fertilizers will increase available P in the soil and will give significant crop response.

At present, most cultivated land in the region losses more N, P and K that it gain and in that zone, continuous cultivation has lead to nutrient mining and loss of topsoil by wind and/or water erosion (**Table 3**).

Although organic amendments such as crop residue, manure or compost are essential in the sustainability of the cropping systems, they cannot prevent nutrient mining. The addition of organic amendments corresponds in most cases to a recycling process which cannot compensate for nutrient exported through crop products. As a result, the use of external input such as inorganic plant nutrient or local sources of P such as phosphate rock is an essential requirement if soil productivity is to be maintained. Thus increase in water use efficiency (WUE) and alleviation of nutrient mining and increase is paramount.

**III. Effect of soil fertility improvement on cowpea production**

Many research results in the region have shown the importance of the improvement of soil fertility for crop production (Mokwunye and Vlek 1986; Pieri 1989; Van Reuler and Jansen 1984; Vander Heide 1989; Bationo and Mokwunye 1991; Sedogo 1993; Delvaux et al. 1993). In the Sahelian zone, the various research work concluded that soil fertility is more limiting to crop and fodder production than rainfall (Penning de Vries and Djiteye1991; Breman and de Wit 1983). The data in **Table 4** clearly indicate that the use of mineral fertilizers will significantly increase water use efficiency. The data in **Table 5** clearly indicate a significant effect of N on cowpea and groundnut fodder production in different agro-ecological zones of the WASAT. These significant responses for legumes N to indicate that the predominantly sandy soils of the WASAT may be deficient in molybdenum required for efficient symbiotic fixation (Hafner et al. 1992). On the sandy acid soil at Bengou in the Sudanian zone at Gaya, significant molybdenum response was obtained at different level of soil fertility management for cowpea (Figure 7). Mühlig-Versen (personal communication) on a study on the effect of molybdenum and P effect on groundnut and

cowpea found that for cowpea found that for cowpea, application of P doubled the above ground biomass compared to the control. Application of molybdenum to the soil was less effective (+29%). The combination of both increased biomass up to 152% over the control. Groundnut responded only marginally to P or molybdenum, but the combination of both increased the biomass by 53% (Synergetic effect) **(Figure 8)**.

Legumes such as cowpea have a high P requirement. P is reported to stimulate root and plant growth, initiate nodule formation as well as influence the efficiency of the rhizobium-legume symbiosis (Robinson et al. 1981). It is also involved in reactions with energy transfer, more specifically ATP in nitrogenase activity (Israel 1987). The data in **Figure 9** clearly indicate a strong response to P by cowpea cultivars at Ikeme in the humid zone and Kamboinse in the Sudanian zone of West Africa, but there are large differences between cultivars for their response to P. The local Kamboinse variety is a fodder type and the application of P resulted in higher fodder production but lower grain production. As reported by several scientists such as Dwivedi et al. (1975); Khan and Zende (1977); Stukenholtz et al. (1966); Takkar et al. (1976) and Youngdhal et al. (1977) the application of P resulted in significant decrease of Zinc concentration in the cowpea grain **(Figure 10)** and this can affect the nutritional quality of cowpea (Buerkert et al. 1998).

Despite the importance of P in these soils, the use of commercial P fertilizers in the WASAT is limited due to the high cost of imported fertilizers. Several countries in the region however, are known to have phosphate deposits. Direct application of indigenous phosphate rocks (PR) can be an alternative to the use of more expensive water-soluble P fertilizers. This practice would also promote savings in scarce foreign exchange. The effectiveness of PR depends on its chemical and mineralogical composition, soil factors, and the crops to be grown (Khasawneth and Doll 1978; Lehr and McClellan 1972; Chien and Hammond 1978). The data in **Table 6** give the relative agronomic effectiveness of Tahoua PR and Kodjari PR in different agro-ecological zone of the WASAT. The data indicate that Tahoua PR agronomic effectiveness outperformed Kodjari PR. These results are in agreement with the chemical composition of the two rocks where the molar $PO_4/CO_4$ ratio is 25 for Kodjari PR and 4.88 for Tahoua PR. As soils in Gaya and Gobery are more acidic and receive more rainfall than the Sadore site, the agronomic effectiveness is higher at those sites. The agronomic effectiveness of the leguminous cowpea is not better than that of the cereal pearl millet crop. This is in contradiction to other reports where legumes have highest strategy to solubilize PR than cereals by rhizosphere acidulation (Aguilar and Van Diest 1981; Kirk and Nye 1986; Hedley et al. 1982) and exudation of organic acids (Ohwaki and Hirata 1992).

The data in **Figures 11** and **12** give the response of cowpea grain and stover to different sources of P fertilizers. The application of P fertilizers can triple cowpea stover production but the higher stover production resulted in lower grain yield. The relative agronomic effectiveness data in **Table 7** indicate that Parc-W PR indigenous to Niger agronomic effectiveness varied from 42% to 54% as compared to the water soluble SSP but the acidulation of PR at 50% (PAPR50) with sulfuric acid can increase the relative agronomic effectiveness to 96% for cowpea stover production. For fodder production TSP relative agronomic effectiveness varied from 77 to 91% indicating that sulfur application is needed for a better growth of cowpea.

Over the past years, research at ICRISAT-Niger has focussed on the placement of small quantities of P fertilizers at planting stage in order to develop optimum farmer-affordable P application recommendation. For cowpea stover production phosphorus use efficiency increased from 44 kg/kg P with the addition of Kodjari PR to 99 when Kodjari PR is broadcast with hill placement of 4 kg P/ha as 15-15-15 (**Table 8**)

Long-term experiments are practical means to address the difficult issues associated with quantitative assessment of sustainability in agriculture. In summarizing the results of long-term soil fertility management in Africa, Pieri (1986) concluded that soil fertility in intensive arable farming in the WASAT can only be maintained through efficient cycling of organic materials in combination with mineral fertilizers and with rotation with leguminous $N_2$-fixing species. The data in **Figure 13** clearly indicate that the application of small quantities of fertilizers and the application of crop residue resulted in

an increase of cowpea fodder yield to 5300 kg/ha. In researcher on-farm management trials, it was found that pocket application of small quantities of manure (3 t/ha) plus 4 kg/ha of P at seedling time will increase cowpea yield from …….. in the control plot to …… **(Figure 14)**.

**IV. Effect of cowpea production on soil fertility improvement**

Despite the recognized need to apply chemical fertilizers for high yields, the use of mineral fertilizers in West Africa is limited by lack of capital, inefficient distribution systems, poor enabling policies and other socio-economic factors. Cheaper means of improving soil fertility and productivity is therefore necessary. Cereal/legume rotation effects on cereal yields have been reported for the WASAT (Bakayoko et al. 1996; Bakayoko et al. 2000; Bationo et al. 1998; Klaij and Ntare 1995; Nicou 1977; Stoop and Staveren 1981; Bationo and Ntare 2000).

Isotopic dilution method with $^{15}N$ was used to determine the nitrogen fixed by cowpea using pearl millet as non-fixing crop. The data in **Table 9** indicate that nitrogen derived from the atmosphere by cowpea varied from 65 to 88% and the total nitrogen fixed by cowpea depends of the level of soil fertility improvement. The quantity of nitrogen fixed by cowpea varied from 27 kg/ha in the control plot to 87 kg/ha in the treatment where the soils were amended with mineral and agronomic plant nutrients.

In order to determine $^{15}N$ recovery from different cropping systems, labeled nitrogen fertilizers were applied to microplot where pearl millet was grown continuously (M – M) in rotation with cowpea (C – M), in rotation with groundnut (G – M), intercropped with cowpea (C/M – C/M) and intercropped with groundnut (G/M – G/M). The data in **Table 10** indicate that at Sadore in 1990, nitrogen use efficiency increased from 20% in continuous pearl millet cultivation to 28% when pearl millet was rotated with cowpea. For both Bengou and Sadore, nitrogen derived from the soil was better used in rotation systems than with continuous millet cultivation.

Bationo and Ntare (2000) carried long-term experiments to investigate the effect of continuous monoculture as compared to crop rotation. At all the three sites in the WASAT, rotation of pearl millet with groundnut and cowpea resulted in higher significant pearl millet yields than in monoculture cropping of pearl millet over the 4-year period **(Figures 15** and **16)**. Legumes also gave significant responses to rotations **(Figures 17)** and this suggest that factors other than N alone contributed in the yield increases in the cereal-legume rotations. Bagayoko et al. (2000) in studies of cereal legumes effects on cereal growth in the WASAT reported that the rotation effect although significant in most of the cases varied with sites and years. At Sadore as an example, whereas grain yield of pearl millet in 1998 was 1557 kg/ha in the continuous millet production, the millet rotated with cowpea yielded 1905 kg/ha and in Gaya for the same year, sorghum grain yield increased by 50% due to rotation with groundnut in the Sudanian zone **(Table 11)**. The data in **Tables 12** and **13** show higher level of mineral N and native arbuscular mychorrhizae in the rotation system as compared to the continuous cultivation of cereals. In sorghum-groundnut system in the Sudanian zone, nematode densities were consistently lower in rotation system compared to continuous sorghum cultivation **(Figure 18)**.

Bationo et al. (2000) studied nitrogen dynamics in different cropping systems. In order to determine N availability, the soil were incubated and mineral nitrogen determined at 7, 21, and 35 days(Keeny 1982). Crop rotation significantly affected mineral nitrogen **(Figure 19)**. The fallow millet rotation supplied more nitrogen than the cowpea-millet rotation, but the latter was more productive for millet production. These results suggest that other factors in addition to biological nitrogen fixation may be involved in the positive effect of legume cereal rotation (Crookston et al. 1988). Crop rotation is known to substantially increase soil microbial activity and this may lead to an increase in nutrient availability.

In the long-term field trials carried out on the sandy Sahelian soil of the Sahel to study the effect of N and P in different cropping systems, the data show that P application has a very significant effect on yield of cowpea and pearl millet and rotation performed better than continuous cultivation of both crop **(Figure 20)**. The data in **Table 14** indicated that the land equivalent ratio varied from 24% to 200% showing that even with the use of external input, intercropping is better than pure cropping. In this long-

term cropping system experiment, it was found higher level of organic carbon in the rotation systems as compared to the continuous cropping systems due in part of the fall of cowpea leaves **(Figure 21)**.

In another long-term soil management trials, application of phosphorus nitrogen, crop residue, and ridging and rotation of pearl millet with cowpea were evaluated to determine the P use efficiency. The results show that soil productivity of the sandy Sahelian soils can very significantly increased with the adoption of improved crop and soil management technologies. Whereas the absolute control recorded 33 kg $ha^{-1}$ of grain yield, 1829 kg was obtained when phosphorus, nitrogen and crop residue were applied to plots that were ridged and followed leguminous cowpea. The plots without rotation yielded 1146 kg $ha^{-1}$ without rotations. Results indicated that for grain yield, P use efficiency will increase from 46 with only P application, to 133 kg/kg P when P is combined with nitrogen and crop residue application and the crop is planted on ridges **(Table 15)**.

**V. Conclusion and new research opportunities**

In the mixed traditional cropping systems cowpea is grown between cereals at very low density as the farmers primary goal is to produce cereal for their family subsistence, and consider the additional cowpea as an additional benefit. This means that farmers need to be assured of sufficient cereal harvest to feed their families before integrating more cowpea in the cropping systems. The yield of cowpea grain in the mixed systems is very low, varying between 50 kg and 300 kg $ha^{-1}$ in marked contrast to over 2000 kg $ha^{-1}$ realized at research station and by large scale commercial enterprise in sole cropping. In addition to the low planting densities, pests and disease control, the inherent low fertility of the soil in the WASAT (particularly P) is one of the major constraint to cowpea production in the region and soil fertility replenishment should be an integral part of any program aimed at reverting trend in cowpea production and the conservation of the environment.

Phosphorus is the most limiting plant nutrient for cowpea production in the WASAT and there is ample evidence that indicates marked differences between cowpea genotypes for P uptake. Understanding the factors affecting P uptake such as the ability of plants to (i) solubilize soil P through acidification of the rhizosphere and the release of chelating agents and phosphate enzymes (ii) explore a large soil volume and (iii) absorb P from low P solution would help increase cowpea production and yield in the semi-arid tropics.

The available and total P values are very low in the region. With these extreme low values of total P, selecting cultivars adapted to low P condition would not be feasible as one cannot mine what is not there. Direct application of indigenous PR can be an economic alternative to the use of more expensive imported water-soluble P fertilizers. The effectiveness of mycorrhizal in utilizing soil P has been well documented (Silberbush and Barber 1983; Lee and Wani 1991; Daft 1991). An important future research opportunity is the selection of cowpea genotypes that can efficiency associate with vesicular-Arbuscular Mycorrhizal (VAM) for better utilization of P applied PR.

Cereal/cowpea rotations have led to increased cereal yields at many locations in the WASAT. Factors such as mineral nitrogen, (VAM) for P nutrition improvement and plant parasitic nematodes have been identified as mechanisms accelarating the enhanced yield of cereals in rotation with cowpea. Most of the research quantified the above-ground N fixed by different cowpea cultivars, but very little is known on the below-ground N fixed by cowpea. In the WASAT, most of the above-ground cowpea biomass are used for animal feed and not used as green manure. Future research need to focus more on the on-farm quantification of the below-ground N fixed by cowpea in order to identify the best cultivar for soil N. The identification and alleviation of technical and socio-economic constraints in order to increase cowpea component in the present cropping systems needs attention in future. As cash crop, farmer will increase their credit access to external inputs such as fertilizers. The enhancement of cowpea component in the present cropping system will not only improve the soil conditions for the succeeding cereal crop, but will provide good quality livestock feed, and the manure produced will be of better quality for soil the fertility amendment.

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**Table 1: Nutrient balance after two years of erosion and deposition, Sadore, Niger**

Relative losses of a bare compared to a protected (plastic mulch) soil at two depths

| Soil properties | ----------[kg $ha^{-1}$ $g^{-1}$]---------- | | | |
|---|---|---|---|---|
| | 0 to 0.1 m depth | 0.1 to 0.2 m depth | Sum# | |
| N total | -14.0 | 3.0 | -11.0 | ±9.8 |
| P Bray | -4.2 | -2.8 | -7.1 | ±1.4 |
| P $H_2O$ | -0.08 | -0.06 | -0.14 | ±0.07 |
| K | -3.2 | -2.2 | -5.4 | ±2.2 |
| Ca | -18.7 | -12.7 | -31.4 | ±9.4 |
| Mg | -1.7 | -1.3 | -3.0 | ±2.3 |
| C organic | -115 | -65 | -180 | ±83 |
| Al total | 10.9 | 11.4 | 22.3 | ±7.5 |

# Sums followed by their standard errors (n=3)
**Source**: adapted from Buerkert et al. 1996

**Table 2: Means and ranges of selected physical and chemical properties of West African semi-arid soils**

| Parameter | Range | Mean |
|---|---|---|
| pH-$H_2O$ (2:1 water:soil) | 3.95 - 7.6 | 6.17 |
| pH-KCl (2:1 water:soil) | 3.41 - 7.0 | 5.05 |
| Clay (%) | 0.7 - 13 | 3.9 |
| Sand (%) | 71 - 99 | 88 |
| Organic matter (%) | 0.14 - 5.07 | 1.4 |
| Total nitrogen (mg $kg^{-1}$) | 31 - 226 | 446 |
| Exchangeable bases (cmol $kg^{-1}$) | | |
| Ca | 0.15 - 16.45 | 2.16 |
| Mg | 0.02 - 2.16 | 0.59 |
| K | 0.03 - 1.13 | 0.20 |
| Na | 0.01 - 0.09 | 0.04 |
| Exchangeable Al (cmol $kg^{-1}$) | 0.02 - 5.6 | 0.24 |
| Effective Cation Exchange Capacity (cmol $kg^{-1}$) | 0.54 - 19.2 | 3.43 |
| Base saturation (%) | 36 - 99 | 88 |
| Al saturation (%) | 0 - 46 | 3 |
| Total phosphorus | 25 - 941 | 136 |
| Available phosphorus | 1 - 83 | 8 |
| Maximum P sorbed | 27 - 406 | 109 |

**Source:** Bationo et al.

**Table 3: Nutrient losses for some West African countries**

| Country | Area (1000 ha) | Losses for the region ($10^5$tones) | | |
|---|---|---|---|---|
| | | N | $P_2O_5$ | $K_2O$ |
| Benin | 2972 | 41388 | 10366 | 32499 |
| Burkina Faso | 6691 | 95391 | 27754 | 78764 |
| Ghana | 4505 | 137140 | 32313 | 90474 |
| Mali | 8015 | 61707 | 17888 | 66725 |
| Niger | 985 | 176120 | 55331 | 146617 |
| Nigeria | 2813 | 1107605 | 316687 | 946157 |

**Table 4: Water use (WU), grain yield (Y) and water use efficiency (WUE) for millet at Sadore and Dosso (Niger)**

| Treatments | Sadore | | | Dosso | | |
|---|---|---|---|---|---|---|
| | WU (mm) | Y (kg/ha) | WUE (kg/ha/mm) | WU (mm) | Y (kg/ha) | WUE (kg/ha/mm) |
| Fertiliser | 382 | 1570 | 4.14 | 400 | 1700 | 4.25 |
| Without fertiliser | 373 | 460 | 1.24 | 381 | 780 | 2.04 |

**Table 5. Effect of nitrogen on pearl millet, cowpea and groundnut yield at three sites in 1988**

| **N Rates kg N/ha$^{-1}$** | **Millet grain** | | | **Cowpea fodder** | | | **Groundnut fodder** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Sadore** | **Bengou** | **Tara** | **Sadore** | **Bengou** | **Tara** | **Sadore** | **Bengou** | **Tara** |
| 0 | 915 | 1172 | 55O | 4069 | 2213 | 2974 | 1470 | 1128 | 1088 |
| 15 | 1098 | 1358 | 671 | 4474 | 2510 | 2963 | 1944 | 1243 | 1681 |
| 30 | 1194 | 1424 | 727 | 4288 | 2548 | 3025 | 2105 | 1278 | 1820 |
| 45 | 1233 | 1539 | 804 | 4264 | 3008 | 3500 | 2486 | 1359 | 2093 |
| S.E.(D.F.27) | 60.0 | 58.3 | 52.3 | 218.3 | 153.7 | 161.3 | 132.7 | 55.0 | 104.3 |
| CV (%) | 23 | 18 | 32 | 15 | 17 | 15 | 19 | 13 | 18 |

**Table 6: Relative agronomic effectiveness for pearl millet and cowpea as compared to SSP (%) Of Tahoua phosphate rock (TPR) and Kodjari phosphate rock (KPR) in three agro-ecological zones of Niger**

| | **Sadore** | | **Goberi** | | **Gaya** | |
|---|---|---|---|---|---|---|
| | **TPR** | **KPR** | **TPR** | **KPR** | **TPR** | **KPR** |
| Grain yield (kg/ha) | 63 | 32 | 76 | 41 | 80 | 57 |
| Total biomass (kg/ha) | 65 | 35 | 60 | 40 | 68 | 63 |
| Cowpea fodder (kg/ha) | 43 | 28 | 73 | 51 | 42 | 42 |
| Cowpea total dry matter (kg/ha) | 56 | 40 | 72 | 51 | 52 | 55 |

Source: **Mahaman et al., 1997**

**Table 7: Relative agronomic effectiveness of different sources of P**

| P sources | 1993 | | 1994 | |
|---|---|---|---|---|
| | Grain | Fodder | Grain | Fodder |
| PRA | 70 | 54 | 49 | 42 |
| PAPR25 | 45 | 58 | 61 | 75 |
| PAPR50 | 72 | 92 | 88 | 96 |
| TSP | 68 | 91 | 65 | 77 |
| SSP | 74 | 87 | 86 | 91 |
| PRB | 50 | 53 | 55 | 49 |

**Table 8: Effect of different sources* of phosphorus and their placement** on cowpea yield and PUE, Karabedji, 1998 rainy season**

| **P Sources and method of application** | **Grain** | | **Fodder** | |
|---|---|---|---|---|
| | **Yield (kg ha$^{-1}$)** | **PUE** | **Yield (kg ha$^{-1}$)** | **PUE** |
| Control | 505 | | 1213 | |
| SSP broadcast | 1073 | 44 | 2120 | 70 |
| SSP broadcast + SSP HP | 1544 | 61 | 3139 | 113 |
| SSP HP | 1050 | 136 | 2021 | 452 |
| 15-15-15 broadcast | 1165 | 51 | 2381 | 90 |
| 15-15-15 broadcast + 15-15-15 HP | 2383 | 110 | 3637 | 142 |
| 15-15-15 HP | 1197 | 173 | 2562 | 337 |
| PRT broadcast | 986 | 37 | 2220 | 77 |
| PRT broadcast + SSP HP | 1165 | 68 | 3127 | 113 |
| PRT broadcast + 15-15-15 HP | 1724 | 72 | 3163 | 115 |
| PRK broadcast | 920 | 32 | 1791 | 44 |
| PRK broadcast + SSP HP | 1268 | 45 | 2588 | 81 |
| PRK broadcast + 15-15-15 HP | 1440 | 55 | 2792 | 93 |
| S.E | 164 | | 313 | |

PUE Kg grain/KgP; HP Hill Placed; TDM Total Dry Matter
**For broadcast, 13 KgP/ha was applied ** For HP, at 4 KgP/ha
*SSP Single superphosphate; 15-15-15 compound fertilizer containing 15% N, 15% $P_2O_5$, 15% $K_2O$; TPR Tahoua Phosphate Rock; KPR Kodjari Phosphate Rock

**Table 9. Nitrogen derived from the air (NdFA%) and $^{15}N$ recovery by cowpea stover, Sadoré, Niger, 1991 rainy season**

| Treatment | Yield (t $ha^{-1}$) | N (%) | N yield (kg $ha^{-1}$) | NdFF (%) | NdFa (%) | N fixed (kg $ha^{-1}$) |
|---|---|---|---|---|---|---|
| Control | 1.75 | 2.18 | 38.1 | 2.43 | 65.1 | 25.6 |
| Molybdenum | 3.08 | 2.28 | 71.4 | 1.37 | 80.4 | 58.1 |
| Carbofuran | 2.58 | 2.19 | 57.4 | 2.04 | 70.8 | 41.4 |
| Manure | 2.42 | 2.44 | 59.7 | 0.79 | 88.6 | 53.3 |
| Phosphorus | 3.58 | 2.01 | 65.2 | 1.56 | 77.6 | 50.6 |
| Complete | 3.75 | 2.66 | 99.8 | 0.80 | 88.6 | 89.1 |
| SE | ±0.47 | ±0.09 | ±10.39 | ±0.18 | ±2.56 | ±9.06 |
| CV (%) | 28 | 6 | 27 | 20 | 6 | 29 |

1. FUE: Fertilizer use efficiency

**Table 10. $^{15}N$ recovery by pearl millet in different cropping systems**

| Treatment | Year | Site | Yield (t $ha^{-1}$) | N Yield (kg $ha^{-1}$) | N-uptake from soil (kg $ha^{-1}$) | N uptake from fertilizer (kg $ha^{-1}$) | Nitrogen use efficiency (%) |
|---|---|---|---|---|---|---|---|
| M-M | 1990 | Bengou | 4.17 | 56 | 39.03 | 17 | 38 |
| G-M | | | 4.94 | 74 | 62.19 | 12 | 49 |
| LSD (0.05) | | | 1.31 | 21 | 16.56 | 11 | 25 |
| CV (%) | | | 13 | 14 | 15 | 26 | 26 |
| M-M | 1989 | Sadore | 3.81 | 48 | 38.32 | 8 | 27 |
| M-G | | | 4.50 | 56 | 45.51 | 10 | 35 |
| LSD (0.05) | | | 1.43 | 22 | 20.07 | 22 | |
| CV (%) | | | 15 | 19 | 21 | 10 | |
| M-M | 1989 | Sadore | 3.25 | 38.34 | 30 | 6 | 19 |
| G-M | | | 3.96 | 45.56 | 37 | 8 | 28 |
| LSD (0.05) | | | 0.63 | 11.04 | 12 | 1 | 4 |
| CV (%) | | | 8 | 16 | 7 | 7 | 24 |

**Table 11. Millet and sorghum dry matter at thinning and grain and total dry matter yield at harvest as influenced by millet/cowpea cropping systems at Gaya, Goberi and Sadoré (Niger) and sorghum groundnut cropping systems at Kouaré (Burkina Faso)**

| Sites and Cropping system | Thinning | | | | | Harvest | | |
|---|---|---|---|---|---|---|---|---|
| | TDM | | Grain yield | | | TDM[b] | | |
| | 1996 | 1998 | 1996 | 1997 | 1998 | 1996 | 1997 | 1998 |
| | | | | Kg ha$^{-1}$ | | | | |
| Sadoré | | | | | | | | |
| Continuous millet | 4 | 6 | 937 | 321 | 1557 | 4227 | 2219 | 6992 |
| Millet after cowpea | 5 | 7 | 1255 | 340 | 1904 | 5785 | 2832 | 8613 |
| *P>F*[a] | *<0.001* | *0.059* | *<0.001* | *0.344* | *<0.001* | *<0.001* | *<0.001* | *<0.001* |
| Goberi | | | | | | | | |
| Continuous millet | 13 | 8 | - | 779 | 956 | 2328 | 3444 | 4220 |
| Millet after cowpea | 16 | 9 | - | 827 | 1151 | 2579 | 3743 | 4800 |
| **P>F** | *<0.001* | *0.063* | - | *0.145* | *<0.001* | *<0.001* | *0.019* | *<0.001* |
| Gaya | | | | | | | | |
| Continuous millet | 13 | 13 | 794 | 378 | 645 | 2601 | 2469 | 2598 |
| Millet after cowpea | 15 | 11 | 889 | 466 | 636 | 2823 | 2684 | 2510 |
| **P>F** | *0.001* | *0.014* | *0.085* | *<0.001* | *0.801* | *0.025* | *0.069* | *0.353* |
| Kouaré | | | | | | | | |
| Continuous sorghum | 30 | 26 | 397 | 786 | 238 | 3056 | 4505 | 2689 |
| Sorghum after cowpea | 36 | 25 | 553 | 884 | 357 | 4191 | 5316 | 3633 |
| **P>F** | *<0.001* | *0.352* | *<0.001* | *<0.001* | *<0.001* | *<0.001* | *<0.001* | *<0.001* |

a. Probability of a treatment effect (significance level)
b. Total dry matter

**Table 12. Effects of cereal-legume cropping systems on soil mineral N In May, June and September 1997 and 1998 at Gaya, Goberi and Kouare. Sampling depth was 0-0.3 m**

| Time | Goberi | | Gaya | | Kouaré | |
|---|---|---|---|---|---|---|
| | Millet/cowpea | | | | Sorghum/groundnut | |
| Cropping systems | Nmin | NO3-N | Nmin | NO3-N | Nmin | NO3-N |
| | | | Mg N kg-1 soil | | | |
| May | | | | | | |
| Continuous | 3.1 | 1.3 | 8.9 | 4.7 | 12.1 | 8.3 |
| Rotation | 3.5 | 1.2 | 11.0 | 6.0 | 23.1 | 18.6 |
| P>F[a] | *0.448* | *0.587* | *0.045* | *0.025* | *0.050* | *0.008* |
| June-July | 5.2 | 3.4 | 9.6 | 5.6 | 14.4 | 11.2 |
| Continuous | 5.2 | 3.2 | 12.1 | 7.9 | 20.0 | 15.9 |
| Rotation | *0.675* | *0.706* | *0.055* | *<0.001* | *0.025* | *0.016* |
| **P>F** | | | | | | |
| September | | | | | | |
| Continous | 1.2 | 0.2 | 6.5 | 3.3 | 10.6 | 6.6 |
| Rotation | 1.6 | 0.2 | 4.9 | 1.8 | 17.9 | 13.8 |
| **P>F** | *0.626* | *0.803* | *0.706* | *0.035* | *0.021* | *0.002* |

**Table 13. Root infection by mycoryiase (AM) in millet (0-0.3 m) affected by cropping system at Sadoré, Goberi and Gaya, Niger**

| Cropping system | 1996 | | 1997 | | | | |
|---|---|---|---|---|---|---|---|
| | Goberi | Gaya | Sadore | | Goberi | | Gaya |
| | 120 DAS[b] | | 35 DAS | 75 DAS | 45DAS | 75 DAS | 50 DAS |
| | AM infection (% of roots) | | | | | | |
| Continuous millet | 35 | 31 | 23 | 44 | 27 | 48 | 11 |
| Millet after cowpea | 39 | 33 | 32 | 50 | 48 | 64 | 31 |
| P>P[a] | *0.280* | *0.325* | *<0.001* | *0.109* | *0.001* | *<0.001* | *<0.001* |

a. Probability of a treatment effect significance level
b. Days after sowing (DAS)

**Table 14. Land equivalent ratios in different cropping systems over a period of four years**

| P. Rate | N Rate | Continuous intercropping | | | Rotation following millet | | | Rotation following cowpea | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Cowpea | Millet | Total | Cowpea | Millet | Total | Cowpea | Millet | Total |
| | 0 | 1.12 | 0.92 | 2.04 | 0.65 | 0.87 | 1.52 | 0.71 | 0.76 | 1.47 |
| 0 | 30 | 0.85 | 1.12 | 1.97 | 0.72 | 0.85 | 1.57 | 0.93 | 0.84 | 1.77 |
| | 0 | 0.77 | 0.72 | 1.49 | 0.65 | 0.69 | 1.34 | 0.58 | 0.73 | 1.31 |
| 15 | 30 | 0.73 | 0.86 | 1.59 | 0.64 | 0.78 | 1.42 | 0.61 | 0.86 | 1.47 |
| | 0 | 0.76 | 0.57 | 1.33 | 0.57 | 0.67 | 1.24 | 0.57 | 0.83 | 1.40 |
| 30 | 30 | 0.77 | 1.00 | 1.77 | 0.76 | 1.06 | 1.82 | 0.48 | 0.88 | 1.36 |

Table 15: Effect of mineral fertilizers, crop residue (CR) and crop rotation on pearl millet yield wasts and PUE wasts, Sadore, Niger, 1998 rainy season.

| **Treatment** | **Without CR, without N** | | **Without CR, with N** | | **With CR, without N** | | **With CR, with N** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **TDM** | | **Grain** | | **TDM** | | **Grain** | | **TDM** | | **Grain** | | **TDM** | | **Grain** | |
| | **Yield** | **PUE** | **Yield** | **PUE** | **Yield** | **PUE** | **Yield** | **PUE** | **Yield** | **PUE** | **Yield** | **PUE** | **Yield** | **PUE** | **Yield** | **PUE** |
| Control | 889 | | 33 | | 2037 | | 58 | | 995 | | 61 | | 1471 | | 98 | |
| 13 kg P/ha | 2704 | 140 | 633 | 46 | 4339 | 177 | 1030 | 75 | 4404 | 185 | 726 | 51 | 240 | 4594 | 1212 | 86 |
| 13 kg P/ha + ridge | 2675 | 137 | 448 | 32 | 4057 | 155 | 946 | 68 | 3685 | 210 | 785 | 56 | 4530 | 235 | 1146 | 81 |
| 13 kg P/ha + rotation | 5306 | 340 | 1255 | 94 | 6294 | 327 | 1441 | 106 | 5392 | 338 | 1475 | 109 | 6124 | 358 | 1675 | 121 |
| 13 kg P/ha + ridge + rotation | 5223 | 333 | 1391 | 104 | 5818 | 291 | 1581 | 117 | 6249 | 404 | 1702 | 126 | 7551 | 468 | 1829 | 133 |
| SE | 407 | | 407 | | 407 | | 407 | | 407 | | 407 | | 407 | | 407 | |

CR Crop Residue; N Nitrogen; TDM Total Dry Matter; PUE (kg grain/kgP); Yield (g/ha)

Figure 1: Agro-climatic zones of West Africa Semi-Arid Tropics (WASAT)

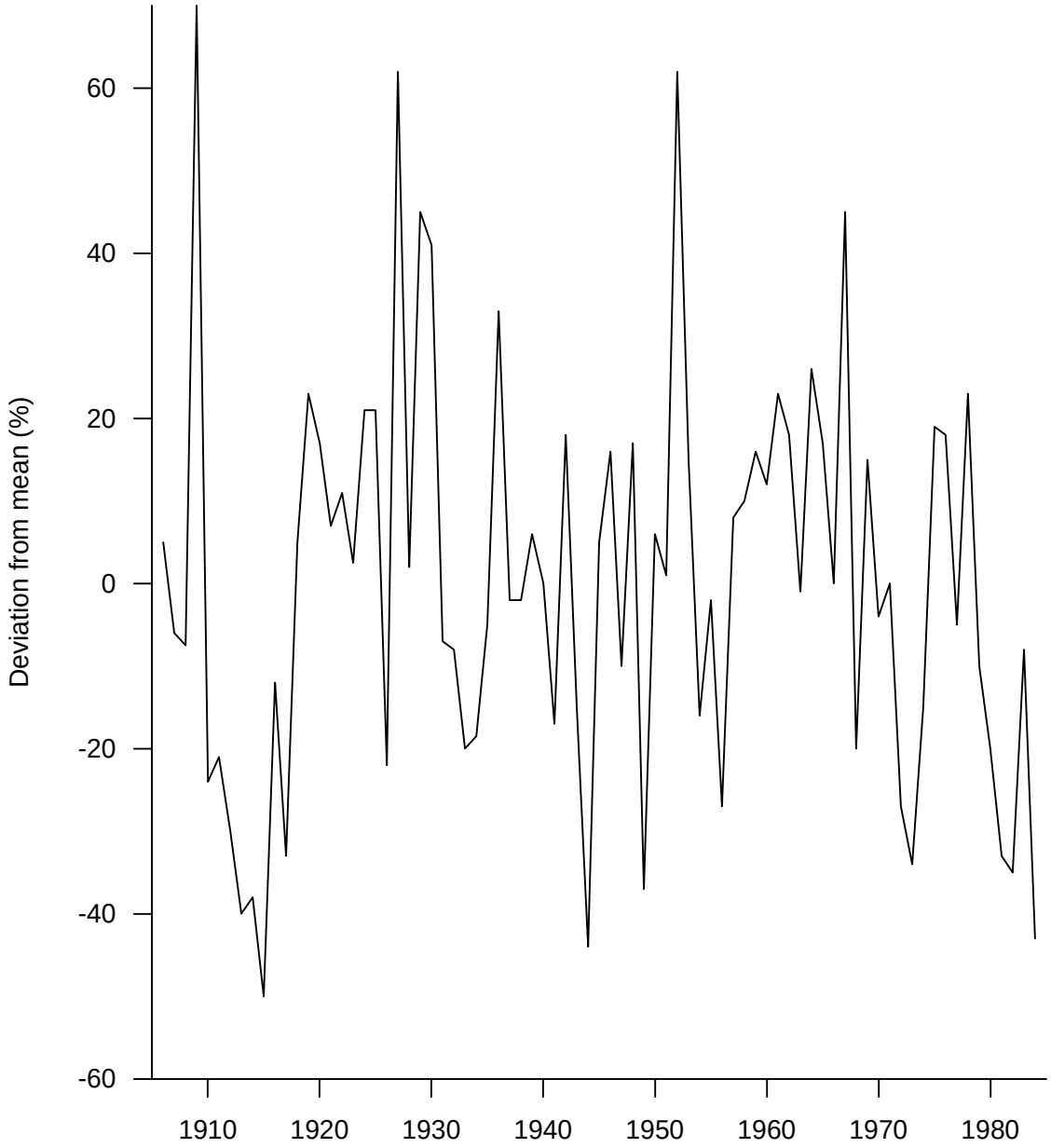



Figure 2: Percentage deviation of annual rainfall at Niamey, Niger.

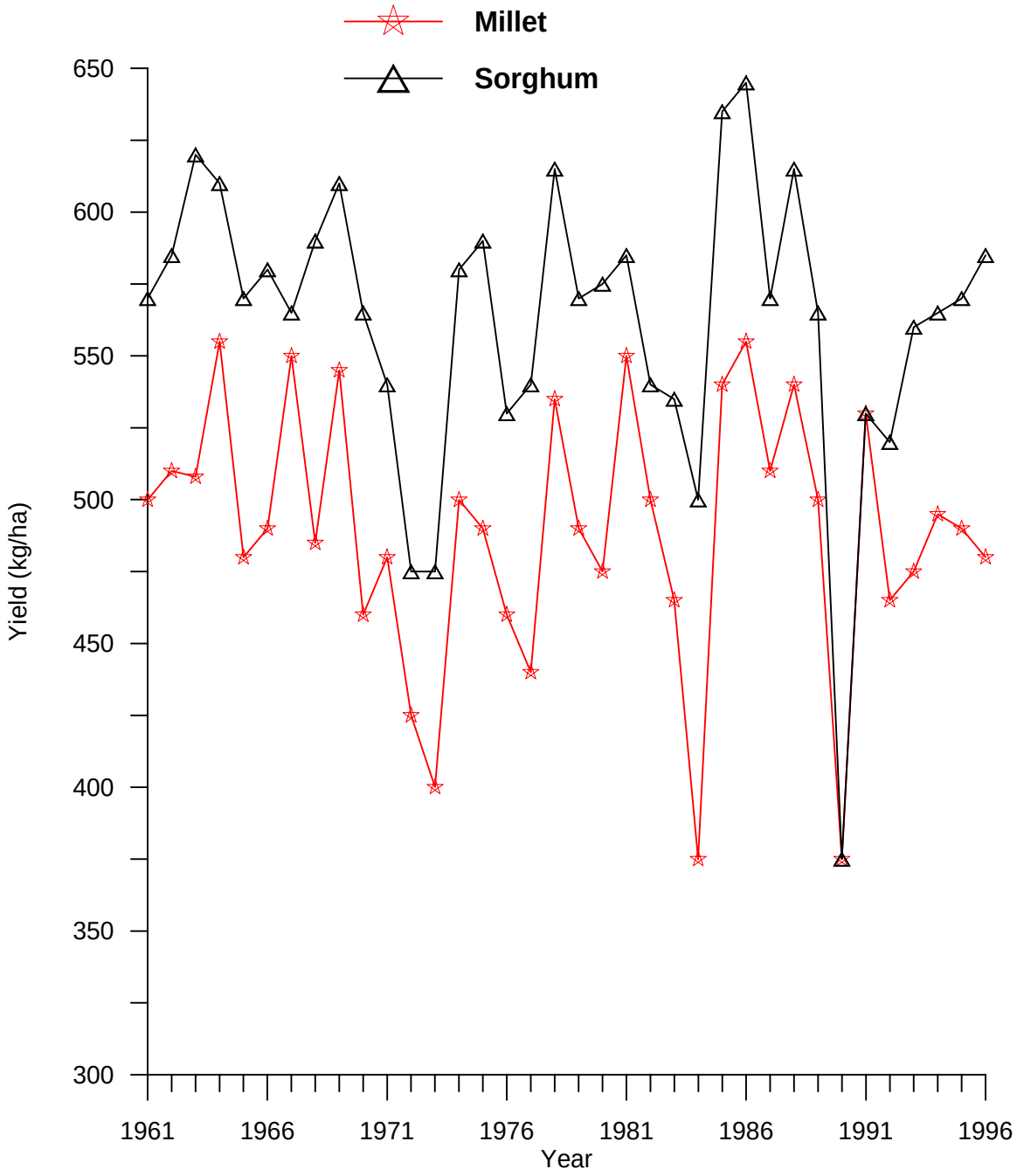



Figure 3:Sorghum and Millet yields in the Sahel

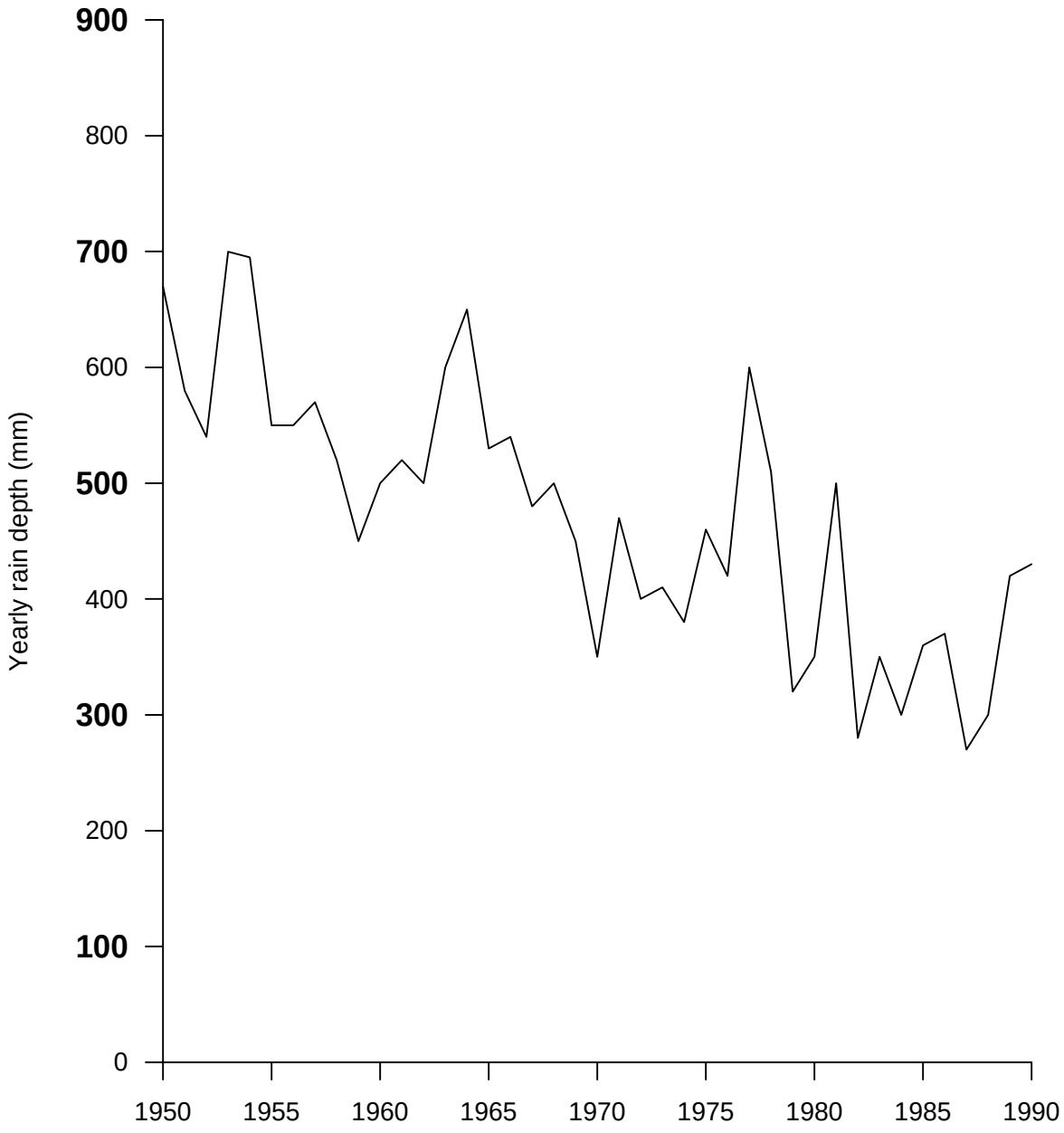



Figure 4: Rain variation (mm) in Douentza, Mali over a 40 year period

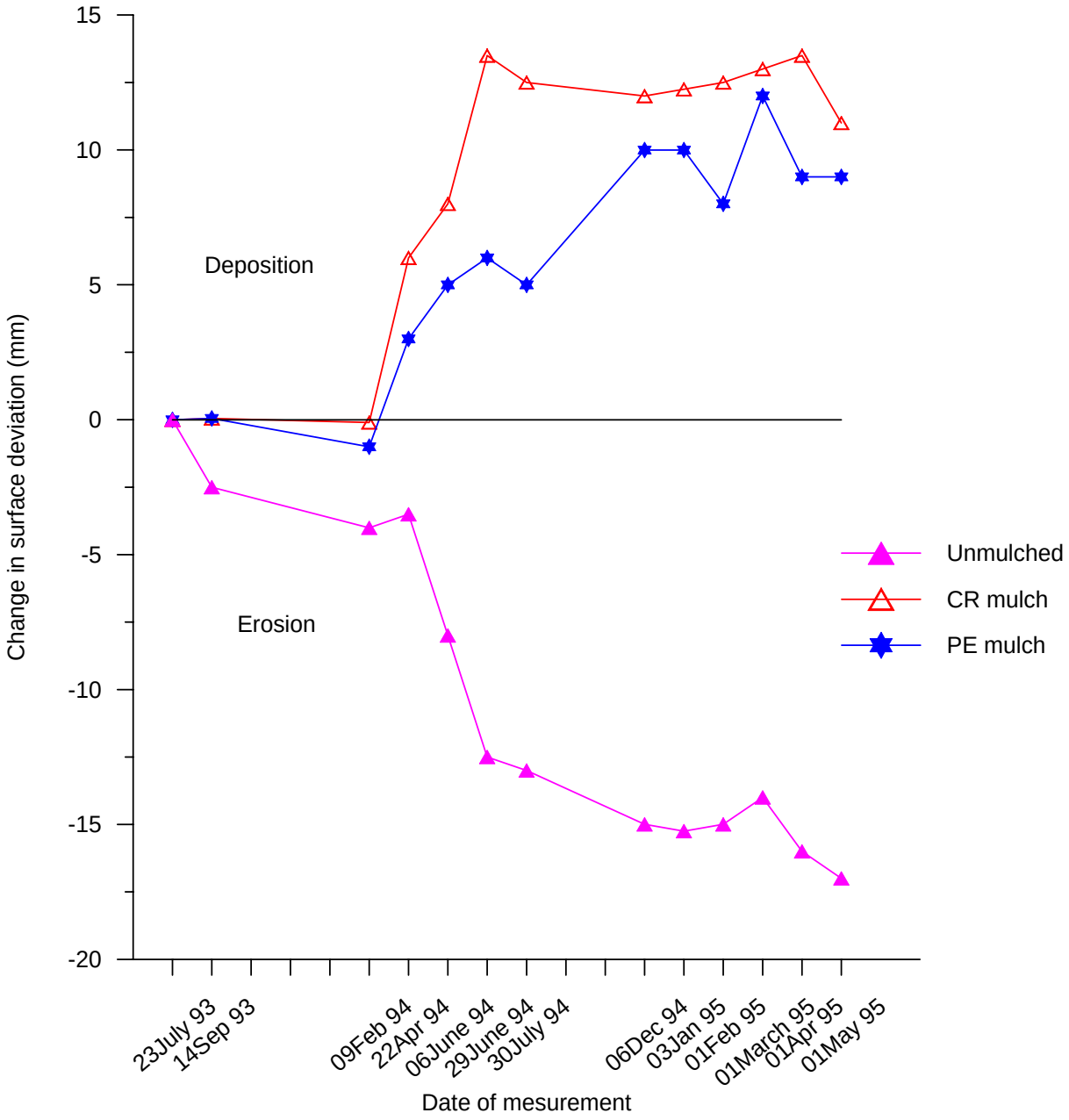



Figure 5: Soil erosion and deposition as measured with U-shaped stanless steel bars. (Buerkert and Hiernaux, 1998)

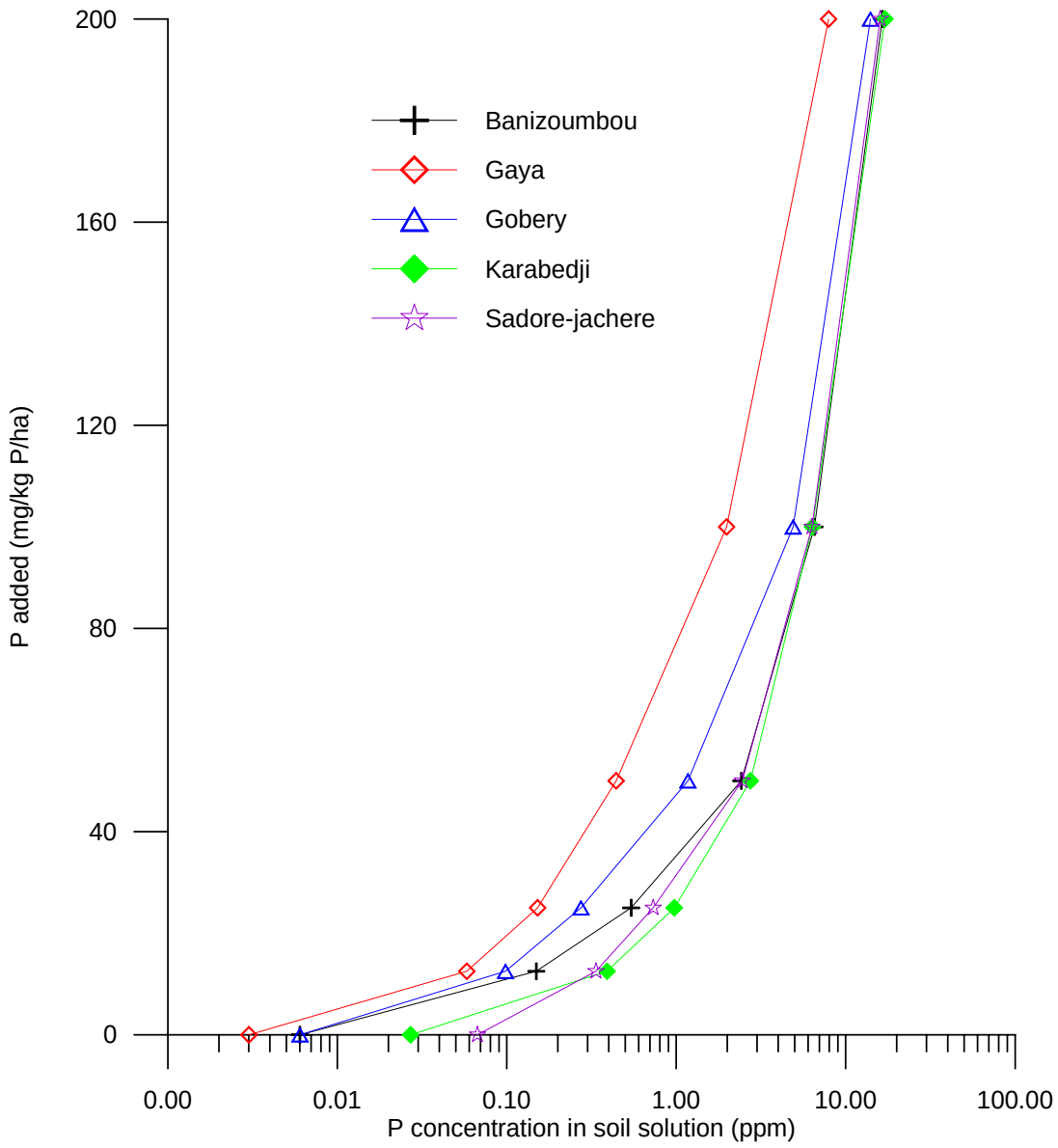



Figure 6: Relationship between phosphorus added and phosphorus in soil solution at equilibrium for selected soils of the West African Semi-Arid Tropics

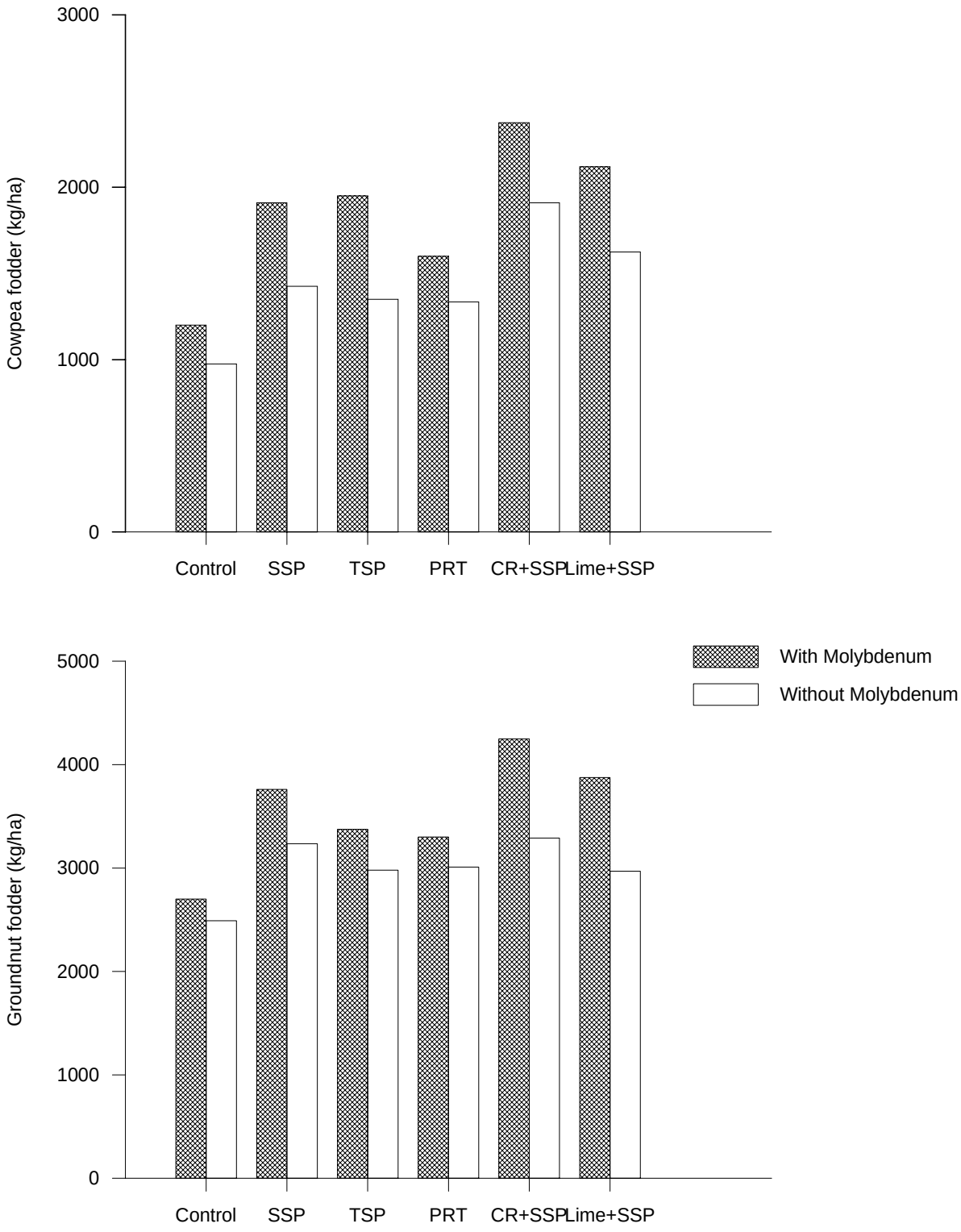



Figure 7: Effects of different phosphorus sources, crop residue, lime and molybdenum on cowpea and groundnut fodder yield. Tara Niger 1993

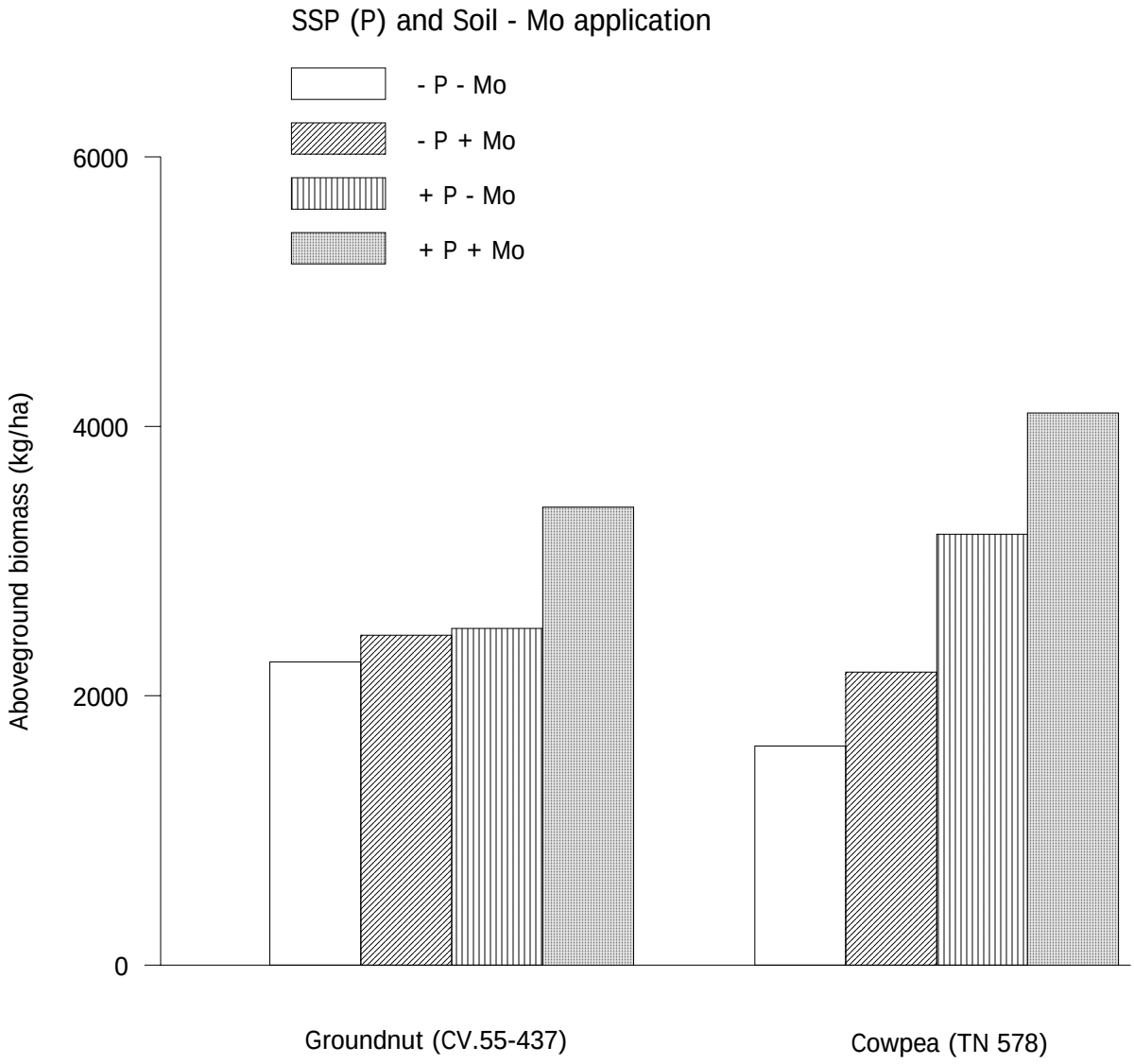
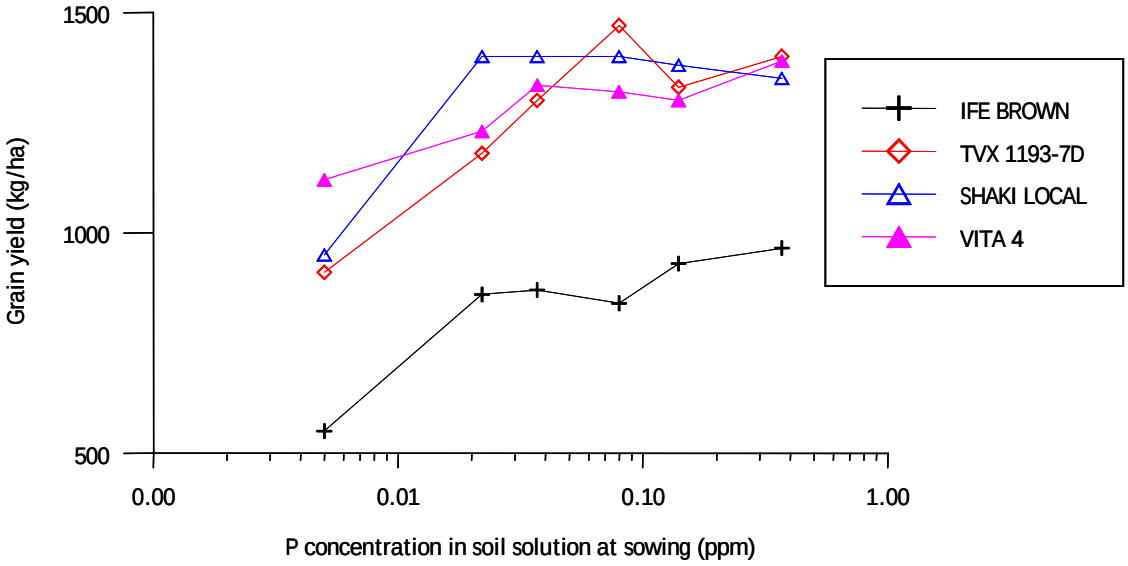



Figure 8: Effects of SSP (13 kg P/ha) and soil applied Mo (500 g Mo/ha) on groundnut and cowpea biomass (kg dry wt/ha) at final harvest. Bengou, 1995



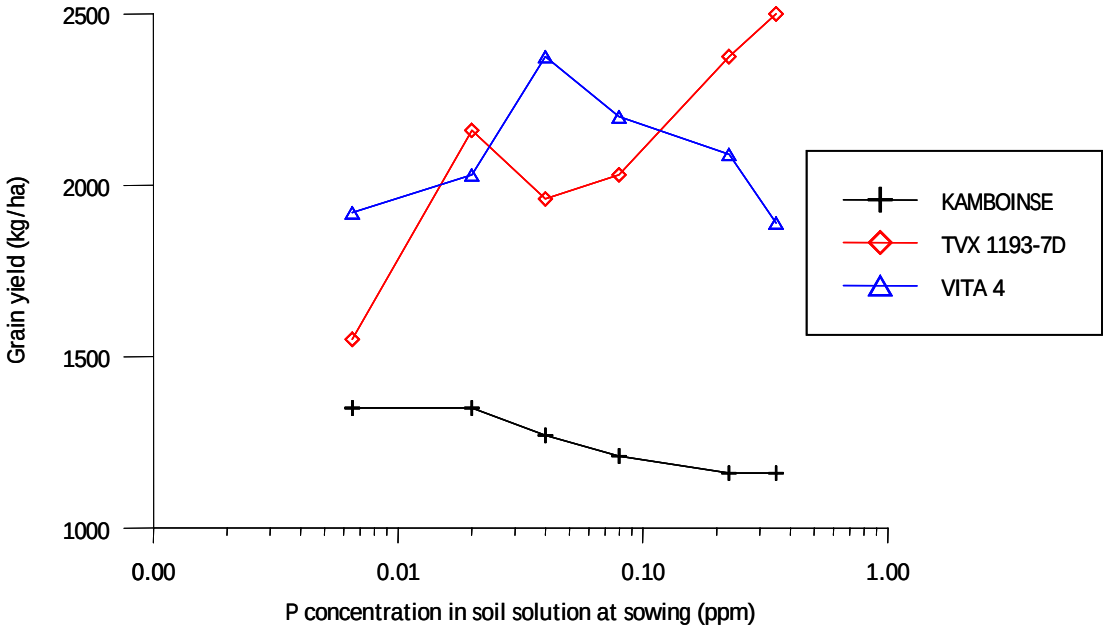




Figure 9: Relationship between grain yield and P concentration in soil solution at sowing in sandy loam paleustatif oxique at Ikenne and Kamboinse

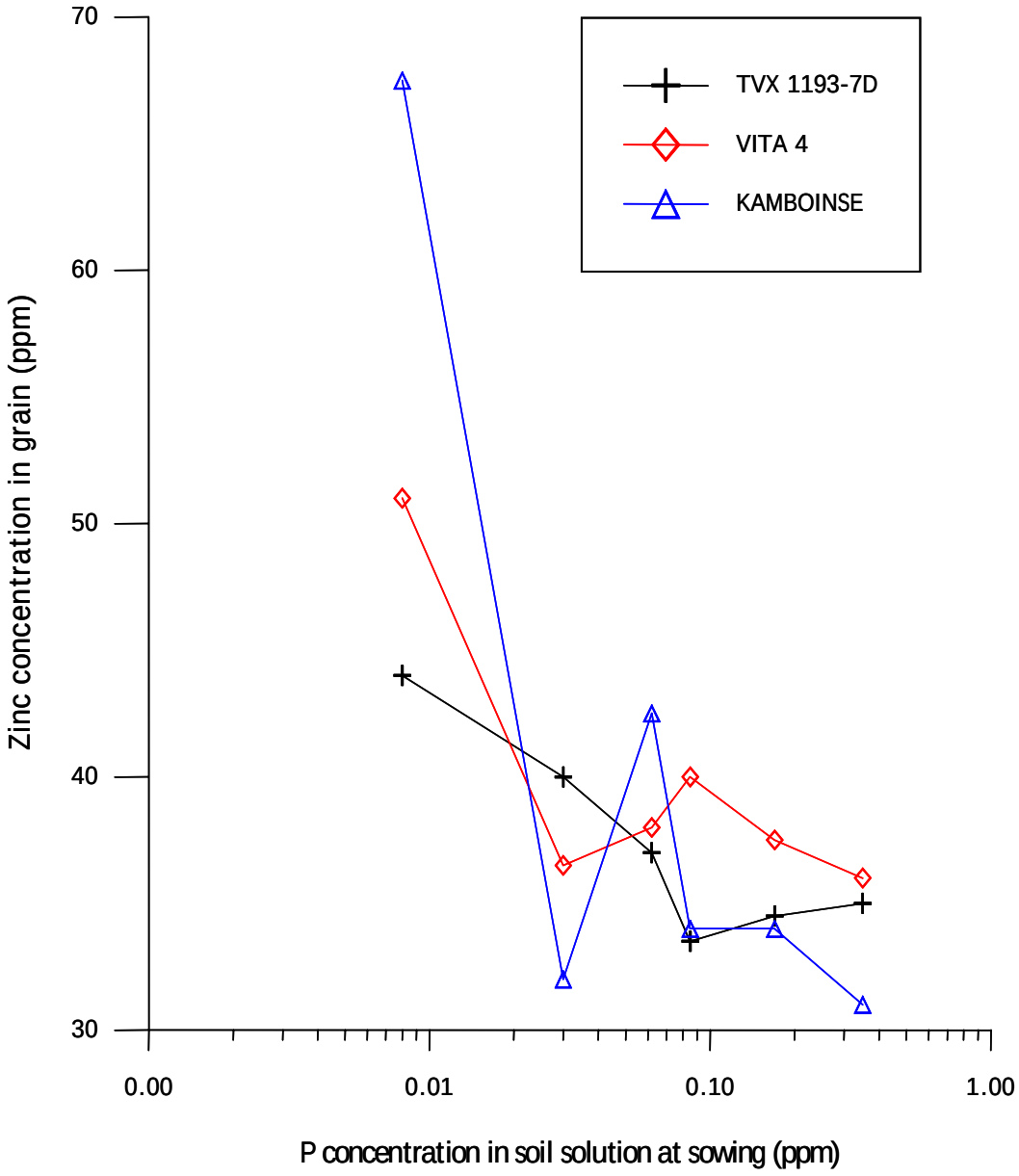



Figure 10: Relationship between zinc concentration in grain and P concentration in soil solution at Kamboinse

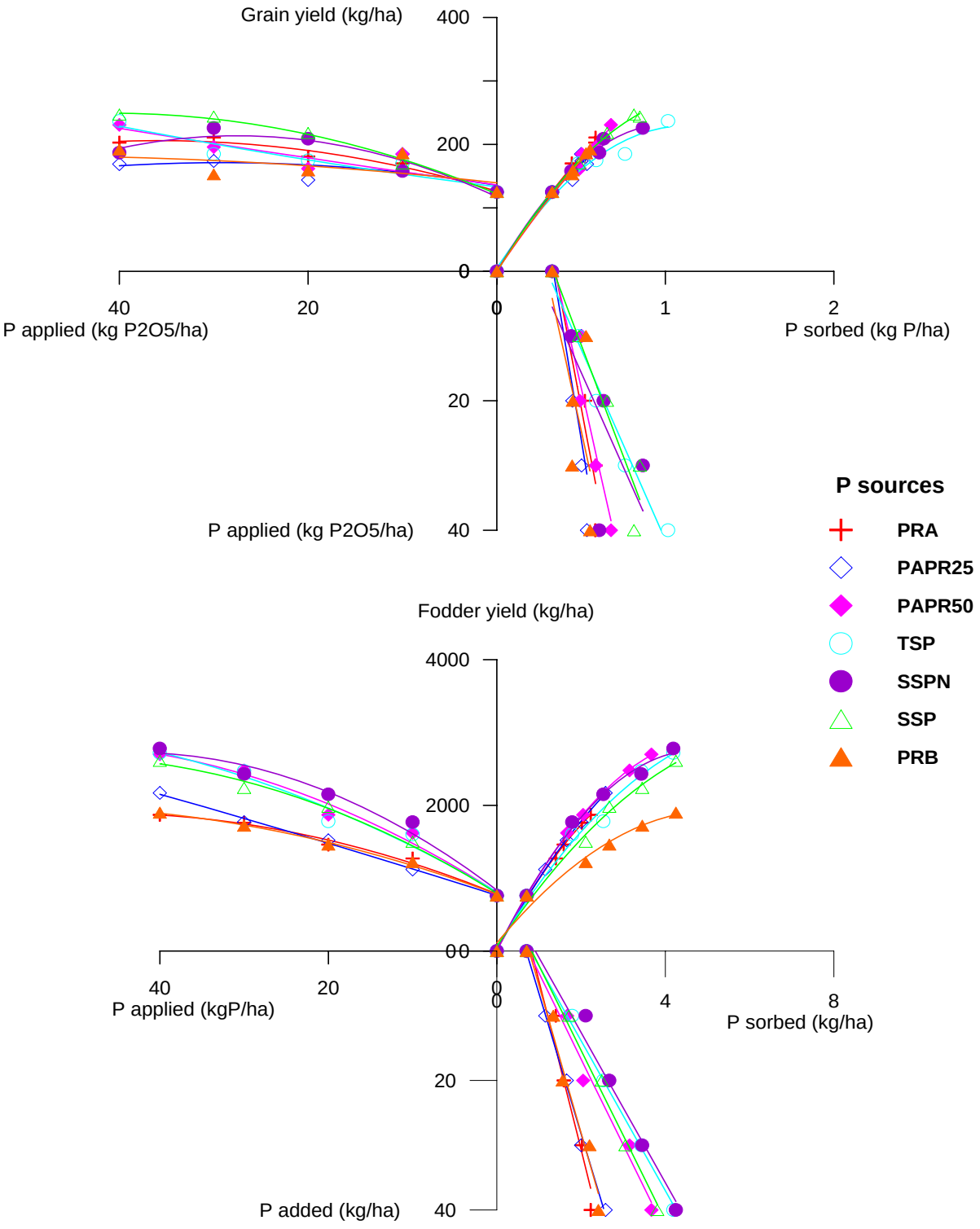



Figure 11: Relationship between cowpea grain and fodder yield with P applied, and between P applied nd P sorbed, Sadore, Niger, 1983.

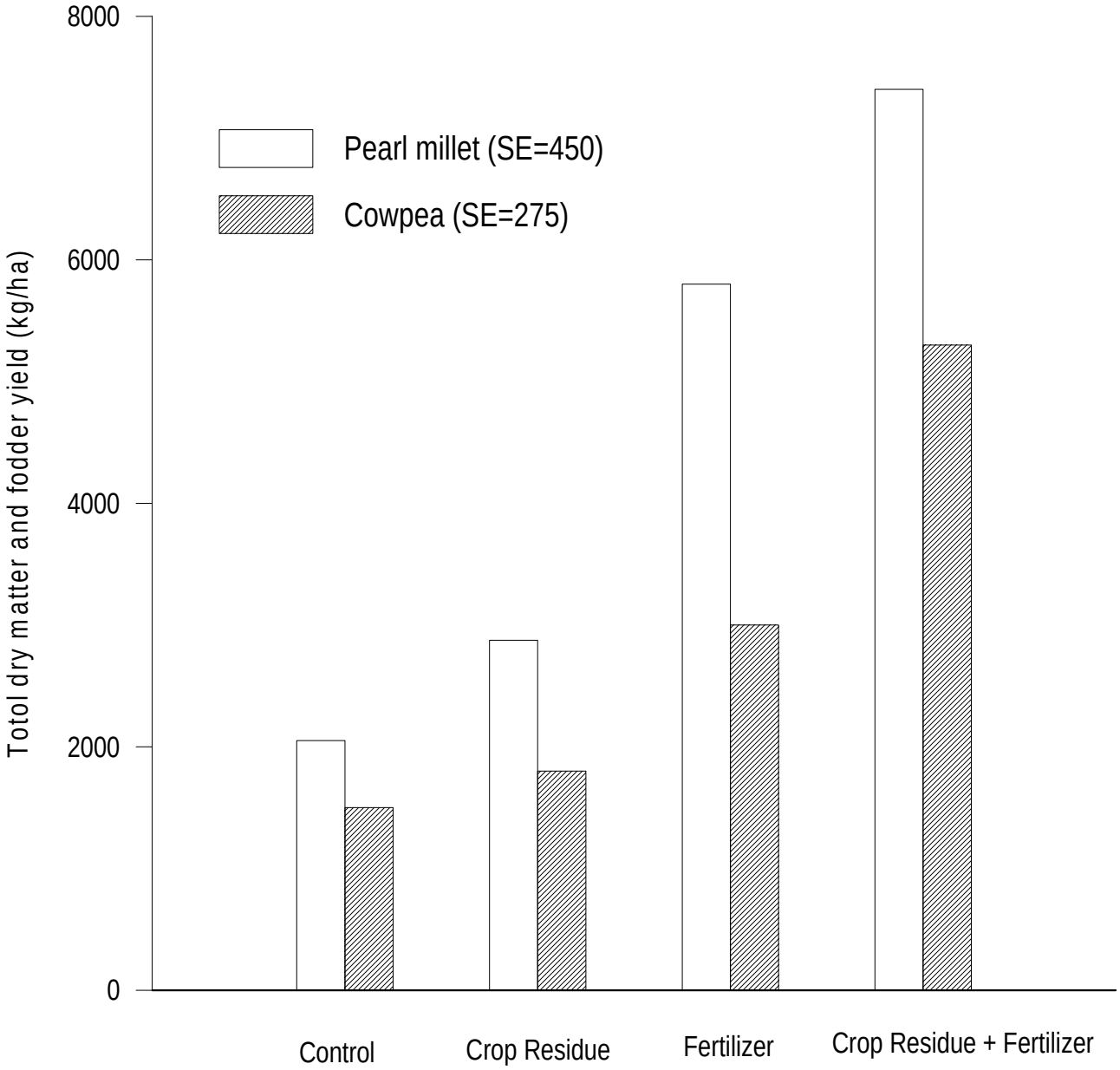



Figure 13: Long term crop residue management at Sadore, Niger 1996

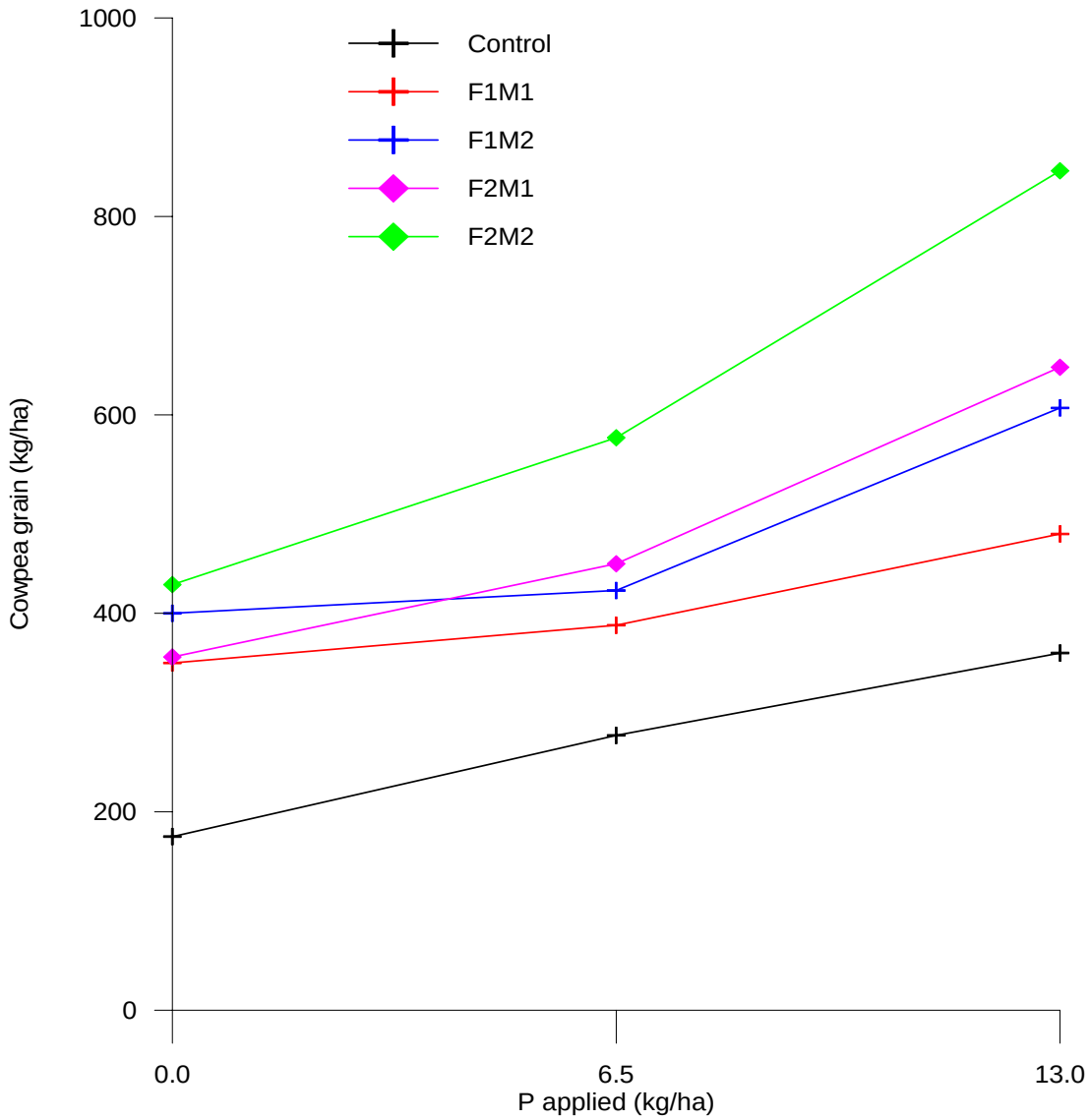



Figure 14: Effects of fertilizer and manure placement on cowpea grain yield, Karabedji 1999

F: manure 1=3 tons; 2=6 tons
M: method of placement: 1=broadcast; 2=hill placed

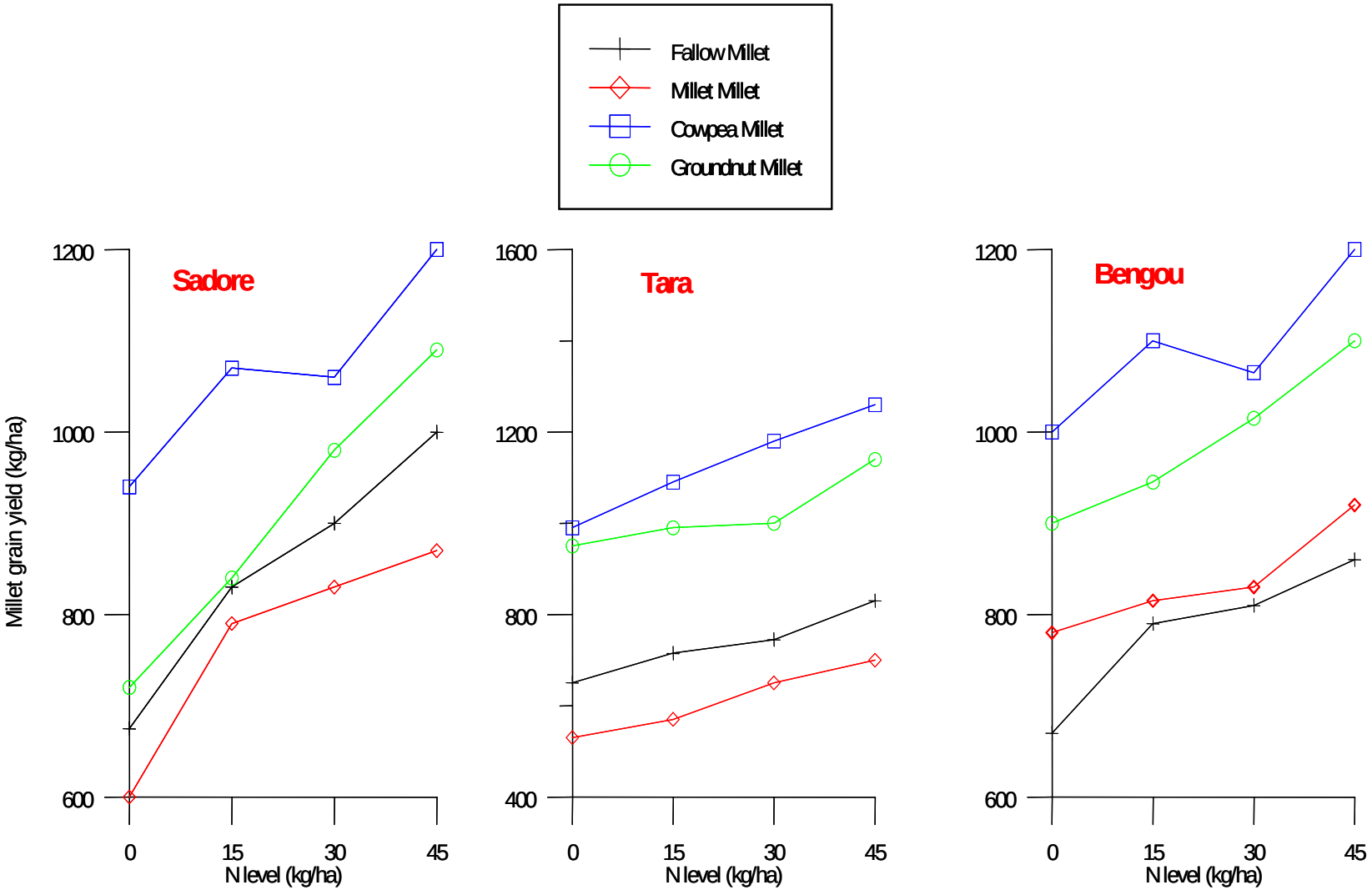



Figure 15: Effects of Nitrogen and rotation on pearl millet grain yield (kg/ha, average of four years) at Sadore, Tara, and Bengou.

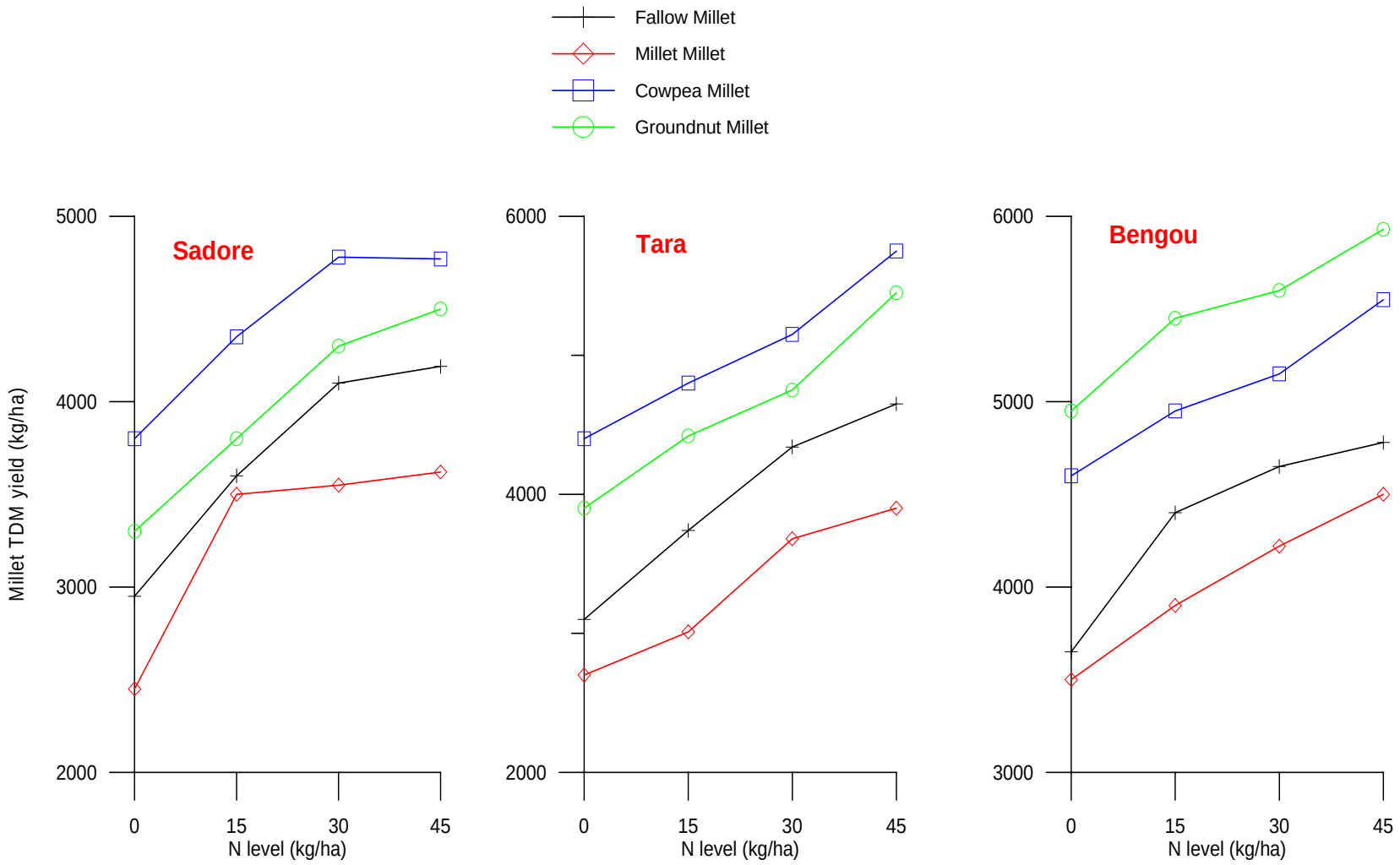



Figure 16: Effects of nitrogen and rotation on pearl millet total dry matter yield (kg/ha, average of four years) at Sadore, Tara, and Bengou

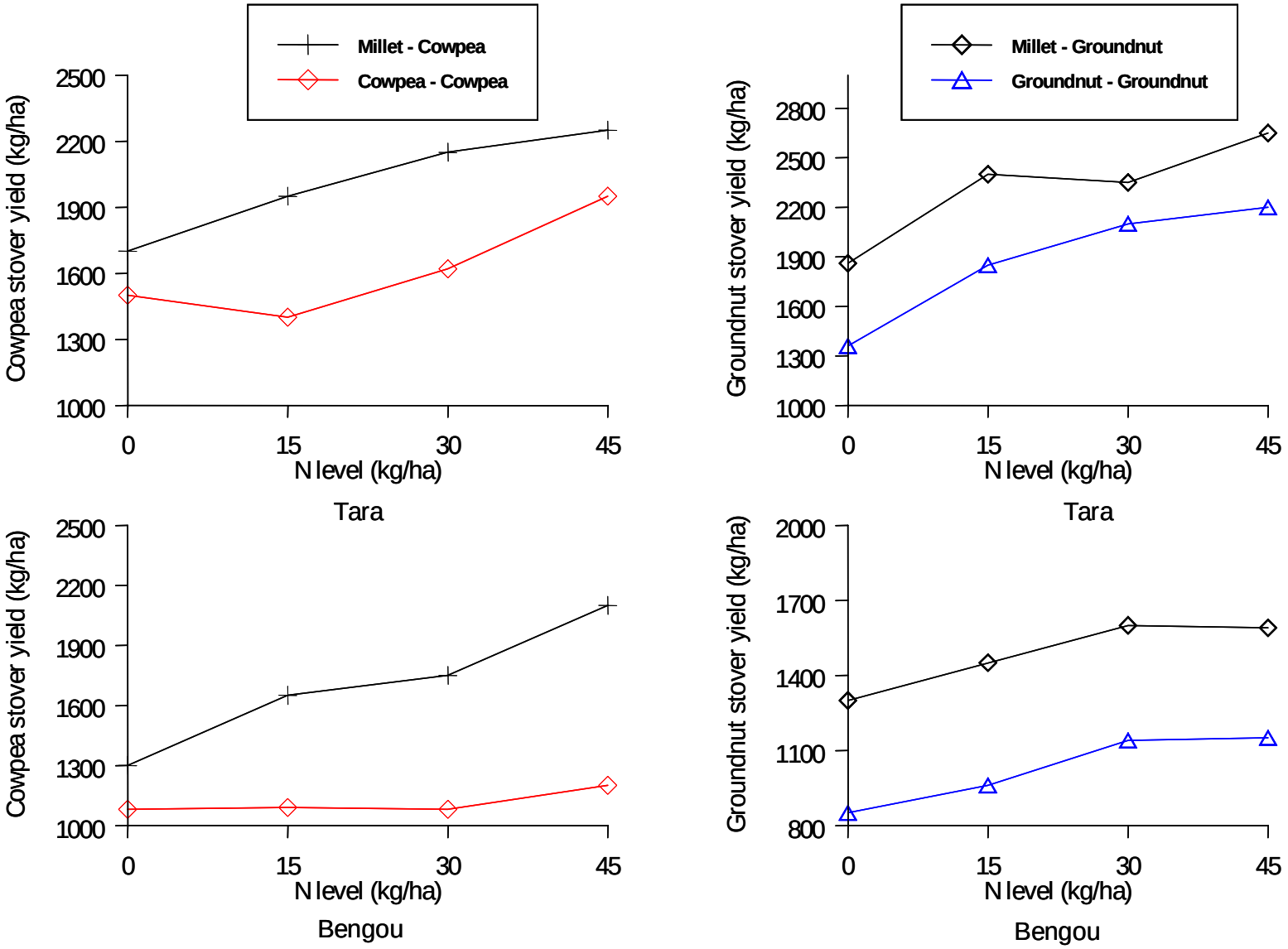



Figure 17: Effects of nitrogen and rotation on legume stover yield (kg/ha, average of four years) at Tara and Bengou

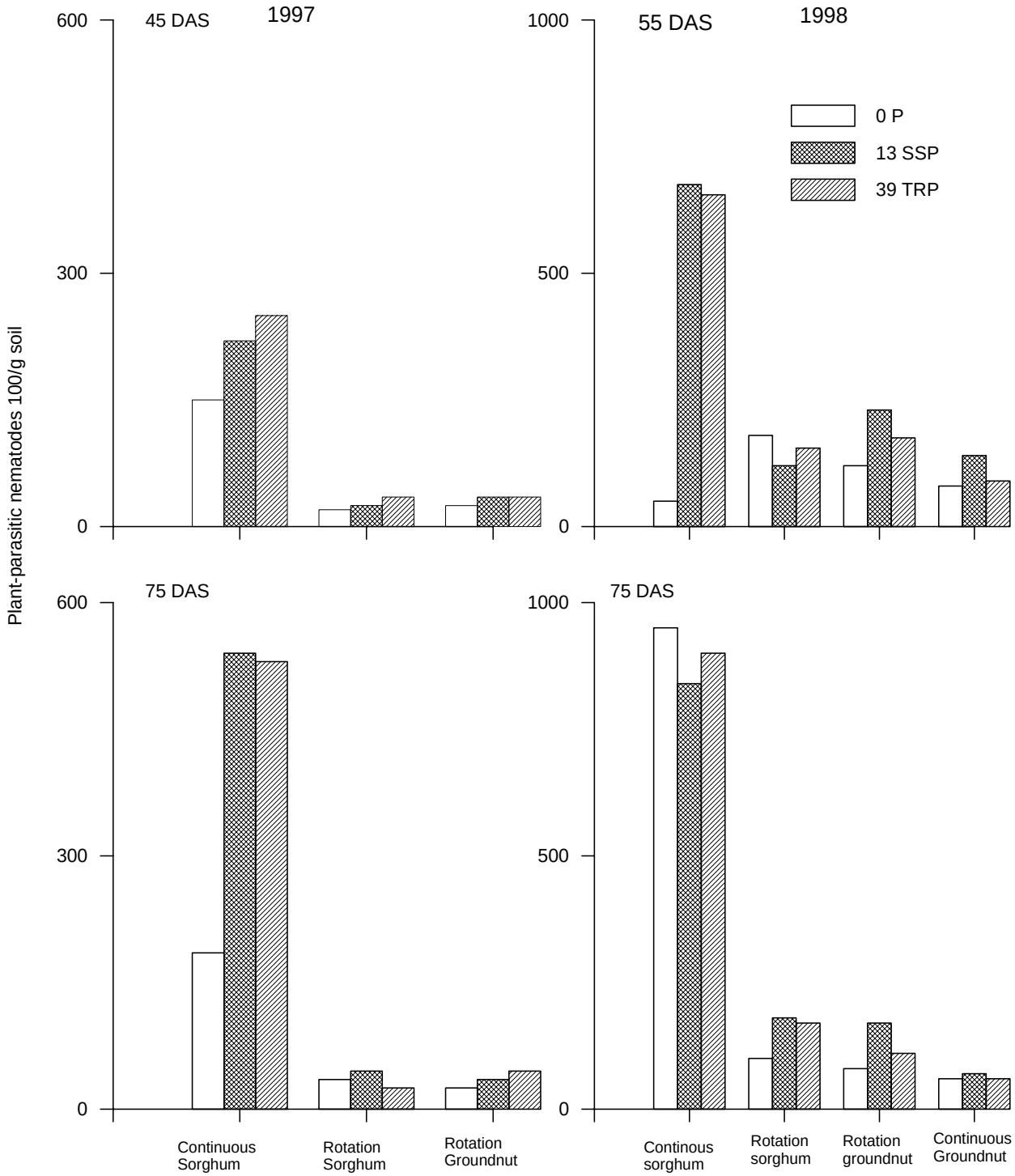



Figure 18: Plant-parasitic nematode numbers as affected by sorghum/groundnut rotations and phosphorus (P) application in 1997 and 1998 at Kouaré. Phosphorus was applied as single superphosphate at 13 kg P/ha (13 SSP) and Tahoua rock phosphate at 39 kg P/ha (39 TRP).
Source: Bagayoko et al. 2000.

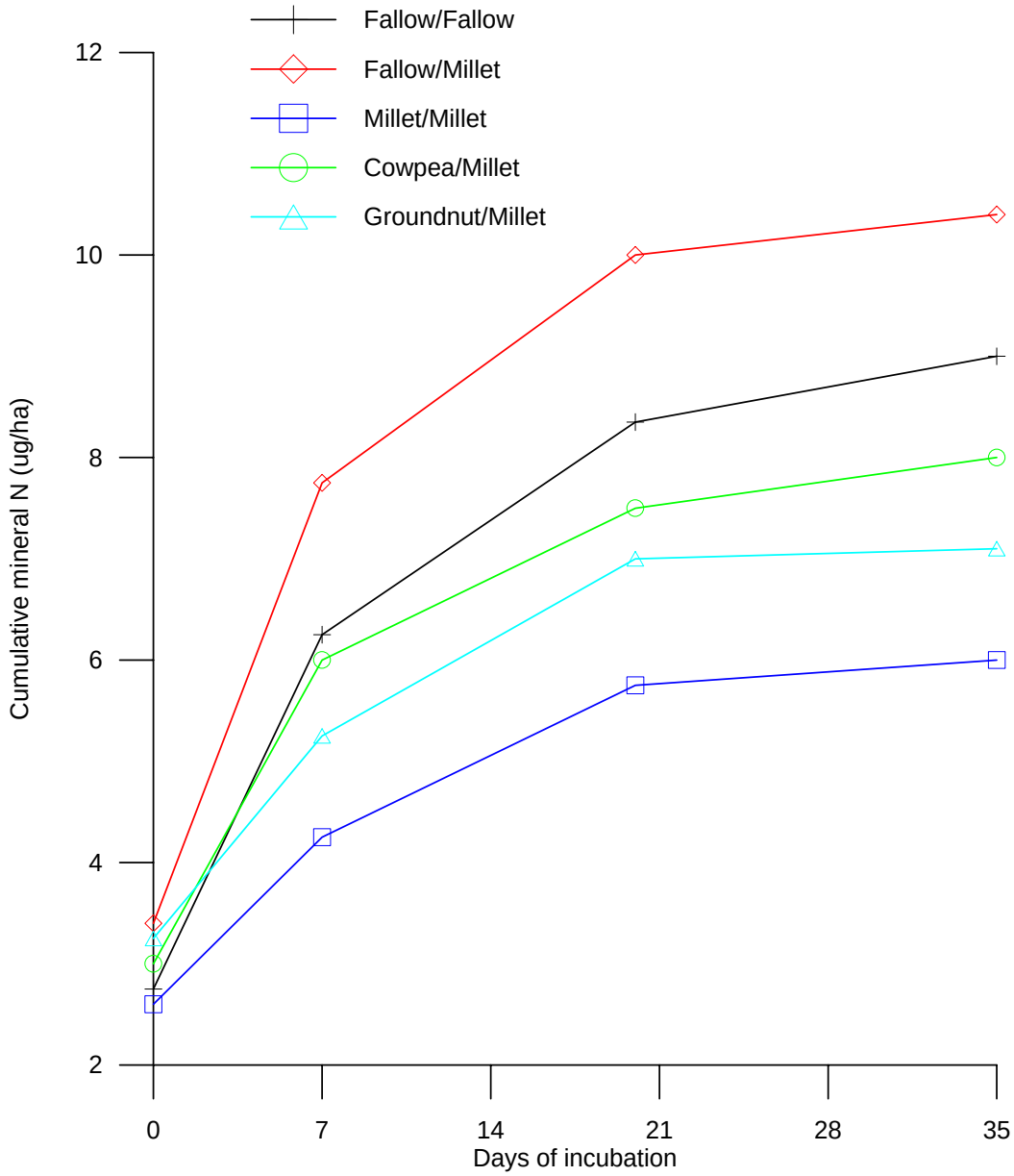



Figure 19: Relationship between cumulative mineral nitrogen and time of incubation of soils from different crop rotations pooled over three sites.

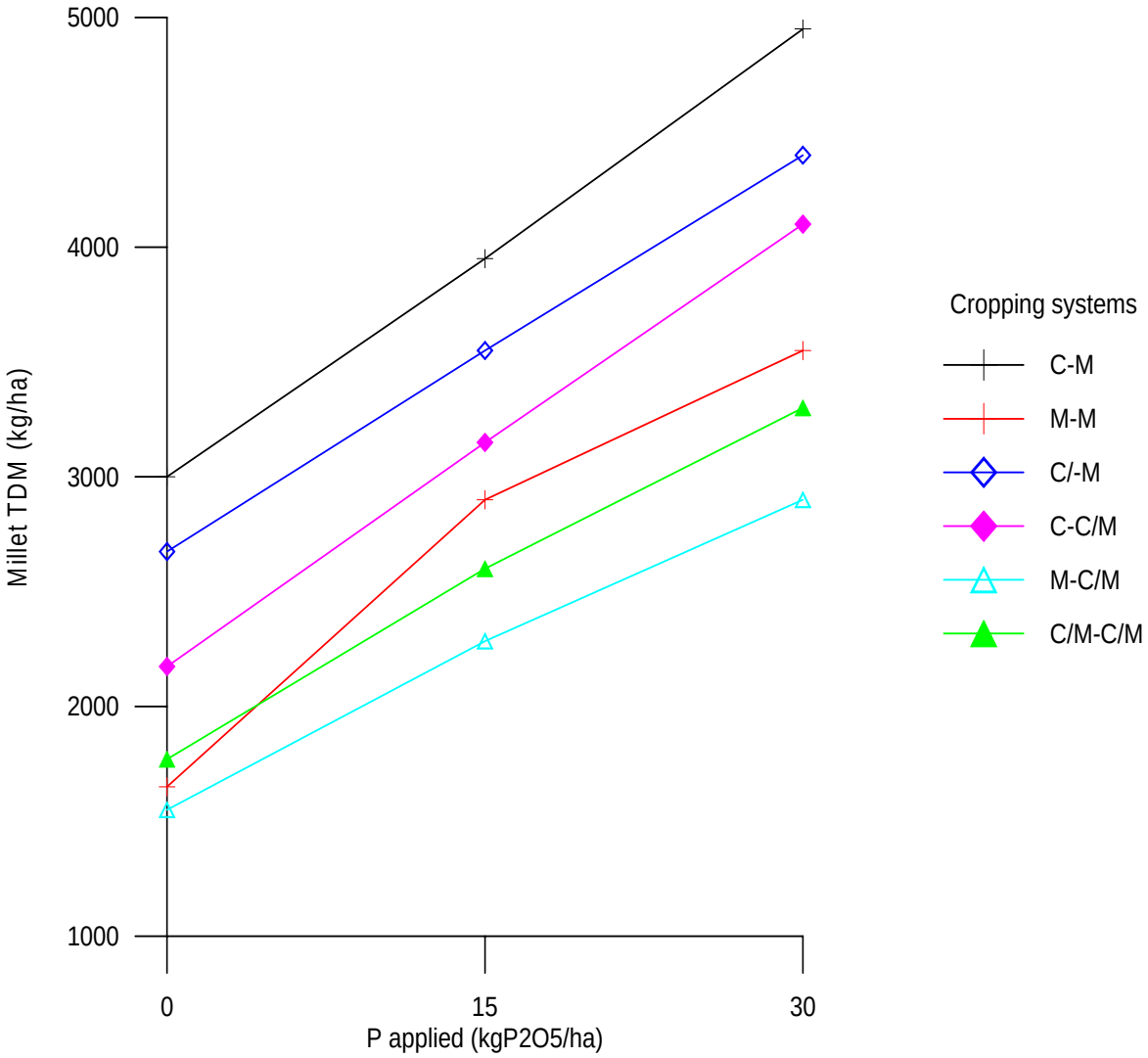
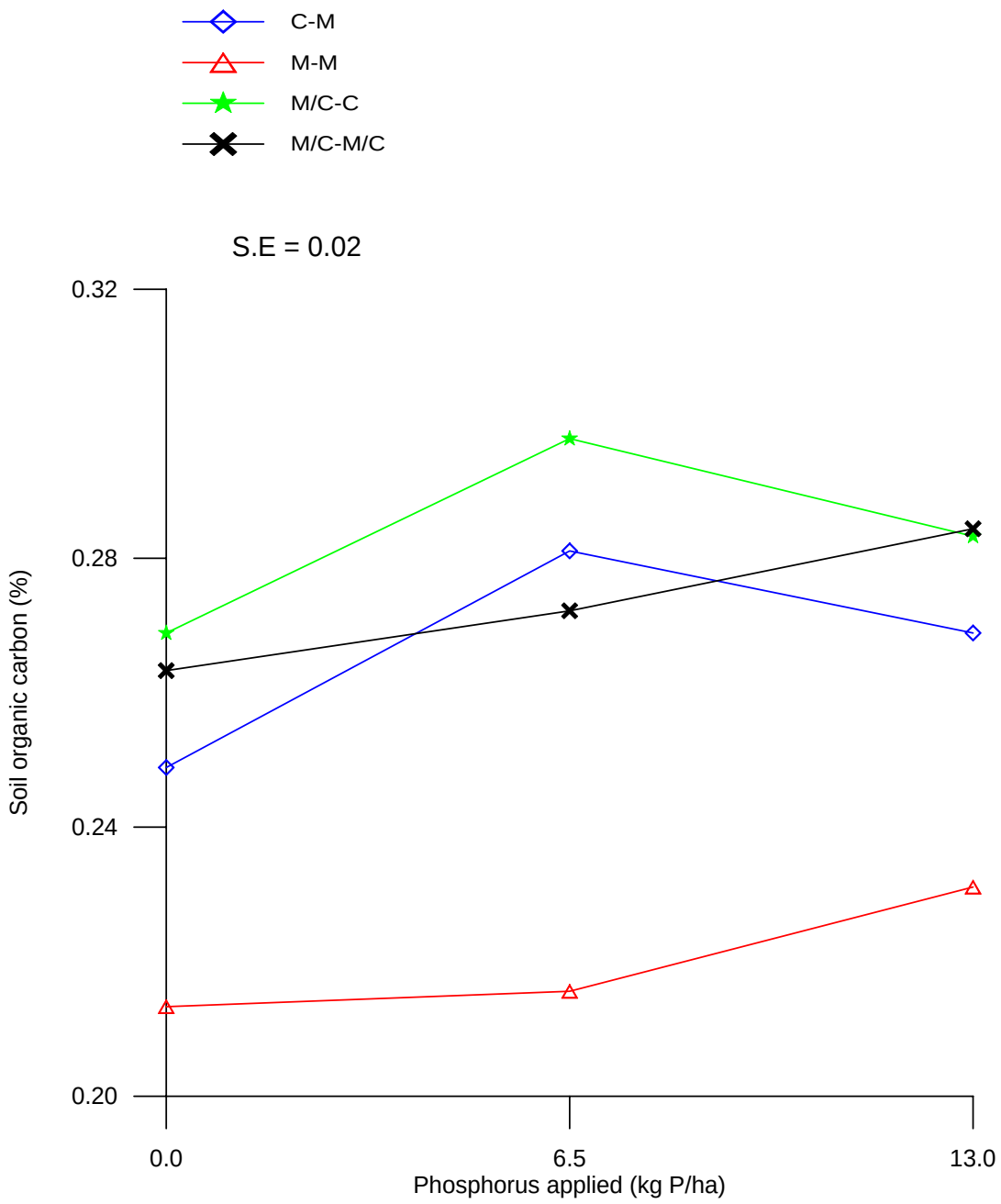



Figure 20: Effects of Phosphorus and Nitrogen on different cropping systems over 4 years, Sadore, Niger




C-M = Millet following Cowpea,
M-M = continuous millet,
M/C-M = Millet following Millet intercropped with Cowpea,
M/C-M/C = continuous Millet-Cowpea intercropped

Figure 21: Effect of phosphorus and cropping system on soil organic carbon, Sadore, Niger 1995

*Draft*

# Sustainable intensification of crop livestock systems through manure management in Western and Eastern Africa: lessons learned and emerging research opportunities

Bationo, A.[1]; Nandwa, S.M.[2]; Kinyangi, J.M.[1]; Bado, B.V.[4]; Lompo, F.[5]; Kimani, S.[6]; Kihanda, F.[7] and S. Koala[8]

[1]Tropical Soil Biology and Fertility Programme, P.O. Box 30592, Nairobi, Kenya.

[2]Kenya Agricultural Research Institute, National Agriculturtal Reseach Laboratories, P O Box 14733, Nairobi, Kenya.

[4] INERA, P.O. Box 910, Bobo-Dioulasso, Burkina Faso.

[6]Kenya Agricultural Research Institute, National Agricultural Resarch Center (Muguga), P.O. Box 30148, Nairobi, Kenya.

[7]Kenya Agricultural Res. Institute, Regional Research Centre (Embu), P.O. Box 27, Embu, Kenya.

[8]International Crop Research for the Semi-Arid Tropics, B. P. 12404 Niamey, Niger.

## Abstract

In the mixed farming system that characterises the Semi-Arid zone of Eastern and Western Africa, low rural incomes, high cost of fertilizers, inappropriate public policies and infrastructural constraints prevent the widespread use of inorganic fertilizers. Under this situation and as population pressure increases and fallow cycles are shortened, organic sources of plant nutrients such as manure, crop residue and compost remain the principal sources of nutrients for soil fertility maintenance and crop production. Estimates of the nitrogen contribution from manure to the total N input budget suggest that up to 80 percent of N applied to crop is derived from manure in both the extensive and the intensive grazing systems.

In this paper, we first discuss the effect of manure on soil productivity and on ecosystem functions and services. This is followed by highlights of the management practices required to increase manure use efficiency before tracking the emerging new research opportunities in soil fertility management to enhance the crop-livestock integration.

Although the application of manure alone produces a significant response, it cannot be proposed as an alternative to mineral fertilizers. In most cases the use of manure is part of an internal flow of nutrients within the farm and does not add nutrients from outside the farm. Furthermore quantities available are inadequate to meet nutrient demand on large areas. Research highlights have indicated that different management practices including time and methods of manure application, sources and method of application, and integrated nutrient management enhance its efficiency.

Research opportunities include ecosystem functions and services of manure use, the establishment of fertilizer equivalency of different manure sources, the assessment of the best ratios of organic and inorganic plant nutrient combinations, the crop livestock trade-offs to solve conflicting demands for feed and soil conservation and the use of legumes directly for soil fertility and for animal feed. The establishment of Decision Support Guides and assessment of the economic viability of manure-based technologies in farmers-focussed research is presented as a powerful management tool intended to maximize output while preserving the environment in the mixed farming system of the semi-arid zones.

## Introduction

Rapid rural and urban population growth, changes in agroecosystems and increased market access in Western and Eastern Africa provides a stimulus to drive agriculture towards intensification, whereby continuous cropping increasingly replaces pasture and fallows; and manure, forages and crop residue become more valuable as part of the intensification-oriented technologies, with increasing off-take from a fixed land base. The ultimate result of this dynamism is the emergent and evolution of mixed crop-livestock systems. This is currently

perceived as the most efficient and sustainable means of food production. The evolution process often include paddocking of livestock on cropland in high potential areas; shift to the system of collection, processing, storage and application of animal dung and urine; shift from field grazing of crop residues and pastures to confined livestock feeding; replacement of hand labor with animal traction and mechanization; and intensification through growing of multipurpose legumes and forages. This calls for new research approach that allows replacement or refinement of old paradigms with new principles notably identification of "best-bet options" and strategies using "whole farm" or holistic approach to working with farmers. Such an approach has resulted in new lessons and insights in management and augmentation of nutrients through crop residue and manure management including livestock-mediated nutrient cycling, crop combination and crop geometry, livestock feeding studies, effect of livestock component on the soil fertility (chemical, physical and biological properties), and also gender, policy and institutional issues.

The major challenge facing researchers attempts to contribute towards sustainable intensification of the crop-livestock systems in SSA, is that of soil degradation whereby poor quality and low inputs of crop residues and boma manure leads to soils of low productivity. Inorganic inputs are often too expensive for the low-resource endowed farmers. In such systems, the demand for organic inputs e.g. manure is likely to increase in response to system intensification. The contribution of manure management to enhance soil productivity is unquestionable (Murwira *et al*., 1995; Pankhurst, 1990). However, there is need for such research to be viewed realistically, especially in the context of the evolving farming systems in the arid and semi-arid lands, notably integrated systems in terms of crops and livestock units which may hinder or compliment each other. There is a growing recognition of the need to develop technologies and policies which ensure optimization enterprises. Implicit in this strategy is the maximization of the contribution of the livestock unit to soil fertility improvement while addressing challenges of increasing intensity of crop-livestock systems.

In this paper we will first discuss the effect of manure on soil productivity and ecosystems services. This is followed by highlighting the management practices to increase manure use efficiency before elaborating on the emerging new research opportunities in soil fertility management to enhance the crop-livestock integration.

## II. Effect of manure on soil productivity and ecosystems services

In the mixed farming systems that characterizes the semi-arid zone of Africa, low rural incomes, high cost of fertilizer, inappropriate public policies and infrastructural constraints prevent the widespread use of inorganic fertilizers. Under this situation and as population pressures increases and fallow cycles are shortened, organic sources of plant nutrients such as manure, crop residue and compost remain the principal sources of nutrients for soil fertility maintenance and crop production (William *et al*., 1985). Estimates of the nitrogen contribution from manure to the total N input budget suggest that up to 80% of N applied to crops is derived from manure in both extensive and intensive grazing systems in East and Southern Africa.

Several scientists have reported the effect of manure on crop yield increases in Western and Eastern Africa (Bationo and Mokwunye, 1991; Bationo *et al*., 1998; Mokwunye, 1980; Pichot *et al*., 1981; Padwick, 1983; Pieri, 1986; de Ridder and van Keulen, 1990; Abdulahi and Lombin, 1978; Powell, 1986; Murwira *et al*., 1995; Pankhurst, 1990; Kihanda, 1996; Kihanda and Gichuru, 2000; Lekasi *et al*., 1998; Probert et al., 1995; Kanyanjua and Obanyi, 1999; Gibberd, 1995; Kihanda and Warren, 1998.

Most of the studies in the literature have focussed on the responses of crops to farmyard manure (FYM) applications. One of the earliest reported increases to FYM application in sub-saharan Africa was by Hartley (1937) in the Nigerian Savannah. It was observed that application of 2 t $ha^{-1}$ FYM increased seed cotton yield by 100%, equivalent to fertilizers applied at the rate of 60 kg N and 20 kg $ha^{-1}$. In Embu, Kenya, FYM significantly increased maize and potato yields in a long-term trial (Gatheca, 1970). The data in Table 1 summarizes the results of a number of

trials on manure conducted in research stations in West Africa. The data shows that manure collected from stables and applied alone produces about 20 to 60 kg N/ha in cereal grain and 70 to 178 N kg/ha in stover per tonne of manure.

In Kenya, Kanyanjua and Obanyi (1999) observed that within the Fetilizer Use Recommendation Project (FURP) sites (averaged over several sites and seasons) the response to manure application was in the order cabbages>potatoes>maize>cowpea and nitisols gave a higher response than acrisols (Table 2). Kihanda *et al*. (1988) while evaluating the effects of inorganic fertilizers, lime, FYM and crop residues on the yield of maize in acidic andosol of Central Kenya found that FYM increased maize biomass by 210%, while lime and P increased yields by 115 and 57%, respectively. They concluded that the large response to FYM application might have been due to a reduction in exchangeable aluminium and manganese allowing the plant to establish better rooting system in addition to providing nutrients, particularly potassium.

In the Sahelian zone of West Africa, Bationo and Mokwunye, 1991, found no difference between applying 5 t $ha^{-1}$ of FYM as compared to the application of 8.7 kg P $ha^{-1}$ as Single Superphosphate and a further application of FYM at 20 t $ha^{-1}$ only doubled pearl millet grain a compared to the application of 5 t $ha^{-1}$ (Table 3).

Gatheca, 1970 reported that an annual application of 5 to 6 t $ha^{-1}$ of manure gave higher yields of maize in Kenya than heavy applications of 20 to 30 t $ha^{-1}$ applied at intervals of four to five years. In the acidic soils of Central Kenya, Mugambi (1978, 1979) noted that application of FYM at 5 t $ha^{-1}$ increased the potato tuber yield by more than 50% above the control. A combination of the same rate of FYM and P at 100 kg P $ha^{-1}$ increased potato yield by more than 100% above the control, an indication that P was also limiting in that soil. The data in Table 4 indicates that the application of 3 t $ha^{-1}$ of manure plus urine produced grain and total bio-mass that were higher as compared to when only manure was applied and crop response to sheep dung was greater than to cattle dung. Research studies indicate that approximately 80-95% of the N and P consumed by livestock is excreted. Whereas N is voided in both urine and faeces, most P is voided in faeces (ARC, 1980; Termouth, 1989). Dar *et al*., 2001 clearly indicated that in the P deficient soils of sandy sahelian soils, the addition of P fertilizer will increase the efficiency of FYM and hill placement of both FYM and P fertilizer was better than broadcasting (Fig. 1).

The data in Tables 5 and 6 respectively from eastern and Western Africa give the variation in the nutrient concentration of manure samples from different sites, indicating that even on the same soil type and rainfall, the response to manure application will greatly depend on the source of manure.

Pieri (1986, 1989) and Sedogo (1993) summarized the results of the long-term soil fertility experiments initiated since the 1960's. One important conclusion that emerged from the experiments is that application of mineral fertilizers is an effective technique for increasing crop yields in the Sudanian zone of West Africa. However, in the long-run the use of mineral fertilizers alone will decrease crop yields but sustainable and higher production is obtained when inorganic fertilizers are combined with manure (Fig. 2).

At Kabete in Kenya, Nandwa (1997), obtained higher yields of maize in a long-term soil fertility management experiments when mineral fertilizers are combined with crop residue and FYM (Fig. 3).

For a modest yield of 2 t/ha of maize the application of 5 t $ha^{-1}$ of high quality manure can meet the N requirement but this cannot meet the P requirements in areas where P is deficient (Palm, 1995). Organic inputs such as manure are often proposed as alternatives to mineral fertilizers, however, it is important to recognize that in most cases the use of manure is part of an internal flow of nutrients within the farm and does not add nutrient from outside the farm and also quantities available is inadequate to meet nutrient demand over large areas because of the limited quantities, the low nutrient content, and the high labour demands for processing and application. The availability of manure for sustainable crop production has been addressed by several scientists. De Leeuw *et al*. (1995) reported that with the present livestock systems in West Africa

the potential annual transfer of nutrient from manure will be 2.5 kg N and 0.6 kg P per hectare of cropland. Although the manure rates are between 5 to 20 t/ha in most of the on-station experiments, quantities used by farmers are very low and ranged from 1300 to 3800 kg $ha^{-1}$ (Williams *et al*., 1995). Hiyami and Ruttan (1985) reported that exclusive use of inorganic fertilizers in Africa will increase food production at best by 2% $yr^{1}$, well below the population growth rate, and not even close to 5 to 6% required to reduce poverty and secure food security. Organic sources of nutrients, however, will be complementary to the use of mineral fertilizers (Quinones *et al*. 1997). Despite its vital role the quantities of manure are not available on-farm for a number of factors. There are simply insufficient number of animals to provide the manure needed. This problem becomes more pronounced especially in post drought years (Williams *et al*. 1995). The amount of livestock feed and land resources available are also limited. Depending on rangeland productivity, it will require between 10-40 hectares of dry season grazing land and 3-10 hectares of rangeland of wet season grazing to maintain yields on one hectare of cropland using animal maure (Fernandez *et al*. 1995).

Manure production by zero-grazing cattle in Kenya has been estimated as 1 to 1.5 t $animal^{-1}$ $yr^{-1}$ (Strobel, 1987). Two animals will be needed to supply a 2 t $ha^{-1}$ of crop, if the manure were of high quality, but eight animals are required if the quality is low.

Ecosystem services are broadly defined to include nutrient cycles, water movement and storage, soil erodibility, pest control and chemical detoxification. These services are key determinants of agricultural productivity and sustainability. Therefore the application of manure and increase in system carbon can be considered to be a major component of sustaining the crop-livestock production systems. Recognition of this fact has led to investment in research on carbon sequestration in tropical agricultural landscapes.

The data in Table 7 in the Sahelian zone of Niger clearly indicates that manure application will not only improve the organic carbon of the soil but by complexing iron and aluminium it will also increase P availability. In the long-term soil fertility management trials, although soil organic carbon decrease in all treatments overtime, the organic carbon value was higher in the treatment where crop residue and manure was applied (Fig. 4).

Past and on-going research has been focussed on the assessment of the relationship between land management practices and carbon storage. Our current understanding is that the carbon sequestration potential of different organic inputs is an analogous index to that of fertilizer equivalency. Further studies are directed at the assessment of the trade-offs between the use of soil carbon for agricultural productivity and its value for carbon sequestration potential and environmental conservation. This is a relatively new area of research especially on assessing the effect of quantity and quality of organics on soil organic matter fractions and crop yields.

Expected benefits from manure application in the context of ecosystem functions include non-nutritional effect on soil physical properties that in turn influence nutrient acquisition and plant growth. The resource, through interactions with the mineral soil in completing toxic cations helps to reduce the phosphorus (P) sorption capacity of the soil.

## III. Management practices to improve manure efficiency

1. Improvement of manure quality

Manure quality varies widely and clear indices of quality determination are sometimes difficult to apply widely. Past research has been focussed on evaluating different ways of managing manure to improve its quality. Preliminary studies suggest that feeding of concentrates; zero-grazing rather than traditional boma; manure stored under cover instead of in the open, concrete floor rather than soil floor results in higher quality of manure (Lekasi *et al*., 1998).

(a) Animal type and diet

The quality of manure has been observed to vary with types of animals and feeds, collection and storage methods (Mueller-Saemann and Kotschi, 1994; Mugwira, 1984; Ikombo, 1984; Probert *et al*., 1995; Kihanda, 1996). A study in Ethiopia showed that the quality of manure declined in the order of chicken > sheep/goat > horse/donkey > cattle manure with respect to % N (1.5, 0.7, 0.5 and 0.4), % P (0.4, 0.4, 0.3 and 0.2) % K (0.8, 0.3, 0.3 and 0.2) and % organic matter (29, 31, 22 and 16), respectively. In a related study conducted in Kenya, Lekasi *et al*. (1998) observed that the nutrient contents (especially N and P) of manure decreased in the order of chicken, pig, rabbit, goat and cattle, with manure mixed with urine having a higher quality than dung alone. Nevertheless, current characterization studies indicate that manure quality is very variable e.g. % N 0.23-1.76; % P 0.08-1.0; % K 0.2-1.46; % Ca 0.2-1.3 and % Mg 0.1-0.5. High quality manure has been defined as that with % N>1.6 or C:N ratios of <10; while low quality manure has <0.6% and C:N ratios of >17. Recent studies have shown poor correlation between manure quality and lignin, polyphenols and soluble fractions of carbon (Kihanda and Gichuru, 2000). Fig. 5 shows the effect of C:N ratio on N mineralization of manures. Fig. 6 shows that the N fertilizer equivalency increases with high N content.

Besides animal type, quality of manure can be enhanced through feed manipulation which is more favourable in intensive grazing systems (eg. stall or zero-grazing units) rather than extensive grazing systems (eg. communal or range etc.). In a study carried out in East Africa, it was reported that manure N concentration increased by more than two fold when the basal diet of barley straw animal feed was supplemented with poultry waste and high quality forage shrubs, *Calliandra* and *Macrotylama* (Delve, 1998). In another study, manure from animals that received P supplements of Busumbu (0.70% P) and Minjingu rock phosphate (0.45% P) increased by two to four-fold above the basal diet of napier (0.24% P), bone meal (0.50% P). However, feeding animals with “unga” commecial feed resulted in much higher values of P in manure (0.95% P).

(b) Composting techniques and materials

While the quality of materials used to make compost manures determines its quality, composting techniques are equally important. High quality manures is often obtained from covered shed composting compared to open-shed composts; and similarly from pit composts compared to heap or surface composting. Furthermore crop residue incorporation has been found to minimize nutrient losses through aerobic volatilisation or anaerobic dentrification. For example, in a study in Kenya it was reported that composting low quality manure with different proportions of either tithonia or lantana, the N content of manure was increased by between 10 and 40 per cent depending on the treatment but no changes in P concentration was found (Kihanda and Gichuru, 2000).

In a study conducted in Zimbabwe, investigating manure nitrogen changes during storage, Nzuma and Murwira (1998) showed that total N measured in anaerobic manure composts at the end of storage was significantly higher than in aerobic manure composts. This aerobic manure compost incorporated with maize straw was 0.9 and 0.6% N for April and July samples respectively, while the values in the absence of straw incorporation were 1.4 and 1.2% N (due to lack of N immobilization). The results also showed that the pH in anaerobic manure compost system ranged from 6.5 to 6.9 while the anaerobic manure composts were more alkaline with pH range of 8.2 to 8.6 (Fig. 7).

The effect of composting on the phosphate rock (PR) dissolution has been study by Bado (1985) and Lompo (1984) in Burkina Faso. The local phosphate rock of Kodjari alone or combined with urea was incorporated in two low quality organic materials for composting during 6 months. The RP and the urea were incorporated in the organic materials at the rates of 4kg of PR (25% P2O5) for 100kg and 12 kg of urea for 1000 kg dry organic matter according to the recommended rates (Lompo, 1984). The organic material was a mixture of 75% of sorghum straws and 25% of cattle manure (using as an inoculums). The effect of composting on the water-soluble phosphorous (WSP) balance before and after composting was evaluated.

The results (Table 8) indicated that the composting of the organic materials with PR involved an enhancement of the total WSP balance. The total WSP was positive for all treatments. A positive balance of 67% to 796% of the total WSP was observed after 6 months of composting. The augmentation of the total WSP may be explained by an increase of the soluble phosphorous from organic matter. It may also due to a probable dissolution of the P of the PR by the organic acids during the composting. May be the two process took place during the composting time.

(c) Handling and storage techniques

Besides heaps and pits, manure may be collected and stored in cattle kraals, bomas, open areas etc. Recent research shows that quality of manure may be affected depending on prevailing conditions. Murwira (1993) reported that under aerobic and high pH conditions in the Kraal, volatilisation of ammonia may occur while the wet soggy anaerobic conditions may lead to dentrification and leaching losses. Such losses are minimized under intensive grazing system such as zero-grazing units with concrete floor and covered roof. In such systems provision of low quality organics as bedding helps to trap the nutrients from the urine. Lekasi *et al*. (1998) reported that manure removed from grazing units with a soil floor had a much lower N and P and higher ash content than manure removed from grazing units with a concrete floor. Factors responsible for enhanced gaseous N loss in composting include increased total N of the material; high temperatures, low pH and frequent turning (Dewes and Hunsche, 1998). On the other hand high dentrification loss are often associated with increased pH and not increase of insoluble carbon compounds as opposed to reducing sugars under anaerobic conditions. Run-off and nitrate leaching losses can also be substantial.

(d) Integrated nutrient management

The beneficial effects of combined manure and inorganic nutrients on soil fertility have been repeatedly shown, yet there is need for more research on the establishment of the fertilizer equivalency of the manures and also determining the optimum combination of these two plant nutrients (INM) taking into account the high variability in the quality. Such information is useful in formulating decision support systems and establishing simple guidelines for management and utilization of the resources. Studies investigating the benefits of sole versus combined application of manures and inorganic fertilizers have given variable and sometimes inconsistent results. At Chisunga N in 100% inorganic and 100% organic have yield of maize lower than combining the two plant nutrient. For example, the application of 100 kg N/ha in the inorganic farms have maize yields of about 3.2 t $ha^{-1}$ but the application of the same quantity with half inorganic form and the other half in inorganic form gave maize yield close to 6 t ha-1. In Manjoro there was no advantage to combine organic and inorganic plant nutrients (Fig. 8). For example, studies in Tanzania indicated that there was no significant difference in maize yields between sole and combined application of 5 t $ha^{-1}$ of manure and 60 kg N $ha^{-1}$ of mineral fertilizer (Richard, 1967). But at a different site in the same country, combination of manure at 5 t $ha^{-1}$ with 40 kg N $ha^{-1}$ mineral fertilizer gave similar maize yield with either manure at 10 t $ha^{-1}$ or mineral fertilizer at 80 kg N $ha^{-1}$ (Kalumuna *et al*., 1999). Disparities in such responses are partly due to addition of different rates and quality of nutrients through compared treatments; and also due to differences in the limiting nutrients and soil moisture at the test sites. For example, in Madagascar, Rabeson (1992) observed that supplementing manure with inorganic N fertilizer, the rice yield increased by more than 100% but supplementing with P did not improve the crop yield, suggesting that N was the most limiting nutrient in that soil. Another cause of inconsistent results may be due to depressing or antagonistic effects of the nutrient source combinations. For example, a study in Zimbabwe showed that while increasing rates of manure, lime and NPK mineral fertilizers increased growth of pearl millet, however, lime had a depressing effect on the effectiveness of manure while the NPK fertilizers increased the effectiveness of manure (Mugwira, 1985). Also,

short-term trials do not give a true picture of the long-term effects of the treatments. Additionally, higher fertilizer equivalencies have been observed in less moist and less fertile soils e.g. sandier and drier soils (Kimani *et al*., 2001). Using data collected in different sites, Mutuo *et al*., 2001 found a linear relationship between the percent fertilizer equivalency and the N content. This linear function indicates that increase of 0.1% N in the tissue of organic amendment, there is a 6% increase in the fertilizer equivalency value and the critical level of N content of organic material for net immobilization or mineralization was found to be 2.2%. This is an agreement with the one of the 2.2% suggested by Palm *et al*. (1995) and Palm *et al.* (1997) in the decision tree for the selection of organic materials (Fig. 9).

(e) Time frequency and method of application

Low quality manure is often observed to depress crop yields. This deleterious effect can be overcome through application of manure ahead of planting time to overcome this effect. In some cases, surface application has resulted in better results than incorporation. In many cases, this depends on the quantity of manure applied. Some studies have investigated the potential to overcome this problem through megadose application instead of annual applications. But such studies from Zimbabwe suggest that there are no differences in crop yields between the two application regimes eg. 7 t $ha^{-1}$ annual application, 14 t $ha^{-1}$ applied every second year and 28 t $ha^{-1}$ applied every fourth year (Mugwira and Murwira, 1997).

(f) Fortification and pelleting

The bulky nature of manures and low quality constraint its transportation and returns to application. To make manure as a biofertilizer easily handleable (less bulky) and applicable, some studies have shown granule pelleting to be a farmer user-friendly packaging system. Other studies have demonstrated that the quality and return to such biofertilizers can be improved through fortification with the addition of inorganic nutrient sources; composting under cover to minimize leaching and loss of nutrients via gases; and the use of high quality biofertilizers on high value crops solely or in combination with inorganic fertilizers.

In high external input systems, large quantities of maize stover or wheat straw can be generated (8–10 t $ha^{-1}$), and this is either burnt or partly grazed, resulting in large nutrient off-takes unless the manure is recycled. To overcome this constraint, fortification trials have been conducted. Okalebo *et al.* (2000) found that combined application of composts of 2 t $ha^{-1}$ of wheat straw or soybean trash with 80 kg N $ha^{-1}$ of mineral fertilizer resulted in higher maize yields (grain and stover) than from application of 80 kg N $ha^{-1}$ of mineral fertilizer alone. Sole application of residue depressed yields. In related studies Muasya *et al*. (2000) found that wheat straw composted with inorganic fertilizer (80 t $ha^{-1}$ compost) resulted in slightly higher wheat yields (3.6 t $ha^{-1}$) than with the same rate of normal compost (3.0 t $ha^{-1}$).

2. Strategies to increase manure quantity

In both regions, manure is produced abundantly under extensive systems eg. in pastoralists and transhumant systems. As these systems decrease, settled arable agriculture increases. In the latter systems farmers own cattle either under confinement or paddocking systems. Lots of manure is accumulated in cattle boma in the East African region. In West Africa, kraaling eg. keeping of livestock on selected areas over a given period of time, helps increase and accumulate manure through urine and dung voided in the field. Recent studies have shown that two nights kraaling results in between higher yields than in unkraaled fields (Powell *et al*., 1998).

## IV. New Research Opportunities

### 1. "Best-bet" manure-based technologies

Past reviews of research on the use of organics (with or without mineral fertilizers) for soil fertility management in tropical agroecosystems (CABI, 1994; Padwick, 1993; Nandwa and

Bekunda, 1998; Palm *et al*., 1997; Palm *et al*., 2001) have shown widespread non-adoption or low adoption of emerging technologies. It has been reported that often the use of organic materials is based on trial and error (Palm *et al*., 2001). At the research and development level, presently and in future, there is a need for priority setting (Kilambya *et al*., 1999) and targeting of a potential "best-bet" technology for smallholder farmers in the form of an agronomic superiority, economic viability, environmentally friendly and culturally acceptable options.

**2. Multidisciplinary/interdisciplinary research agenda**

Wider adoption of soil productivity technologies requires that their profitability for smallholder farmers be carefully evaluated. The imperative for future manure research is to adopt a holistic framework for closer interaction between soil productivity subject matter specialists, economists, environmentalists, extensionists and policy makers. There is a need for more horizontal and, above all, vertical networking to create momentum and synergy in soil productivity management research. Lack of multidisciplinary research has been reported to lead to inadequate discounting of soil quality by economists in the context of a "future generations sustainability quest" (Young, 1998). Furthermore, other workers have reported a poor relationship between farm product price and nutrient withdrawal (mining) in the context of nutrient replacement cost. Recent work in Kenya showed that 32% of the average net farm income amounted to the replacement of mined nutrients of many farms and farmers, 54% of whom are estimated to live below the poverty line, i.e. on one US dollar per day (de Jager *et al*., 1998). The proposed new approach should provide synergies between applied or strategic research to adaptive research, and also between farmers' indigenous technical knowledge and their main scientific knowledge, and therefore result in higher rates of technology adoption. Future multidisciplinary research should also investigate yield depression attributed to phytotoxicity associated with manure management (Elliott *et al*., 1978), plant diseases (Cook *et al*., 1978) and pests (Musiek and Beasley, 1978).

**3. Farmer/client participatory research approach and methodologies**

There is a need for a shift from a top-down to bottom-up research approach because the use of the former approach in soil productivity management consultative/collegial research in the past has proved retrogressive, especially for heterogeneous, risk-averse farm households. Future manure and other nutrient input management research should use participatory research approaches eg. farmer's field school, participatory learning action research (Defoer et al., 1998), in the context of the target farming systems, integrating different disciplines and with participation of farmers (Martin and Sherington, 1997; Haverkort *et al*., 1991).

**4. Guidelines on the use of manures**

A majority of manure are often characterized as intermediate–low-quality resources and hence are prescribed to be used in a mixture with mineral fertilizer (Palm *et al*., 2001). Future research is required to identify the "best-bet" low-quality manure that can be mixed with high-quality organic resources to satisfy the short-term goal of nutrient availability and the long-term goal of building SOM. Such research should come up with cases for proper discounting of resource conservation estimates (Smaling *et al*. 1997).

**5**. The benefits of manures, like other organics, over mineral fertilizers is both the short-term effects and residual or long-term effects. Future research opportunities include the development of guidelines that link quality of manure to their short-term fertilizer equivalency value and longer-term residual effects through SOM turnover and formation.

6. Future research opportunities exist on building on past Organic Resource Database (ORD) to develop Decision Support System (DSS) guides and simple tools, based on both scientists and

farmer perspectives to guide the choice and utilization of manure depending on their varied quality and quantities. This will require research that correlates scientific indicators (chemical content and nutrient release) with farmers indicators of manure quality (texture, colour, smell, white fungi/sand, homogeneity and longerity of composts).

7. Research opportunities exist on the establishment of the relationship between manure quality and a number of variables that influence quality eg. feeds manipulation, composting techniques, manure handling and storage method. These type of research should include determination of strategies that minimize nutrient losses and leaching, erosion, volatilisation and dentrification.

8. Future research opportunities include the development of a systematic framework for investigating integrated nutrient management based on fertilizer equivalence values and pertinent ecosystem services and functions. This research should conduct the determination of economic and social trade-offs of improved soil fertility management alternatives to manures eg. legumes, high quality organics, green manures, forage legumes in traditional mixed farming systems.

9. There are future research opportunities on the determination of the biophysical and socio-economic boundary conditions for the adoption of manure management-based techniques.

**Conclusion**

There is considerable information on manure management in Western and Southern Africa. The results of the comparative analysis from the regions suggest that different lessons can be learned from each stakeholder. As an example, it is clear that scientists in West Africa can benefit by learning more of the technologies developed in West Africa where compost with manure is fortified with phosphate rock and scientists in West Africa can also learn on the work done in East Africa on the assessment of manure fertilizer equivalency, the technologies based on the identification of the best combination ratios of organics and inorganics and the systematics characterization of manure for its nutrient contents and lignins and polyphenols in order to apply the organic matter decision tree.

Crop response to manure or in combination with inorganic fertilizers is variable and site specific. The difference in response may be due to several factors eg. soil fertility status quality of manure and environmental factors. This means that modelling and decision support systems will have an important role in future research. Other new research opportunities include topics such as the crop livestock trade-off by developing new strategies that minimize competition between crops and livestock such as conflicting demands of crop residue for feed and soil cpnservation, the legume for soil fertility management per se of feed for livestock the increase of inorganic fertilizer use efficiency, due to better management of manure, the relationships between manure quality and build-up of soil organic matter, the other benefits of manure use and the socio-economic and policy implications.

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**Table 1: Results of manuring experiments at three sites in semi-arid West Africa**

**Panel A:** Manure only

| Location | Amount of manure applied (t/ha) | | Crop response[1] (kg of DM/t manure) | | |
|---|---|---|---|---|---|
| | | Crop | Grain | Stover | Reference |
| M Pesoba, Mali | 10 | Sorghum | 35[2] | n.s. | 1 |
| Saria, Burkina Faso | 10 | Sorghum | 58 | n.s. | 2 |
| Sadore, Niger 1987 | 5 | Pearl millet | 38 | 178 | 3 |
| | 20 | Pearl millet | 34 | 106 | 3 |

**Table 1: Results of manuring experiments at three sites in semi-arid West Africa (cont.)**

**Panel B:** Manure with inorganic fertiliser

| | Amount of | | | Crop response[1] (kg of DM/t manure0 | |
|---|---|---|---|---|---|
| Location | Manure (t/ha) | Fertiliser (kg/ha) | Crop | Grain | Stover |
| M Pesoba, Mali | 5 | NPK: 8-20-0 | Sorghum | 90[4] | n.s. |
| Saria, Burkina Faso | 10 | Urea N: 60 | Sorghum | 80 | n.s. |
| Sadore, Niger | | | | | |
| 1987 | 5 | SSP P: 8.7 | Pearl millet | 82 | 192 |
| 1987 | 20 | SSP P: 17.5 | Pearl millet | 32 | 84 |

1. Responses were calculated at the reported treatment means for crop yields as: (treatment yield - control yield)/quantity of manure applied.
2. Response of sorghum planted in the second year of a 4-year rotation involving cotton-sorghum-groundnut-sorghum. Manure was applied in the first year.
3. Manure plus urine
4. Estimated from visual intrapolation of graph
n.s. implies not specified

**References:** 1. Pieri (1989); 2. Pieri (1986); 3. Baidu-Forson and Bationo (1992)

Source: Williams et al. 1995

**Table 2: Crop yields (averaged over several sites) as influenced by levels of FYM application**

| Crop | FYM rates and crop yields (t $ha^{-1}$) | | | | Response equation | $R^2$ |
|---|---|---|---|---|---|---|
| | 0 | 2.5 | 5.0 | 7.5 | | |
| Nitisols | | | | | | |
| Maize | 3.72 | 4.00 | 4.34 | 4.76 | Y = 3.68 + 0.138 FYM | 0.99 |
| Potatoes | 9.12 | 10.20 | 10.60 | 11.80 | Y = 9.16 + 0.337 FYM | 0.98 |
| Cabbages | 13.70 | 21.20 | 27.60 | 29.30 | Y = 14.97 + 2.128 FYM | 0.97 |
| Acrisols | | | | | | |
| Maize | 1.88 | 2.00 | 2.00 | 2.07 | Y = 1.90 + 0.021 FYM | 0.93 |
| Cowpeas | 0.77 | 0.78 | 0.83 | 0.82 | Y = 0.77 + 0.079 FYM | 0.88 |

(Source: Kanyanjua and Obanyi (1999).

**Table 3: Effects of manure and phosphorus from different sources on Pearl Millet grain yield, at Sadore, Niger, 1988**

| Treatments | Grain yield (tons $ha^{-1}$) |
|---|---|
| Control | 0.362 |
| 8.7 kg P $ha^{-1}$ as single superphosphate (SSP) | 0.734 |
| 5 tons manure $ha^{-1}$ | 0.723 |
| 8.7 kg P $ha^{-1}$ as SSP + 5 tons manure $ha^{-1}$ | 1.093 |
| 39.3 kg P Parc W phosphate rock $ha^{-1}$ | 0.485 |
| 39.3 kg P Parc W phosphate rock ha-1 + 5 tons manure $ha^{-1}$ | 0.952 |
| 17.5 kg P $ha^{-1}$ as SSP | 0.851 |
| 20 tons manure $ha^{-1}$ | 1.457 |
| 17.5 kg P $ha^{-1}$ as SSP + 20 tons manure $ha^{-1}$ | 1.508 |
| | |
| SE | ±0.089 |
| CV (%) | 27.9 |

Note: The manure had 0.405% total P and 1.21% total N
Source: Bationo and Mokwunye 1991

**Table 4: Effect of cattle and sheep dung and urine on pearl millet grain and total above-ground biomass, Sadore, Niger 1991**

| Type of manure | Dung application rate kg/ha | With urine | | Without urine | |
|---|---|---|---|---|---|
| | | Grain yield (kg/ha) | Total biomass (kg/ha) | Grain yield (kg/ha) | Total biomass (kg/ha) |
| Cattle | 0 | - | - | 80 | 940 |
| | 2990 | 580 | 4170 | 320 | 2170 |
| | 6080 | 1150 | 7030 | 470 | 3850 |
| | 7360 | 1710 | 9290 | 560 | 3770 |
| | s.e.m. | 175 | 812 | 109 | 496 |
| Sheep | 0 | - | - | 80 | 940 |
| | 2010 | 340 | 2070 | 410 | 2440 |
| | 3530 | 1090 | 6100 | 380 | 2160 |
| | 6400 | 1170 | 6650 | 480 | 2970 |
| | s.e.m | 154 | 931 | 78 | 339 |

Adapted from Powell et al. 1998

**Table 5: Nutrition content of FYM samples collected from different parts of Sub-Saharan Africa (mainly Eastern and Southern Africa)**

| | Nutrient content (%) | | | | |
|---|---|---|---|---|---|
| Country (Reference) | N | P | K | Ca | Mg |
| UK (Hemingway, 1961) | 1.76 | 0.24 | 1.29 | 0.74 | 0.34 |
| Kenya (Ikombo, 1994) | 1.62 | 0.50 | 1.34 | 0.26 | Nd* |
| Kenya (Kihanda, 1996) | 1.19 | 0.24 | 1.46 | 0.97 | 0.26 |
| Zimbabwe (Mugwira, 1984) | 0.6-1.3 | 0.1-0.2 | 0.7-1.0 | 0.2-0.3 | 0.1-0.2 |
| Ethiopia (Mueller and Kotschi, 1994) | 0.3 | 0.2 | 0.2 | nd | nd |
| Kenya (Probert *et al*., 1995) | 0.23-0.70 | 0.08-0.22 | 0.28-1.14 | 0.58-2.02 | nd |
| Madagascar (Rabeson, 1992) | 0.8-1.7 | 0.6-1.0 | 0.7-1.4 | 0.5-1.3 | 0.3-0.5 |
| Chicken manure: Mueller-Saeman and Kotshi, 1994 | 1.5 | 0.4 | 0.8 | - | - |
| Sheep/goat manure: Mueller-Saeman and Kotshi, 1994 | 0.7 | 0.4 | 0.3 | - | - |
| Cattle manure: Mueller-Saeman and Kotshi, 1994 | 0.3 | 0.2 | 0.2 | - | - |
| Horse/donkey manure: Mueller-Saeman and Kotshi, 1994 | 0.5 | 0.3 | 0.3 | - | - |

nd* not determined

Source: Adapted from Kihanda and Gichuru 2000

**Table 6: Nutrient composition of manure at selected sites in semi-arid West Africa**

| Location and type of manure | Nutrient composition (%) | | | Reference |
|---|---|---|---|---|
| | N | P | K | |
| Saria, Burkina Faso | | | | |
| Farm yard manure | 1.5 - 2.5 | 0.09 - 0.11 | 1.3 - 3.7 | 1 |
| Northern Burkina Faso | | | | |
| Cattle manure | 1.28 | 0.11 | 0.46 | 2 |
| Small ruminant manure | 2,20 | 0.12 | 0.73 | 2 |
| Senegal | | | | |
| Fresh cattle dung | 1.44 | 0.35 | 0.58 | 3 |
| Dry cattle dung | 0.89 | 0.13 | 0.25 | 3 |
| Niger | | | | |
| Cattle manure | 1.2 - 1.7 | 0.15 - 0.21 | - | 4 |
| Sheep manure | 1.0 - 2.2 | 0.13 - 0.27 | - | 4 |

Source: Williams et al. 1995`

**Table 7: Changes in soil nitrogen, pH, organic matter, and Bray $P_1$ in 1987 after additions of manure in 1984 and 1986**

| Treatments | Total N | pH | | Organic | Bray P1 |
|---|---|---|---|---|---|
| | (%) | | | matter | (ppm) |
| | | H2O | KCL | (%) | |
| Control | 153 | 4.98 | 3.88 | 0.29 | 5.33 |
| 5 tons manure ha-1 | 202 | 5.37 | 4.25 | 0.39 | 10.31 |
| 17.5 kg P ha-1 as SSP | 148 | 5.05 | 4.03 | 0.30 | 15.50 |
| 20 tons manure ha-1 | 285 | 6.21 | 5.03 | 0.58 | 22.90 |
| SE | 15 | 0.14 | 0.16 | 0.06 | 2.58 |
| CV (%) | 18.7 | 5.18 | 7.42 | 29.63 | 37.46 |

**Source: Bationo and Mokwunye 1991**

**Table 8: Percentage change of water soluble phosphorus after 6 months of composting**

| Treatments | (%) |
|---|---|
| Sorghum Straw(75%) +Manure(25%) | 67 |
| Sorghum Straw(75%)+Manure(25%) + PR | 172 |
| Sorghum Straw(75%) + Manure(25%) +PR+ Urea | 196 |

+

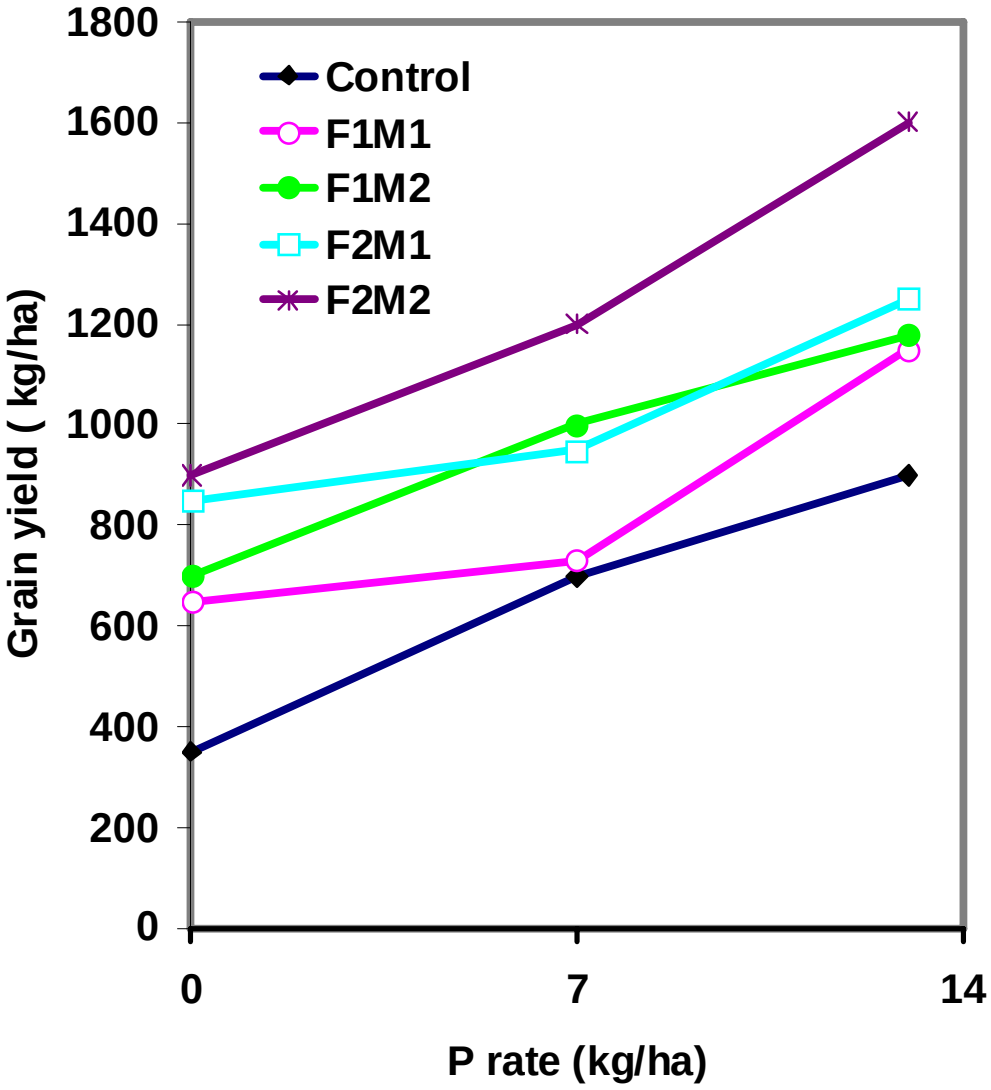


**Fig 1. Effects of manure placement methods and P fertilizer on milllet grain yield**
**F = Manure1 = 3 ton, 2 = 6 ton**
**M = Methods of application 1 = broadcast, 2 = hillplaced**

**Source: Dar et al., 2000**

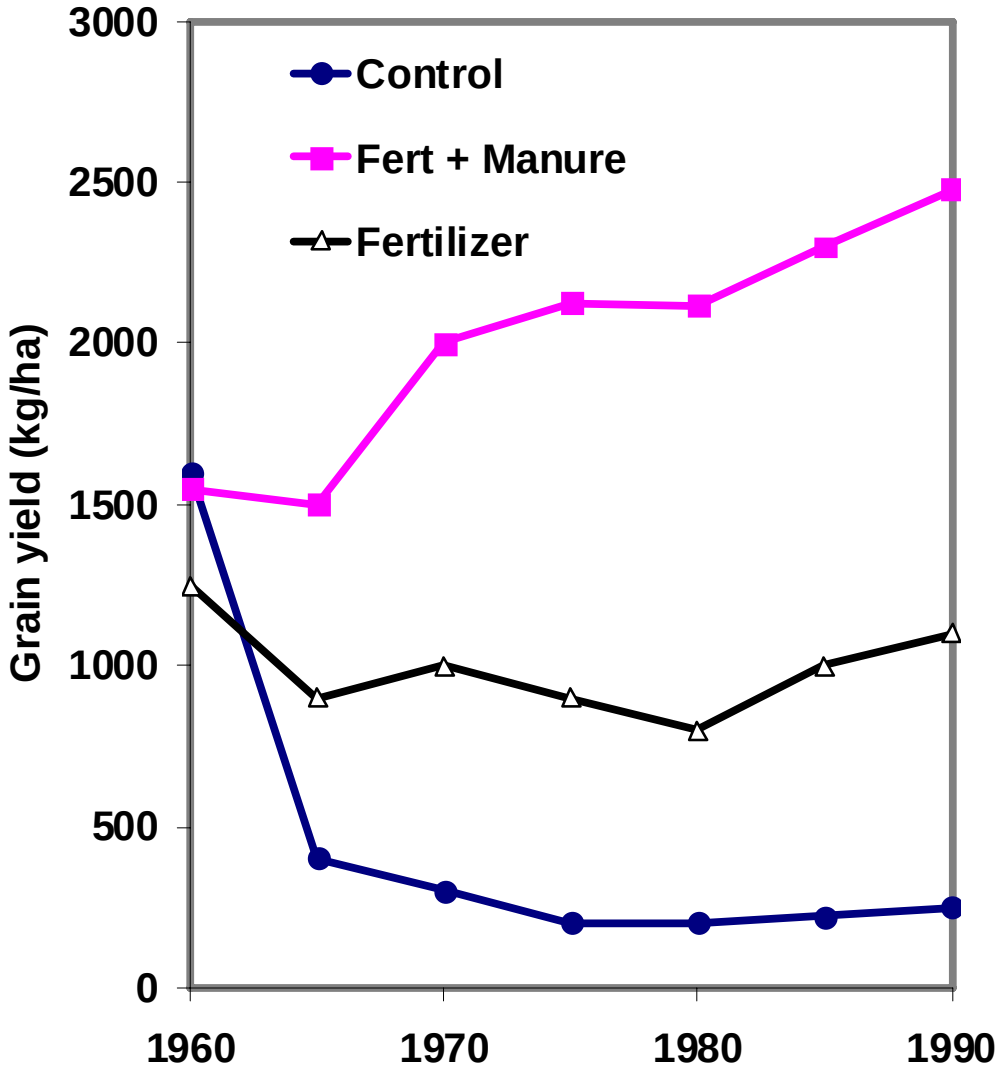


**Fig 2. Sorghum grain yield as affected by mineral and organic fertilizers over time.**

**Source: Sedogo, 1993**

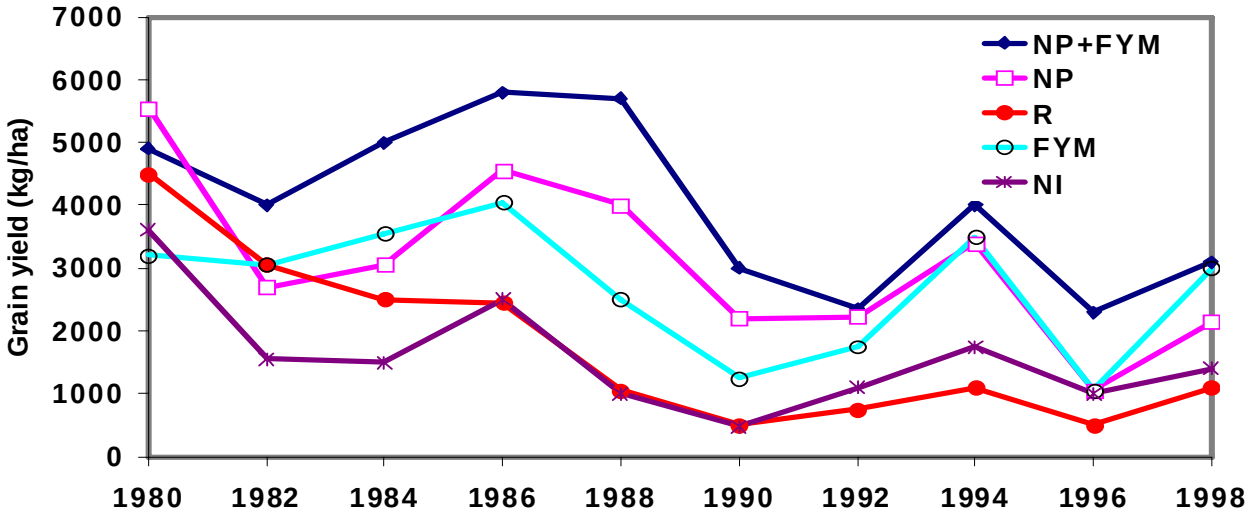


**Fig 3. Maize yield trends for long-term trial for the period 1980 to 1998 at Kabete Nairobi, Kenya.**

**Source: Nandwa, 1997**

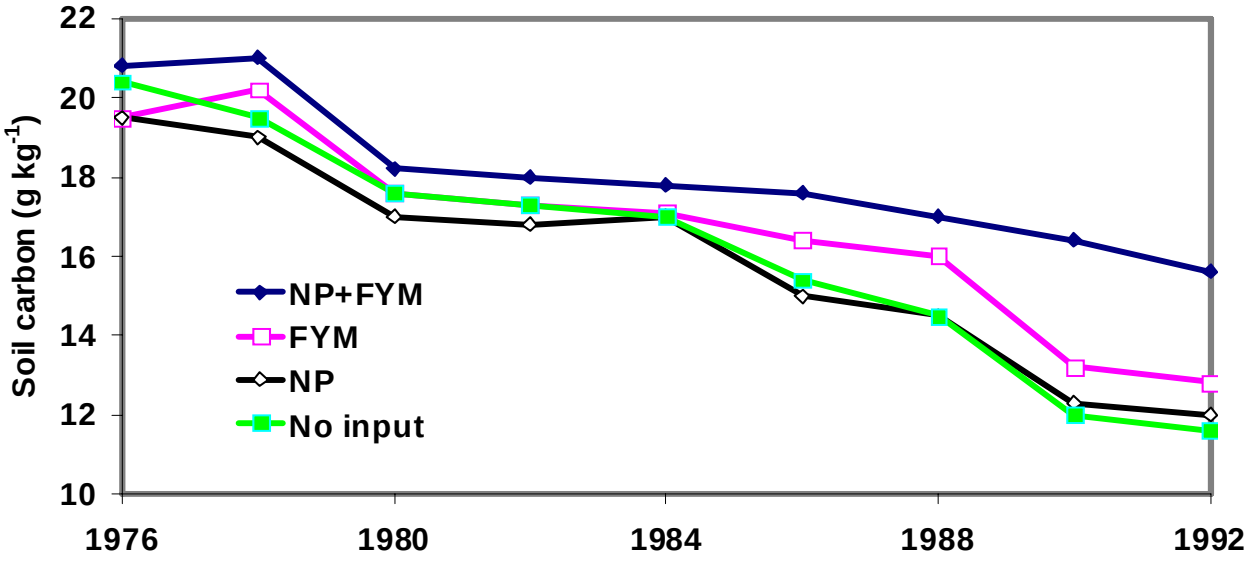


**Fig 4. Effect of application of farmyard manure, mineral fertilizer on soil organic C at 0 to 25cm depth at Kabete, Kenya.**

**Source: Nandwa, 1997**

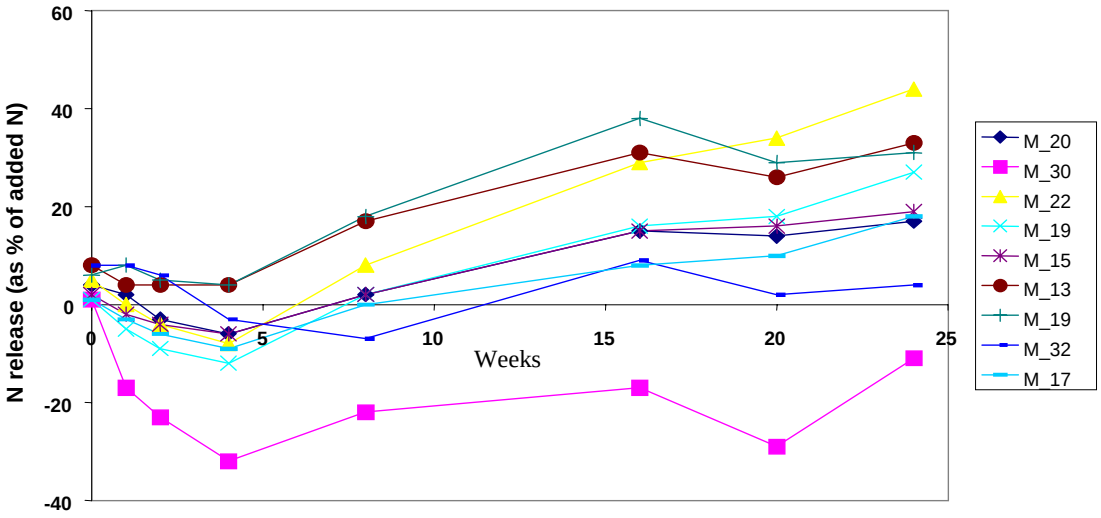


Figure 5. Nitrogen mineralisation of manures with different C:N ratios collected from cut and carry systems in Kenya. (numbers on right of legend indicate C:N ratio)

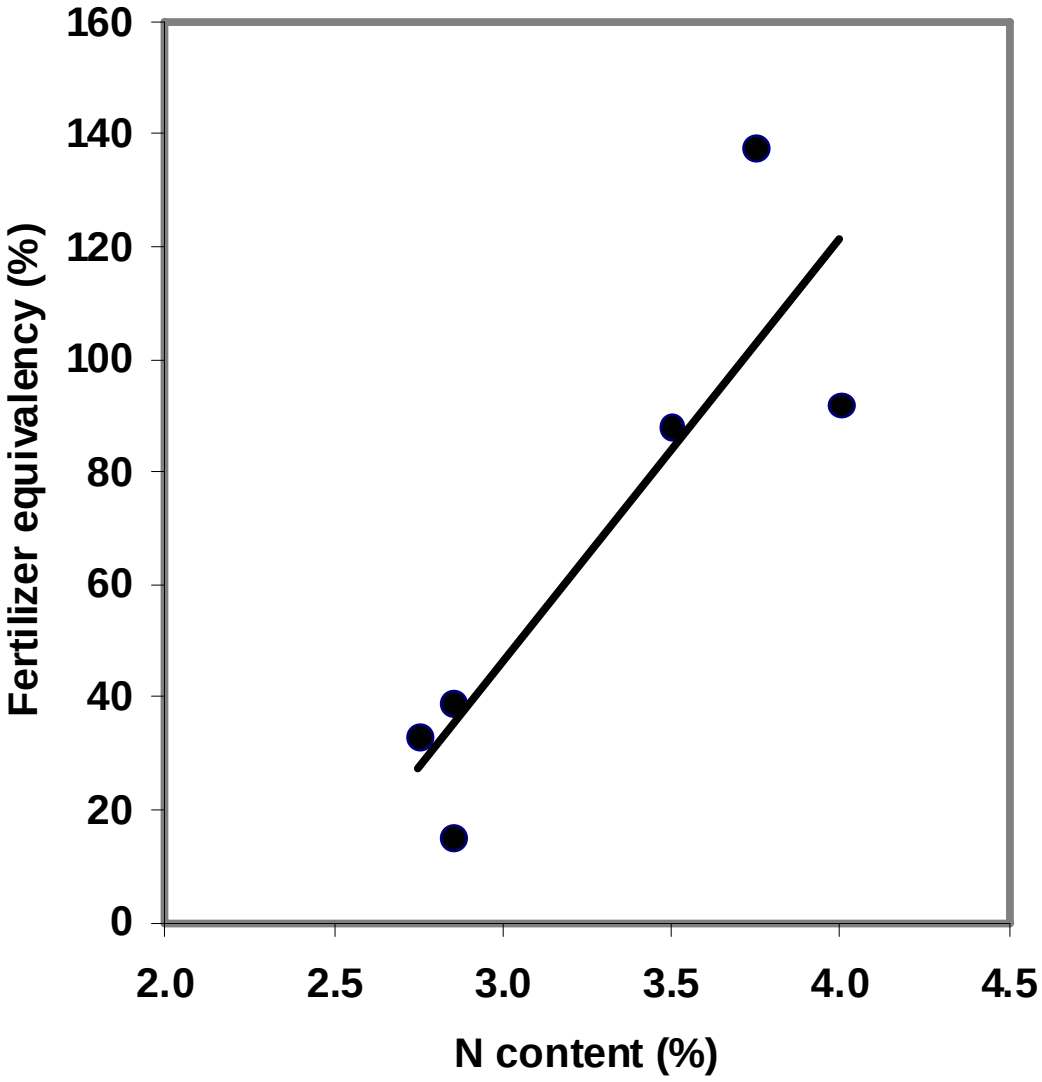


**Fig 6. Relationship between percent fertilizer equivalencies and N content of organic materials**

**Source: TSBF, 2000**

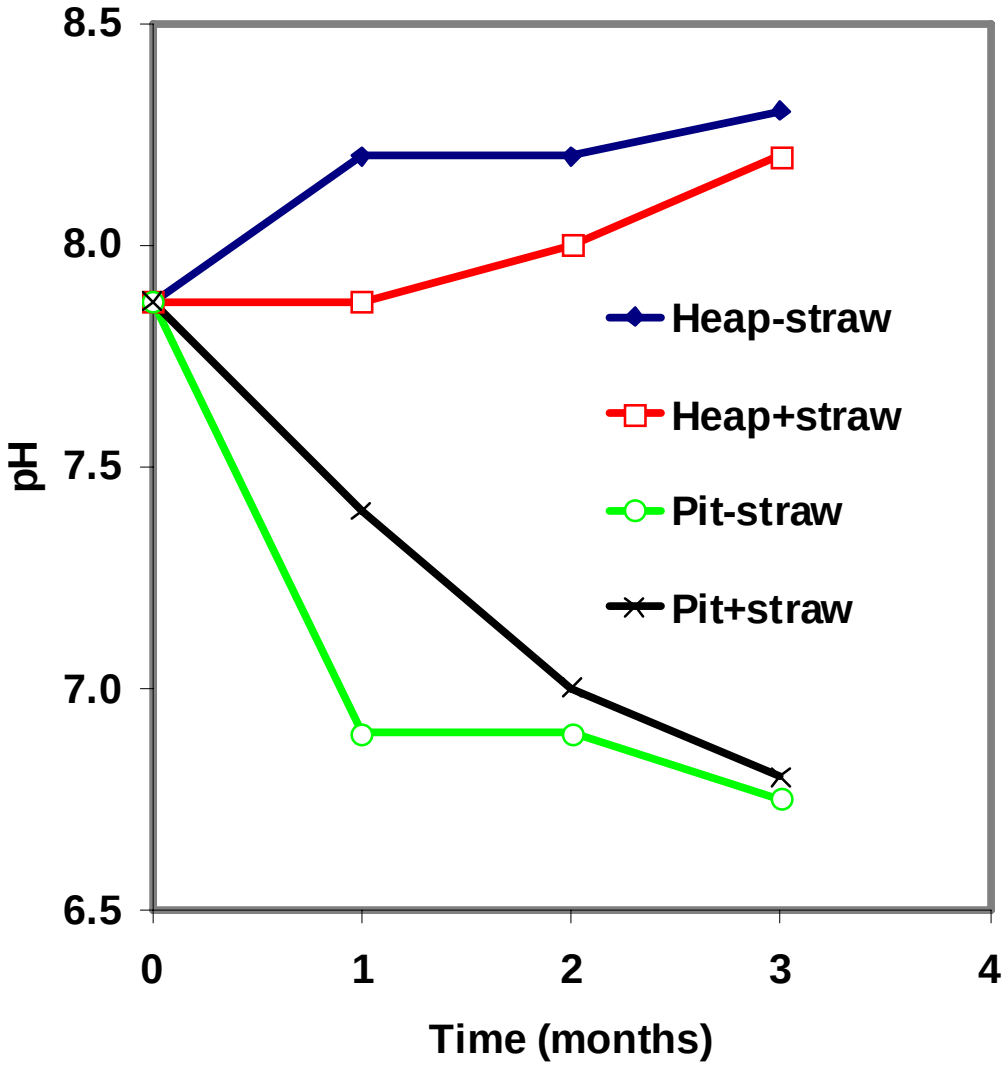


**Fig 7. Effects of methods of manure storage and crop residue incorporation on soil pH.**

**Source: TSBF, 2000**

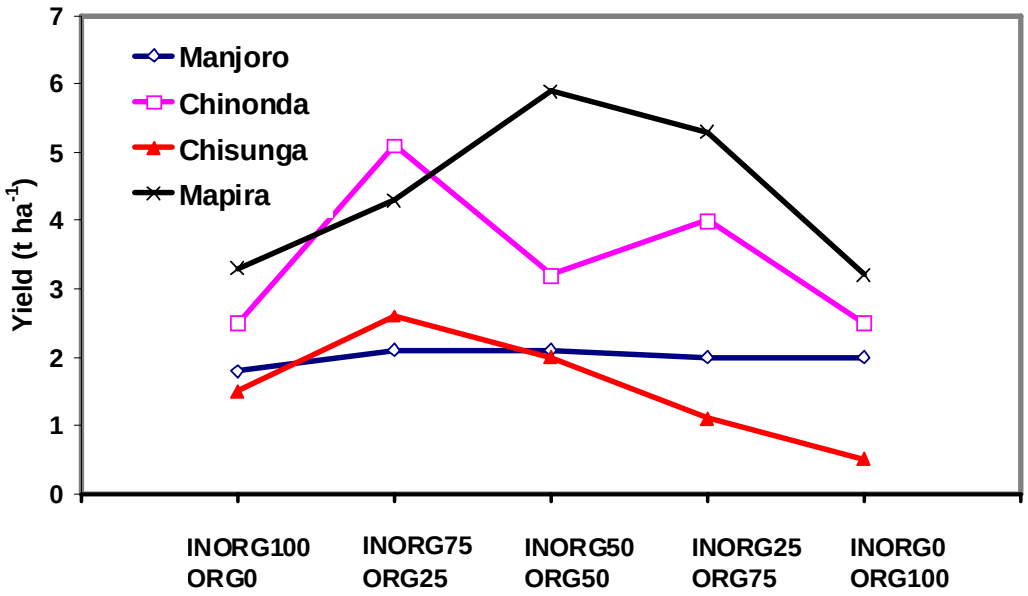


**Fig 8. Grain yield obtained from 100kg N applied in different proportions of manure and inorganic fertilizers, Murewa, Zimbabwe.**

**Source: TSBF, 2000**

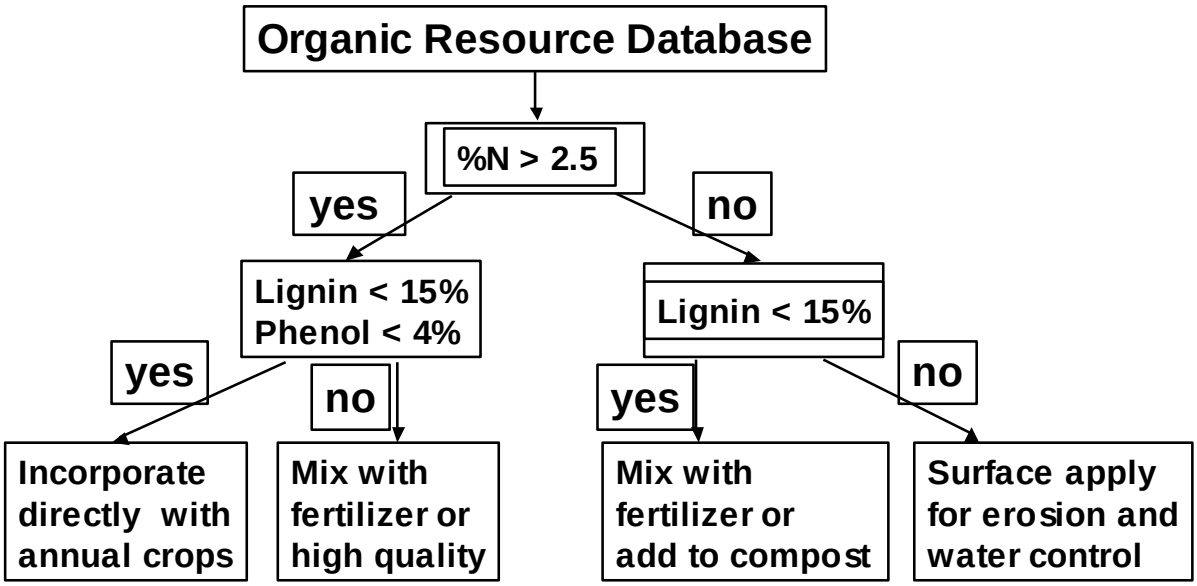


**Fig 9. An Organic matter Management Decision Tree for Nitrogen**

**Source: Cheryl Palm, TSBF 1997**

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## Carbon and nutrient accumulation in secondary forests regenerating from degraded pastures in central Amazônia, Brazil

Ted R. Feldpausch[1], Marco A. Rondón[2], Erick C.M. Fernandes[1], Susan J. Riha[3] and Elisa Wandelli[4]

[1]*Department of Crop and Soil Sciences, Cornell University, Ithaca, NY, 14853, USA*
[2]*Centro Internacional de Agricultura Tropical, Apdo. Aéreo 6713, Cali, Columbia*
[3]*Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, NY, 14853 USA*
[4]*Embrapa Amazônia Ocidental, C.P. 319, Manaus, AM, 69.000, Brazil*

### Abstract

Over the past three decades, large expanses of forest in the Amazon Basin were converted to pasture, many of which later degraded to woody fallows and were abandoned. While the majority of tropical secondary forest (SF) studies have examined post-deforestation or post-agricultural succession, we examined post-pasture forest recovery in ten forests ranging in age from 0 to 14 yrs since abandonment. We measured aboveground biomass and soil nutrients to 45 cm depth, and computed total site C and nutrient stocks to gain an understanding of the dynamics of nutrient and C buildup in regenerating SF in central Amazônia. Aboveground biomass accrual was rapid, 11.0 Mg $ha^{-1}$ $yr^{-1}$, in these young SF. After 12 to 14 yrs, they accumulated up to 128.1 Mg/ha of dry aboveground biomass, equivalent to 25 to 50% of primary forest biomass in the region. Wood N and P concentrations decreased with forest age. Aboveground P and Ca stocks accumulated at a rate of 2.4 and 42.9 kg $ha^{-1}$ $yr^{-1}$; extractable soil P stocks declined as forest age increased. Although soil stocks of exchangeable Ca (207.0 ± 23.7 kg/ha) and extractable P (8.3 ± 1.5 kg/ha) were low in the first 45 cm, both were rapidly translocated from soil to plant pools. Soil N stocks increased with forest age (117.8 kg $ha^{-1}$ $yr^{-1}$), probably due to N fixation, atmospheric deposition, and/or subsoil mining. Total soil C storage to 45 cm depth ranged between 42 and 84 Mg/ha, with the first 15 cm storing 40 to 45% of the total. Total C accrual (7.04 Mg C $ha^{-1}$ $yr^{-1}$) in both aboveground and soil pools was similar or higher than values reported in other studies. Tropical SF regrowing on lightly to moderately-used pasture rapidly sequester C and rebuild total nutrient capital following pasture abandonment. Translocation of some nutrients from deep soil (>45 cm depth) may be important to sustaining productivity and continuing biomass accumulation in these forests. The soil pool represents the greatest potential for long-term C gains; however, soil nutrient deficits may limit future productivity.

**Keywords:** secondary forest; abandoned pasture; carbon sequestration; plant nutrient stocks; soil nutrient stocks; nutrient loss; Oxisol; succession; Amazon.

### Introduction

Primary forest conversion for subsistence agriculture, industrial logging and pasture establishment continues to be the predominant cause of tropical deforestation (Laurance, 1999). These activities have left a large portion of the tropical biome disturbed and in various states of natural regeneration (Brown and Lugo, 1990), stagnation (Fearnside and Guimaraes, 1996; Sarmiento, 1997; Silver et al., 2000), or managed recovery (Fernandes and Matos, 1995; Parrotta et al., 1997). Of the estimated 58.8 million ha of forest cleared in Brazilian Amazônia over the past three decades (INPE, 2002), approximately 24 million ha were converted to pastures (Serrão et al., 1995). Depending on management (replacement of exported or lost nutrients, stocking rates, burning frequency, etc.), region, and soil type, pasture productivity may

decline after 7 to 10 years and may be recleared or abandoned to recolonizing secondary vegetation; approximately 50% of the first-cycle pastures have reached this advanced stage of degradation (Serrao et al., 1993). Based on an analysis of 1990 land use data in the Amazon, Fearnside (1996) calculated an equilibrium will be reached where ~47% of all deforested land would be regenerating forest on degraded or abandoned pastures.

Although highly altered, these lands are valuable for human use (Brown and Lugo, 1990), and provide important ecosystem services such as watershed protection, sources and havens of biodiversity, erosion prevention, soil fertility recovery by improved fallows (Szott et al., 1991), and atmospheric C sinks (Fearnside and Guimaraes, 1996, Silver et al., 2000). However, the potential of the abandoned land to recover and maintain these roles is dependant on the intensity of previous land use (Uhl et al., 1988; Nepstad et al., 1990; Aide et al., 1995; Alves et al., 1997), soil nutrient limitations (Cochrane and Sánchez, 1982; Smyth and Cravo, 1992; Laurance et al., 1999), and seed inputs and seedling establishment (Nepstad et al., 1996). These impediments to vegetation regrowth may be more extreme in abandoned pastures compared to agricultural land, resulting in lower aboveground productivity (Fearnside and Guimaraes, 1996; Silver et al., 2000), and longer regeneration times.

Pasture productivity declines rapidly with decreasing soil P availability, facilitating invasion by secondary forest (SF) species better adapted to infertile soil (Toledo and Navas, 1986); yet, soil fertility and biomass recovery is variable and dependant upon several factors. Degraded pastures are characterized by depleted soil nutrient stocks, low vegetation biomass, low primary forest seed inputs, high seed predation, depleted seed bank of forest species and low stump sprouting (Nepstad et al., 1990), as well as soil surface sealing and compaction (Eden et al., 1991). Consequently, predicting the long-term growth rate of secondary vegetation on degraded pastures and the return of primary forest characteristics becomes a complex task.

New attention has focused on fast-growing SF due to their potential to sequester large quantities of C in short time-periods. For example, worldwide tropical forests store approximately 206 Pg C in the soil (Eswaran et al., 1993), and tropical SF of less than 20 years have the potential to accrue soil C at a rate of 1.3 Mg $ha^{-1}$ $yr^{-1}$ (Silver et al. 2000). The growth rate of young SF is expected to increase with rising atmospheric $CO_2$ levels (DeLucia et al., 1999); however, high C allocation to short-lived tissues such as leaves and faster turnover of litter C may limit the potential C sink (Schlesinger and Lichter, 2001). Furthermore, soil nutrient limitations may constrain primary productivity under $CO_2$ enrichment (Oren et al., 2001).

Soil nutrient impediments to productivity under native vegetation are substantial in the Brazilian Amazon. Cochrane and Sánchez (1982) estimated that only 7% of the land area is free from major plant growth limitations; soil P deficiencies (<7 mg/kg) constrain productivity in 90% (436 million ha), and Al toxicity (Al saturation of ≥ 60%) occurs over 73% of the Brazilian Amazon. Low soil Ca (Smyth and Cravo, 1992) restrains productivity, P deficiencies (Gehring et al., 1999) limit SF growth, and the vegetation is unable to effectively capture leaching soil N (Schroth et al., 1999). Mismanagement may compound these deficiencies since pasture use-intensity appears to negatively influence regenerating vegetation biomass (Uhl et al., 1988) and nutrient stocks (Buschbacher et al., 1988). Because SF recovery is variable and dependent on previous land-use and soil fertility, the magnitude and rate of the above- and below-ground C accumulation in these regenerating SF is still relatively unknown.

Determining nutrient constraints to regrowth and the status of secondary vegetation is an important step in managing and/or enhancing abandoned site rehabilitation. We examined the dual roles of SF to rehabilitate site productivity and to increase C sinks and investigated potential soil nutrient limitations to these two processes. We examined aboveground and soil C accrual and nutrient stocks in degraded pastures that had been abandoned for a varying number of years. Our objective was to study the influence of regenerating vegetation on C and nutrient budgets following pasture abandonment. We hypothesized that C and N pools would recover with time following post-burn volatilization, while other nutrients would be redistributed from below- to above-ground pools resulting in reduced soil pools.

## Methods

*Study area*

The study areas are located in Amazonas, Brazil, in the central Amazon Basin, north of the city of Manaus along the road BR-174. The study area spans approximately 26 km (2° 34' S, 60° 02' W and 2° 20' S, 60° 04' W). The terrain is undulating with an elevation of 50-150 m. The plateau soil is classified as dystrophic, isohyperthermic, clayey kaolinitic, Hapludox with approximately 80–85% clay (*latossolo amarelo* according to the Brazilian classification system). Slope soils are composed of Ultisols and valley bottoms by Spodosols. The plateau soils have a low cation exchange capacity and are infertile but are strongly aggregated and well drained (Van Wambeke,1992).

The regional climate is tropical humid and the mean temperature is 26.7°C. Mean annual rainfall in Manaus is 2.2 m, with March and April as the wettest months with over 300 mm of precipitation. A mild dry season occurs from August through October, with mean monthly precipitation falling below 100 mm, and in some El Niño years to as little as 50 mm (Lovejoy and Bierregaard, 1990).

The native vegetation of this region is closed-canopy, dense, evergreen *terra firme* forest (Veloso et al., 1991). Species recovery with SF development is significantly different in areas used as pasture compared to areas cut but not managed (Mesquita et al., 2001). Old growth, native vegetation remains the dominant cover in this area. The establishment of new pastures is now rare, and active pastures are a diminishing, short-lived feature of the landscape north of Manaus. However, SF are increasingly found along the primary roads where efforts to raise cattle on large ranches failed some 10 to 20 years ago.

A majority of the pastures were mechanically cleared in the early 1980's, commercial timber may or may not have been removed, the slash burned in place or mechanically piled in windrows, and the area planted with exotic African grasses such as *Brachiaria brizantha* or *B. humidicola* (Rendle). Standard pasture management for the region includes at least one application of 50 kg P/ha. The animal stocking rate and number of years that the pastures were grazed were variable. Overgrazing and annual burning to increase economic returns in the short-term accelerated pasture degradation through increased nutrient loss and soil compaction. However, even in the absence of overgrazing (1–2 animal/ha) increases in bulk density occur (0.4 $g/cm^3$ increase from forest values after 12 years as pasture), leading to reduced infiltration, sheetwash, and pasture decline (Eden et al., 1991). Declining pasture productivity is characterized by a reduction in the forage to weed ratio as bare ground develops and herbaceous and woody plants begin to invade. When unpalatable plants begin to dominate, livestock productivity drops, animal mortality increases and the pasture is eventually abandoned. Fire and/or labor intensive hand weeding of seedlings and roots may lengthen pasture life by reducing woody biomass while encouraging grass growth; however, species of *Vismia*, a fast-growing early successional tree, resprout rapidly after burning and dominate abandoned pastures.

*Site and plot selection*

Ten SF were selected within three *fazendas* (cattle ranches) now in various stages of grazing, pasture abandonment or pasture reclamation: Fazenda Rodão (km 46), the Brazilian Agency for Agricultural Research (Embrapa Amazônia Ocidental) Agricultural District of SUFRAMA (DAS) pasture research site (km 53), and Fazenda Dimona (km 72), all along the road BR–174. Within each forest located on plateau Oxisols, we established four plots of 100 $m^2$ to 400 $m^2$, each with three subplots ranging in size from 35 to 225 $m^2$ depending on forest age. Forests ranged from 0 to 2 yrs to 12 to 14 yrs since pasture abandonment. Secondary forest selection was based on forest age and independence from adjacent plots within the same ranch. We selected a range of forests spanning the age of available SF in the area; however, all SF age classes do not occur at all farms. We conducted farmer interviews to determine site histories and when grazing was abandoned. The date at which the pastures were abandoned is not definitive, as cattle may infrequently graze the area until all palatable forage is replaced by woody successional vegetation. The regenerating forests within the ranches are biologically and physically distinct, each with a unique management history and vegetation cover.

*Biomass and tissue analysis*

Within each subplot, we measured diameter at breast height (DBH at 1.3 m above ground level; *Cecropia* were measured above prop-roots) for all live tree stems ≥1cm, tagged the stems, and recorded all species. Using two sets of allometric equations, Nelson et al. (1999) for stem >5 cm DBH and Mesquita (in preparation) for those 1 to 5 cm DBH, we calculated dry biomass for each tree and converted the estimates to Mg/ha. The two sets of equations were developed either on the EMBRAPA research site (Nelson et al., 1999) or within the same region (Mesquita, pers. comm). They provide a better estimate of SF biomass than previous equations (Saldarriaga et al., 1988; Uhl et al., 1988; Brown et al., 1989; Overman et al., 1994) developed in the Amazon Basin (Nelson et al., 1999). The Nelson equations provide valid biomass estimates from 1 to 30 cm DBH. However, since these SF have more stems in the smaller diameter range of the Mesquita equations (1 to 5 cm DBH), by using the two sets of equations rather than one, we improve biomass estimates.

We used species-specific equations for the dominant tree species *Vismia cayennensis* (Jacq.) Pers., *V. japurensis* Reich. (Clusiaceae); *Cecropia* (Moraceae; mainly *C. sciadophylla* Mart. and *C. purpurascens* C.C. Berg); *Bellucia* (Melastomataceae); *Goupia glabra* Aubl. (Celastraceae); *Laetia procera* (Poepp) Eichl. (Flacourtiaceae), and a mixed-species equation for all others. The pioneer *Cecropia*, uncommon on these sites, occurs less frequently in areas where grazing continues during secondary vegetation establishment (Mesquita et al. 2001).

To produce an aboveground forest estimate of nutrient concentrations (and nutrient stocks on a per hectare basis) within each forest, we randomly selected 15 trees ≥1 cm DBH and collected mature, upper canopy sun leaves using a telescoping tree pruner or climbing the boles. From the same trees, we drew two wood core samples (wood and bark) at 1.3 m height on opposite sides of the bole. Foliage and wood samples were pooled into three sample composites of five trees, oven dried at 70ºC, ground and homogenized, and analyzed for C, N, P, K, Ca, and Mg using standard EMBRAPA laboratory operating procedures (Silva, 1999).

*Vegetation stocks calculations*

We developed a foliage:wood ratio (Mesquita, in prep.) for partitioning biomass into wood and foliar components. We then estimated aboveground carbon and nutrient stocks in each forest by multiplying mean nutrient concentrations for foliage and wood samples by the allometric estimates of each biomass component as partitioned by the foliage to wood ratio for individual trees. Our estimates of nutrient pools do not include aboveground biomass <1cm DBH, forest litter, or root biomass.

*Soil analysis*

We sampled soil to 45 cm in three depth classes (0–15, 15–30, 30–45 cm) within each of four plots per forest. The four soil samples per depth in each forest (120 soil samples) represent a composite of four to six sub-samples per sample. Soil composites were combined in the field, air dried in solar dryers, charcoal and roots removed, hand milled with a roller, sieved to 2 mm, and analyzed for C, N, P, K, Ca, and Mg. Charcoal is common in local surface soils and is present at times to 45 cm depths in both pasture and forest soils. As charcoal is heterogeneously distributed in the soil, charcoal contamination poses an important impediment to resolution in reporting soil C concentrations. We estimate that carbon concentrations in this study, as with other studies within the Amazon basin, may generally overestimate total soil carbon stocks as a result of charcoal contamination (M.A. Rondón, unpublished data). To reduce the charcoal contribution to soil C estimates, large pieces were removed while the samples were wet and again with a forceps after drying before grinding; however, the small fragment size makes total removal difficult.

Extractable soil P and K were analyzed using a double acid extraction (0.05 M hydrochloric acid and 0.0125 M sulfuric acid) and exchangeable Ca and Mg with 1 M potassium chloride. Total soil N was determined by the Kjeldahl technique and soil C (%) by wet digestion (Silva, 1999). Soil nutrient pools (kg/ha) of C, N, P, K, Mg, and Ca were calculated using mean soil bulk density data measured to 45 cm depth from abandoned pastures and SF in the same area (T.R. Feldpausch; S.A. Welch, unpublished data).

Nutrient concentrations were multiplied by bulk densities for each depth class to provide soil nutrient stocks on a per hectare basis.

*Statistical analysis*

Statistical analyses were performed using Minitab 12.1 (Minitab Inc.). Statistical comparisons for C and nutrient concentrations and stocks were conducted separately for the different vegetation tissue types and soil depths using linear and log-linear regression and a $p<0.05$ significance level. Soil and vegetation concentrations, and soil stocks values were log transformed. Pooling the data for age classes and using regression analysis, we tested for trends in C and nutrients within aboveground and soil pools, as partitioned by depth, foliage or wood, versus time (years after pasture abandonment).

## Results

A total of 1901 stems were measured in 2320 $m^2$, of which 138 standing dead and 177 lianas were excluded from biomass calculations due to allometric equation limitations in computing such components. Of those stems considered in biomass estimations, 68% were less than 5 cm DBH, while no stems were greater than 30 cm DBH. The two recently abandoned pastures of 0–2 years had no stems ≥1cm DBH, the minimum diameter used for the allometric equations.

*Vegetation nutrient concentrations*

Wood N and P concentrations declined with SF age ($r^2 = 0.85$, 0.75; $p<0.001$), with an average reduction of 50 and 60% in wood N and P from the youngest to the oldest forests. Foliage N and P concentrations tended to decline with forest age, although non-significantly. Compared to wood, foliage contained an average of 5.7 times more N and 3.7 times more P (Table 1).

Foliar and wood Ca concentrations did not show a trend with age, but the concentrations were high relative to other nutrients. Calcium concentrations in wood were comparable and at times higher than wood N values. n the foliage, Ca concentrations represented an average of 43% of N values. Foliage contained an average of 2.5 times more Ca than wood. Potassium and Mg foliar and wood concentrations showed no trends with forest age.

*Vegetation nutrient stocks*

Although woody biomass accumulated more quickly than foliage, nutrient stocks for all nutrients accumulated more quickly in foliage (Figure 1). Foliar N stocks (42.6 kg $ha^{-1}$ $yr^{-1}$; $r^2=0.94$; $p<0.001$) increased much more rapidly than woody stocks (15.5 kg $ha^{-1}$ $yr^{-1}$; $r^2=0.91$; $p<0.01$) with time after abandonment. Phosphorus stocks in foliage accrued twice as fast as wood P stocks. However, foliar Ca stocks (22.3 kg $ha^{-1}$ $yr^{-1}$; $r^2=0.92$; $p<0.001$) accrued at a similar rate to wood stocks (20.6 kg $ha^{-1}$ $yr^{-1}$; $r^2=0.90$; $p<0.001$) (Table 2).

*Soil nutrient concentrations*

Within each forest, soil carbon and nutrient concentrations generally decreased with depth (Table 3). Total soil N concentrations generally decreased with depth; however, deeper soil profile (30–45 cm depth) N concentrations increased with time after pasture abandonment ($r^2 = 0.57$; $p<0.001$), while the shallower depths showed a weaker soil N trend with time. Soil extractable P concentrations tended to decrease at all soil depths over time, with significant reductions in surface layers (0-15 cm depth) with increasing time since abandonment ($r^2 = 0.46$; $p<0.05$). Near surface Ca levels (0–15 cm depth) ranged from 0.13 to 0.33 $c.mol_{(+)}/kg$. Calcium concentrations were low below 15 cm depth, with overall means of 0.07 $c.mol_{(+)}/kg$ at 15–30 cm and 0.07 $c.mol_{(+)}/kg$ at 30–45 cm depths.

Table 1: Mean C and nutrient concentrations in foliage and wood from ten secondary forests regenerating from degraded pasture in central Amazônia, Brazil[a].

| SF age (yrs) | Fazenda and forest no. | C | N | P | K | Ca | Mg |
|---|---|---|---|---|---|---|---|
| | | % | g / kg | | | | |
| *Foliage* | | | | | | | |
| 0 to 2 | DAS-1 and Rodão-1 | 46.65 (1.80) | 17.11 (0.78) | 0.87 (0.04) | 3.71 (0.35) | 7.25 (0.74) | 2.31 (0.06) |
| 2 to 4 | Rodão-4 | 45.51 (0.33) | 16.42 (0.06) | 0.65 (0.03) | 2.75 (0.00) | 6.42 (0.17) | 1.88 (0.02) |
| 4 to 6 | DAS-2 and Rodão-3 | 48.25 (1.26) | 16.08 (0.82) | 0.89 (0.04) | 5.59 (1.16) | 5.28 (0.14) | 2.04 (0.28) |
| 6 to 8 | Dimona-1, -3 and Rodão-2 | 45.69 (0.59) | 14.60 (0.50) | 0.56 (0.03) | 5.38 (0.71) | 6.59 (0.41) | 2.13 (0.19) |
| 12 to 14 | DAS-3 and Dimona-2 | 49.38 (0.64) | 15.02 (0.16) | 0.58 (0.02) | 5.14 (0.29) | 7.86 (0.12) | 2.77 (0.12) |
| Overall Mean | | 47.12 (0.54) | 15.66 (0.31) | 0.70 (0.03) | 4.78 (0.36) | 6.70 (0.24) | 2.25 (0.10) |
| *Wood* | | | | | | | |
| 0 to 2 | DAS-1 and Rodão-1 | 51.40 (0.49) | 3.71 (0.31) | 0.31 (0.01) | 2.23 (0.33) | 4.05 (0.58) | 0.98 (0.11) |
| 2 to 4 | Rodão-4 | 47.64 (0.41) | 2.99 (0.39) | 0.19 (0.01) | 1.19 (0.10) | 2.76 (0.29) | 0.69 (0.05) |
| 4 to 6 | DAS-2 and Rodão-3 | 47.45 (1.16) | 2.80 (0.15) | 0.21 (0.03) | 1.69 (0.31) | 2.01 (0.21) | 0.47 (0.04) |
| 6 to 8 | Dimona-1, -3 and Rodão-2 | 47.68 (1.05) | 2.52 (0.14) | 0.16 (0.01) | 1.76 (0.17) | 2.33 (0.19) | 0.55 (0.06) |
| 12 to 14 | DAS-3 and Dimona-2 | 51.05 (1.99) | 1.87 (0.12) | 0.09 (0.02) | 1.28 (0.11) | 2.51 (0.30) | 0.58 (0.07) |
| Overall Mean | | 49.05 (0.63) | 2.73 (0.14) | 0.19 (0.01) | 1.68 (0.12) | 2.69 (0.19) | 0.64 (0.04) |

[a]Each mean nutrient concentration value represents n=3 samples of a five tree composite in each forest. Mean (standard error).

Table 2: Rate of total nutrient accumulation, vegetation nutrient immobilization (a), and soil nutrient flux to 45 cm depth (b). Results from ten secondary forests regenerating from degraded pastures in central Amazônia, Brazil.

| | N | P | K | Ca | Mg |
|---|---|---|---|---|---|
| | kg $ha^{-1}$ $yr^{-1}$ | | | | |
| Total vegetation and soil (a + b)[a]: | 175.9 ($r^2$=0.62; p<0.001) | 1.8 ($r^2$=0.75; p<0.01) | 24.7 ($r^2$=0.88; p<0.001) | 42.2 ($r^2$=0.84; p<0.001) | 12.9 ($r^2$=0.79; p<0.001) |
| a. Total foliage and wood | 58.1 ($r^2$=0.94; p<0.001) | 2.4 ($r^2$=0.93; p<0.001) | 25.1 ($r^2$=0.92; p<0.001) | 42.9 ($r^2$=0.92; p<0.001) | 12.5 ($r^2$=0.92; p<0.001) |
| Foliage | 42.6 ($r^2$=0.94; p<0.001) | 1.6 ($r^2$=0.95; p<0.001) | 14.5 ($r^2$=0.90; p<0.001) | 22.3 ($r^2$=0.92; p<0.001) | 7.8 ($r^2$=0.90; p<0.001) |
| Wood | 15.5 ($r^2$=0.91; p<0.001) | 0.8 ($r^2$=0.72; p<-.01) | 10.6 ($r^2$=0.89; p<0.001) | 20.6 ($r^2$=0.90; p<0.001) | 4.7 ($r^2$=0.93; p=<0.001) |
| b. Total soil[b]: | 117.8 ($r^2$=0.44; p=0.04) | - 0.66 ($r^2$=0.34; p=0.08) | ~ 0 (N.S.) | ~ 0 (N.S.) | ~ 0 (N.S.) |

[a] Represents a new linear regression with the sum of the subtotals.
[b] Total nitrogen and extractable P, K, Ca, and Mg. N.S. indicates a non-significant change.

Table 3: Mean soil carbon and nutrient concentrations, and pH from ten secondary forests regenerating from degraded pasture in central Amazônia, Brazil[a].

| SF age (yrs) | Fazenda and forest no. | C | N | P | K | Ca | Mg | Ph |
|---|---|---|---|---|---|---|---|---|
| | | ---- (g / kg) ---- | | ---- (mg / kg) ---- | | ---- ($cmol_{(+)}$ / kg) ---- | | (KCl) |
| *0–15 cm depth* | | | | | | | | |
| 0 to 2 | DAS-1 and Rodão-1 | 15.39 (2.27) | 1.23 (0.13) | 4.83 (0.57) | 20.98 (2.40) | 0.13 (0.02) | 0.09 (0.01) | 4.1 (0.03) |
| 2 to 4 | Rodão-4 | 20.77 (2.64) | 1.25 (0.09) | 3.09 (0.17) | 18.11 (0.82) | 0.18 (0.01) | 0.07 (<0.01) | 4.0 (0.02) |
| 4 to 6 | DAS-2 and Rodão-3 | 20.71 (2.01) | 1.42 (0.16) | 6.30 (0.86) | 33.20 (4.76) | 0.16 (0.04) | 0.14 (0.02) | 4.0 (0.03) |
| 6 to 8 | Dimona-1, -3 and Rodão-2 | 22.91 (0.85) | 1.49 (0.05) | 2.46 (0.30) | 23.92 (2.49) | 0.33 (0.11) | 0.18 (0.04) | 4.0 (0.03) |
| 12 to 14 | DAS-3 and Dimona-2 | 19.51 (2.77) | 1.75 (0.04) | 1.55 (0.17) | 19.45 (0.55) | 0.16 (0.05) | 0.11 (<0.01) | 4.0 (0.01) |
| Overall mean | | 20.19 (0.94) | 1.46 (0.05) | 3.55 (0.36) | 23.78 (1.52) | 0.21 (0.04) | 0.13 (0.02) | 4.0 (0.01) |
| *1 –30 cm depth* | | | | | | | | |
| 0 to 2 | DAS-1 and Rodão-1 | 9.17 (1.43) | 0.74 (0.06) | 2.03 (0.53) | 8.46 (0.71) | 0.08 (0.01) | 0.05 (<0.01) | 4.2 (0.02) |
| 2 to 4 | Rodão-4 | 17.14 (0.70) | 0.91 (0.06) | 1.87 (0.17) | 10.53 (0.47) | 0.11 (0.01) | 0.05 (0.01) | 4.2 (0.02) |
| 4 to 6 | DAS-2 and Rodão-3 | 10.63 (1.08) | 0.86 (0.08) | 1.40 (0.13) | 10.86 (1.63) | 0.08 (0.01) | 0.05 (0.01) | 4.1 (0.02) |
| 6 to 8 | Dimona-1, -3 and Rodão-2 | 12.09 (0.55) | 0.88 (0.02) | 0.86 (0.13) | 11.19 (0.88) | 0.05 (0.01) | 0.04 (0.01) | 4.1 (0.02) |
| 12 to 14 | DAS-3 and Dimona-2 | 11.46 (0.76) | 1.01 (0.01) | 0.70 (0.00) | 8.56 (0.31) | 0.07 (0.02) | 0.05 (<0.01) | 4.1 (0.02) |
| Overall mean | | 11.65 (0.52) | 0.88 (0.03) | 1.25 (0.13) | 10.02 (0.48) | 0.07 (0.01) | 0.05 (<0.01) | 4.1 (0.01) |
| *30–45 cm depth* | | | | | | | | |
| 0 to 2 | DAS-1 and Rodão-1 | 6.57 (0.57) | 0.55 (0.02) | 1.15 (0.41) | 5.56 (0.28) | 0.06 (0.01) | 0.04 (0.01) | 4.2 (0.02) |
| 2 to 4 | Rodão-4 | 12.25 (0.86) | 0.65 (0.07) | 1.15 (0.16) | 7.14 (0.46) | 0.10 (0.02) | 0.04 (<0.01) | 4.2 (0.02) |
| 4 to 6 | DAS-2 and Rodão-3 | 10.84 (2.36) | 0.65 (0.02) | 0.86 (0.09) | 5.84 (0.97) | 0.07 (0.01) | 0.04 (<0.01) | 4.2 (0.02) |
| 6 to 8 | Dimona-1, -3 and Rodão-2 | 8.12 (0.66) | 0.69 (0.01) | 0.39 (0.10) | 6.28 (0.58) | 0.05 (0.01) | 0.04 (0.01) | 4.1 (0.02) |
| 12 to 14 | DAS-3 and Dimona-2 | 16.08 (2.49) | 0.77 (0.02) | 0.58 (0.09) | 5.84 (0.39) | 0.05 (0.01) | 0.04 (<0.01) | 4.1 (0.01) |
| Overall mean | | 10.46 (0.89) | 0.67 (0.01) | 0.74 (0.09) | 6.06 (0.28) | 0.06 (0.01) | 0.04 (<0.01) | 4.2 (0.01) |

[a] Mean values are n=4 per depth in each forest from a composite of four to six sub-samples per sample and summarized by age class. Total carbon and nitrogen, extractable P and K, and exchangeable, Ca, and Mg. Mean (standard error).

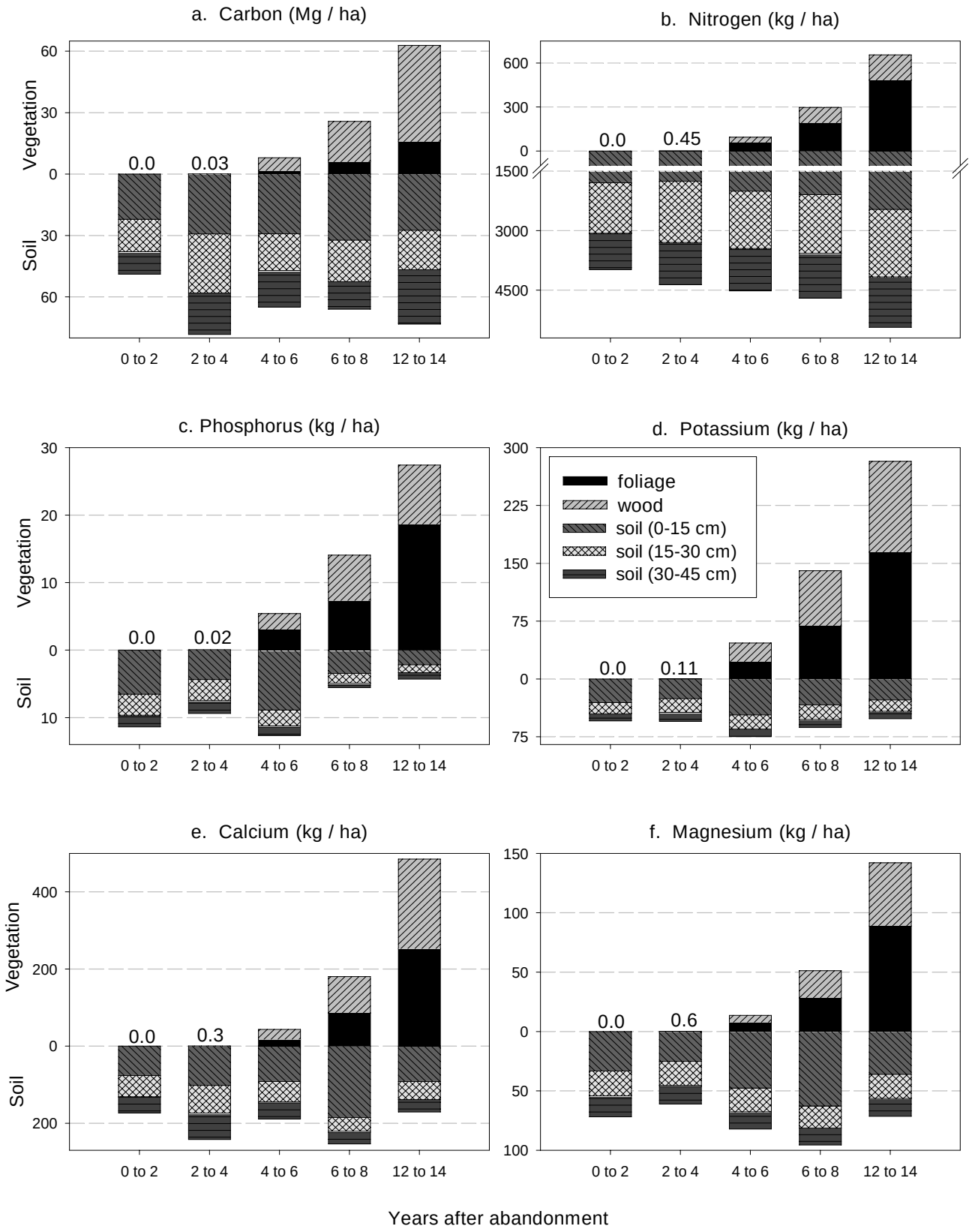


Figure 1 a – f: Total C, N, extractable P and K and exchangeable Ca and Mg in soils to 45 cm depth and live aboveground vegetation ≥1 cm DBH in ten secondary forests regenerating from degraded pastures in central Amazônia, Brazil. Mean nutrient stocks for each forest (see Table 1 for forest grouping by age-class) calculated from soil and vegetation nutrient concentrations times soil bulk density or aboveground biomass. Note the scale difference between N soil and aboveground stocks. Values above time 0 – 2 and 2 – 4 indicate aboveground quantities only.

*Soil nutrient stocks*

Soil extractable nutrient stocks were generally lower in deeper soil pools. Within the oldest forests, soil C, N, and Mg nutrient stocks were greater than aboveground nutrient stocks while the other nutrients resided predominantly within forest vegetation (Figure 1).

Soil N stocks, relative to aboveground stocks, were high, and increased with forest age at a rate of 117.8 kg $ha^{-1}$ $yr^{-1}$ ($r^2 = 0.44$; $p<0.05$). Pastures abandoned for twelve or more years stored 1.5 Mg/ha more total N to 45 cm depth than areas abandoned for two or fewer years (5.4 and 3.9 Mg N/ha). In all forests, surface nitrogen stocks (0–15 cm) represented approximately 40 to 45% of the total soil nitrogen to 45 cm depth (total 45 cm range: 3.3 to 5.5 Mg N/ha) (Figure 1).

Extractable soil P stocks to 45 cm tended to decline with increasing forest age (-0.66 kg $ha^{-1}$ $yr^{-1}$), a trend most pronounced within the upper 0–15 cm. This surface layer represented 46 to 70% of total soil P stocks to 45 cm depth, with the younger areas, on average, storing 4.2 kg/ha more P in the first 15 cm than the oldest areas. Considering the entire measured soil profile (0–45 cm depth) higher extractable soil P stocks were observed in stands of 0 to 6 years (11.5 ± 4.6 kg/ha) compared to stands of 6–14 years (5.1 ± 2.1 kg/ha). Soil P in the 0–15 cm class was more variable than in deeper layers. Potassium, Ca, and Mg stocks remained constant with time after abandonment (Table 2).

*Total nutrient stocks*

There was a significant net gain in combined vegetation and soil nutrient stocks for all nutrients (Table 2). The total system P accumulation rate was slow and reflective of the counteracting decrease in soil P stocks with increasing forest age. Total system N stocks increased most rapidly followed by Ca. While total (biomass plus soil) nutrient stocks for all nutrients increased over time, in soils, only N increased significantly.

*Carbon sequestration*

Standing biomass. Foliar dry biomass in the ten forests grouped according to age after pasture abandonment (0–2, 2–4, 4–6, 6–8, 12–14 years) was 0.0, 0.02, 3.47, 13.10, 32.15 Mg/ha (Figure 1). Average biomass accrual for all SF through the first 12–14 years after pasture abandonment was 11.0 Mg $ha^{-1}$ $yr^{-1}$ ($r^2$=0.95, $p<0.001$), or 5.6 Mg C $ha^{-1}$ $yr^{-1}$ ($r^2$=0.94, $p<0.001$). As expected, carbon stocks in wood (4.2 Mg C $ha^{-1}$ $yr^{-1}$) accrued more quickly than foliage C (1.4 Mg C $ha^{-1}$ $yr^{-1}$) as forests matured (Table 4).

Table 4: Relationship between years after pasture abandonment (X) and the accumulation of aboveground biomass and carbon, and soil carbon (Mg $ha^{-1}$ $yr^{-1}$) in ten secondary forests regenerating from degraded pastures in central Amazônia, Brazil.

| Dependent Variable | Equation | ( $r^2$ ) | ( p ) |
|---|---|---|---|
| *Biomass*[a] | | | |
| Foliage | Y = 2.85 X – 6.61 | 0.94 | < 0.001 |
| Wood | Y = 8.18 X – 17.32 | 0.95 | < 0.001 |
| Total foliage and wood | Y = 11.0 X – 23.92 | 0.95 | < 0.001 |
| *Carbon* | | | |
| Foliage[a] | Y = 1.40 X – 3.36 | 0.94 | < 0.001 |
| Wood[a] | Y = 4.15 X – 9.18 | 0.94 | < 0.001 |
| Total foliage and wood[a] | Y = 5.55 X – 12.54 | 0.94 | < 0.001 |
| Total soil[b] | Y = 1.49 X + 5.59 | 0.20 | = 0.20 |
| Total foliage, wood, and soil | Y = 7.04 X + 43.31 | 0.85 | < 0.001 |

[a] All live trees ≥1 cm DBH with biomass converted to C based on site-specific foliage and wood C concentrations.
[b] Total soil C to 45 cm depth.

The greatest total biomass (128.1 Mg/ha) was measured in a SF with 12–14 years since abandonment; the areas abandoned 6–8 years had an average biomass of 54.4 Mg/ha, while the areas abandoned 4–6 years an average of 16.4 Mg/ha (Figure 1). Woody biomass in the ten SF by years after pasture abandonment was 0.0, 0.05, 12.92, 41.25, 92.24 Mg/ha in the 0–2, 2–4, 4–6, 6–8, and 12–14 year-old forests.

*Soil Carbon*. Soil carbon storage (excluding roots) tended to increase with forest age, with the oldest forests storing an average of 25 Mg/ha (65%) more total soil C to 45 cm depth than the youngest forests. Surface layers (0–15 cm) stored significantly more C (28.4 ± 2.4 Mg/ha) than deeper layers (18.3 ± 1.5 Mg/ha), from 24 to 50% of the total soil carbon to 45 cm depth in all forests ($p<0.001$). However, the oldest forests, 12–14 yr-old, stored as much carbon in the 30–45 cm layer as in the 0–15 cm surface layer. Additionally, the deeper soil profile (30–45 cm) was the only depth showing significantly increasing C stocks with time after abandonment ($r^2=0.21$; $p<0.001$). Considering all forests, total soil C to 45 cm depth increased non-significantly at a rate of 1.49 Mg $ha^{-1}$ $yr^{-1}$ during the first 12–14 yrs of succession (Table 4).

*Total C accrual.* In vegetation and soil (excluding roots), the ten SF accrued a total of 7.04 Mg C $ha^{-1}$ $yr^{-1}$ during the first 12–14 years after abandonment ($r^2=0.85$; $p<0.001$) (Table 4).

## Discussion

*Nutrient accrual*

The vegetation withdraws large quantities of exchangeable Ca from low exchangeable soil reserves. After N, vegetation Ca stocks were accumulating most quickly with forest age. Wood and foliage N:Ca ratios were low, ranging from 0.7 to 1.4 for wood and 1.9 to 3.0 for foliage. In contrast, primary forest vegetation reported N:Ca ratios were 3.1 for trunks, branches and coarse roots, and 4.4 for leaves (Fernandes et al., 1997).

The high rate of Ca immobilization in vegetation but lack of reduced soil exchangeable Ca over time in our study indicates, (1) soils adequately replenish immobilized Ca from unavailable forms (Table 2); and/or (2) the vegetation is withdrawing Ca from deeper than 45 cm depth. A similar trend of a high percentage of total system Ca content in vegetation and high Ca uptake from low soil reserves of exchangeable Ca has been reported for temperate forests (Johnson and Henderson). The highly weathered Oxisols of our study provide negligible Ca from parent materials; however, atmospheric deposition may replenish depleted soil reserves by adding 0.8–12 kg $ha^{-1}$ $yr^{-1}$ (Vitousek and Sanford Jr., 1986; Schroth et al., 2001). For young tropical fallow vegetation, low root length density and low nutrient demand make Ca and nitrate ions susceptible to downward movement (Szott et al., 1999), which may be retrieved with increased rooting depth in later successional stages. Trees have been reported to increase soil nutrient availability over time (Sanchez et al., 1985) and net increases in total system stocks of N and Ca have been observed in older fallows, probably as a result of atmospheric deposition, $N_2$ fixation and uptake from subsoil (Szott et al., 1991). However, pasture soils were found to have higher exchangeable soil Ca concentrations than plantations, secondary and primary forests (McGrath et al., 2001), indicating that after the initial increase of soil Ca from cutting and burning, colonizing trees act as sinks, reducing soil Ca. Although soil Ca stocks are currently maintained in these SF, the high rate of Ca relocation from soil to vegetation, large vegetation Ca stocks, and high concentrations relative to N indicate extreme Ca demands for biomass production, which may create a soil Ca deficit and limit future vegetation growth.

The rapid total soil N stock and N concentration increase below 30 cm depth with forest age can be only partially explained by external inputs (Figure 1, Table 3). Nitrogen fixing plants may contribute 10–150 kg $ha^{-1}$ $yr^{-1}$ to soils (Fernandes et al., 1997; Szott et al., 1999) and atmospheric deposition may add 5.5–11.5 kg $ha^{-1}$ $yr^{-1}$ (Jordan et al., 1982; Vitousek and Sanford Jr., 1986; Schroth et al., 2001), explaining a fraction of the increasing total soil N. The remaining contribution to the high soil N accumulation rates could be subsoil mining of leached nitrate. Increasing extractable soil N with depth

below topsoil have been measured in young SF (J. Lehmann, pers comm.); high deep soil N concentrations may be attributable to leaching from surface layers after slash-and-burning and cropping, followed by a reduced nutrient capture potential of shallow rooted colonizing secondary vegetation. Primary forest also loses nitrate to the subsoil (Schroth et al., 1999). These large N pools were deep (1-2 m) and considered at the lower limit of uptake by young SF. Leaching of surface N can be rapid in Oxisols because of the high macroporosity and hydraulic conductivity, but leaching below 0.6 m is delayed, apparently because of $NO_3^-$ adsorption to the net positively charged subsoil (Melgar et al., 1992). Deep nutrient pools may provide a source of N as forests mature and root systems develop. Leaching of surface N (0–15 cm) to deeper layers could also explain the increase in N concentrations ($r^2$= 0.75; $p<0.001$) we observed below 30 cm depth with forest maturation. Unless deep N mining occurs with root development, N losses to subsoil due to leaching may negatively affect surface soil fertility.

Compared to primary forest nutrient storage in soil (of the total aboveground and soil stocks), the SF stored comparable amounts of N, less P, but more Ca. Soil storage of exchangeable Ca and total N in the oldest SF accounted for an average of 26 and 89% of total nutrient storage, respectively, but just under 14% of extractable P (Figure 1). This contrasts with compartmentalization within primary vegetation, where soil storage of exchangeable Ca and total N may account for <1 and 73% of total nutrient storage, and extractable P in soil accounts for 69% of the total storage (Sanchez, 1987).

Increases in soil nutrient concentrations are followed by greater vegetation tissue concentrations in successional vegetation. Secondary forest vegetation growing on nutrient poor soil produced wood with three times less P and leaves with 50% less P than vegetation where soil P limitations were removed through P fertilizer additions (Gehring et al., 1999). The reduction in foliar P concentrations with increasing forest age observed in our study (Table 1) may indicate that this nutrient is becoming limiting as soil P levels decline (Figure 1).

Total aboveground and soil nutrient stocks increased as forests matured; yet, for P, uptake and soil P supply indicates a potential growth limitation. Concomitant decrease in extractable soil P and increase in biomass over time may be attributable to relocation from below- to above-ground pools. Plants appear to be taking up more soil P than is available (Table 2). This suggests a rapid transfer of soil P from plant unavailable to available forms or deep soil mining as the available pool is depleted with plant growth. However, subsoil P retrieval probably contributes <1 kg $ha^{-1}$ $yr^{-1}$ (Szott et al., 1999). The net reduction in soil P stocks from the soil (0.66 kg P $ha^{-1}$ $yr^{-1}$) with increasing forest age, indicates inadequate replacement of available soil P with plant P uptake, a trend also observed elsewhere (Johnson et al., 2001). Should this trend continue, P may become limiting to growth unless other factors (1) reduce P uptake by plants, (2) increase P uptake from subsoil, (3) increase the rate at which unavailable forms of soil P shift to plant available P forms to replenish immobilized plant available soil P.

Pools of plant available (extractable) nutrients are significantly lower than the total in soils (Brown and Lugo, 1990), and the plant availability of the soil P depends on the extent of fixation or immobilization. Phosphorus fixation for Oxisols is lower in the central Amazon Basin than Oxisols in other regions of the Amazon; however, levels of plant available P in the soils are similar (Lehmann et al., 2001a). Total soil P in primary forest can be lower than under the SF replacing the vegetation (Lehmann et al., 2001b), indicating storage in biomass can significantly reduce soil extractable P stocks. Pastures grasses such as *Brachiaria* spp. may increase P availability by exuding acid phosphatase into the rhizosphere and hydrolyzing plant unavailable forms of organic phosphates (Dias-Filho et al., 2001), a benefit lost as secondary vegetation replaces the pasture grasses. Root associations with both VA-mycorrhizae and ectomycorrhizae may help the colonizing vegetation access P even at low soil P concentrations; and, in the case of ectomycorrhizae, to access P from poorly accessible pools (Boot et al., 1994). Since these colonizing species have the ability to take up P in excess of immediate growth requirements (Boot et al., 1994), P uptake by maturing trees may decline before plant levels become limiting to biomass accumulation. Fallow vegetation increased mineralizable N and available P compared to continuous cropping, probably as a result of deeper rooting (Tian et al., 2001).

Further research is needed to develop and evaluate management strategies that promote soil P acquisition, such as increasing rooting depth of regenerating vegetation.

*Carbon accrual*

*Aboveground.* Rapid biomass accrual in the SF, 11.0 Mg $ha^{-1}$ $yr^{-1}$, was similar to other Amazonian findings (Uhl et al., 1988; Brown and Lugo, 1990; Alves et al., 1997), lower (Hartemink, 2001), and higher than a 20 year mean annual rate (6.17 Mg $ha^{-1}$ $yr^{-1}$) in a review of tropical SF succession (Silver et al., 2000). The high C accumulation storage in the 12–14 yr-old areas represents 25–50% of equivalent primary forest biomass (230 – 500 Mg/ha) in Amazonia (Alves et al., 1997; Fujisaka et al., 1998; Laurance et al., 1999).

Aboveground carbon accrual slows with age as colonizing trees mature, die, and are replaced by slower growing species. Secondary forests in the Bragantina region of the Amazon basin were accruing biomass more rapidly in 10 yr-old (5.5 Mg $ha^{-1}$ $yr^{-1}$) than in the 20–40 yr-old SF (3.3 Mg $ha^{-1}$ $yr^{-1}$) (Johnson et al., 2001). And a review of 44 secondary tropical forests showed wet forests accumulating biomass significantly faster during the first 20 of 80 years of regrowth (Silver et al., 2000). Their rates through the first 10 and 20 years are still less than the rate we report through the first 12–14 years (Table 4).

*Belowground.* Our study indicates a trend of increasing soil C storage through the first 12–14 years (Figure 1); however, the soils are storing comparable to less C than other SF of similar or greater age (Silver et al., 2000); (Johnson et al., 2001). Although our forests only showed a weak C storage gain, other studies indicated that soil C storage (excluding roots) increases significantly with SF age, and can approach mature forests levels after 80 years regrowth (Silver et al., 2000).

Contrary to aboveground biomass accumulation rates, which proceed faster in SF following agriculture (Fearnside and Guimaraes, 1996), soils accumulate C almost twice as fast when regeneration follows pasture rather than agriculture, although this effect is only distinguishable after 20 years of recovery (Silver et al., 2000). Delays in aboveground C accrual with forest growth in early years following pasture abandonment may be offset, to a certain degree, by enhanced soil C accumulation.

Compared with soil C storage in pasture (49.5 Mg/ha; 0–30 cm depth) (Moraes et al., 1996), tropical plantation (90 Mg C/ha) and SF (61 Mg C/ha) (0–25 cm depth) (Silver et al., 2000), the SF soils in this study were storing 47.9 Mg C/ha to 30 cm and 66.1 Mg C/ha to 45 cm depth. Since aboveground C accrual appears higher than other sites, and soil C lower than other SF sites, high litter turnover and soil respiration rates at our sites may be reducing soil C residence time in this high rainfall area.

These factors pose important management implications to carbon sequestration. By choosing to maintain areas as pasture, directing SF colonization and succession after abandonment, or establishing plantations or agroforestry systems, land managers can influence the distribution of aboveground and soil C storage and the rate at which carbon accumulates within those pools. Maintaining the land cover as forest for longer time-periods rather than as degraded pasture is a more favorable practice to increase C storage.

*Predictive limitations*

The ≥1 cm DBH limitation imposed by the allometric equations may significantly underestimate biomass and nutrient stocks in the absence of root and biomass measurements of young SF vegetation <1cm DBH. Grasses tend to allocate a significant portion of total plant biomass within root structures (Nepstad et al., 1994) and necromass, shrubs and herbaceous vegetation dominating early pasture succession and SF understories contribute considerable quantities to C and nutrient stocks, especially P (McKerrow, 1992). Wood core measurements may overestimate nutrient concentrations in young stands since a greater portion of the sample core is nutrient rich bark. An underestimate of biomass as a result of DBH allometric limitations is inversely related to forest age. As stand dominance shifts from small- to large-stem diameter plants with understory shading and self-thinning, a greater percentage of the total stems are measured and contribute to biomass and nutrient calculations. Also, although we located our abandoned pasture study sites on plateaus, the pastures span the rolling topography. Nutrient limitations may be more severe on hillsides where erosion is more pronounced and forest recovery slower than the rates we predict.

*Implications for succession, carbon sequestration, and nutrient barriers*

After two and a half decades of neotropical studies of SF regeneration, we still lack the ability to make strong predictions about nutrient storage and successional shifts in forest development, and regeneration times for abandoned pastureland to attain primary forest equivalent biomass. This is largely due to an historic research focus on forest succession following agriculture rather than pasture. Since biomass recovery is significantly slower following pasture than agriculture (Fearnside and Guimaraes, 1996; Steininger, 2000), it is important to increase our understanding of pasture succession and determine potential nutrient limitations.

The paucity of forest recovery studies on abandoned pastureland and lack of detailed soil C and nutrient data make predicting forest regeneration on highly altered lands difficult. In a review of SF biomass accumulation (Silver et al., 2000), only 13% of the SF (18 of 134) were previously pastures. Additional data from SF regenerating from pasture are needed to determine long-term C accumulation rates, potential nutrient limitations to regeneration, and the time needed to attain both structural and functional properties of mature forests. This is especially relevant since primary forest biomass is positively associated with soil nutrient levels, suggesting that soil nutrient loss through pasture installation may result in lower mature regenerated forest biomass than the original forest (Laurance et al., 1999). Although studies such as ours help to fill this void, there is a need for long-term rather than chronosequential studies of forest recovery following pasture abandonment.

**Summary**

In this study, we show that during early successional years, biomass accumulation in light to moderately used pastures is rapid after abandonment and that soil C storage is higher in older forests. However, a slower soil C accrual rate than regenerating SF in other regions, may negatively offset total long-term C gains. The higher proportion of soil C storage compared to aboveground pools will be an important consideration of future 'carbon credit' management, as this pool is more recalcitrant to perturbations. Aboveground C re-accumulation from post-burn values is high, yet represents a finite pool which is rapidly attained in a relatively short time-period. Managing forest regeneration to maximize soil C storage, rather than aboveground pools, may prove to be more useful or meaningful when attempting to increase SF C sequestration.

Furthermore, the colonizing vegetation can extract large nutrient quantities from the soil, even when in low supply. There was not only a shift of nutrients from soil to aboveground pools, but total system nutrient stocks were increasing over time. Most of the C, N, and Mg were stored within soils, while P, K, and Ca resided within vegetation. This has important consequences to total forest nutrient stocks, in the event of removal of aboveground vegetation. In the absence of nutrient additions, removal of the vegetation a second time (pasture re-clearing or logging) could compromise the SF potential to regenerate as a result of nutrient limitations. Even after P fertilization when the areas were pasture, soil P stocks remained low. The vegetation was withdrawing more soil P than can be replenished, creating a soil P deficit which may limit system productivity. Low exchangeable soil Ca stocks seemed to be adequately replaced, apparently from atmospheric inputs and depths below 45 cm, as growing vegetation took up large nutrient quantities. Nevertheless, as vegetation Ca demands were high and soil stocks low, lack of Ca may limit future productivity.

These results demonstrate the regenerative capacity of tropical SFs to sequester C and to rebuild the nutrient capital following pasture abandonment. Aboveground carbon accrual is rapid but belowground gains represent the largest potential area for continued accumulation and management. Relocation of some nutrients from deeper soil layers may represent a substantial source of nutrients for plant growth and may be vital to sustaining long-term productivity and biomass accumulation. We recommend additional studies to explore P and Ca nutrient limitations to forest productivity and long-term measurements of soil nutrient fluxes and forest growth. Understanding nutrient limitations to resource capture will provide new options to manage forest regeneration and increase C accumulation on these globally important nutrient-limited soils.

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# Slash-and-char – a feasible alternative for soil fertility management in the central Amazon?

Johannes Lehmann[1]*, Jose Pereira da Silva Jr[2], Marco Rondon[1], Manoel da Silva Cravo[3], Jacqueline Greenwood[1], Thomas Nehls[4], Christoph Steiner[4], and Bruno Glaser[4]

[1] *College of Agriculture and Life Sciences, Department of Crop and Soil Sciences, Cornell University, Ithaca, NY 14853, USA;*
[2] *Embrapa Amazonia Ocidental, 69011-970 Manaus, Brazil;*
[3] *Embrapa Amazonia Oriental, Belem, Brazil;*
[4] *Institute of Soil Science, University of Bayreuth, 95440 Bayreuth, Germany. * corresponding author: CL273@cornell.edu*

## Abstract

The application of charcoal to nutrient-poor upland soils of the central Amazon was tested in lysimeter studies in comparison to unamended control soils to evaluate the effects of charcoal on plant nutrition and nutrient leaching. Testing the application of charred organic matter was stimulated by the fact that anthropogenic soils in the Amazon (so-called "Terra Preta") with high soil organic matter contents contain large amounts of pyrogenic carbon. These soils also show high cation exchange capacity and nutrient availability. Charcoal additions significantly increased biomass production of a rice crop in comparison to a control on a Xanthic Ferralsol. This increase was largely an effect of improved P, K, and possibly Cu nutrition, whereas N and Mg uptake decreased in charcoal amended soils. In order to improve crop growth, fertilizer applications of N, S, Ca, and Mg may be necessary in addition to charcoal for optimizing rice growth. Combined application of N with charcoal resulted in a higher N uptake than what would have been expected from sole fertilizer or charcoal applications. The reason is a higher nutrient retention of applied ammonium by the charcoal amended soils. Charcoal applications therefore acted in two ways, first as a direct fertilizer and secondly as an adsorber which retained N. The amount of charcoal which can be produced from forest biomass is significant and corresponds to charcoal amounts needed for effectively improving crop growth. The slash-and-char technique is an alternative to burning of the above ground biomass and only the biomass from the same cropping area will be used for charring. Field trials need to be conducted to investigate the efficiency of charcoal production and applications under field conditions.

**Keywords:** Amazon; Humid Tropics; Ferralsols; Leaching; Nutrient Cycling; Slash-and-Burn

## Introduction

Upland soils in the humid tropics such as in the central Amazon are highly weathered and therefore possess low plant available nutrient contents (Cravo and Smyth, 1997). This is a result of both high rainfall and low nutrient retention capacity. Applied nutrients are rapidly leached below the root zone of annual crops (Melgar et al., 1992; Cahn et al., 1993). Two basic approaches can be used to reduce nutrient leaching, first to apply slow-releasing nutrient forms such as organic fertilizers or secondly to increase adsorption sites and thereby retain applied inorganic nutrients.

Slash-and-burn is one of the main land use system in the Amazon. Secondary or primary forest is cut and burned to clear the field but also to release plant-available nutrients from slashed plant biomass. The ash from the burned biomass increases soil pH and supplies nutrients to crops which show elevated nutritient levels and yields (Sanchez et al., 1983). This effect of the ash accumulation is, however, rather short-lived. Already after a few cropping seasons the soil nutrient availability decreases and field crops have to be fertilized for optimum production (Sanchez et al., 1983) or the fields have to abandoned and new forests have to be slashed and burned. Although adequate applications of mineral fertilizers were

shown to sustain yields in the Amazon (Smyth and Cassel, 1995), our efforts are intended to improve the use of biomass and nutrients contained in the plant biomass as well as that of applied fertilizer nutrients, since fertilization is expensive and crop production often has to rely on soil nutrients alone.

It is well known that about 50% of the carbon in the above ground biomass of forests can be lost upon burning (Kauffman et al., 1995). Sixty and 43% of the biomass N and S and 18, 7 and 7% of the P, Ca, and K were lost from the site (Kauffman et al., 1995). A large portion may be deposited or absorbed in surrounding ecosystems but does not contribute to the fertility of the cropped soil. The first approach should therefore aim at improving the efficiency of land clearing to preserve C and nutrients. Slash-and-mulch was successfully tested in Eastern Amazonia when fertilizer was applied (Kato et al., 1999) and has a long history in the per-humid tropics (Thurston, 1997). We are seeking an alternative technique that can be applied to the existing slash-and-burn system with minimal changes and that has the potential of being used in tree cultures as well.

*Anthropogenic dark earths - evidence of sustainable soil management*

Instead of burning the above ground biomass to clear the agricultural field, the biomass may be charred to produce charcoal and added to soil. Testing the application of charred organic matter was stimulated by the fact that anthropogenic dark earths in Central Amazonia (so-called "Terra Preta do Indio") with high soil organic matter contents contain large amounts of pyrogenic carbon (Glaser et al., 2001). These soils also show high cation exchange capacity, nutrient availability and organic matter (Sombroek, 1966; Kern and Kämpf, 1989). The origin of the dark earths is not entirely clear, and several conflicting theories were discussed in the past. Currently the most convincing theory states that these soils were not only used by the local population but a product of indigenous soil management as proposed by Gourou (1949).

Soil fertility increases have been observed on remnants of charcoal hearths in the Appalachian Mountains (Young et al., 1996). Tryon (1948) showed higher nutrient availability in clayey to sandy soils from the Western United States after additions of charcoal produced from conifer and hardwood. Coal from geological deposits were successfully tested for the improvement of soil physical properties (Piccolo et al., 1996). No information, however, is available about the effects of charcoal applications on nutrient availability of highly weathered soils in the humid tropics such as the central Amazon. It is also unclear whether the cation exchange capacity can be improved thereby leading to higher nutrient retention and to lower nutrient losses by leaching.

A slash-and-char technique does not advocate the destruction of existing primary forests. It should be a carbon- and nutrient-conserving alternative to existing slash-and-burn techniques. In this way, carbon will rather be retained in the system compared to slash-and-burn, since only the biomass from the same cropping area will be used for producing the charcoal.

*Charcoal additions for soil fertility improvement*

*Experimental description*

*Pot experiment*. A greenhouse study was carried out at the Embrapa Amazonia Ocidental near Manaus, Brazil. The mean temperature in the greenhouse was between 28-32ºC. We used two different soils for our experiments: (1) a Xanthic Ferralsol taken from a secondary forest (approximately 15 years old) with high clay contents (65%), medium organic C (39 g $kg^{-1}$) and N contents (31.7 g $kg^{-1}$); (2) a Fimic Anthrosol obtained from a farmers field under fallow with low clay (5%) and high sand contents (85%), high organic C (84.7 g $kg^{-1}$), available P (318 mg $kg^{-1}$) and Ca contents (656 mg $kg^{-1}$), but low to medium total N (49.6 g $kg^{-1}$), available K (4.0 mg $kg^{-1}$) and Mg contents (57 mg $kg^{-1}$). Both soils have not been fertilized prior to the experiment.

Free-draining lysimeters were constructed with a diameter of 0.2m and a height of 0.1 m which were filled with either 3 kg of the Ferralsol or the Anthrosol. The effect of soil type, mineral fertilizer and charcoal on growth, nutrient uptake and leaching was tested using rice (*Oryza sativa* L.) as a test plant.

Charcoal was applied at 20% weight which was produced by local farmers originating from secondary forests. The charcoal was ground by hand to a grain size of about 1 mm. Fertilizer was applied at 30, 21.8, and 49.8 kg $ha^{-1}$ for N, P, and K using ammonium sulfate, TSP, and KCl, respectively. Lime was applied at 2.1 Mg $ha^{-1}$ [all recommendations for rice from Araujo et al. (1984) Circular Técnica 18, Embrapa, unpublished].

After the soil was filled into the lysimeters, water was gently poured onto the soil at a daily rate of 6.85 mm (2500 mm $y^{-1}$). After four days the electrolyte content in the leachate had stabilized and fertilizer was added and rice was planted (five stands per pot with three plants per stand). Water was applied and drained daily, but only selected samples were analyzed. Nutrient contents were determined daily for the first week, twice a week for three weeks and after 5 and 10 days. The sampling was stopped when the rice was cut at 37 days after planting. The amount of leachate was determined by weight and a subsample was retained for further analyses and frozen. Cumulative leaching for the entire experimental period was calculated from the measured leachates and amounts were interpolated linearly. Plant samples were dried at 70ºC for 48 hours and weighed.

In a second pot experiment, seedlings of *Inga edulis* were planted in pots with 26 cm diameter and 10 $dm^3$ soil (Xanthic Ferralsol) in four replicates. Charcoal was added at 0, 1, 5, 10, and 20% weight corresponding to 0, 13.3, 66.7, 133.4, and 266.7 Mg C $ha^{-1}$ (C concentration of charcoal 70.8%). Fertilizer was applied at 100 kg N $ha^{-1}$, 50 kg P $ha^{-1}$, and 60 kg K $ha^{-1}$ as urea, triple super phosphate and KCl, respectively. Additionally, 2 Mg $ha^{-1}$ lime were added. Stem diameter was determined at 5-cm above soil level, and tree height was measured including the length of the uppermost leaf at 80 day after planting.

*Adsorption experiment.* In a laboratory experiment, we studied the adsorption of different nutrients by charcoal. The charcoal was made from the wood of black locust (*Robinia pseudoacacia*). Cubes of dried wood with 10 g were isothermically combusted in closed metal containers at 350ºC for 40 minutes (65 replicates). Wood and charcoal were weighed with an accuracy of 0.1%. The charcoal was ground coarsely with mortar and pestle to pass a 2 mm sieve. One gram of charcoal was added to 10 mL of solution containing 0, 20, 50, 100, 200 mg $L^{-1}$ using 20-mL PE bottles. In a preliminary experiment, the adsorption dynamics were determined for 10, 30 minutes, 1 and 6 hours, 1 and 3 days and 1 week using a horizontal shaker. Adsorption changed until one day, but did not differ thereafter. Therefore, adsorption experiments were done with a shaking time of one day. The effect of coating with dissolved organic matter (DOC) was tested with a manure extract. Ten grams cow manure were shaken with 20 mL deionized water and filtered. The filtrate was diluted 50 times and 10 mL of the solution was shaken with 1 g of charcoal for 24 hours. Afterwards the same adsorption experiment with different concentrations only of $NH_4^+$ was performed as described above with and without additions of 10% azide to inhibit microbial activity.

*Chemical analyses.* The aboveground biomass of rice was ground with a ball mill and analyzed for nutrients and organic carbon. C and N analyses were performed with an automatic CN analyzer (Elementar, Hanau, Germany). The K, Ca, Mg, Fe, Zn, Cu contents in the plant biomass were determined after wet digestion with sulfuric acid using atomic absorption spectrometry (AA-400, Varian Associates, Inc., Palo Alto, CA). The P contents were measured photometrically in the same extract with the molybdenum blue method.

The K, Ca, and Mg contents in the leachate and adsorption solution were measured using atomic absorption spectrometry, nitrate ($NO_3^-$) and ammonium ($NH_4^+$) concentrations were determined photometrically with a continuous flow analyzer (RFA-300, Alpkem Corp., Clackamas, OR and Scan Plus analyzer, Skalar Analytical B.V., Breda, The Netherlands) after reduction with Cd and reaction with salicylate, respectively.

*Statistics*. Treatment effects of the bioassay were analyzed by analysis of variance (ANOVA) with a randomized complete block design. Mean separation was done using the least significant difference test (LSD).

*Charcoal as a fertilizer*

Charcoal additions increased biomass production of a rice crop by 17% in comparison to a control on a Xanthic Ferralsol (Figure 1). This increase was largely an effect of improved P, K, and possibly Cu nutrition. Nitrogen and Mg uptake decreased in charcoal amended soils which resembled the uptake pattern of rice grown on an Amazonian dark earth (Fimic Anthrosol; Figure 1). Charcoal additions had no significant effects on S, Ca, Fe, Zn, and Mn uptake (P>0.05). In addition to charcoal, fertilization was necessary with N, S, Ca, and Mg for optimizing rice growth.

The soil fertility improvement of the dark earth was largely an effect of enhanced P, Ca, and micronutrient availability such as Mn and Cu. Crop nutrition of S and K was not better and that of N and Mg was even lower in rice grown on a dark earth in comparison to the Ferralsol. Fertilization was necessary for those elements and was effective in increasing total nutrient uptake (Figure 1).

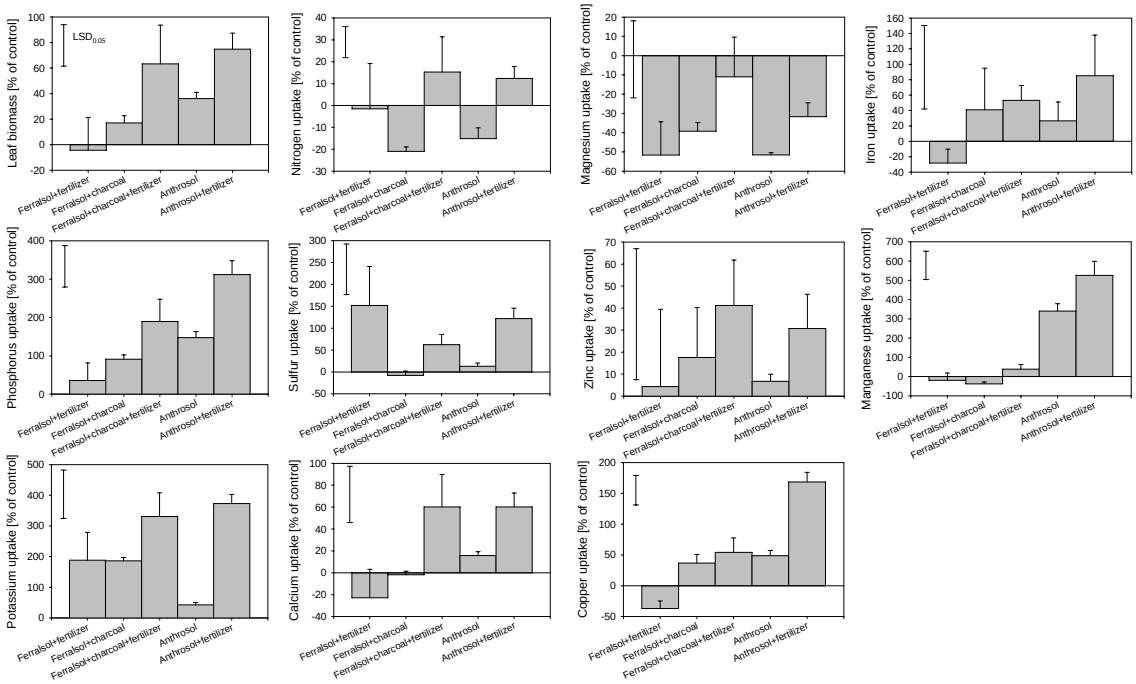


Figure 1: Biomass production and nutrient uptake by rice (*Oryza sativa*) after additions of charcoal and fertilizer to a Xanthic Ferralsol or a Fimic Anthrosol after 37 days (means and standard errors; N=4).

Therefore, charcoal directly amended the soil with plant-available nutrients such as P, K, and Cu. If fertilizer was applied together with the charcoal some nutrients showed a higher uptake efficiency than the added effects of fertilization and charcoal amendment would suggest. This was the case for N, Ca, and Mg. In the following we discuss the reasons for a higher efficiency of a combined application.

*Charcoal as an adsorber*

Under the high leaching conditions in upland soils of the central Amazon, reduction of nutrient losses by leaching is an important aim in order to improve nutrient availability for plants. Immediately after fertilizer application, nutrient contents significantly increased as shown for ammonium (Figure 2) and leveled off to background levels only 21 days after fertilization. This was also the case with K, Ca, and Mg (data not shown).

Leaching from the unfertilized Ferralsol was reduced when charcoal was applied and resembled the low values found in the Anthrosol (Figure 2). Ammonium concentrations in the leachate were also significantly lower in the fertilized Ferralsol after charcoal applications. These results indicate that ammonium was adsorbed by the charcoal and elevated N uptake by rice after the combined application of charcoal and fertilizer (Figure 1) was an effect of ammonium retention. This retention could not be found for other cations or anions, because K, Ca, and Mg were in higher supply with charcoal additions. After several cropping cycles, the nutrients in the charcoal may be depleted and results may differ from those shown here. Since N was applied as ammonium, nitrate contents in the leachate were controlled by biological transformation rather than physical adsorption.

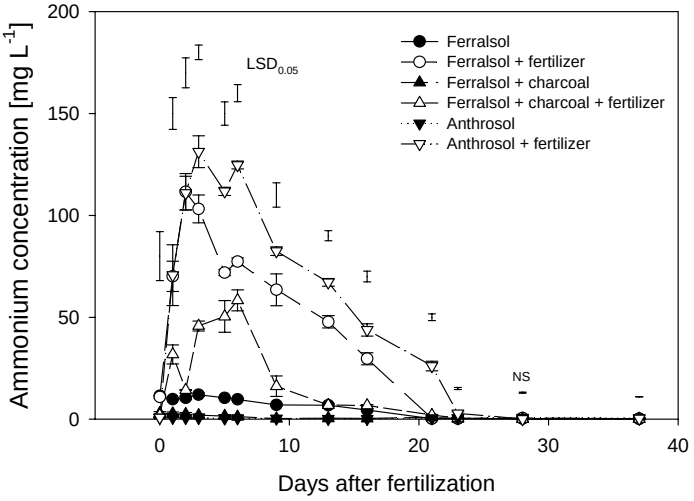


Figure 2: Ammonium concentration in the leachate of a Xanthic Ferralsol amended with charcoal and fertilizer compared to a Fimic Anthrosol; main effects significant at P<0.001 apart from one (NS not significant P>0.05) (means and standard errors; N=4).

In accordance with the leaching results, only ammonium was adsorbed by charcoal (Fig. 3) whereas all other nutrients (P as $PO_4^{2-}$, Ca, Mg, K) showed higher concentrations in the equilibrium solution than added (data not shown). The process of adsorption is largely a co-adsorption with soluble organic matter, as an addition of dissolved organic carbon (DOC) from a manure extract increased ammonium adsorption. A microbial immobilization or nitrification during shaking can be excluded, since the adsorption was similar when microbial activity was suppressed by additions of azide (Fig. 3).

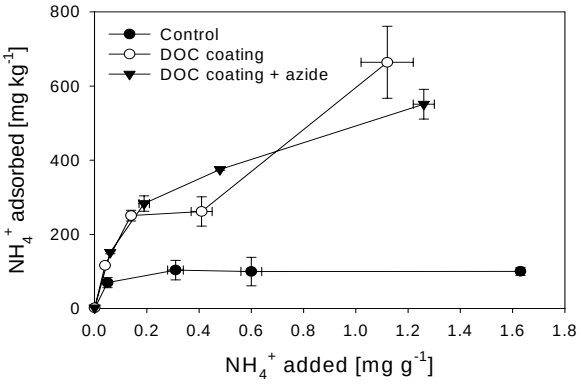

Figure 3: Ammonium adsorption by charcoal produced from black locust (*Robinia pseudoacacia*) in comparison to charcoal coated with manure or additional suppression of microbial activity using 10% azide (means and standard errors; N=2).

*Slash-and-char in smallholder agriculture*

If a slash-and-char technique was to be successful, (i) the quantity of applied charcoal must be produced from the same area of land that is cropped, and (ii) the periods of charcoal production must at least correspond to those of land clearing practiced so far. In other words, the slash-and-char technique must work with the same resources as conventional methods and be an alternative to slash-and-burn or slash-and-mulch. The amount of charcoal which can be produced from different forest vegetation primarily depends on the woody biomass available, and additionally on the production procedure such as charring environment (e.g., oxygen), temperature and time (e.g., Glaser et al., 2002). The average recovery of charcoal mass from woody biomass is 31% according to the published data compiled in Table 1. The effect of different charcoal production methods on its recovery in agricultural fields is not well known and the charring environment such as temperature and charring time is usually poorly documented. The carbon contents of charcoal do not vary much and lie around 63-83% with a mean of 76% (Table 1). The carbon recovery from charred woody biomass is relatively high with 54% (Table 1) due to the high carbon contents of charcoal.

Several published values of above ground biomass from secondary and primary forests in the central Amazon show a high proportion of woody biomass (Table 2). Biomass of secondary forests increase with age but depend largely on site conditions and previous land use. Larger amounts of charcoal can be produced from primary (57-66 Mg C $ha^{-1}$) than secondary forests calculated with the average conversion from Table 1. But also secondary forests may produce charcoal equivalents of up to 32 Mg C $ha^{-1}$ after only 4 years (Table 2). The pot experiment shown in Figures 1 and 2 was conducted with a charcoal amount of 135 Mg C $ha^{-1}$ (20% weight in 10 cm depth), but also 67 Mg C $ha^{-1}$ (10%) were shown to significantly improve biomass production of cowpea (Lehmann et al., unpublished). In a pot experiment with *Inga edulis*, tree height and stem diameter significantly increased through the addition of charcoal (Figure 4; ANOVA P=0.041 and 0.007, respectively). Already at the lowest application rate (13.3 Mg C $ha^{-1}$), charcoal additions were equivalent to fertilizer applications. Therefore, the charcoal amounts produced from the same area of land which is used for cropping during one charring event are sufficient for improving crop performance and for reducing nutrient leaching. Lower amounts of 7.9 Mg C $ha^{-1}$ were shown to have only minor effects on rice yield in the first cropping season under field conditions (Steiner and Nehls, unpublished data) but more information is needed from field experiments. With increasing charcoal additions, growth of *Inga* decreased when no fertilizer was applied but increased with fertilizer applications.

Table 1: Biomass conversion into charcoal

| Tree species | Charring temperature [°C] | Production method | Charcoal recovery by weight [%] | n | Charcoal carbon content [%] | Carbon yield[1] [%] | Source |
|---|---|---|---|---|---|---|---|
| Acacia mangium | 450 | laboratory furnace | 37.9 | 60 | 76.4 | 64.4 | Lelles et al. (1996) |
| Eucalyptus grandis | 470 | laboratory furnace | 33.8 | 60 | 80.7 | 60.6 | Vital et al. (1986) |
| *Eucalyptus camaldulensis* | 450 | laboratory furnace | 32.4 | 25 | 76.3 | 54.9 | Vital et al. (1994) |
| Deciduous trees | 500 | laboratory furnace | 30.2 | 8 | 84.7 | 56.8 | Zhurinsh (1997) |
| *Pinus sylvestris* (sawdust) | 300 | laboratory furnace | 21.6 | | 62.8 | 30.1 | Glaser et al. (1998) |
| *Robinia pseudoacacia* | 350 | laboratory furnace | 33.2 | 65 | 71.3 | 52.6 | this study |
| *Leucaena leucocephala* | not given | metal kiln | 27.4 | | 83.1 | 50.6 | San Luis et al. (1984) |
| Coconut trunk | not given | metal kiln | 25.0 | | 77.8 | 43.2 | San Luis et al. (1984) |
| Mixed tropical wood, Manaus, Brazil | not given | brick kiln | 41[3] | | 74.8 | 68.2 | Correa (1988) |
| Miombo woodland[2] | not given | earth kiln | 23.3 | | n.d. | - | Chidumayo (1991) |
| Mixed tropical hardwood | not given | earth pit | nd | | 69.0 | - | FAO (1985) |
| **Average** | | | **30.6** | | **75.7** | **53.5** | |

[1] Percentage of charcoal carbon from the carbon in wood. Assuming 45%C in wood; determined for *R. pseudoacacia* at 45.7%.

[2] Total conversion of 93% of the woody biomass from a miombo woodland, representing 97% of the total above ground biomass.

[3] Calculating a conversion of 16 $m^3$ to 9 $m^3$ with a density of 0.7 and 0.51 Mg $m^{-3}$ for wood and charcoal, respectively.

Charred organic matter from leaves was not accounted for in the calculation and the conversion to charcoal is currently not known. The contribution of leaves to charred organic matter from secondary or primary forests may be small, however, since the proportion of leaves in these forests usually lies below 10% (Table 2). Nevertheless the contribution to total nutrient input may be significant and has to be considered in nutrient budgets

Table 2: Above ground live biomass of secondary and primary forests in the Amazon.

| Region | Type | Age of forest | Total above ground biomass [Mg ha$^{-1}$] | Woody biomass [Mg ha$^{-1}$] | Wood C content[1] [%] | Charcoal yield from biomass[2] [Mg C ha$^{-1}$] | Source |
|---|---|---|---|---|---|---|---|
| Rondonia and Para | 2nd regrowth | 4 | 134.2 | 119.6 | 49.6 | 31.7 | Hughes et al. (2000) |
| Rondonia and Para | 3rd regrowth | 4 | 90.6 | 72.7 | 49.6 | 19.3 | Hughes et al. (2000) |
| San Carlos, Venezuela | Secondary forest | 5 | 40.1 | 35.2 | nd | 8.5 | Uhl and Jordan (1984) |
| Paragominas, Para | Secondary forest[3] | 3.5 | 16.3 | 12.9 | nd | 3.1 | Buschbacher et al. (1988) |
| Paragominas, Para | Secondary forest[3] | 8 | 35.0 | 30.4 | nd | 7.3 | Buschbacher et al. (1988) |
| Paragominas, Para | Secondary forest[4] | 8 | 86.5 | 81.8 | nd | 19.7 | Buschbacher et al. (1988) |
| Zona Bragantina, Para | Secondary forest | 2.3 | 22.2 | 16.5 | nd | 4.0 | Gehring et al. (1999) |
| Zona Bragantina, Para | Secondary forest | 10 | 54.9 | 49.8 | 47.3 | 12.6 | Johnson et al. (2001) |
| Zona Bragantina, Para | Secondary forest | 20 | 65.5 | 59.2 | 47.9 | 15.2 | Johnson et al. (2001) |
| Zona Bragantina, Para | Secondary forest | 40 | 128.8 | 119.8 | 47.6 | 30.5 | Johnson et al. (2001) |
| Manaus, Amazonas | Primary forest | - | 264.6 | 251.2 | 48.9 | 65.7 | Fearnside et al. (1993) |
| Altamira, Pará | Primary forest | - | 262.5 | 222.3 | 49.1 | 58.3 | Fearnside et al. (1999) |
| Ariquemes, Rondonia | Primary forest | - | 272.2 | 260.0 | 44.4 | 63.5 | Graça et al. (1999) |
| Belem, Para | Primary forest | - | 256.7 | 247.6 | 48.8 | 59.9 | Mackensen et al. (2000) |
| Zona Bragantina, Para | Primary forest | - | 229.6 | 225.1 | 47.3 | 57.0 | Johnson et al. (2001) |

[1] Where no information was available, C contents were estimated at 45 %.
[2] Calculated using the mean conversion of wood biomass to charcoal from Table 1.
[3] With previous pasture use of moderate intensity.
[4] With previous pasture use of low intensity.

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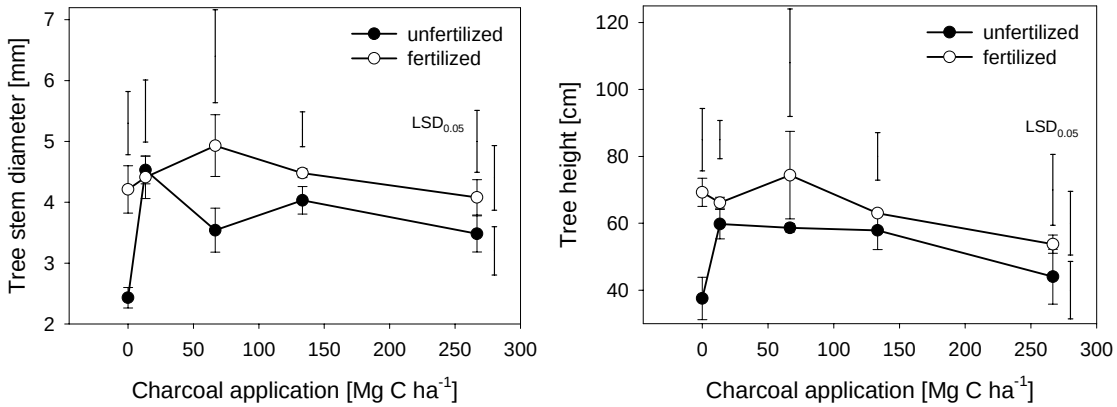


Figure 4: Tree growth of *Inga edulis* seedlings in pots amended with mineral fertilizer and increasing amounts of charcoal after 80 days (means and standard errors; N=4; Rondon et al., unpublished data).

## Conclusions

Charcoal applications directly increased nutrient availability such as P and K and additionally increased nutrient retention for ammonium. Whether a net nutrient retention of other cations occurs after excess nutrients have been leached or taken up by plants remains to be shown. In this respect the long-term dynamics of soil fertility with charcoal applications are very interesting in comparison to burning or mulching. It may be assumed that nutrients bound to charcoal are more persistent than those in ash or mulch but direct evidence needs to be gathered.

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*Agriculture, Ecosystems and Environment (in review)*

# Effects of Land Use Change in the Llanos of Colombia on Fluxes of Methane and Nitrous Oxide, and on Radiative Forcing of the Atmosphere

M. Rondón[1], J.M. Duxbury[2] and R.J. Thomas[3]

[1] *Centro Internacional de Agricultura Tropical (CIAT), Apartado Aéreo 6713, Cali, Colombia.*
[2] *Cornell University. Department of Soil and Crop Sciences. Bradfield Hall, Ithaca, NY. USA.*
[3] *ICARDA, P.O. Box 5466, Aleppo, Syria (formerly CIAT, Colombia)*

## Abstract

The Colombian savanna (Llanos), covers 26 million hectares and is one of the few remaining frontiers where agriculture can expand. Current land use includes native savanna vegetation on clay-loam and on sandy-loam Oxisols, gallery forest, introduced improved pastures and cropland. Little is known about the fluxes of greenhouse gases in this ecosystem. Here we report field measurements of fluxes of methane and nitrous oxide for various land uses and estimates for their annual budgets in the Llanos. Emission of greenhouse gases due to burning of native vegetation and the contribution of methane emissions by termites and cattle have been included to estimate the radiative forcing potential of the atmosphere (global warming potential) for the Llanos.

Soils under pastures were found to be net annual sources of methane, while soils under other land uses were net annual sinks via methane oxidation. Soils under gallery forest showed the highest methane sink. Soil texture influenced fluxes of GHG. Annually, sandy-loam soils oxidized more methane than clay-loam soils (both under native vegetation). Soils of the Llanos were estimated to oxidize 6.4Gg/y of methane. Soils of the gallery forest covering 10% of the area of the Llanos, represent 48% of total methane sinks. All soils were minor sources of nitrous oxide with land under upland rice cultivation having the highest emission rates due to the input of fertilizer-N or green manure. Net emission by soils was estimated to be 12.4 Gg/y and soils were the major factor in the nitrous oxide budget of the region.

Annual emission of $CH_4$ by cattle (0.10Tg) is the main single source of this gas in the Llanos followed by direct emissions from biomass burning (0.06Tg/y). Termites contributed very little to net methane emissions.

Considering the main sources and sinks of trace gases, it was estimated that the Llanos is a net source of 0.164 Tg $CH_4$/y and 0.021 Tg $N_2O$/y. For a 20-year time horizon, the global warming potential of the Llanos under current land use distribution is 22.2 Tg $CO_2$ equivalents which is less than 0.005% of estimated global planetary radiative contribution. Therefore, the Llanos can be considered as an "environmentally friendly ecosystem". The doubling in area under improved grass-legume pastures and cropland expected by the year 2020 will reduce this contribution to 16.5 Tg $CO_{2\ \text{equivalents}}$, mainly due to the reduction in emissions from biomass burning and to $CO_2$ sequestration as soil organic carbon by deep-rooted grasses.

## Introduction

The Eastern plains (Llanos) of Colombia cover an area of 26 million ha and are the only land in Colombia available for agricultural expansion. The climate is sub- tropical with distinct wet and dry seasons. The natural landscape is a mosaic of grass covered, rolling savanna dissected by numerous rivers and streams that are bordered by evergreen gallery forest. Small termite mounds are abundant in the grasslands. The gallery forest accounts for nearly 10% of the total area (Rippstein and Girard, 1995). Low soil fertility and frequent natural or induced fire prevent forest from re-colonizing the land (Rippstein et al., 2001). Over the past two centuries the native grassland has been grazed by low productivity livestock and currently supports 3 million cattle (Rivas, 2000).

The soils of the Llanos are very acid (pH <4.3) Oxisols (Typic Haplustox), low in nutrients and very high in aluminum saturation (>80%). There are two contrasting textural groups; approximately 90% of the soils are clay-loams and 10% are sandy-loams. The soils are generally poorly drained and prone to compaction that can be induced by tillage or by cattle trampling (Amézquita, 1998). Despite these limitations, agricultural activities have intensified in the region during the last decade. Oil palm, rice, maize, soybeans, sorghum and improved pastures are now appearing, especially in the vicinity of the main cities and connecting roads. Intensification will be accelerated in the coming decades and various crops and management strategies have been developed to allow sustainable use of the Llanos (Friesen et al., 1997). The most promising among these are improved pastures with mixtures of grasses (e.g, *Brachiaria sp.*) and forage legumes (e.g. *Desmodium ovalifolium, Arachis pintoi, Centrosema acutifolium*), and rotations of cowpea or soybeans as green manures with varieties of upland rice or acid tolerant maize (Friesen et al., 1997b).

The Llanos is a complex ecosystem from the perspective of exchange of greenhouse gases between the land and the atmosphere, and agricultural intensification can be expected to have a large impact on these exchanges. In the natural system, fire and termites cause emissions of $CO_2$, CO, $CH_4$, NO, $N_2O$ and volatile organic compounds to the atmosphere (Delmas, 1997;). Cattle are important sources of $CH_4$ and forage quality has a large impact on the amount of $CH_4$ emitted per unit of live weight gain or milk production. Soils are sources or sinks for carbon, $N_2O$ and $CH_4$. Improved pastures have shown major increases in carbon stocks in soils of the Llanos (Fisher et al., 1994). Several studies in temperate ecosystems have found that the conversion of natural lands to agriculture may reduce oxidation rates of $CH_4$ and/or increase emissions of $N_2O$ by soils (Sitaula et al., 1995; Mosier et al., 1991; Davidson et al., 1995, Willison et al., 1995). High doses of N-fertilizers stimulate $N_2O$ emission but can reduce $CH_4$ oxidation (Bronson and Mosier, 1994). Less information is available for soils of the tropics; Nobre (1995) found that the conversion of native Cerrados in Brazil to high input agriculture increased $N_2O$ emissions by a factor of ten relative to natural environments. On the other hand, Lauren et al. (1995) found little impact of land conversion to pasture or cropland on $CH_4$ and $N_2O$ fluxes from a soil near Brasilia. Soils at this site were net sinks for atmospheric $CH_4$ throughout the year and oxidized from three to six times more $CH_4$ than similar land uses in temperate regions. Emission rates of $N_2O$ were very low compared to temperate system counterparts. Venezuelan savannas are believed to be small net sources of $CH_4$, although only short-term measurements have been reported (Sanhueza et al., 1995).

Changing land use in the Llanos will influence more that one of the factors responsible for exchange of greenhouse gases with the atmosphere. Conversion of savannas to pastures or cropland eliminates fire and reduces the population of termites, thereby reducing emissions of $CO_2$, CO, $CH_4$, NO, $N_2O$ and volatile organic compounds. Improved pastures will enhance carbon sequestration in soils and the higher quality forage will reduce emissions of $CH_4$ per unit of production. However, improved pastures also allow higher stocking rates, leading to increases in $CH_4$ emission by cattle per unit area of land. Conversion of land to cropland is expected to reduce the soil $CH_4$ sink strength and increase $N_2O$ emissions. The objectives of this study were to assess annual fluxes of $N_2O$ and $CH_4$ for the main land uses found in the Llanos, to use this and other data to make estimations of the radiative forcing potential (Global Warming Potential (GWP)) of this ecosystem under current conditions and to predict the effect of expected changes in land use over the next two decades on regional GWP. Results can be used to inform policy makers on decisions affecting the future development of the region.

## Materials and Methods

### *Experimental Sites*

Field research was conducted at the Corpoica-CIAT Carimagua station, in the middle of the Colombian Llanos (4° 37' N latitude; 71° 19' longitude). The altitude is 175 masl, and annual rainfall and mean temperature were 2498 mm and 28°C respectively for the period of the study (Nov 1997 to Dec 1998). Oxisols of two contrasting textures, a clay-loam (18% sand, 47% silt, 35% clay) and a sandy-loam (64% sand, 17% silt, 19% clay), typical of the Llanos were used in this study.

Six study sites representing native and agricultural systems were chosen. Four sites were selected from treatments in a long-term agro-pastoral/crop rotation experiment that was established on a clay loam soil in 1992 to evaluate the sustainability of several cropping and management systems in the Llanos. Details of the experiment are presented elsewhere (Friesen, 1996). The systems used were: native savanna, legume-grass pasture (B. *dictyoneura* + *A. pintoi*), upland rice as a monocrop and upland rice in a rotation with cowpea as green manure. Experimental plots were strips 20-m wide by 200-m long. A native savanna site on a sandy-loam soil (30-km southwest of the main site) and gallery forest site (9 km to the north of the main site) on a clay loam soil were also studied.

*Soil properties*

A detailed characterization of soil physical and chemical parameters to a depth of 30 cm was performed in May 1998. Bulk density was measured by the sand replacement method and resistance to penetration by a cone penetrometer. Both parameters were measured using procedures described by Smith and Mullins (1991). Four replicate undisturbed core samples were taken at 5-cm depth increments for determination of air permeability following the method of Koorevaar (1983). Samples were collected in metal cylinders (5-cm diameter, 5-cm height) that were capped immediately after collection. Saturated hydraulic conductivity, particle size distribution, soil porosity and pore size distribution were measured as described by Smith and Mullins (1991) and susceptibility to uniaxial soil compaction as described by Culley (1993). Chemical parameters measured were pH (water 1:1), soil organic matter (wet combustion), N content (micro Kjeldahl), and available P (Bray II). Chemical analyses followed the procedures of Hendershot et al. (1991). In April and October 1998, levels of nitrate and ammonium were determined in samples collected down to 1-m depth.

*Gas Flux Measurements*

The vented closed chamber technique (Conen and Smith, 1998; IAEA, 1992) was used to monitor fluxes of $CH_4$ and $N_2O$ between the soil and the atmosphere. Four replicate PVC rings (10-cm high by 30-cm diameter) per treatment were permanently inserted 7-cm into the soil. White polyethylene vented chambers (10 cm high and 30 cm diameter) were attached to the rings just prior to each 1-hour measurement period. A 5 cm wide rubber band cut from a tire innertube was used to seal the joint between the chamber and the ring. The top of a chamber was fitted with a septum to facilitate extraction of gas samples, a hole for insertion of a digital thermometer, and a venting glass tube to prevent pressure differentials between the chamber and the atmosphere. The dimensions of the venting tube (0.5 cm diameter, 8 cm high) were selected as described by Hutchinson and Mosier (1981), and the tube was inserted 5 cm inside the chamber.

To reduce temperature increases within chambers, a reflecting white cover was placed over the chamber during the period of sampling. Gas samples were collected in 20 mL teflon-valved glass syringes at 0, 20, 40 and 60 minutes after installing the chamber. Immediately after collection, 15 mL of gas were transferred to high vacuum pre-evacuated glass containers (10 mL in volume). The glass containers were pre-evacuated to $2\text{-}3 \times 10^{-6}$ mbar, using a freeze dryer that also allowed capping of the evacuated vials with butyl rubber caps, which are impermeable to $CH_4$ and $N_2O$ (IAEA, 1992). An aluminum over-cap was crimped over the rubber cap to effectively seal the flask and avoid accidental opening. Preservation of samples in these containers was found to be longer than 6 months, however analysis of samples was always completed within four weeks of collection.

At the time of gas sampling, composite soil samples (0-10 cm) were collected from around each chamber for determination of moisture content. Soil temperature was measured within the area of the chamber just before and after the sampling period. Air temperature inside the chamber was recorded at every sampling interval to later account for the change in the density of the air inside the chamber as a function of temperature. Gas flux measurements were initiated on November 1997. Sampling frequency was at three-week intervals, except for the first month when three samplings were made. The order and time of sampling was standardized; sampling was started at 8 am, 9:30 am, 11 am and 2:00 pm for the

sites under clay-loam savanna, rice, rice-cowpea and pasture respectively. Samples from the sandy-loam savanna and the gallery forest were collected the next day beginning at 10 am and 3 pm respectively.

A Shimadzu model 14A gas chromatograph (GC) equipped with FID and ECD detectors was set up to simultaneously analyze $CH_4$, $N_2O$ and $CO_2$ in the same sample, while venting $N_2$, $O_2$ and $H_2O$ (Rondón, 2000). A 14 port, two-position valve (Valco Instruments) was used to inject samples via a 2-mL gas loop and to re-direct the stream of gas to the ECD detector just after the $CH_4$ peak was obtained with the FID detector. The system used a pre-column (1-m) and a main column (3-m), both were 1/8 inch stainless steel tubing filled with Porapaq Q (80-100 mesh), and a carrier gas ($N_2$) flow rate of 25 mL $min^{-1}$. An electrically operated pneumatic actuator was used to precisely time the switching of the valve. CLASS VP software (Shimadzu) was used to control the actuator as well as the GC. The GC temperatures were 24°C at injection port, 60°C for the columns and 320°C for the ECD detector. For each gas sample, a 3 mL sub-sample was withdrawn from the glass vials using a 5 mL glass syringe fitted with a Teflon valve and injected into the GC via the sample loop. The existence of positive pressure inside the vials was checked at the time of sample withdrawal. Analysis time per sample was 5.5 minutes. Gas retention times were 2.1 minutes for $CH_4$, 3.8 min for $CO_2$ and 4.8 minutes for $N_2O$. Class VP software was used to calculate the concentrations (ppm) of the gases relative to the standards. Compressed air and Scotty prepared mixtures containing 1 and 3 ppm $CH_4$ and 0.9 and 5 ppm $N_2O$ were the most commonly used standards. For samples high in $CH_4$ or $N_2O$, other standards were used (i.e. 10, 100 ppm $CH_4$ and 10, 100 ppm $N_2O$) as appropriate.

*Gas Flux Calculations and Statistical Analysis*

Differences in gas concentrations over time were used to calculate gas flux to/from soil for each chamber using the condition of a linear increase for at least three points to accept a flux measurement. When the linearity condition did not occur, the four samples were reanalyzed and the chamber was not considered in the calculations of flux averages if the problem persisted. For $CH_4$, fluxes are shown as net oxidation rates (net $CH_4$ consumption by the soil) with emissions from soil shown as negative values. For $N_2O$, positive fluxes represent emissions from soil. Annual fluxes were estimated by integrating the net area under the curve for the plot of gas flux over time. The method was applied to each of the four chambers in every land use, in order to calculate the reported average value. Annual fluxes represent the balance between periods of net emission and net consumption.

Comparisons of annual flux averages between land-uses were made by one-way analysis of variance using SYSTAT version 8 software. Comparison of means was done using Tukey's HSD method. A level of significance of ≤5% was used.

## Results and Discussion

*Environmental and Soil Parameters*

Weekly rainfall and minimum, maximum and average temperatures for the period of measurement are shown in Figure 1. Annual rainfall in the study year (2323 mm) was slightly higher than the 20-year average for the station (2150 mm). March was also wetter than usual while September was drier than usual. In general, the Llanos has a dry season from November to April and a wet season from May to October. A clear alternation of dry and wet days is common in the rainy season, which helps to prevent the soil from becoming waterlogged for long periods of time. The number of days without rainfall (222) exceeded that of rainy days (142) during the year. Towards the end of the dry season, strong solar radiation and frequent winds dried grassy vegetation. Deep rooted shrubs and the gallery forest, with the ability to extract water from deep in the soil, remained green throughout the year. Temperatures are fairly constant through the year with a maximum daily variation of 10°C. For most of the day, temperature remains in a narrow band from 26-29°C. No significant correlation was observed between air temperature and gas fluxes.

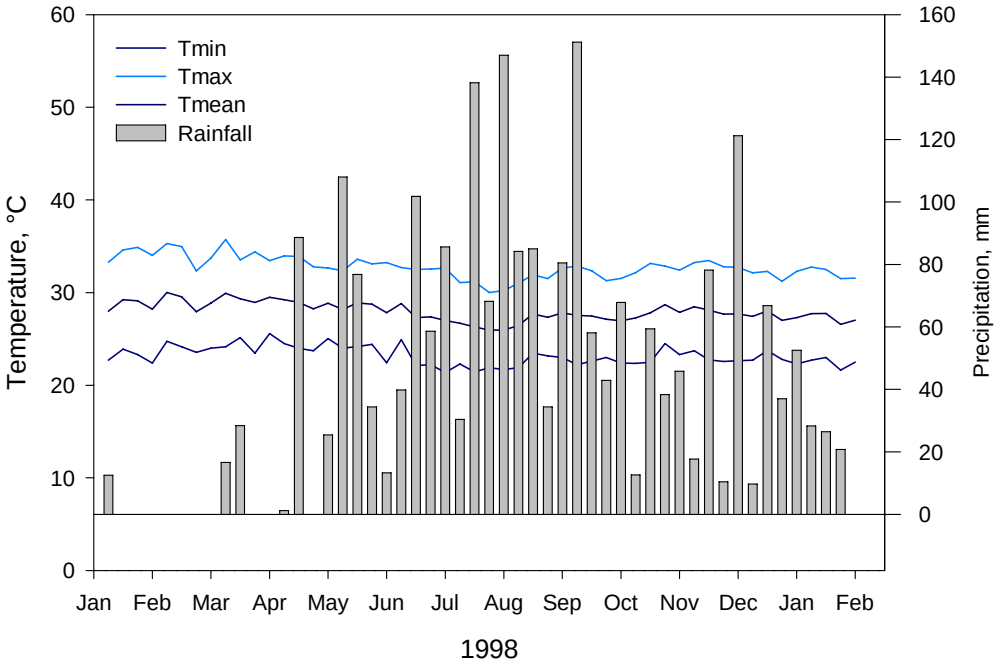


Figure 1. Weekly precipitation, maximum, minimum and average temperature at Carimagua Research Station. Tropical savannas of Colombia

The annual variation in soil water content, expressed as % water filled pore space (WFPS), in the top 10 cm of the soils is shown in Figure 2. The sandy-loam soil clearly has an intrinsically lower water retention capacity than the clay-loam soil and became extremely dry during the dry season (Figure 2A). Soil under the forest tended to be slightly drier than the clay loam savanna soil during the rainy season and slightly wetter during the dry seasonThis difference is likely a result of the combination of higher organic matter content (Figure 3G) and associated higher total porosity (Figure 3D) in the forest soil, together with reduced evaporation, as the soil is not directly exposed to sunlight. Soil under the pasture consistently retained more moisture than soils under other land uses (Figure 2B) and the difference is accentuated during the peak of the rainy season (June to August). Other studies have also found that pastures tend to retain more water than other land uses on the same soil (Roth, 1999; Keller et al., 1993). Water content in the cropped soils was very similar to that in the clay loam savanna, although laboratory measurements indicated that the amount of water that could be retained in the plow layer was reduced by cultivation (Figure 3B). Figure 3B also shows that conversion of land from savanna to pasture increased soil water retention capacity.

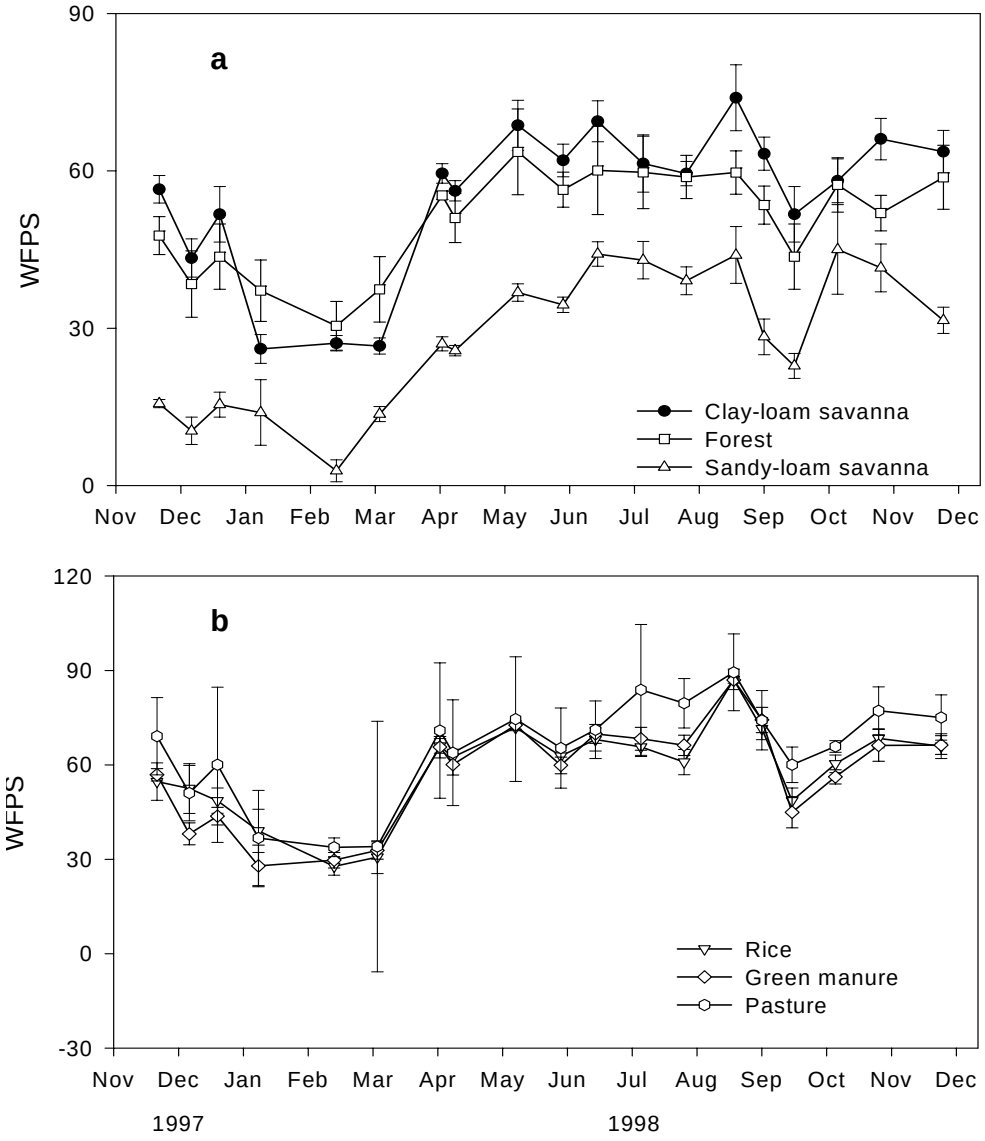


Figure 2. Water filled pore space (WFPS) in soils under various land uses in the Llanos

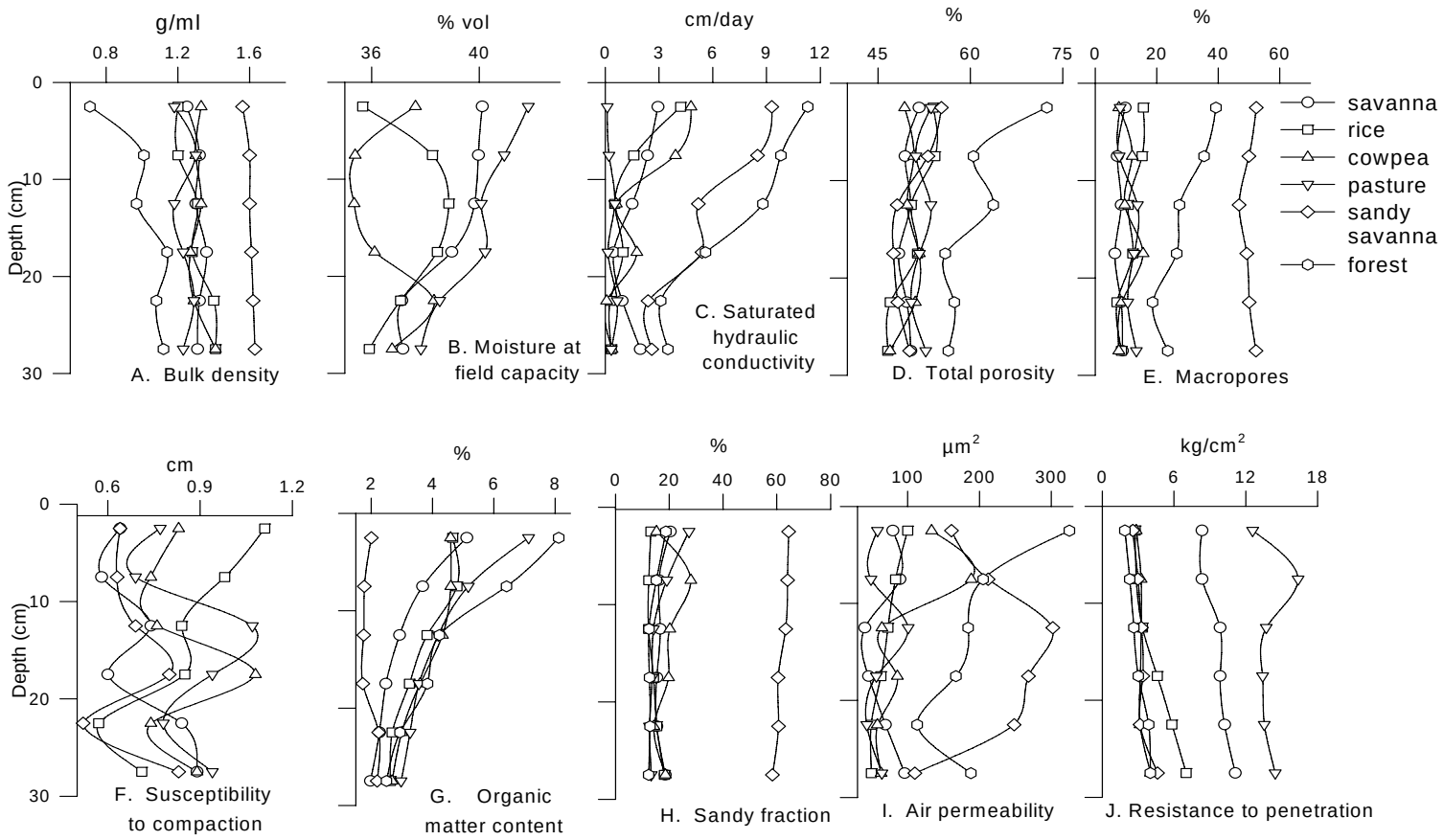


Figure 3. Selected soil properties for various land uses in Colombian savannas

With the exception of the gallery forest soil, saturated hydraulic conductivity was generally low in the clay loam savanna soils, which explains the characteristic wetness of this environment. Poor drainage was exacerbated by conversion of savanna to pasture. Reduced water conductivity in the pasture (Figure 3C) is attributed to sub-surface soil compaction as can be seen from the increased resistance to penetration in the 5-10 cm depth (Figure 3J), probably as a result of cattle trampling. In fact, susceptibility to compaction (Figure 3F) is higher for the whole profile in the pasture compared to the corresponding savanna. Lower susceptibility values for the 5 to 10 cm and 20 to 25 cm layers of the pasture indicate that these layers are already compacted. Other researchers (Mosier and Delgado, 1997; Keller et al., 1993) have also reported subsurface compaction and increased water retention in pastures. As expected, hydraulic conductivity (Figure 3C) is higher in the sandy soils than in the clay-loam soils, demonstrating the influence of soil texture. The greatest hydraulic conductivity was found in the gallery forest soils, probably as a result of improved aggregation due to higher SOM contents, coupled with increased presence of root channels and faunal activity which, in turn, results in low soil bulk density values.

*Fluxes of Greenhouse Gases*

*Methane*

Methane oxidation rates from November 1997 to December 1998 for soils under native vegetation and agricultural use are shown if Figures 4A and B, respectively. The temporal variation in $CH_4$ oxidation rate is high, with average values ranging from +120 μg $CH_4$ $m^{-2}h^{-1}$ for the forest in December to -320 μg $CH_4$ $m^{-2}h^{-1}$ (net emission) for pastures, in August. Spatial variability within a land use was also high, with RSD values ranging from 10% to 400%. However, for most of the sampling dates, RSD was in the range 60 to 120%, which is comparable to other studies on similar soils in the tropics (Poth et al., 1995; Cofman et al., 1998; Scharfe et al., 1990; Keller, 1994). The highest spatial variability was found with soils under rice, while forest and sandy savanna soils showed consistently lower variability.

Methane fluxes followed distinct patterns according to rainfall and soil moisture regimes. During the dry season (November to April), soils under all land uses were net sinks for atmospheric $CH_4$. Oxidation of $CH_4$ was progressively reduced as the soils became wetter in the rainy season (May to October). Soils of the clay loam savanna and the pasture eventually became a source of $CH_4$ during the period of peak rainfall (Figure 1) when soils were at their wettest (Figure 2).

The gallery forest soil consistently had higher $CH_4$ oxidation rates than the other ecosystems and none of the four sampling areas were ever a source of $CH_4$. Low bulk density (Figure 3A), high water infiltration rates (Figure 3C), high air permeabilities (Figure 3I) and low resistance to penetration (Figure 3J) are physical attributes of soil in the gallery forest that explain these results. In contrast, all other land uses on the clay loam soil have lower values than the gallery forest soil for air permeability and hydraulic conductivity through the 30 cm sampling depth. The clay loam savanna and pasture soils showed the most physical constraints to drainage and gas transport in the top 10cm of soil, consistent with these two systems becoming a source of $CH_4$ during the wet season. The pasture soil had the highest water filled pore space (Figure 2B) and the highest $CH_4$ emissions of all systems during the month of July. Converting the clay loam savanna into cropland, reduced $CH_4$ oxidation rates during the dry season (Figure 4A and B), probably as a result of reduced availability of water. On the other hand, tillage improved drainage and aeration, reducing the length of time that agricultural soils become anaerobic, which results in only small emissions from these soils in the wet season.

Soil texture was an important factor affecting $CH_4$ fluxes in the two savanna sites. Methane oxidation rate in the sandy savanna soil was lower than that in the clay loam savanna during the dry season, probably because low water retention (Figure 2) reduced the population and/or activity of $CH_4$-oxidizing bacteria (Boekx et al., 1997; Bottner 1985) relative to the clay loam savanna soil. The greater total porosity, and especially macro-porosity (Figure 3F and 3G), favored the prevalence of aerobic conditions in the sandy savanna soil, which was never a substantial source of $CH_4$.

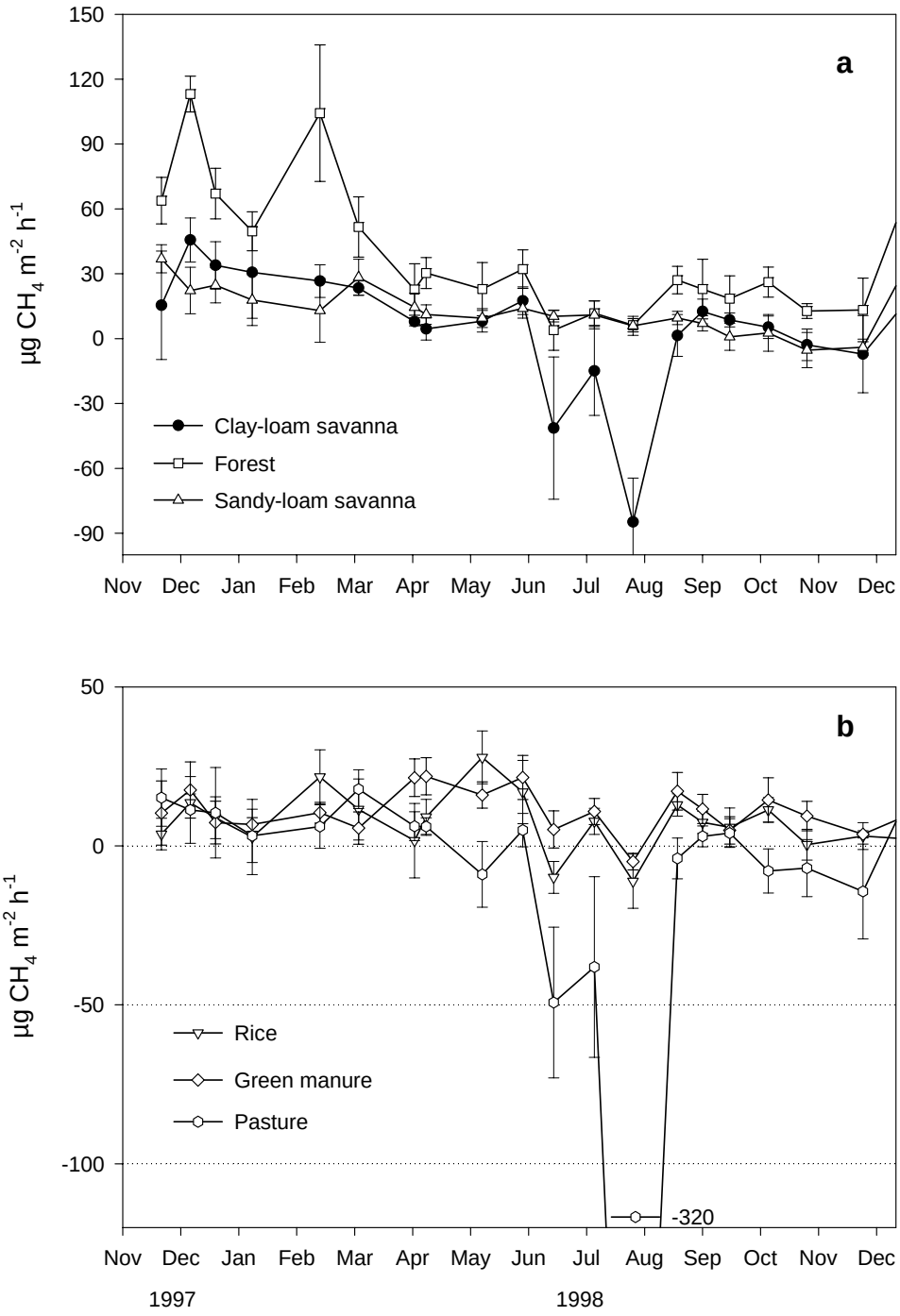


Figure 4. Land use effect on methane oxidation by soils in Colombian savannas. Positive numbers indicate net methane consumption by the soil (net sink)

Estimates of annual $CH_4$ fluxes are presented in Figure 5A. The gallery forest soil, with a sink strength of 3.05 kg $CH_4$ $ha^{-1}y^{-1}$, constituted the highest sink for $CH_4$. The $CH_4$ sink strength in the gallery forest is similar to values reported for a wet forest in Puerto Rico (Steudler et al., 1991), and other types of tropical forest in Central and South America (Keller, 1994; Keller and Reiners, 1994; Keller and Wofsy,

1986). The annual $CH_4$ sink strengths in the sandy and clay loam savanna soils were only about one-third and one-twelth of that of the gallery forest soil, respectively. Methane sink strength in the Llanos clay-loam savanna soil (0.26 kg $CH_4$ $ha^{-1}y^{-1}$) is similar to values reported for grasslands on Oxisols of Puerto Rico (Mosier and Delgado, 1997), and higher than values reported by Sanhueza et al. (1995) for comparable savannas in Venezuela, which were found to be a minor source of $CH_4$. However, methane sink strength on well aerated, high clay Oxisols of the Brazilian savanna (Cerrados) was 1 to 2 times higher than that of the Llanos savannas (Lauren et al., 1995).

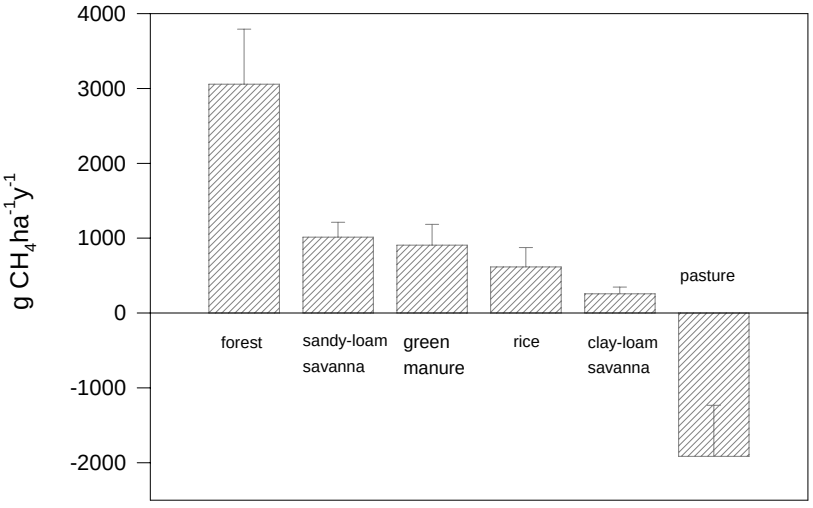


Figure 5. Annual methane oxidation by soils in Colombia savannas

Conversion of clay loam savanna to cropland increased $CH_4$ sink strength by 2.5x to x kg $CH_4$ $ha^{-1}y^{-1}$ for rice mono-cropping and by 4x to y kg $CH_4$ $ha^{-1}y^{-1}$for the rice-cowpea rotation These results contrast with several reports (Sitaula et al., 1995; Mosier et al., 1991, Bronson and Mosier, 1994) showing a decrease in methane consumption rate when soils were fertilized with ammonium fertilizer sources. (However, information to specifically address effects of N status/source (fertilizer or green manure) on $CH_4$ oxidation capacity was not collected in the present study. Presumably, removal of physical constraints to gas exchange counteracted any negative effect of fertilizer on $CH_4$ oxidation rate.

Conversion of clay loam savanna to pasture changed the soil from a net sink to a net source (1.92 kg $CH_4$ $ha^{-1}y^{-1}$) of $CH_4$. A similar result was found for conversion of tropical forest in Costa Rica to pasture (Keller, 1983). Several other pastures sites in temperate (Van der Pohl, 1999) and tropical regions (Mosier and Delgado, 1997) have been found to be net sources of atmospheric $CH_4$. Keller and Reiners (1994) found that the condition of pastures greatly affected $CH_4$ emissions, with emissions from abandoned, degraded pastures being nearly five times higher than from pastures in good condition. The pasture plots used in the present study were 7-years old, originally planted with *B. dictyoneura* and *A. pintoi*, and supporting a stocking rate of 3 head/ha. Signs of pasture degradation were evident at time of sampling: low persistence of the legume, increased bulk density, subsurface compaction, reduced air permeability, occurrence of isolated termite mounds etc. Options are available to improve the management of these pastures in ways that reduce soil compaction and prevent or slow pasture degradation (Amezquita, 1998).

*Nitrous Oxide*

Fluxes of $N_2O$ from soils of the native and agricultural systems over the one-year study period are shown in Figures 6a and 6b, respectively. Spatial variability in $N_2O$ emissions was higher than that for $CH_4$, with RSD values mostly in the range of 100 to 200%, although values as high as 400% were

sometimes found. This level of variability is similar to that found in other studies (Williams et al., 1999; Ruser et al., 1998; Veldkamp et al., 1998; Keller and Reiners, 1994).

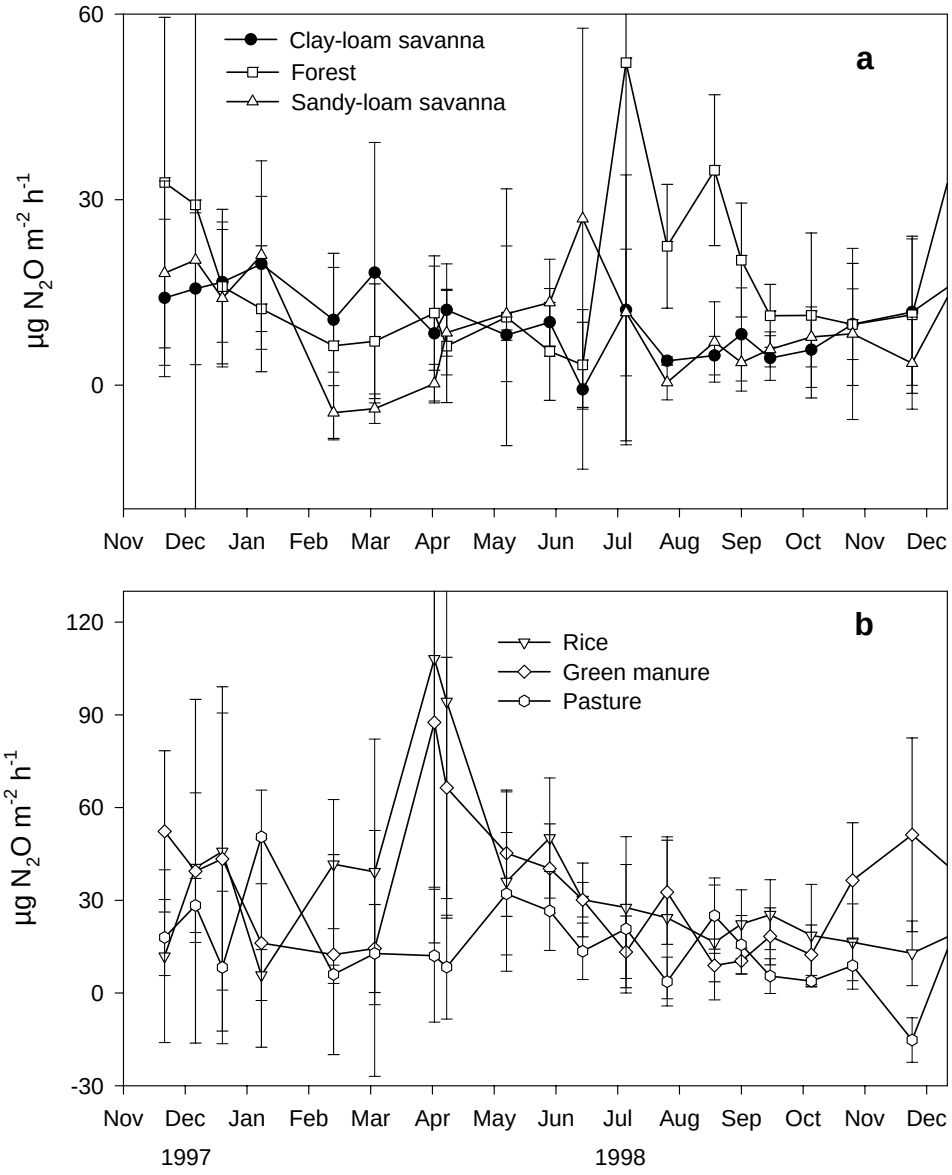


Figure 6. Land use effect on emission of nitrous oxide from soils in Colombian savannas

Soils of all land-uses were net sources of $N_2O$ for most of the year, although small sink strengths occurred in the sandy soil savanna at the end of the dry season and in the pasture soil at the end of the rains. Emission rates from natural ecosystem soils were generally low, with the gallery forest the main contributor. A peak of emissions was approximately coincident with the peak of the rainy season in the gallery forest. No consistent difference was found between the savannas on soils of contrasting texture. Observed low emission rates in native land uses may be partially the result of the small amount of nitrogen that is cycled in these nutrient-limited soils (Figure 7) and low soil pH, which reduces both nitrification and denitrification rates (Broadbent et al., 1965; Jackson, 1967).

The increase in external nitrogen inputs and cycling increased $N_2O$ emissions in all of the agricultural systems compared to the clay loam savanna. Biological N fixation contributes to the improved productivity of the grass-legume pasture (Thomas et al., 1997), and the cowpea green manure is estimated to supply 100-120 kg N $ha^{-1}y^{-1}$ in the rice-cowpea rotation (Friesen et al., 1997). The mono-crop rice received 80 kg N $ha^{-1}y^{-1}$. Enhanced nitrogen cycling in the pasture is due also in part to nitrogen return via urine and dung from the cattle. Yamulki et al (1998), estimated that 7% of urine-N is lost as $N_2O$. Both tillage and fertilization/green manuring contribute to increased nitrogen levels in cropped soils. The highest emissions of $N_2O$ in the cropped systems were observed in April, coincident with N additions and high soil nitrate levels (Figure 7).

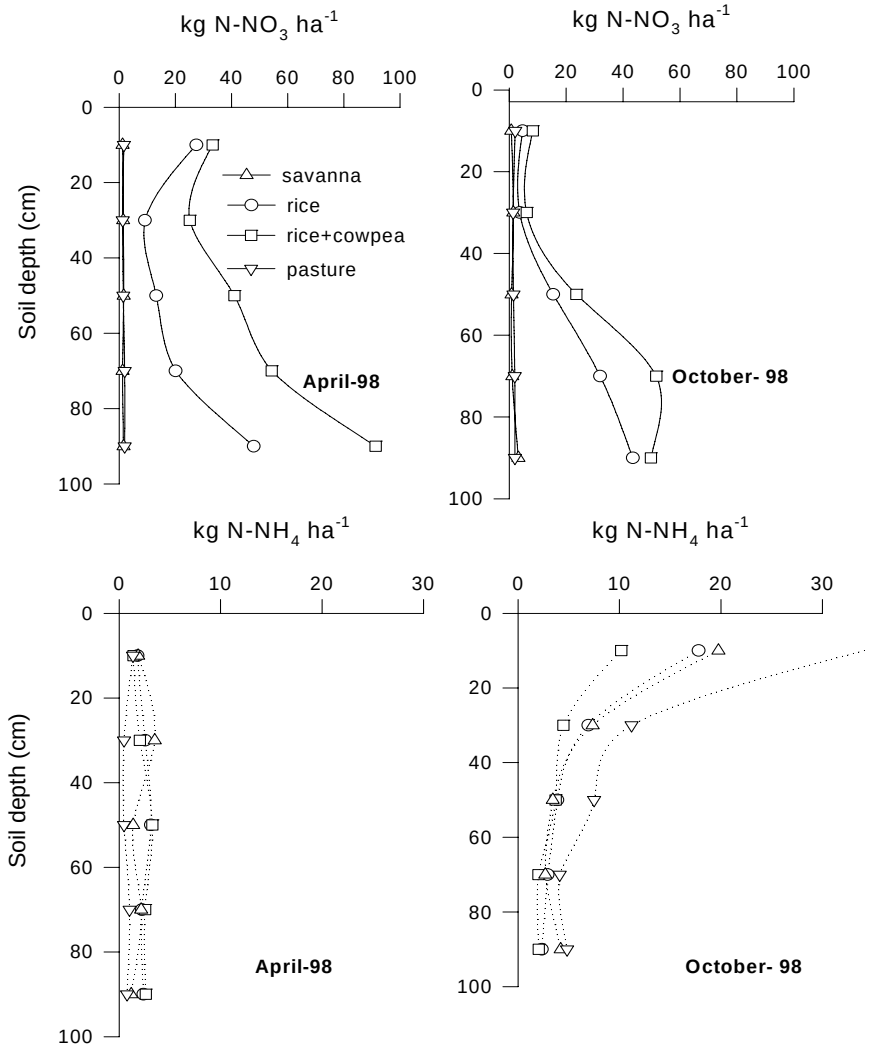


Figure 7. Nitrate and ammonium levels in the soil profile

Integrated annual net fluxes of $N_2O$ are summarized in Figure 8. All land uses were a net source of $N_2O$. Within the natural ecosystems, the annual emissions from the gallery forest (1.44 kg $N_2O$ $ha^{-1}y^{-1}$), were significantly higher than those from the clay-loam savanna (0.94 kg $N_2O$ $ha^{-1}y^{-1}$; $p<0.01$) and the sandy savanna (0.76 kg $N_2O$ $ha^{-1}y^{-1}$; $p<0.05$). The annual emission of $N_2O$ from the gallery forest is low (HOW LOW??) compared to rainforest in Central America (Keller, 1994), similar to estimates for the forests in the Amazon (Culman, 1995) and eastern Venezuela (Sanhueza et al., 1990), and higher than values for semi-deciduous dry forest in Mexico (Davidson et al., 1993).

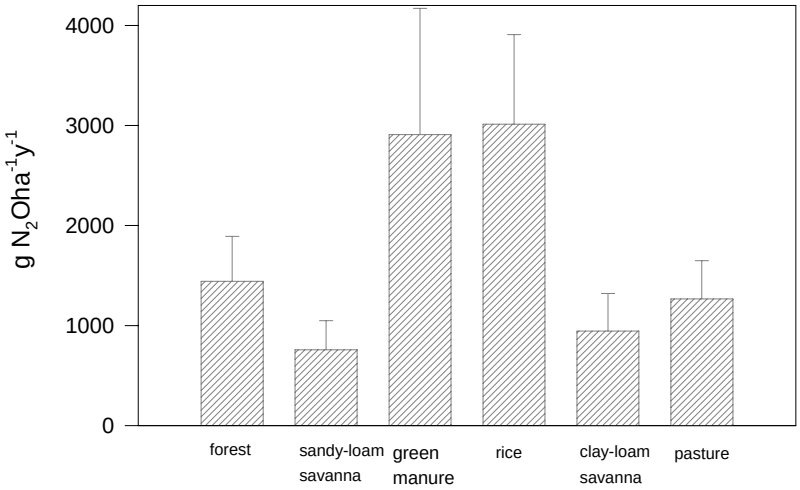


Figure 8. Annual nitrous oxide emission from soils in Colombia savannas

Emission rates for the savannas are similar to those reported for the Brazilian Cerrados (Nobre, 1995; Lauren et al., 1995) and for native grassland bordering the Guyana rain forest in Venezuela (Sanhueza et al., 1990), but were higher than those reported for the more comparable savannas of Venezuela (Hao et al., 1988).

Conversion of clay loam savanna to a grass-legume pasture did not significantly increase $N_2O$ emissions although legumes are known to do this (Galbally et al., 1992; Duxbury et al., 1982). A possible reason is the relatively low proportion of legume in the pasture studied. The annual emission value of 1.27 kg is lower than values for temperate grasslands (Williams, 1999; Ball et al., 1997a; Van den Pohl, 1999) or from fertilized pastures in Costa Rica (Veldkamp et al., 1997), but falls within the range found for degraded pastures in Costa Rica (Keller and Reiners, 1994), and Puerto Rico (Mosier and Delgado, 1997).

Annual emissions of $N_2O$ were significantly increased ($p<0.01$) by slightly more than three-fold when clay loam savanna was converted to cropland. There was no difference in emissions between the two rice systems (Figure 8), where N is supplied predominantly through inorganic fertilizer in the monocrop and via organic sources in the rotation. This result does not support the suggestion (Freney, 1997), that more $N_2O$ is emitted from organic than inorganic N sources. The observed emission rates in the rice systems of 2.8-3.0 kg $N_2O$ $ha^{-1}y^{-1}$ correspond to 1.8% of external nitrogen inputs after removing the contribution of the background flux from the savanna soil. This proportion is higher than the value of 1.25% x fertilizer-N which has been frequently used as an average for fertilized fields (Mosier et al., 1995), but lower than the more recently suggested proportion of 1.25% x fertilizer-N + 1 (Hopkins et al., 1997). The data is similar to other studies on tropical acid Oxisols (Mosier et al., 1998), where the conversion of the native ecosystem to agriculture, with additions of 100kg N as fertilizer, resulted in a five-fold increase in $N_2O$ emissions from soil.

**Budgets for Soil Sources of Methane and Nitrous Oxide in the Llanos**

*The Radiative Forcing Potential of the Llanos*

*The role of the soil*

Table 1 shows figures for the area of the various land uses found in the Llanos, as well as their estimated contribution to annual net fluxes of methane and nitrous oxide. Data for coverage area corresponds to the nearly 14 Mha of the so called well-drained savanna which is more suitable for intensification of agriculture or pastures (Rivas, 2000).

By contributing about half of the total methane sink, soil in the gallery forest plays a key role in the net balances of this trace gas in soils of the Llanos. Given the relatively small area covered with forest, any disruption could have an important impact on regional soil methane sink strength. To illustrate this, if current forest area were reduced by 50%, the net methane sink by soils from the Llanos would be also reduced by 50%. Crops included in this study are not the only ones currently used or likely to be used in the future, and therefore a degree of uncertainty arises in regional gas budgets when it is assumed (as in Table 1) that rice as a monocrop and in rotation with green manure are representative of the effect of cropland in the region. However, given that the area under crops is still small, their potential contribution to changes in balances of methane in the Llanos is probably not too high, even under the scenario of a two fold increase in cropland expected for the next two decades (Smith at al., 1997). The annual sink strength of methane in soils from the Llanos (0.0078 Tg/y) represents around 0.02% of the estimated 40 Tg/y global soil sink strength (Minami, 1997).

Total $N_2O$ emissions are greatly controlled by the native land uses (savannas and gallery forest), due to their high area coverage. Crops and pastures contribute currently in similar proportions to the overall budget of this gas in the Llanos. The global annual emission is low (0.1%) with respect to the estimated global planetary emissions of 13Tg/y (Bowman, 1994).

Table 1 Contribution of land uses to the budgets of $CH_4$ and $N_2O$ from soils in the Llanos

| Land Use | % of the area | Area x$10^6$ ha | $CH_4$ oxidation rate g $ha^{-1}y^{-1}$ (^) | Annual $CH_4$ oxidation Mg | $N_2O$ emisión rate g $ha^{-1}y^{-1}$ | Annual $N_2O$ emission ton | % of total $CH_4$ sinks | % of total $N_2O$ sources |
|---|---|---|---|---|---|---|---|---|
| Silty-Clay savanna | 69 | 9.5 | 256 (90) b | 2432 | 944 (375) ab | 8968 | 27 | 61 |
| Sandy savanna | 13 | 1.8 | 1014 (199) c | 1825 | 758 (291) a | 1364 | 20 | 9 |
| Gallery forest | 10 | 1.4 | 3057 (736) a | 4280 | 1442 (449) b | 2019 | 48 | 14 |
| Cropland (*) | 4 | 0.5 | 762 (267) c | 381 | 2961 (1079) c | 1481 | 4 | 10 |
| Pasture | 5 | 0.6 | -1915 (683) d | -1149 | 1266 (382) b | 760 | - | 5 |
| Llanos total | 100 | 13.8 | 532 (201) | 7769 | 1032 (389) | 14591 | | |

(*)Average of the values found for rice monocrop sites and cowpea - rice rotations. (^) Values in parenthesis are standard errors. In a column, values followed by the same letter indicate non-significant difference at $p<0.05$.

*The contribution of termites*

At least two types of termites are found in soils of the Llanos: subterranean soil-feeding termites and mound building termites (Decaëns, 1995). In a study conducted simultaneously with this, Rondón (2000) has shown that essentially all methane generated by subterranean termites is oxidized by soils before escaping into the atmosphere. The only contribution to net emissions of this gas is made by species of mound building termites of the genus Spinitermes. Annual estimated fluxes due to termites were reported as 6.7 and 7.2 g $CH_4$/ha for pastures of *B. humidicola* and native savanna respectively (Rondón, 2000). These values are fairly low compared to net soil sinks in the region, and consequently methane emissions by termites does not constitute an important component in the budgets of this gas in the Llanos. Soils under other land uses did not have termite mounds. To extrapolate annual fluxes of methane from termite mounds to the overall area of the Llanos covered with native savanna (in clay and sandy soils) and with pastures, it has been assumed that the density of 36 active mounds per hectare reported by Rondón (2000), for native savannas and 26 for pastures, applies throughout the Llanos. The integrated annual methane flux coming from termite mounds in the Llanos is 76 Mg $CH_4$/year. This value is only about 0.0004% of the total global emissions of 19.7 Tg $CH_4$ attributed to termites (Sanderson, 1996).

*The "hot" effect of biomass burning*

Towards the end of the dry season, vegetation in the savanna becomes too dry to be of value for cattle. To favor the re-growth of higher quality grasses, ranchers frequently burn their savannas. This, in addition to common natural fires results in a complete burning of the savannas at least every two years. Burning affects fluxes of GHG by two mechanisms: direct emission to the atmosphere in the form of the products of combustion, and indirect effects created by disturbances of the normal fluxes of gases from the soils. In a parallel study, Rondón (2000) measured both direct emissions of methane and nitrous oxide and long-term effects of burning on soil-atmosphere exchange. Extrapolating annual emissions to the area of the Llanos which is susceptible to burning (9.96 million hectares), direct emissions of methane due to burning were estimated to be 67,728 Mg $CH_4$/y, while indirect effects represent a reduction in 723 ton $CH_4$/y in the soil sink capacity (Rondón, 2000). The net annual release of methane by burning is then 68451 Mg per year, which is nearly 11 times higher than total methane oxidation by soils. Burning consequently has a major role in the annual budget of methane in the Llanos. The combined release of nitrous oxide in the region due to burning is 6928 Mg $N_2O$/year, which is about 37% of the total emissions of this gas by soils in the region. Its contribution is then also important though not dominant in the regional balance of nitrous oxide.

*The "gaseous" role of cattle in the Llanos*

Methane emission by cattle is a well-documented process, believed to be responsible for annual emissions on the order of 90 Tg (Johnson, 1996) or approximately half of total agricultural sources (Cole et al., 1997). Unfortunately there is a complete lack of data regarding methane emission by cattle grazing native savanna vegetation or improved pastures in the Llanos. Cattle population in the well drained Llanos is estimated to be around 2.5 million animals (Fedegan, 2000). Kurihara et al., (1999) reported methane emissions by cattle fed on tropical grasses of the order of 113g $CH_4$/cow-day. Though grasses are different, assuming the same methane production rate for cattle in the Llanos, the estimated production of methane by cattle in the region would be approximately 103,000 ton/year. This is about 16 times higher than the net sink by soils. This demonstrates the key role of cattle in controlling the budget of methane in the Llanos.

The total number of cattle in the Llanos is not expected to increase significantly in the near future due to market and demand constraints. What is expected with the introduction of improved pastures, is that cattle will move from native savannas frequently in remote locations, to improved pastures near to the roads and infrastructure. There are probably good opportunities to improve balances of methane in the region by offering better quality forage for the cattle. Future research in the Llanos should in consequence, try to account for the effect of improved diets on local methane budgets.

**Balances of $CH_4$ and $N_2O$ in the Llanos: four actors in the scene, just one landscape**

In Table 2 results from the contribution of the major components of gaseous exchange are presented, and extrapolated to the respective area of influence to generate total annual fluxes for the Llanos. Data in Table 2 indicates that all together, the savanna ecosystem constitutes a net source of atmospheric methane, being largely controlled by direct emissions generated by burning and by the unfortunate 'bad breath" of cattle. The Llanos emits only about 0.03% of the total estimated global annual emissions of methane (535Tg, IPCC, 1997), and about 0.1% of total annual emissions of nitrous oxide. Covering an area of approximately 0.094% of the planetary land area, the region shows emissions of $N_2O$ similar to planetary averages, while emission of $CH_4$ is only around one third of average global emissions. The Llanos can consequently be labeled as an environmentally friendly ecosystem. Despite that, there are opportunities to further reduce emissions of GHG's in the region.

Table 2 Net annual fluxes of $CH_4$ and $N_2O$ in Colombian savannas

| Contributing factor | $CH_4$ flux g $ha^{-1}y^{-1}$ | $N_2O$ flux g $ha^{-1}y^{-1}$ | Total area affected Mha | Net $CH_4$ flux Mg $y^{-1}$ | Net $N_2O$ flux Mg $y^{-1}$ |
|---|---|---|---|---|---|
| Flux from Soils (*) | -563 | 1,057 | 13.8 | -7,769 | 14,591 |
| Effect of burning on soil emissions | 73 | 456 | 10 | 723 | 4,538 |
| Direct emission in burning products | 6,800 | 240 | 10 | 67,728 | 2,390 |
| Emission by cattle (♣) | 24,747 | -- | 4 | 103,110 | -- |
| Termite mounds | 7 | 0.008 | 11 | 76 | 0.1 |
| Total in the Llanos | | | 13.8 | 163,868 | 21,519 |
| Total flux in the Llanos (Tg/y) (^) | | | | 0.164 | 0.021 |

(*) Value was calculated as the weighed average of fluxes and areas under various land uses in the region (Table 1).
(♣) An average stocking rate of 0.6 heads/ha was assumed for the Llanos (Rivas, 2000)
(^)Termite mounds were considered for the soils under savannas and pastures.

*Mitigation strategies*

Data in Table 2 indicates that mitigation strategies should be directed towards reducing the frequency of fires and reducing emissions by ruminants. Probably there is a little opportunity to favorably alter emission factors by burning at other times during the dry season, this impact has to be evaluated. Burning is however very important for maintaining the productivity and functioning of the ecosystem and also to permit the current economic exploitation of the savannas.

Therefore, unless more profitable management options are offered to farmers, there is little opportunity to reduce the scope of fires in the savannas. Pastures could play a role here, as they are economically feasible options for the development of the region (Vera, 1997). As was mentioned before, improved pastures with mixtures of high productivity grasses and forage legumes could also play a role in reducing emissions of methane by animals in the region.

In Table 3, the combined effect of all components on the balances of methane and nitrous oxide has been integrated to provide annual emissions per unit area in each land use. Though pasture soils were found to be a net source of methane, the fact that burning is eliminated in well managed pastures counteracts emissions by soil. However, given that stocking rate is increased six fold when converting a unit area of savannas into pastures, there is a 4.6 fold increase in the net release of methane to the atmosphere per unit area due to the cattle. Taking all the factors into consideration, conversion of savannas to cropland is the only alternative identified in this study, which can convert the savanna ecosystem into a net sink of methane, by eliminating the sources (burning and termites) and enhancing the soil sink. This option would however increase net emissions of nitrous oxide and consequently a "compromise solution" should be adopted when trying to include the environmental perspective within the development programs for the Llanos. It is clear however, that under the low fertilizer application rates expected to be used in the Llanos, crops will provide a good alternative to the development of the region in an "environmentally friendly way".

Clearly, regenerating forest on deforested land will provide the best alternative to mitigate emission of greenhouse gases in the Llanos. Unfortunately this is not an option easy to implement, because fire normally prevents the advance of forest into the savanna. This implies that measures to prevent the fire from reaching the borders of the forest should be reinforced, but that normally involves high cost in building roads which the farmers will not be able to afford if they are only for the sake of the environmental benefit. One possibility to cope with this problem would be to foster the use of areas near

the borders of the forest as pastures or croplands. It is however reasonably to expect that governmental subsidies should be employed to make this option feasible. Perhaps there is an opportunity to recruit some funds by selling the equivalent GHG offset resulting from recovering forest (Moffat, 1997).

Table 3. Annual integrated emission of $CH_4$ and $N_2O$ per hectare in various land uses in the Llanos.

| | Savanna | Sandy savanna | Gallery forest | Pastures | Crops |
|---|---|---|---|---|---|
| $CH_4$ | 27.3 | 26.5 | -3.1 | 125.7 | -0.8 |
| $N_2O$ | 1.6 | 1.5 | 1.4 | 1.3 | 3.0 |

Values are in kg $ha^{-1}y^{-1}$ (Negative values indicate a net sink)

*Soil carbon, a solid component in the greenhouse gas analysis*

Soils of the Llanos have been found to be able to sequester important amounts of atmospheric carbon when deep rooted grasses are introduced in these lands. Net C sequestration by pastures of *Brachiaria humidicola* in the top 1m deep soil was reported as 25.9 ton C in a ten year period, while grass-legume pastures of *B. humidicola* and the forage legume *Arachis pintoi* increased such amounts to 70.4 ton/10 years (Fisher et al., 1994). Though in this study fluxes of $CO_2$ were not considered, It is clear that the extent of the reported carbon accumulation in soils under pastures plays a main role in configuring the complete scenario of GHG's in the Llanos. Consequently, an analysis will be attempted here to include this component.

*The radiative forcing strength of the Llanos*

As a mechanism for integrating the combined effect of all greenhouse gases involved in the Llanos, the $CO_2$-equivalent global warming potential (E-GWP) of $CO_2$, $CH_4$ and $N_2O$ has been calculated for two time horizon scenarios (20 and 100 years), for every land use in the Llanos. In a 20-year time scenario, $CH_4$ has a GWP equivalent to 62 times that of $CO_2$, while that of $N_2O$ is 275 times compared to $CO_2$. In the 100 years time horizon, the corresponding GWP values for $CH_4$ and $N_2O$ are respectively 23 and 296 times that of $CO_2$ (IPCC, 2001). The calculation of integrated E-GWP expressed as equivalent kg of $CO_2$, was done by multiplying the per hectare annual emission of $CO_2$, $CH_4$ and $N_2O$ from each contributing factor, by the land area associated with that factor and then by the relative GWP of each gas. Adding together the values obtained for each factor gives the overall equivalent E-GWP for the Llanos, expressed as equivalent units of $CO_2$. For the calculation, it was assumed that burning does not make a net contribution to emissions of $CO_2$, because the CO2 released by fire is reabsorbed from atmosphere during vegetation regrowth. Stocking rate of cattle was assumed as 0.5 head/ha in clay and sandy savannas and 3 head/ha in pastures. The same $CH_4$ emission factor for cattle was used for improved pastures and for native savannas. Soil emissions of $CH_4$ and $N_2O$ were assumed to be the same in grass alone and in grass-legume pastures. Figure 9 shows calculated E-GWP values (for one year total emissions of all GHG's) on a hectare basis for the various land uses and has been calculated for two time horizons, 20 and 100 years of influence. Figure 9 includes the reported (Fisher et al., 1994) values for carbon sequestration in pastures of grass-legume (0.1Mha) with a high rate of carbon sequestration (70.4 ton C/ha in a 10-year period), as well as pastures of grass alone (0.5Mha) with lower rate of carbon accumulation (25.6 ton C/ha in a 10-year period). Annual carbon sequestration by pastures was calculated assuming the same rate of accumulation for each year, and then converting it into $CO_2$.

All natural land uses (savannas and forests) show positive equivalent E-GWP values, indicating that they are contributing to the radiative forcing of the atmosphere. The gallery forest is clearly the best natural land use from the perspective of the heating effect on the atmosphere. Its equivalent E-GWP is very low in both time scenarios. At the 20-year horizon, the warming contribution from the gases emitted during one year by one hectare of forest is equivalent to that of the $CO_2$ emitted by the combustion of 35 gallons of gasoline (fuel for 8 hours trip of a small car!). Including all the sources and sinks, the radiative

power of savannas is low and decreases when the 100 year time scenario is used, because most of the contribution is in the form of $CH_4$, which is a short lived gas in the atmosphere. Crops have integrated E-GWP lower than that of the savannas in the 20 year scenario and approximately the same as the savannas in the 100 year scenario. The conversion of savanna land into cropland does not have a detrimental effect on the E-GWP.

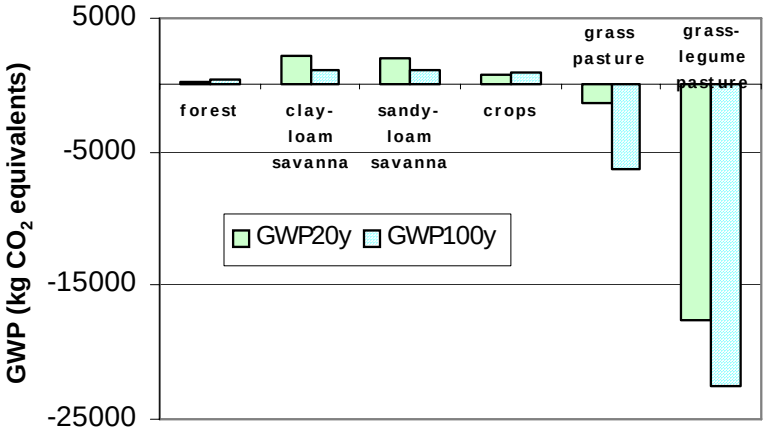


Figure 9. Global warming potential –GWP for various land uses in the llanos under two time horizons scenarios (20 and 100 years). GWP is expreed as kg of $CO_2$ equivalents. Values represent the contribution of annual emissions per hectare.

The inclusion of pastures in the Llanos plays a much more important role in affecting the overall E-GWP. Due to the modest emissions of methane and nitrous oxide from pastures and the very high sequestration of atmospheric $CO_2$ as soil organic carbon, pastures can convert the system from a modest source into an important net sink of radiatively important species. The rate and persistence of C accumulation plays a major role in the strength of the sink, especially in the 20-year horizon. Even with rates of C accumulation in soil of around half of the reported value for grass alone pastures in Carimagua, the equivalent E-GWP of annual emissions from one hectare of pastures would be zero.

*The Llanos in the year 2020*

Land use patterns in the Llanos are expected to change in the next two decades. Studies suggest (Smith et al., 1997; Rivas, 1999), that the area of crops could increase up to two times the current values while the area under pastures will also double in the same period. The area under grass-legume pastures is expected to grow from 0.1 to 0.3 Mha, while the area under grass alone pasture will continue to dominate and will increase from 0.5 to 0.9 Mha. This expansion will be at the expenses of the clay-loam savanna, which has slightly better levels of soil nutrients than the sandy savanna. The area under gallery forest will probably decrease by 10% in the next 20 years assuming the same rate of current intervention. Annual rate of C-sequestration by pastures in soil was assumed as reported for grass alone and grass-legume pastures at Carimagua (Fisher et al., 1994).

Table 4 shows results of a calculation of the integrated E-GWP for the Llanos at present and in the year 2020 for a 20-year time horizon. Under current land use distribution, the Llanos as a whole plays a minor role in the radiative forcing in the earth's atmosphere. Its integrated E-GWP of 9.6 Tg of $CO_2$ equivalents is only about 0.004% of estimated global planetary radiative contribution of about 242,000 Tg of $CO_2$ equivalents (IPCC, 2001).

Table 4. Integrated E-GWP for the Llanos under present and expected land use distribution in the year 2020. Values are equivalent Tg of $CO_2$ calculated for a 20-year time horizon.

| Land use | E-GWP kg $CO_2$equivalents per ha | Area (Mha) | | Integrated E-GWP ( Tg of $CO_2$ equivalents) | |
|---|---|---|---|---|---|
| | | present | Year 2020 | present | Year 2020 |
| Forest | 207 | 1.4 | 1.26 | 0.29 | 0.26 |
| Savanna | 2140 | 9.5 | 8.54 | 20.33 | 18.28 |
| Sandy savanna | 2042 | 1.8 | 1.8 | 3.68 | 3.68 |
| Croplands | 767 | 0.5 | 1.0 | 0.38 | 0.77 |
| Grass alone pasture | -1358 | 0.5 | 0.9 | -0.68 | -1.22 |
| Grass-legume pasture | -17674 | 0.1 | 0.3 | -1.76 | -5.30 |
| Total | | | | 22.24 | 16.46 |

In Figure 10, in addition to the 20-year time horizon a longer term 100-year time horizon has been used to calculate effects of present and expected land use distribution in the Llanos. The development of the Llanos will have small net benefits to the environment by reducing the radiative force of the atmosphere. This benefit will be accentuated in the longer term scenario. Once more the minor role of the Llanos in the context of warming of the planet is emphasized.

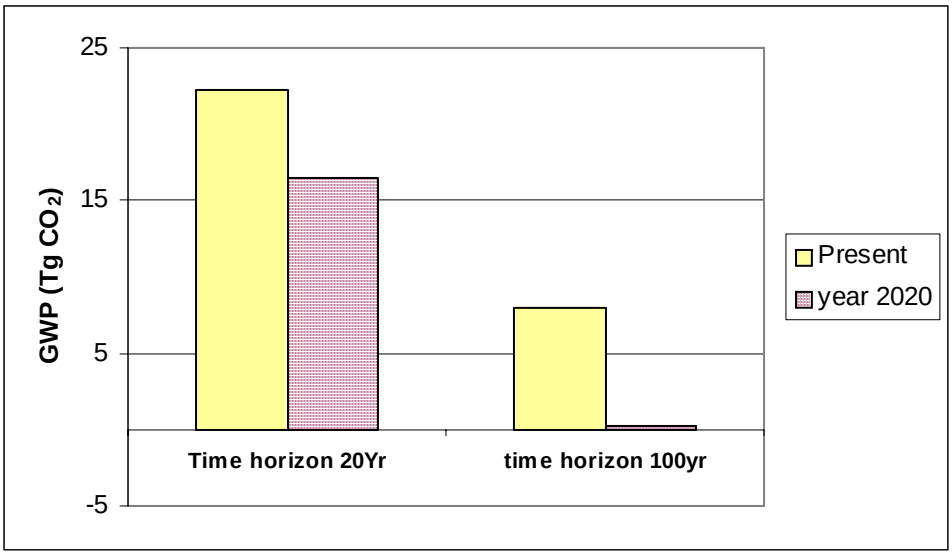


Figure 10. Integrated GWP for the Llanos under present land use and expected land distribution in the next two decades. Two time horizons (20 and 100 years) are considered.

**Conclusions**

This study presents the first data set on fluxes of methane and nitrous oxide for the Colombian Llanos. Results indicate that gallery forest is an important sink for atmospheric methane, while savannas are a minor sink. Therefore, preservation of the gallery forest should be of priority concern as this environment also provides a home for a large biodiversity of endemic plants and animals.

Conversion of soils into cropland does not reduce their methane oxidizing capacity and some of the management practices could even increase their sink strength. This may be the result of eliminating some of the physical constraints that limit the gas exchange between soil and the atmosphere (soil compaction, surface sealing etc.). On the other hand it also increases emissions of nitrous oxide and is equally expected to increase losses of soil carbon as a result of tillage. Despite this, given that the main contributing factors (burning and cattle) are excluded in cropland, it can be anticipated that agriculture will be a better option than savanna for reducing the radiative forcing of the Llanos.

Emission of methane by biomass burning is a key factor in the balance of this gas in the Llanos. Any action that can reduce the area submitted to burning and or the frequency of burning events, will improve the radiative balance in the region. In this respect, conversion of savanna into croplands or pastures is clearly an advantage because burning is eliminated in such land uses. Promoting the re-colonization of the land by gallery forests constitute a win-win situation as it will not only eliminate the burning, but also will increase the methane soil sink strength.

Fire plays a key role in maintaining the biodiversity in the savanna, in addition to other important though not fully understood ecological roles. Consequently, complete suppression of the burning is not a desirable option. Appropriate corridors to maintain the continuity of the savanna ecosystem should always be considered.

Cattle-associated emissions of methane dominate methane budgets in the Llanos. Improving estimates of their actual contribution as well as exploring promising opportunities to reduce their impact by offering forages of higher nutritional value, are important topics for research in the near future.

Natural ecosystems as well as converted lands constitute small net sinks for $N_2O$ in the Llanos. Emission rates are related with the amounts of nitrogen cycled in the soil; nitrogen inputs in the form of fertilizer or green manure cause enhanced emissions. Strategies to manage these inputs in order to minimize nutrient losses and reduce environmental impact require further attention.

In general fluxes of methane and nitrous oxide from soils in the Llanos can be considered low, but fall within the range reported for similar environments in Africa (Seiler et al., 1984), Central America (Mosier et al., 1998), Brazil (Lauren et al., 1995) and Venezuela (Scharffe et al., 1980), and even for tall grass prairies in temperate regions (Tate and Striegl, 1993).

Though pastures will increase methane emissions from cattle due to the increase in the stocking rate as compared to savanna, by avoiding the fire and by sequestering atmospheric $CO_2$ in the form of soil organic carbon, pasture is the only land use option identified in this study, that can shift the land from a net source into a net sink of atmospheric GHG's.

*Influencing the direction of change*

This study has shown that the Llanos are only a very minor contributor to the warming of the atmosphere and that expected intensification of agriculture and cattle production in the coming two decades would not have negative effects on the radiative forcing potential of the region. Despite this, there are other well identified constraints for the sustainability of the natural resource base, whose impact should never be forgotten. Pasture degradation is major cause of pasture abandonment specially in the Brazilian Cerrados and the Amazon. Degradation could result not only in reduced C sequestration in soils but even turn them into net sources of Carbon (Da Silva et al., 2000). Though current pasture degradation is not too severe in the Llanos, unless appropriate management practices were adopted, this could become a critical problem in the region, whose environmental consequences are still to be evaluated.

In the jargon of optometrics, 20-20 means perfect vision. We hope that appropriate vision will be used by policy makers in the design of development plans for the Llanos which allows the region to continue being an environmentally friendly ecosystem in the year 2020.

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**Proceedings LBA Meeting, Manaus, 2002**

# Carbon Storage in Soils from Degraded Pastures and Agroforestry Systems in Central Amazônia: The role of charcoal

Marco A. Rondon[1], Erick C.M. Fernandes[2], Rubenildo Lima[3], Elisa Wandelli[3]

[1]*Centro Internacional de Agricultura Tropical CIAT.*

[2]*Department of Crop and Soil Sciences Cornell University - Ithaca, NY 14853 USA*
[3]*EMBRAPA - CPAA, Manaus, AM Brazil.*

## Introduction

*The vicious cycle of deforestation*: Vast areas of the Amazon rainforest have been cleared in the last decades to be converted into pastures. After few years of use, the land is degraded as a result of nutrient depletion, soil compaction and surface sealing. Productivity declines severely and pastures become abandoned, giving place for a succession to secondary forest. A new forest area is then usually cleared to start the process again. Abandoned lands are characterized by very low storage of nutrients and reduced stocks of soil organic carbon (SOC). Some alternatives do exist to recuperate degraded land including the establishment of agroforestry systems. These options are expected to help in restoring soil nutrients and allow C sequestration in both biomass and soils. This poster presents information on C storage in soils under 10 year old agroforestry systems and secondary vegetation, as well as on primary forest for an area in the Central Amazon.

*The Charcoal contribution.* Natural and anthropogenic fires are frequent in the Amazon forest. Combustion of plant material is never complete specially for roots, and this result in variable amounts of residual charcoal being added to the soils. Charcoal is ubiquitous in Amazonian soils and is present in a range of size particles: from coarse (>2 mm diameter) usually found mostly at the soil top layers, to very fine particles (<50 μm) distributed along the soil profile.

Charcoal is mainly carbon in an extremely inert form but until now not much effort has being devoted to define this as a separate C pool in soils. Given its inherently heterogeneous distribution, charcoal presence creates problems when trying to assess the effect of a given land management option on C sequestration by soils. Changes of SOC are normally small for short to medium terms and could be masked by the "noise signal" created by the charcoal. This noise also confounds interpretation of the dynamics of SOC when the $^{13}C$ technique is used (Desjardins et al., 1996). To be able to separate any difference in SOC resulting from different land use, charcoal contribution to total soil C has to be assessed. In this study we evaluated the contribution of different charcoal size classes to total soil C.

## Materials and Methods

The project is being conducted at EMBRAPA-CPAA research station at km 54 north of Manaus, Brazil. In a long-term experiment, four alternatives to recover degraded land in the Central Amazon have been studied: establishment of two silvopastoral (SPS) and two agroforestry (AFS) systems: SPS included ASP1 (medium fertilizer inputs) combining *Brachiaria brizantha*, *Desmodium ovalifolium* and mahogany (*Sweithenia macrophyla*) and low input ASP2 in which *B. Brizantha* has been replaced by *B. humidicola*. AFS were: AS1 based on palm species(*Bactris gasipaes and Euterpe olearaceae*) and also includes Cupuaçu (*Theobroma grandiflorum and Colubrina acreanaea* ). AS2 is based in native and exotic fruit trees (6 species) and also includes Mahogany and Brazil nut (*Bertholletia excelsa*). Secondary vegetation of similar age to the AFS and primary forest soils have been used as controls. Three repetitions of every

system and control were evaluated. The area has a mean annual rainfall of 2250 mm and average temperature of 28°C. Soils are high clay Oxisols, very low in fertility.

Given the complexity of the AFS studied, to obtain a representative sample of soil from a given systems is a complex task. Soil sampling was based on a species-interaction strategy. In each plot (3000 $m^2$), a composite soil sample of five sites was taken from each of the main plant-plant interaction found in the plot. Samples were separated at 0-5, 5-15, 15-30, 30-60 and 60-100 cm depth. Soil was air dried and gently dissagretated to <4mm diameter. A type Jones sample divider was used to separate soil in three size classes: 2-4 mm, 0,5-2mm and less than 0,5 mm diameter. Charcoal was separated by hand in a subsample of the 2-4 mm (G) and 0.5–2mm (M) size. Then, the original sample (free from medium to large size charcoal) was reconstituted to be analyzed for total C and nutrients. In a subset of samples, the fine fraction was used to determine black carbon content using the methodology of Kuhlbusch (1995). Finely ground soil (<53 um) was oxidized with repeated doses of NaOH (four times), HCl, $HNO_3$, $H_2O_2$, $H_2O$ and finally thermally oxidized in a Oxygen-rich environment at 350C for 3 hours. C content in the original sample and the final residue were determined in a dry combustion CHN analyzer. C content in the residual soil after the chemical and thermal oxidation is defined as black carbon, and in addition to charcoal it includes the most highly resistant components of SOM.

**Results and Discussion**

*Charcoal.* Figure 1 shows the relative contribution from charcoal in each size class to total charcoal for the case of the ASP1 system. Charcoal in medium and large sizes is more abundant in the surface and subsurface layers and decays strongly as soil gets deeper. It is worth nothing however, that medium size particles are found even at 1m depth suggesting or localized burning of deep roots or migration of charcoal from the surface probably through root or soil fauna channels. Variability in charcoal content in the M and G size classes was high indicating non-homogeneous distribution of charcoal in soils. The contribution of the fine fraction is much more homogeneously distributed through the soil profile.

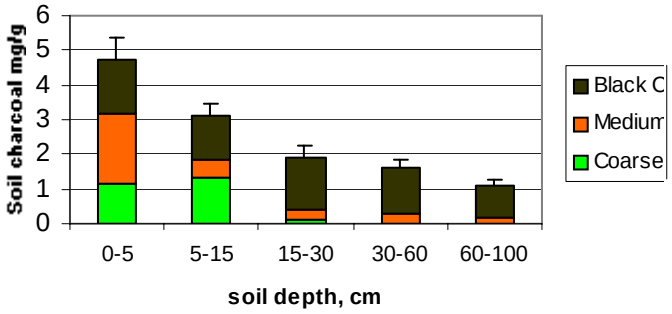


Figure 1. Charcoal distribution in various soil particles sizes. System ASP1.

Figure 2 represents the relative contribution of charcoal fractions to total soil C. It can be seen that charcoal can account for between 5 and 15% of total soil C, with higher proportions found in the top soil layers.

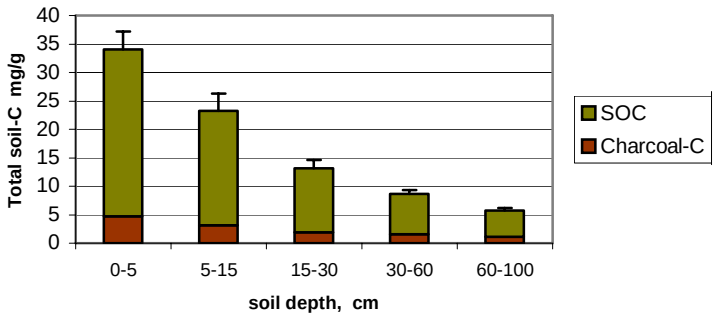


Figure 2. Charcoal contribution to total soil-C. System ASP1.

*Soil C stocks.* There were found significant differences among C stocks in most soil layers except in the surface layer where variability was the highest. Figure 3 shows the C stocks stored in the 60-100 cm depth soil layer. Carbon storage at that layer was higher in the primary forest soil as compared to other systems, being followed by the fruit based system (which includes some large trees), suggesting an important contribution from deep roots to C buildup. The ASP2 low input system presented the lowest C storage at such depth. This is in agreement with lower aerial biomass estimates for such system reported by McCaffery (Poster in this meeting).

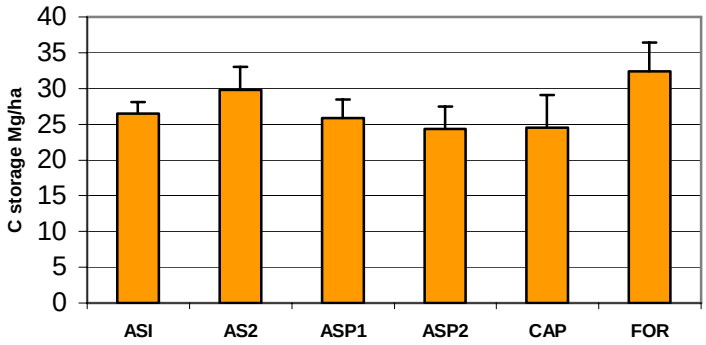


Figure 3. C storage in soils at 60-100 cm depth

In Figure 4, total C storage in the soil profile is presented for all systems (data correspond to C content after removing the coarse and medium size charcoal fragments). Significant differences were found between systems. When the charcoal contribution is taken into account, such differences become hidden. Forest soils store the highest amount of C (121 $Mg.ha^{-1}$), followed by the AS2 system with 116 $Mg.ha^{-1}$. On the other extreme, soils under secondary vegetation and ASP2 system presented the lowest stock (106 $Mg.ha^{-1}$). Results in this study indicate that agroforestry systems permit a moderate recovery of soil C stock relative to the control under secondary vegetation. Rates of C accrual are in the order of 1.8 $Mg.ha^{-1}.y^{-1}$. This contrasts with much higher rates reported for temperate and tropical regions (Bruce et al., 1999). It is worth mentioning however, that the initial soils were highly degraded after supporting cattle grazing for more that 12 years. Application of fertilizer was also very low to the systems. This suggests that there is space for increasing C accumulation rates through the practice of agroforestry.

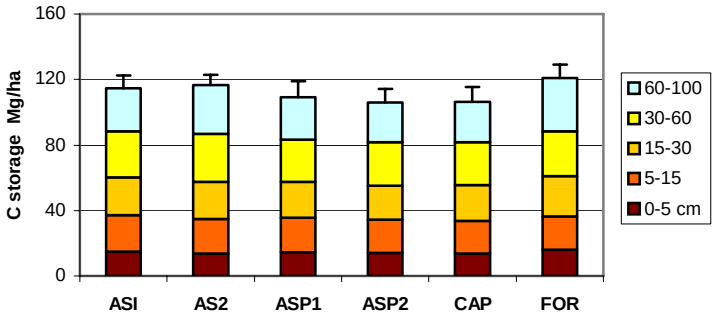


Figure 4. C storage in soil under various land uses in the Central Amazon

## Conclusions

Charcoal is an ubiquitous constituent of the soils in the Central Amazon and appreciable amounts can be found even at 1 m depth. Coarse fragments are located preferentially at the surface layers showing high heterogeneity in its spatial distribution. Fine particles distribute rather homogeneously through the soil profile. Charcoal derived-C can account for as much as 15% of total soil C. Separation of coarse and medium size charcoal fragments is very important to allow appropriate comparison between SOC in different land use systems in areas where fire is a factor in the natural or human influenced management of the forest. Although charcoal separation and the assessment of black carbon is a time consuming process, given that charcoal is a remarkably stable pool, once a baseline has been established for a certain site, the same information could be used in future studies.

Though various studies have shown that soils under pastures enable high rates of C sequestration (Fisher et al., 1994) in our sites, the lack of fertilizer inputs and the high initial degradation of the land prevented a significant accrual of SOC as compared to soils under secondary vegetation.

Even under unfavorable initial conditions, agroforestry systems allow net C accumulation in soils, permitting the soils to move in a 10 years time period, from 87% to 95% of the total C stocks in the primary forest.

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# Biodiversity and ecosystem services in agricultural landscapes – are we asking the right questions?

M.J. Swift[1], A-M.N. Izac[2] and M. van Noordwijk[2].
[1]Tropical Soil Biology and Fertility Institute of CIAT
[2]International Centre for Research in Agroforestry

## Abstract

The assumed relationship between biodiversity or local richness and the persistence of 'ecosystem services' (such as sustained productivity and regulation of water flow and storage) in agricultural landscapes has generated considerable interest and a range of experimental approaches, but the abstraction level aimed for may be too high to yield meaningful results. Many of the experiments on which evidence in favour or otherwise are based are artificial and do not support the bold generalizations to other spatial and temporal scales that are often made. Future investigations should utilise co-evolved communities, be structured to investigate the distinct roles of clearly defined functional groups, separate the effects of between- and within-group diversity and be conducted over a range of stress and disturbance situations. An integral part of agricultural intensification at the plot level is the deliberate reduction of diversity. This does not necessarily result in impairment of ecosystem services of direct relevance to the land user unless the hypothesised diversity-function threshold is breached by elimination of a key functional group or species. Key functions may also be substituted with petro-chemical energy in order to achieve perceived efficiencies in the production of specific goods. This can result in the maintenance of ecosystem services of importance to agricultural production at levels of biodiversity below the assumed 'functional threshold'. However it can also result in impairment of other services and under some conditions the de-linking of the diversity-function relationship. Avoidance of these effects or attempts to restore non-essential ecosystem services are only likely to be made by land-users at the plot scale if direct economic benefit can be thereby achieved. At the plot and farm scales biodiversity is unlikely to be maintained for purposes other than those of direct use or '***utilitarian'*** benefits and often at levels lower than those necessary for maintenance of many ecosystem services. The exceptions may be traditional systems where ***intrinsic*** or 'non-use' values continue to provide reasons for diversity maintenance. High levels of biodiversity in managed landscapes are more likely to be maintained for reasons of intrinsic ('non-use'), ***serependic*** or 'option' values or utilitarian (direct use') than for ***functional*** or 'indirect use' values. The major opportunity for both maintaining ecosystem services and biodiversity outside conservation areas lies in promoting diversity of land use in ways that meet these requirements at the landscape scale. This requires however an economic and policy climate that favours diversification in land-use products and diversity among land users.

## Introduction

The role of biological diversity in the provision of ecosystem goods and services and the way this role can be valued and managed during agricultural intensification is much debated but still poorly understood. A key problem in all debates on biological diversity is that the abstraction 'diversity' has often not been distinguished from the specific attributes of the community of organisms that is under study in any particular location or system For instance if the interest lies in the functional roles of the community these may depend on the 'structure' of the vegetation and the relationships between different 'functional groups', rather than on diversity as such. Experiments based on random species assemblages may be appropriate tests for hypotheses about 'diversity' per se, but tell us very little about the largely self-selected assemblages that make up natural ecosystems. In the case of agro-ecosystems, whilst the dominant crops or livestock are artificial, by far the majority of the species are self-selected. So, are we asking the right question? Does the loss of diversity at plot-to-global scales imply a threat to critical ecosystem functions? Can we identify thresholds in such a process?

Global diversity derives from the lack of overlap in species, genetic or agro-ecosystem composition between geographic or temporal domains as embodied in the niche concept. While 'agricultural development' affects local (ie. plot level) diversity, it probably has even stronger effects by homogenizing at higher scales, facilitating the movement of 'invasive species' and the introduction and spread of 'superior' germplasm of desirable species. Scale is thus of overriding importance in our analysis and we may well find that answers may appear contradictory between different ways of defining temporal and spatial boundaries to the system under consideration. In this review we will first consider the concepts of 'biodiversity' and 'ecosystem functions', and then the evidence that links relevant aspects of the two, before we embark on an exploration of how this relationship depends on scale and can be 'managed'.

**The biological basis of ecosystem goods and services**

Humans have evolved as part of the world's ecosystems, depending on them for food and other products and for a range of functions that support our existence. Natural ecosystems, as well as those modified by humans, provide many services and goods that are essential for humankind (Matson et al., 1997). Efforts and interventions to manipulate (agro)ecosystems to meet specific production functions, represent costs to the rest of the ecosystem in terms of energy, matter and biological diversity, and often negatively affects goods and services that so far were considered to be free and abundant. These are anthropocentrically regarded as services because they provide the biophysical necessities for human life or otherwise contribute to human welfare (UNEP, 1995; Costanza et al., 1997). Most if not all of these services are based on a 'lateral flow', or movement across the landscape of biomass (such as food, fibre and medicinal products derived from the sea, inland waters or lands outside of the domesticated 'agricultural' domain), living organisms and their genes, or earth (nutrients), water, fire or air elements. Examples of ecosystem services particularly important for agroecosystems and agricultural landscapes are: maintenance of the genetic diversity essential for successful crop and animal breeding; nutrient cycles; biological control of pests and diseases; erosion control and sediment retention; and water regulation. At a global scale other services become important such as the regulation of the gaseous composition of the atmosphere and thence of the climate. A list of such services is given in the first column of Table 1 of the Appendix, and their connection to lateral flows is discussed by Van Noordwijk et al (Table x, this volume).

These ecosystem goods and services are biologically generated. The community of living organisms within any given ecosystem carries out a very diverse range of biochemical and biophysical processes that can also affect neighbouring systems. These can be described at scales ranging from the subcellular through the whole organism and species populations to the aggregative effect of these at the level of the ecosystem (Mooney and Schultze 1993). All ecosystems have permeable boundaries with respect to material exchanges but the within–system flows usually dominate those between systems, such as between land-use or land-cover types within a landscape. For purpose of this paper we define *ecosystem functions* as *the minimum aggregated set of processes (including biochemical, biophysical and biological ones) that ensure the biological productivity, organisational integrity and perpetuation of the ecosystem*. There are no agreed criteria for defining a minimum set of such functions but for the purposes of this paper the second column of Table 1 lists ecosystem functions alongside the ecosystem services they provide. Further explanation of these relationships is given below but it is useful to note that these functions can be pictured as having a hierarchical relationship. The energy captured in primary production is utilised in the herbivore and decomposer food chains. Interactions between these three subsystems occur through nutrient exchanges and a variety of biotic regulatory mechanisms as well as by energy flow. In particular the balance between the constituent processes of primary production and those of decomposition determines the amount of energy and carbon maintained within the system and is the major natural regulator of the gaseous composition of the atmosphere at a global scale (see Swift 1999).

**Biological diversity and its values**

Most discussions and empirical studies on biodiversity have focused on issues of a relatively small range of organisms. In contrast, the Convention on Biological Diversity defines its area of concern as:

" …the variability among living organisms from all sources, including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems" (Heywood and Bates, 1995). Diversity within each one of these three fundamental and hierarchically related levels of biological organisation can be further elaborated as follows: genetic diversity is the variation within and between species populations; species diversity refers to species richness, that is, the number of species in a site, habitat, ecological zone or at global scale; ecosystem diversity means the diversity of assemblages (and their environments) over a defined landscape, ecological zone or at global scale.

Biodiversity in this paper refers to the totality of the species (including the genetic variation represented in the species populations) across the full range of terrestrial organisms i.e. invertebrate animals, protists, bacteria and fungi, above- and below-ground, as well as the vertebrates and plants which often constitute the main concerns of biodiversity conservation. With a definition as broad and inclusive as this, it is highly unlikely that any clear and precise statements about relationships between 'biodiversity' and functions can be formulated and tested that can be helpful in guiding human activity. Similar to the situation with 'watershed functions' we may find that discussions on components of the overall biodiversity concept in relation to land use are more productive and open to progress than those that stay at the aggregate level. In the section immediately following we shall refer to the diversity within ecosystems (often termed alpha diversity) and in later sections to that at the broader scale of the landscape (which embraces concepts of both beta and gamma diversity).

The analysis of biodiversity and its management is highly influenced by the perspective used. In particular different sectors of society attribute different values to biodiversity. Broadly speaking four different types of value can be usefully recognised, although different terminology is often used..First is the ***intrinsic*** or 'non-use' value of diversity to humans, which comprises its cultural, social, aesthetic, and ethical benefits. Some groups in society attribute high social and religious values to individual species or communities of organisms; others derive value from the simple fact of high diversity per se in such systems as tropical rainforests or coral reefs. Second is the ***utilitarian*** or direct use value of components of biodiversity, i.e. the subsistence, financial and monetary benefits of species or their genes derived by one or other sectors in society. The direct use value may be private and accrue to the land managers (farmers, local community, government). This is most obvious with respect to high value agricultural crops but also applies to the other types of good listed in Table 1. For instance, the pharmaceutical industry values the tropical forest tree *Prunus africana* very highly because its bark contains chemicals used for manufacturing a drug. Another example is that in Africa, many farmers living near natural (and protected) forests withdraw substantial monetary benefits from their hunting and from collecting plants and tree products in these forests (Pottinger and Burley, 1992).

Thirdly, biodiversity can be said to have ***serependic*** or 'option' value. This is the belief in future but yet unknown value of biodiversity to future generations, for example the presence of a microorganism with an as-yet undiscovered genetic potential for industrial products. These three types of value of biodiversity are ethnocentric and depend very much upon the cultural values and preferences of different sectors of society. This is why some authors, interested in such values, stress that 'the conservation of biological diversity depends as much on society's ethical views as on facts' (Barrett 1993).

Finally, biodiversity and the integrity of processes that maintain and generate diversity have ***functional*** significance. This may be the 'indirect use' value of Kerry Turner (1999). Part of this functional significance may be of direct utilitarian value for *Homo sapiens* in the production of goods and services that can be priced. Beyond this lie a range of ecosystem services that are of acknowledged benefit to humans but which generally lie outside the boundaries of recognised utilitarian benefit. The purpose of this paper is to analyse the functional values of biodiversity with particualr reference to the diversity in agricultural landscapes but it also has a more general significance for life over and beyond this single species. This non-human significance, however, can only be translated into a 'value' that can play a role in human decisions via human 'champions' and thus cannot in practice be separated from the intrinsic value.

## What is the relationship between diversity and function?

### Concepts

Biologists have for many decades speculated on the question of why there are so many species of living organism. As explored in the theory of island biogeography, the diversity within any ecosystem at any point in time is the result of a 'self selection' process, that involves co-evolution of the species comprising the biological community within a given ecosystem by interactions among them and with the abiotic environment through time. This is not an isolated process. New species may enter an ecosystem from neighbouring areas, some establishing themselves and others failing to do so. Partly as a result of successful newcomers or new adaptations emerging in existing ones (be they competitors, predators, pests or diseases), and partly as a result of fluctuations in abiotic environmental conditions, some of the existing species may become (locally) extinct over any period of time. The species richness of any given ecosystem or land unit is therefore a dynamic property. In agro-ecosystems farmers take a dominant role in this dynamic by the selection of which organisms are present, by modifying the abiotic environment and by interventions aimed at regulating the populations of specific organisms ('weeds', 'pests', 'diseases' and their vectors and alternate hosts). The dynamic nature of the (local, patch level) diversity of any system, whether natural or agricultural, is often underrated, as is the importance of the selection pressure and process. The diversity of any system is not adequately represented simply by the number of species (or genotypes) present, but by the relationships between them in space and time. Attempts to assemble combinations of the same number of species under slightly different conditions and in particular without the history of interaction often fail (Ewel et al 1991). But what makes any existing species combination into a 'system' is still largely elusive. Some insights obtained in analysing food webs may help. For example Neutel (2001) showed that the majority of belowground food webs constructed from random combinations of organisms did not meet dynamic stability criteria, even though all parameters such as abundance of groups and dynamic properties were chosen in a 'normal' range when considered one-by-one. Yet, systems with the actual parameter combinations that are attained in the field do [DID?] meet stability criteria, suggesting that partly uncovered rules about the proportionalities and co-variance within the normal range are crucial.

Debate on the relationship between biological diversity and ecosystem function has a long history which has taken on new vigour (and sometimes even rancour) since the advent of the Convention on Biological Diversity (see Woodwell and Smith 1969 for the older literature and Schulze and Mooney 1993, Mooney et al 1995, 1996, and many of the citations below for more recent discussion). Vitousek and Hooper (1993) contributed a major focus to this debate through hypothesising three different possible relationships between plant diversity and broad-based ecosystem functions such as the rate of primary production (Figure 1). Their analysis of current evidence led them to propose that the asymptotic relationship shown as Curve 2 in Figure 1 was the correct one. This suggests that whilst the essential functions of an ecosystem, such as primary production, require a minimal level of diversity to maximise efficiency this effect is saturated at a relatively low number. Swift and Anderson (1993) proposed that this relationship could also apply to the decomposer system. Examples of essential functions in this case are the basic suite of catabolic enzymes (e.g. for cellulolysis, lignin degradation etc), the facilitation role that invertebrates play by reducing particle size by their feeding activity, and biophysical processes of pore formation and particle aggregation. It is interesting to note however that the communiies of organisms contributing to the ecosystem function of decomposition are taxonomically much more diverse than those of primary production.

### Experimental approaches

Over recent years a number of authors have reported on experiments investigating the links between diversity and specific functions (e.g. see Ewel et al 1991, Naeem et al 1994, Naeem and Li 1997; Tilman and Downing 1994; Tilman et al 1996,1997; Hooper and Vitousek 1997) that appear to broadly corroborate the predictions of the Vitousek-Hooper hypothesis for primary production. This has however generated an equal amount of discussion in refutation and the issue remains significantly a matter of interpretation and opinion (see Grime 1997; Hodgson et al 1998; Lawton et al 1998; Wardle 2000; Naeem

2000). There is no space here to review these studies in detail. Each one of the experiments quoted can be criticised in one way or another. The strictest interpretation of many of the experiments would be that the conclusions apply only to the specific combinations of organisms used in the tests, and in most cases these are assemblages constructed for experimental purposes rather than naturally co-evolved communities. At a fundamental level such experiments suffer from a basic methodological paradox – in order to describe and understand diversity and complexity we need to simplify it, and take away the self-selection that governs real-world diversity. Dealing with the totality is impossible. For instance there is no single (or combination of) methods that would allow for the total inventory of the species richness of even a small volume of soil. It is thus difficult to draw general conclusions about 'diversity' as such and in particular with respect to naturally co-evolved communities. The results of such 'un-natural' experiments may however be more applicable to agricultural systems that in one sense can be said to have been assembled in a similar way.

**The minimum diversity required within a functional group**

One potentially valuable interpretation of the Vitousek-Hooper relationship has been that the minimal level of diversity required to maximise the production function consists of representatives of an essential set of 'functional groups' of plants. A functional group may be defined *' a set of species that have similar effects on a specific ecosystem-level biogeochemical process'*. As Vitousek and Hooper put it the 'essential' plant species are those that contribute in different ways to the key ecosystem functions – in the case of primary production by exploiting different components of the available resources by differences in canopy structure to maximise light capture or symbionts and root architecture to optimise capture of water and nutrients. Drawing together the threads of this discussion we [hypothesise that?] suggest that *'the minimum diversity essential to maintain any given ecosystem function can be represented by one or a few functionally distinct species i.e. one or a few representatives of a small range of functional groups*' is a useful null-hypothesis to guide investigations of the functional significance of biological diversity in agricultural systems. It may need further operationalization for specific ecosystem contexts, however. The total diversity required then depends on the number of functions that are recognized and to the degree of overlap in 'functional groups' between these different functions.

**Which functional groups of organisms are essential?**

The functional group concept is briefly discussed in the Appendix to this paper and Table 1 lists a minimal set that we propose are needed to provide the ecosystem goods and services we have been addressing.

The classification of plants into functional groups has drawn a great deal of recent attention because of the recognition of the pressure being exerted on terrestrial ecosystems by global climate change (Smith et al 2000) The primary producers (together with the vertebrate herbivores) are our major source of food and are also the source of fibre and other useful materials such as latex. Molecules with antibiotic, therapeutic, pesticidal or similar biological activities utilised by humans are however synthesised by many groups of organisms (e.g. bacteria and fungi) and are often very specific in origin. Diversity is therefore an essential pre-requisite for maintenance of supply, particularly of new products, although the capacity to biologically generate or synthesise new compounds under laboratory conditions has been greatly increased by the advent of genetic engineering.

Decomposition and mineralisation of organic matter of plant and animal origin and synthesis and decomposition of soil organic matter are carried out by a very diverse community of invertebrates, protists, bacteria and fungi. Other elemental transformations often are carried out by a diverse set of functional groups with very specific biochemical capacities, for example certain of the bacteria of the nitrogen cycle. Diversity within these groups varies from very low to high, but it can be experimentally demonstrated that a single species per function may be sufficient under a given set of environmental conditions.

The dominant biological properties regulating water flow and storage in the soil are the plant cover, the soil organic matter content and soil biological activity. Macrofauna such as earthworms, termites and

other invertebrates influence the pore structure. Bacteria and fungi modify the extent of aggregation of soil particles. All these organisms and an additional range of decomposer organisms influence synthesis and decomposition of soil organic matter. Control of erosion and trapping of sediment is regulated by the architecture of the plants at and below the soil surface, the amount (and hence the rate of decomposition and movement) of surface litter, and the physical quality and organic matter content of the soil.

Under natural conditions the interactions between the populations of organisms at the various trophic levels i.e. plants, herbivores, symbionts, parasites, decomposers, predators and secondary predators result in a dynamic balance of population sizes. The total diversity is huge but any single population is only influenced by a relatively small number of interactions. Biological regulation of a specific pest, pathogen or disease vector of interest to humans is therefore dependent on a significant level of diversity among its parasites or predators. These in their turn may depend on other elements of diversity for their survival e.g. the presence of microhabitats, alternative hosts, nesting or egg laying sites, or refuges often provided by the vegetation.

Chemical transformation of toxic organic elements, chelation or absorption of basic elements and removal of toxic levels of nutrients or other chemicals from ground, running or soil water may be carried out by a diverse range of bacteria, fungi or protists often in association with invertebrates. In well-established waste disposal systems these organisms form 'guilds' which function in a very integrated way. As with decomposers distinct guilds may operate across different ranges of environmental gradients of temperature, pH, moisture, etc.

The earth's climate is regulated by the content of 'greenhouse' gases in the atmosphere –($CO_2$, $CH_4$, $N0_x$, etc). Carbon dioxide is emitted or taken up under one circumstance or other by the majority of living organisms and is thus a phenomenon of such generality as to defy attempts to relate its dynamics to changes in diversity other than the totally catastrophic. Methane and the nitrous oxides are however the product and/or substrate for a relatively small number of bacterial species in the soil associated with soil, decomposing organic matter or the gut flora of animals. Diversity change may thus be more significant in these cases.

It is worth noting that even when the discussion of function-diversity relationships is reduced to considering only functional groups, the minimum extent of necessary diversity that is implicated is still very high.

**What is the significance of diversity within functional groups?**

If the above hypothesis is correct and ecosystem functions can be maintained by the minimal number of representatives of the essential functional groups then the questions remains as to what is the significance of the often high diversity within functional groups – which takes us back to the basic biodiversity question 'why are there so many species'? Answers to this question depend strongly on the scale of consideration. Different species often occupy similar ecological roles in geographically separated areas, and one of the major threats to local species is the lateral flow of organisms once such geographical barriers disappear. Replacement of local species by intrusive exotics does not necessarily change ecosystem processes, or local richness, although there are dramatic exceptions for specifically successful (from the perspective of the invader, at least) invasions. Such invasions are likely, however, to reduce global diversity and in fact have been identified as one of the major drivers of 'global change'

Vandermeer et al (1998) summarized the main issues in the discussion on the role of diversity in agro-ecosystems in the following three hypotheses of links between diversity and function:

1. Biodiversity enhances ecosystem function because different species or genotypes perform slightly different functions (have different niches);
2. Biodiversity is neutral or negative in that there are many more species than there are functions and thus redundancy is built into the system;
3. Biodiversity enhances ecosystem function because those components that appear redundant at one point in time become important when some environmental change occurs.

It is valuable to note that these are not necessarily mutually exclusive hypotheses, as they may refer to different space and/or time aspects of the system and the function of specific concern. We need to clearly separate the question of how the current diversity came into being (the 'self organization' of the system, based on the success in the evolutionary history of all component species) from the human or teleological perspective of the relevance of this diversity. Just as we have to distinguish between 'diversity per se' and 'diversity of actual systems', we have also to recognize that not all components of a system have the same probability of being lost as a result of simplification of agro-ecosystems and some functions may therefore be more resilient than others. Differences in life histories of the key groups of organisms confer different temporal and spatial contexts to their role in the ecosystem and their responsiveness to its self-organising properties.

The third of Vandermeer et al's (1998) hypotheses is extremely pertinent to the question of how much of this diversity is needed to maintain ecosystem goods and services in the face of agricultural intensification and other aspects of ongoing 'global change'. There is certainly substantial experimental evidence that the many key functions can be maintained by only small numbers of species within a particular functional group. For example monotypic cover by perennial plants can be as effective as a diverse community in controlling erosion. Although the decomposer community of a particular soil may be very diverse only a minority of the hundreds of species of fungi, bacteria or invertebrates participate in the decomposition process at a given time and place. The extent of redundancy implied by this can be demonstrated under laboratory conditions where decomposition can be fully mediated by single species cultures of enzymatically-diverse organisms such as white-rot basidiomycete fungi whilst in nature the same process may be carried out by several species of fungi, bacteria and animals (Swift 1976, Giller et al 1997).

The third hypothesis raises questions whether key functions can be maintained by one (and the same) species under all circumstances. This addresses the issue of the capacity of ecosystems to adapt to changing circumstances that result from elements of stress and disturbance. The capacity of a system to respond to and recover from disturbance is termed its resilience. This property has been attributed to the degree of connectivity within an ecosystem, a feature that depends at least in part on the composition and diversity (Holling 1973, 1986; Allen and Starr 1982). Diversity within functional groups may provide an important means for increasing the probability that ecosystem performance can be maintained or regained in the face of changing conditions. For the below-ground community for instance there is evidence that the same enzymatic function is carried out by different species of bacteria or fungi from the same soil under different, and even fluctuating, conditions of moisture stress or pH (see Griffin 1972 for discussion of this). In the case of plants different species may play a similar functional role in different seasons, under varying conditions of climatic or edaphic stress and in different stages of patch-level succession.

**Resilience and diversity thresholds**

Functional diversity thresholds are thus likely to be higher in the real world than in the relatively controlled situations under which most of the experiments on diversity-function relationships have been conducted. Recognition of the importance of diversity to the property of resilience suggests furthermore that the implication of equilibrium in the way that Figure 1 is drawn (see also figures 2 and 3) may be misleading. The shifts between different states of functional efficiency with changes in diversity are more likely to be rather abrupt. Perhaps a case could be made recognising resilience as an ecosystem service rather than a property. An alternative view, however, is to see resilience as a property which varies among functions rather than a unitary ecosystem property. The decomposition function for example, may be substantially more resilient than that of the regulation of specific pest populations.

Resilience is a concept that requires consideration of different spatial scales. The resilience of any local system after shocks that lead to local loss of diversity depends strongly on the ability of organisms to recolonize from the neighbourhood, and thus on the distance to the nearest suitable habitat and the dispersal of the organisms in question.

## Managing biodiversity and ecosystem services in agricultural landscapes

### What is the impact of agricultural intensification on biodiversity and ecosystem functions?

Our main concern in this paper is with biodiversity issues in agricultural landscapes i.e. landscapes containing agroecosystems. Agroecosystems can be defined as (natural) ecosystems that have been deliberately simplified by people for purpose of the production of specific goods of value to humans. The simplification down to one or a few productive plant or animal species is implemented for greater ease of management and specialisation of product to suit market demands, especially in highly mechanized forms of agriculture. In an ecological sense the system may be seen as one which is maintained by a high frequency of disturbance, in an early successional stage (Conway, 1993). In such systems a distinction has been made between 'planned' and 'associated' diversity (Swift et al 1996; GCTE 1997). The *planned diversity* is the suite of plants and livestock deliberately retained, imported and managed by the farmer. The composition and diversity of this component strongly influences the nature of the *associated biota* – plant, animal and microbial. The issue is more complex than the single issue of the extent of planned biodiversity that is maintained however. Agroecosystems are managed by substitution and supplementation of many of the natural ecosystem functions by human labour and/or by petro-chemical energy or its products. In addition to their direct effects on production these interventions provide the means to reduce the risk associated with reliance on ecosystem services, although it can be argued that this is serving to substitute one set of risks for another – that of dependence on the market. Furthermore whilst substitutions may buffer some of the functions they also run the risk of further damaging others. For instance the addition of pesticides may control diseases of immediate negative impact but also kill non-target organisms with other functions such as pollination or soil fertility enhancement.

During agricultural intensification the diversity of crops and livestock is reduced to one or a very few species of usually genetically homogenous species. The varieties are selected or bred for yield (e.g. high plant harvest index), taste and nutritional quality. Plant arrangement is commonly in rows, fallow periods are bare, sequences may be monospecific (varietal) or of two or rarely more species. This is in contrast to natural ecosystems where the genetic diversity of plants (both within and among functional groups) is high but varies in relation to environment. The effects of land use change and agricultural intensification on biodiversity and associated functions are still poorly understood but conversion to agriculture almost always results in fewer species of both planned and associated biota with lower genetic variation and representing less functional groups. Nonetheless the extent of diversity in even so-called monocultures may be underestimated by plot-level assessment of diversity at any point in time. A rapid interannual turnover of the germplasm is often employed to stay ahead of the evolutionary race with pests and diseases, adding a time dimension to diversity that may exceed evolution in natural systems, albeit with respect to a narrow genetic base. This varietal turnover depends however on 'externalized' functions of maintaining genetic diversity in gene banks, and on the mechanisms of rapid multiplication and transfer of such germplasm. This situation contrasts with that of extensive agricultural systems where diversity is deliberately maintained within the system with or without external exchange. Here a plot-level assessment may have more relevant boundaries of measurement, although lateral flows of organisms exist here as well. Production systems based on perennial crops and trees provide less opportunity for rapid turnover of varieties for obvious reasons, and there clearly is a much stronger need here for maintaining plot-level diversity as a risk management strategy (Van Noordwijk and Ong, 1999).

### Primary production

Whilst many recent experiments have tended to confirm that community primary production may be maximised by a low-number diversity of functional types (see above) there is also abundant evidence that mono-typic stands can reach the same levels of production within relatively narrow environmental conditions. Biomass production is however not the only function or service performed by plants in ecosystems. The secondary functions related to ecosystem services may be more biodiversity-sensitive than that of food production. 'Intensive' production systems for specific high-value products (e.g. spices) can however be very diverse. Another exception may be in relation to pharmaceutical and agro-chemical

goods. Most products of these types are initially gathered from natural or secondary vegetation or derived from microbial cultures obtained from soil. Once the markets for such products are established, however, the required control over the concentrations of biologically active substances, and the opportunities for monopolization tend to favour more technically advanced modes of production. Maintaining global diversity is thus essential for both present and future needs although the synthetic capacity brought by the molecular biological revolution is fast rendering this less so. Herbivore diversity is highest in heterogeneous systems with high plant and resource diversity but monotypic vertebrate herds can reach equivalent levels of production in simplified grazing systems. Pest epidemics tend to occur in circumstances of low genetic diversity of the host plants or livestock.

**Nutrient cycling**

Nutrient cycles become more open in agricultural systems with losses of nutrient through offtake in harvest, run-off from compact surfaces, increased volatilisation through a changed surface environment and increased leaching associated with decreased soil organic matter content. These losses can be substituted by inorganic inputs but the efficiency of return to the plant is often low and fertilisation is usually required at levels far in excess of direct crop demand, which further exacerbates the losses and can leads to pollution of groundwater etc. There is substantial evidence demonstrating gains in crop productivity from nutrient additions through mixtures of organic and inorganic sources of nutrients compared with either alone (e.g. Swift et al 1994). Maintenance of organic inputs to the soil is thus an important management strategy for efficient use of external inputs. Advantages in utilising a variety of such inputs have also been demonstrated because of the strong influence of input chemistry (''resource quality') on patterns of mineralisation. The diversity of organisms involved in nutrient cycling may be substantially reduced under agricultural intensification but there is little evidence of significant effects on decomposition and mineralisation processes which has been attributed to a high level of functional redundancy among decomposer fungi, bacteria and microregulators such as nematodes or collembola (e.g. see Beare et al 1997, Giller et al 1997). The significance of this loss of diversity should not however be assumed to be inconsequential. In particular it is unclear how the resilience of the system under conditions of change is influenced by such loss. Organisms with very specific functions, such as those exhibited by some bacteria of the nitrogen cycle, often show specialisation to particular soil conditions such as pH and specific genotypes may be lost as a result of soil degradation. Specific strains of dinitrogen-fixing bacteria may also be lost a result of agricultural intensification resulting in the need for subsequent inoculation (Kahindi et al 1997).

**Organic matter dynamics**

Soil organic matter (SOM) is a keystone component of the ecosystem in the sense that its impact on overall system performance exceeds its relative share in the energy flow through the system. Soil organic matter (SOM) stores and buffers nutrient concentrations, influences water storage in the soil and is a major factor in determining soil structure and thence erosivity. Above all it is a store of energy in the soil that drives many of the soil-based processes. SOM synthesis and decomposition is brought about by much the same community of organisms as those involved in decomposition of plant litter. A well-charted phenomenon is the decline in SOM as a result of conversion of natural ecosystems to agriculture. Farmers utilize the nutrients mineralised as part of this decline of the SOM capital to support high initial levels of crop production after clearance. Soil tillage is also an effective additional way of stimulating the breakdown of SOM and plays a key role in promoting crop yields after land conversion to agriculture, until a new and lower equilibrium between breakdown and formation of SOM is reached. The level of the new SOM equilibrium, with its consequent impact on nutrient cycling, soil water regimes and erosivity, is related to the quantity of plant litter input, which is almost invariably lower than that of natural systems. Crops in intensive systems are usually selected for high harvest indices, and there may be uses for crop residues other than soil fertility maintenance (e.g. fodder or fuel). The SOM content is thus related to the quantity, diversity and mode of management of organic input to soil. A key feature of agroecosystem management is thus the trade-off between the gains in production from 'mining' the SOM versus the

potential negative impact on its other ecosystem services and in particular on system resilience. This 'trade-off' between the different values of SOM has been rarely recognised but become a matter of greater interest as society has begun to realize the potential value of sequestering carbon in soil as a means to slow down the rate of global climate change. A research question of continuing interest is whether the functional properties of SOM are in any way influenced by the diversity of organic materials from which it is synthesised.

**Watershed functions**

The most important factors regulating water infiltration and retention are the extent of ground cover by plants and/or plant litter. The reduction in these, including interposing of periods when ground is bare, leads to greater run-off and diminished infiltration as well as increasing the risk of erosion. Substitution by mechanical tillage can ameliorate as well as aggravate these effects. Monospecific cover can be just as effective as a divers one with respect to limiting run-off and erosion, trapping sediment and promoting infiltration, but to be effective it has to be present year round. Diversity of organic inputs is likely to have a positive effect by widening the probability of differences in timing of litterfall and rates of disappearance from the soil surface. As soil protection on slopes depends more on partially decomposed litter with good ground contact than on fresh leaves that can be easily washed away, the role of plant diversity on slopes is likely to be greater than on flat lands. The macrofauna moving between litter layer and soil strongly influence partitioning of water between surface runoff and infiltration as well as modifying water movement within soil. Interesting examples of the influence of these 'ecosystem engineers' show how circumstance specific diversity effects may be. Soil engineers making macropores in the soil are not welcome in all circumstances. In bunded rice fields, farmers make an effort to destroy soil structure by puddling to reduce the porosity of the soil and building dykes to contain the water. These earthworks may be destroyed by the actions of earthworms and surveys by Joshi et al. (1999) in the Ifugao Rice Terraces (IRT), in the Philippines showed that 125 out of 150 farmers interviewed ranked earthworms as the most destructive pest of terraced rice fields. In a second example the conversion of Amazonian rainforest to pastures has been shown to lead to extinction of the natural earthworm community, which have been replaced in some circumstances by a single exotic species, *Pontoscolex corethrurus*. This has a negative effect on pasture productivity because the introduced worms compact the soil, whereas the native species improve soil structure (Chauvel et al 1999). Inoculation with species from the forest might reverse this effect, but remains to be tested.

**Risks of pests and diseases**

As already indicated the decreased genetic diversity of plant cover increases the risk of pest attack. Simplification of the ecosystem and in particular the use of broad-spectrum pesticides also decreases the diversity of natural enemies and increase risks of pest attack (Lawton and Brown 1993). Pesticides also have negative effects on non-target beneficial organisms including pollinators and beneficial soil biota.

**Greenhouse gas emissions**

Land-use change alters the balance of gas emissions and thence influences global climates. There are very large increases in the $CO_2$ output during clearing from natural vegetation and break down of soil organic matter reserves that are rarely if ever balanced by regrowth. The output of methane may be significantly increased in systems such as paddy rice and intensive cattle production and of nitrous oxides by N-fertilisation. These changes are linked to alterations in soil structure that dominate changes in the activity of a variety of soil organisms (e.g. methanogenic and methanotrophic bacteria) but we are not aware of any documented case where such effects are linked to the absence of functional groups or to biodiversity change per se.

**A hierarchy of functions**

There are a few general conclusions that may be drawn from this brief review of the impacts of agricultural intensification on the relationship between biodiversity and ecosystem services. *First* that

whilst there are a number of clear examples where changes in diversity have threatened the provision of ecosystem services, especially relating to the regulation of pests and diseases, there are also others where the changes in biodiversity seem to be functionally neutral, at least within relatively stable environmental conditions. *Second* there may be some functional groups, particularly micro-organisms such as the decomposers, where the degree of functional redundancy is such that the resilience of the function is very high. These two observations may be generalised by stating that there are no rules to be derived for agricultural systems concerning the importance of biodiversity with respect to the maintenance of ecosystem services that apply across all functional groups and environmental circumstances. Both the concept of 'diversity' and that of 'ecosystem function' are too broad to make generalizations at this level testable. There is a need and potential however to investigate the issues of thresholds of diversity-function relationship within specific functional groups and under circumstances of change in stress and/or disturbance.

Finally we should re-emphasise the importance of the hierarchical control exerted by the plants over the other functional groups (Figure 4, Appendix). This is a particularly important feature when determining management options, not only at the field and farm scale but also at that of the landscape. The plant, decomposer and herbivore subsystems of the biological community interact in a variety of ways but the productivity, mass, chemical diversity (resource quality) and physical complexity of the plant component exerts the strongest influence and is the single most important determinant of both the diversity and the functional efficiency of the other two subsystems. Wardle et (1999a and b) and Yeates et al 1999 showed for example that arthropod and microbial communities were not adversely affected by agricultural intensification provided the type of management (eg. mulching) provided for increases in the quantity and quality of the organic inputs. The maintenance of total system diversity and of the major part of the ecosystem services is thus predominantly determined by the nature of the plant community. This is also of course the main point at which humans intervene in the agroecosystem – to decide the species richness, the genetic variability and the organisation in space and time of the planned biota in the vegetation subsystem.

**Implications for the design and management of agricultural landscapes**

A substantial research investment has been made into agricultural systems that fall short of the full extent of genetic homogenisation and petro-chemical substitution. Examples are agroforestry and other inter-crops, rotations, mulch-based, minimum tillage and integrated livestock-arable systems. All these systems are characterised by maintenance of diversity of plant functional groups above the level of monocropping. The scientific justification for such approaches has generally been made on grounds of greater functional sustainability and the wider spread of risk associated with more diverse products as well as on the recognition that it is line with the management choices of the majority of the rural poor in the tropics. For farmers labour saving and low investment and risk may be the preferred attributes of these systems.

The simplicity of monocultures at field level is only possible as long as farms are part of a germplasm delivery system with rapid access to externalised gene banks and have access to risk buffering mechanisms such as insurance schemes or agricultural subsidies. Large parts of tropical agriculture still operate in a range where such 'externalized' risk management options do not exist and where thus a choice for monocultures carries unaffordable risks. At the farm level ecosystem resilience can be extended beyond resources maintained on farm or in the accessible neighbourhood by being part of a larger agricultural production and germplasm delivery system

Ewel (1986) and Moreno and Hart (1979) are among those who have advocated using plant functional groups as a basis for the (plot level) design of multi-plant agroecosystems. These designs also rely, explicitly or implicitly, on the impact that the effect of increasing the diversity of the vegetation system will have in enhancing the associated biodiversity both above- and below-ground and thence the probability of maintaining ecosystem services over a wider range of stress and disturbance. The evidence comparing such systems is almost entirely however based on assessments of yield, Vandermeer et al (1998) reviewed the literature on inter-cropping of all types and concluded that yield gains in comparison with mono-crops depends on the specific complementarities in resource use and seasonal development of

the components. As risks for the farmer depend on farm level diversity of potentially productive resources rather than on plot-level diversity, the focus of much agroecological research may have been too narrow.

Another key aspect that needs to be changed is the continuing separation of different aspects of management interventions on the base of disciplinary experience, such as soil or nutrient management from pest management. Interventions to ameliorate the impacts on any one of the different ecosystem services (as well as on productivity) are likely to influence others. Practices targeted at productivity but well documented in terms of their supportive, ameliorative or regenerative effect on other ecosystem services should be a top priority.

**Does the relationship between diversity and ecosystem services change across scales?**

Almost all the evidence that exists for the relationship between diversity and function is for the plot (and often the micro-plot or laboratory chamber) scale. But in order to provide policy makers with appropriate advice on the functional value of diversity it is necessary to consider the ways in which the three factors we have been considering – biodiversity, agricultural productivity and profitability, and ecosystem services – intersect at the landscape scale. Whilst the inter-relationships that we have described at the plot (patch) scale may help in understanding what happens at the landscape scale there is also the possibility that the rules change as one shifts across the scales. The productivity of any land-use system can be expressed on an area basis and the aggregate productivity across a landscape on the basis of the fractions occupied by different land uses. Biodiversity however has more complex scaling relationships and cannot simply be aggregated in this way. Nor can many of the functions that have been discussed here.

Much of the diversity in a landscape may exist at scales beyond the farm (between farm variability being larger than within-farm diversity), and the dynamics of diversity thus depend on the degree to which different farms remain (or become more) different. As agricultural research and extension have been based on the economies of scale that are perceived as attainable by homogenisation of farms with similar demands for inputs and services and similar outputs for markets, the trend in agricultural intensification has often resulted in the reduction of inter-farm diversity. This process is generally supported by policy interventions which tend to promote homogeneity in farmer goals, practice and behaviour, at least of over the short term. The agents of change in biodiversity beyond farm level are essentially different from those on farm.

In Figure 2 we hypothesise that the relationship between species richness and specific ecosystem services at the landscape scale may follow a relationship analogous with that of the Vitousek-Hooper model – together of course with all the attendant qualifications. That is to say that ecosystem services at the landscape scale are optimised by a diversity of land-uses, but the number that are required for optimisation is relatively small. If the hypothesis is correct then it would suggest that the presence of a relatively small number of different land-use types should be sufficient to satisfy the functional needs of the majority of ecosystem services. This generality needs however to be detailed for any given landscape into specifics with respect to not only the types but also their sizes, shapes, patterns on the landscape and practices of management.

It can be further hypothesised that at the higher scales of landscape and region the frequency and intensity of disturbance and stress (both natural and anthropogenic) is greater than those at the plot or farm scale and increasingly beyond the control of the land users. Prevention of decreases in the stability of agroecosystems and management of restoration become more difficult and costly and eventually become impossible from both biological and economic perspectives because connectivity is too high and disturbances too large. . The ecosystem services that enhance the resilience and adaptation of systems, such as biodiversity, thus become more and more important a feature of sustainable management as the scale of operation widens.

Figure 3 hypothesises a number of relationships implied in the above discussion. We have argued that at the plot and farm scales individual land managers and farmers manage biodiversity largely through simplification (i.e., by decreasing connectivity and maintaining agroecosystems at a stage of early succession) and substitution. Decreases in connectivity may, under specific conditions reach a threshold level of irreversibility, in which case the agroecosystem loses its resilience. However, the individual land

user can in most cases manage and control agroecosystem disturbances and stresses, such as pest outbreaks or sudden changes in relative prices, by making adjustments in the management of resources (land, water, germplasm, knowledge, labour, capital) at the farm scale. This is pictured as the shift from Curve 1 to Curve 2 in Figure 3, which hypothesises some of the scalar implications of the diversity-function relationship. We know, as shown for small-scale farms in Kenya by Osgood (1998), that many farmers do value genetic and species diversity on their farms, as they are aware that it minimises economic risk by enhancing on-farm diversification of plant and animal production. The history of agriculture provides many examples of how even extreme reductions in biodiversity can be managed, through periods of disturbance, by individual land users by substitution (e.g. chemicals, labour). Therefore, even though biodiversity has important ecological functions at the farm scale, it is nevertheless possible to decrease biodiversity levels very substantially at that scale while maintaining the productivity and resilience of agroecosystems. We postulate however that at higher scales the control and management of disturbances and stresses becomes more and more problematic and costly and the resilience function of biodiversity thus becomes an increasingly important issue in management.

**Keep it simple: maintain ground cover**

We have already emphasised the over-arching influence of the plant cover and diversity on the associated functional diversity and thence on the properties of resilience. The simplest rule for managing landscapes is thus to say that if the vegetation is diverse then the associated diversity and functions will be taken care of. The immediate implication of this is that monotypic landscapes – vast areas of the same crop or livestock system – are likely to be the most vulnerable to the same dangers to ecosystem services pictured earlier for the farm or plot scale. Examples of these effects are the pollution of ground water by nitrates and pesticides in large-scale chemical-based agriculture and the difficulty of controlling epidemics in genetically homogeneous stands of vast area. These however seem simply to be the same issues as those at the plot scale only writ larger. The mechanisms for correction are also the same – diversifying the type of land-use system in space and time.

**Landscape mosaics**

The majority of agricultural landscapes in the tropics, in contrast with most of the northern temperate zones, are indeed mosaics of different land uses. The most sensitive of the ecosystem services at the plot scale is probably the biological pest control system. The management opportunities for this increase with widening scale as greater opportunity for diversity in both genetic signals and physical structure of the vegetation permit a wider diversity and larger reservoir of control organisms. Many of the endangered invertebrates and microorganisms of the soil community are mobile, or may be carried by vectors, and can thus recolonise degraded areas from within mosaics that provide suitable reservoirs. Others (e.g. earthworms) are less so however and re-inoculations may be necessary. In each of these cases the size, pattern of arrangement and rotation in time of land-uses on the landscape will have significant effect on the efficiency of ecosystem service provision. Management at the landscape scale offers greater opportunity than at the plot and farm for varying land-use over time. Izac and Swift (1994) argued that sustainable land management could most easily be achieved at this scale by means of balance between aggrading and degrading areas i.e. between patches of high exploitation and those of fallow or rest. Soil organic matter change is a specific and far-reaching example. In areas of intensive production and harvest the soil carbon content may decrease but under fallow or tree-based production it can be re-built. The balance between these two options affect nutrient cycling, soil structure, water regimes and the emission of greenhouse gases. The policy requirements for such integrated management of landscape mosaics are however very different to the production-related approaches that currently prevail in favour of landscape homgenisation.

The third hypothesis of Vandermeer et al (1998) predicts that a higher diversity of species will be required to provide a buffer against stress and disturbance at the landscape scale than will be the case for any single patch within it (i.e. gamma diversity will be higher than the sum of alpha diversity). This is pictured in Figure 3 by the difference between curves 1 and 3. Humans can intervene relatively easily

(although not necessarily cost-effectively) at the plot scale to substitute for diversity loss – as represented by the difference between curves 1 and 2. At the landscape scale however intervention by humans, including these substitutive actions, will tend to widen the range of stress and increase the frequency of disturbance and further extend the diversity-function relationship (Curve 4 in Figure 3). Substitutive management for purposes of restoring ecosystem services (analogous to the Curve 1 to 2 relationship in Figure 3) is likely to be prohibitively expensive at this scale and may suffer from a 'free rider' problem where it is difficult to get all beneficiaries to share the costs. We contend therefore that the implication of this hypothesis is of very high risk associated with ignoring landscape scale management and focussing only on policies that promote plot scale interventions. Plot scale activities are more likely to exacerbate landscape scale problems than repair them. On the other hand landscape scale interventions offer great opportunity for improvements at the plot scale by increasing overall integration and resilience. There is thus more functional justification for arguing in favour of maintaining or enhancing biological diversity at the landscape scale than there is at the scale of the plot.

This model is of course simplistic and does not provide any guide to other features such as the size, shape and position (pattern) of patches on the landscape or on the temporal relationships between them. The hierarchical relationship between ecosystem services should assist in developing rules for these aspects. The regulation of erosion and water flows operates at a higher level in the hierarchy of controls than do aspects of nutrient cycling, soil structure and gas emissions or pest controls. Van Noordwijk et al (this volume) discuss these higher-level aspects of landscape management under the title of 'watershed services'. The lower level services such as nutrient cycles and biological control activities may then be built in through focus on aspects such as the degree of connection between the patches and the location, direction and intensity of the flows between them. It may be useful to classify land-use types into 'functional groups' in a manner analogous with that for species in order to develop more meaningful relationships between diversity and function at the landscape scale.

**Policy implications**

The changes associated with agricultural intensification, including the attendant processes of diversity reduction and substitution of function, are made in response to food need, market opportunity, and perceptions of increased management efficiency associated with mechanisation. These factors remain a dominant reality within market-orientated agriculture where a small number of specific products have high value and specialisation thus becomes a desirable target. Van Noordwijk and Ong (1999) discussed the paradox that urban consumers have access to an increasingly diverse array of food resources that are produced on specialized farms of greatly reduced internal diversity. Observed changes in diversity at a one scale may thus not represent changes at higher systems levels. The risks to agroecosystem services of simplifying ecosystems and substituting biodiversity by labour and chemicals (e.g., in pest control) are those of losing some keystone functions including the ability of an agroecosystem to adapt to change without further substitutive interventions. The evidence, as briefly described above, that ecosystem services might be significantly impaired in agroecosystems as intensification increases is substantial although the role of biodiversity is far from clearly understood. The farmer may not perceive these effects to be serious if the economic environment enables continuing profit based on subsidies related to the substitution process. This has been the basis of agricultural development in Europe and North America for many decades. It thus appears that to attain the essential goal of profitability, even without petro-chemical substitution, agroecosystem diversity is likely to be kept low and that associated with this low diversity there is a risk of crossing threshold levels for the maintenance of ecosystem services the restoration of which is likely to be extremely costly, let alone feasible. Decisions about the management of agroecosystems in market economies do not normally take into consideration the costs of interfering with ecosystem services, including those in which biodiversity plays a strong influence. But when agroecosystems are driven across thresholds from a desired to an undesirable state, the costs to society of being in this new undesirable state, or of restoration of a more desirable one if it is feasible, can be extremely high. Therein lies the risk of simplifying ecosystems. Holling (1986) provided a seminal analysis of the consequences of a number of such irreversibilities.

Policies for sustainable agriculture, i.e. to promote integrative practices that focus on the conservation of resources (including genetic diversity) as well as productivity, have proved elusive. If the policy needs are extended to include the management of biodiversity at the landscape scale in order to protect and enhance a wide range of ecosystem services, the problem becomes more acute. There are two particular reasons why the problem is exacerbated at higher scales. First, population pressure and globalisation of trade and the concomitant land use changes (expansion of cities into agricultural lands and of agriculture into marginal areas) result in increased frequency and intensity of disturbances and stresses by comparison with those at the farm scale. The capacity to correct these effects also diminishes because the sensitivity of the systems increases in concert with their connectivity as one moves up the hierarchy of scales (Holling, 1986).

Second, the higher the scale under consideration, the more difficult it is for the increased numbers of individual land users to develop an effective management strategy for agroecosystem disturbances, that takes ecological interactions and connectivity into consideration. Even at the scale of small watersheds, it is not often the case that land users have been successful in developing collective and effective means of control and management of disturbances. Furthermore, even if these land users have full knowledge of the relevant level of connectivity necessary to ensure resilience at the watershed scale, different sectors of society place differing levels of importance on ecosystem services and diversity. Farmers in tropical countries are unlikely to place as high a value on these functions of landscape diversity as does the community at large or the national society. They are furthermore highly unlikely to value the serependic (i.e. future) value of diversity, which is much more likely to be valued by national and global communities.

In economic terms, farmers value some of the on-farm benefits of diversity and very few of the off-farm benefits, for the usual reasons that costs and benefits outside of the managers' domain (i.e. externalities) are generally not taken into account by individual decision-makers. The argument is however not simply about off-farm effects of biodiversity being ignored. Farmer knowledge varies greatly. There may be for many a number of on-farm ecosystem services that farmers may be unaware of (e.g., the role of micro-organisms), and thus cannot value, as well as services they may be aware of but will not consider important (e.g., reduction of greenhouse gas emissions). The same services may be valued by other groups in society, with a different perspective and set of interests. What is a beneficial service for one group may also be a cost for another (e.g. the perception of earthworms as 'pests' for paddy rice farmers, the trade-off between carbon sequestration and SOM mining). For these reasons, management of ecosystem services, and of biodiversity at the landscape scale, as well as management of disturbances in agroecosystems in land use mosaics, is unlikely to be optimal, from either an ecological or an economic perspective, in the absence of specific policy or institutional interventions. Lack of knowledge of threshold levels in connectivity at different scales, different perspectives on the value of biodiversity, externalities and difficulties in large groups of land users coming together in developing effective means of controlling disturbances at the landscape scale thus result in biodiversity being managed by individual farmers in a sub-optimal manner.

We therefore conclude, on the basis of the relationships we have hypothesised earlier, that it will prove very costly to manage ecosystem services at the watershed, landscape and higher scales unless the functional value of biodiversity for productivity at the plot and farm scale and its interaction with 'externalities' beyond are perceived and valued. Furthermore, unless in particular the role of biodiversity in enhancing resilience is understood and factored into effective policy or institutional interventions, ecosystem diversity is unlikely to be maintained at the landscape scale without deliberate policy interventions at national and sub-national levels which take into account the real value of maintaining ecosystem services, given the externalities they generate and given their contribution to resilience. The biggest challenge is in the realization that most of diversity as well as much of its positive role in resilience probably exists beyond the farm scale, and that thus diversity of management decisions by farmers rather than any specific management system is key to its maintenance in the landscape. These policy implications and the need for diversity enhancing communal action remain largely unexplored territory.

There are two final comments that can be made to close this discussion. First that the absence of clear evidence should not be taken as evidence for the absence of effects and thus as a reason for doing nothing. Some economists have proposed that, in view of our relatively poor understanding of the exact roles of biodiversity in ecosystems on the one hand and of the potentially devastating effects of biodiversity loss on the other hand, a precautionary principle should be used in managing diversity. This principle acknowledges that while we may not be able to justify what some see as redundant species, there may be an extinction threshold that would result in an unacceptable level of ecosystem failure. Consequently, extreme care and precaution must be taken, and it is preferable to err on the conservative side (Perrings, 1991). The precautionary principle introduces an important concept, namely that of the risk of managing agroecosystems in such a way that threshold levels of biodiversity loss in relation to ecosystem services are ignored. The 'risk premium' that the precautionary principle suggests is hard to quantify as yet. Second that even if the evidence that high levels of biodiversity are not important for maintenance of ecosystem functions or services holds, that does not contradict the valuation of biodiversity for other reasons.

**Concluding remarks**

In the above discussion we have quoted or proposed a range of hypotheses concering the relationships between biological diversity and ecosystem functions, and their implications for the management of agriultural landscapes. The general relationships that have been proposed may have to be replaced by more specific hypotheses of the relation between components of overall biodiversity and specific environmental functions, bounded in space ant time. Sweeping generalizations from experiments that are necessarily restricted in space and time, and for example do not include major parts of the diversity-generating processes (including 'lateral flows' of dispersal and migration for re-establishment), are unlikely to be helpful in guiding the development of agro-ecosystems that have to provide for short, medium and long term service functions. Future investigations should utilise co-evolved communities, be structured to investigate the distinct roles of clearly defined functional groups, separate the effects of between- and within-group diversity and be conducted over a range of stress and disturbance. This might include: testing the basic functional-biodiversity rule by experimentally determining the minimal level of diversity between and within functional groups that is necessary to maintain productivity, integrity and perpetuation of ecosystems; characterising the functional groups of organisms necessary to maintain specific ecosystem services; determining the ecosystem function and service effects that ensue from elimination or substitution of key functional groups, including particular investigation of controls over below-ground diversity and function exerted by particular plant functional groups and other keystone organisms; and determining (and developing indicators for) the biodiversity thresholds for different ecosystem services. An interesting extension of the latter study might be to investigate whether similar thresholds exist for the intrinsic, utilitarian and serependic values of biodiversity.

Society as a whole has an interest in ecosystem services that are manifested substantially at scales above that of the field plot or farm. At the scale of the watershed or landscapes there is, in comparison with any single patch, a greater range of environmental stress and higher frequency of disturbance, including of extreme events. The maintenance of ecosystem services at these scales thus requires either a higher diversity of species within functional groups or a greater investment in substitutive management to maintain ecosystem services. These increments in diversity and/or investment are unlikely to be simply additive in view of the significant shifts in complexity that occur with shifts across scale. Optimal maintenance of ecosystem services at the landscape scale may be most readily achieved by a mosaic of a relatively few land-use types. This model is however likely to be overly simple because of: (a) differences in functional impact of different land-use types; and (b) the importance of organisation at the landscape scale in terms of the size, shape and location pattern of the constituent land-uses.

In developing appropriate land-use scenarios landscapes should be compared with respect to the aggregate values of their component land-uses for intrinsic, utilitarian and functional (ecosystem service) values of biodiversity. This would be assisted by establishing a typology of land-uses in terms of their efficiency in maintaining ecosystem service and in the trade-offs between this and profitability. The

results of the ASB project provide a model for this approach with respect to the interactions between carbon sequestration potential and profitability. The relative costs and benefits of segregating the intrinsic, utilitarian and functional uses of biodiversity between different land-use or landscape units compared with integrating them within such units is another parameter that should be of significant value for policy development.

This review confirms two unsurprising but crucial elements for policy development: first that whilst a number of important analogies can be drawn across scales with respect to the management of the relationships between biodiversity and ecosystem services, there are also emergent properties that necessitate different approaches; second that the value placed on the relationship between biodiversity and function (ecosystem services) by individual land-users is markedly different than those perceived by the community at different levels of society. We have indicated a number of biological and socio-economic issues that need to be clarified in order to provide more explicit advice to policy makers. No single optimal value can be placed on the biodiversity within a landscape. Land-use decisions are likely to be optimised if decision makers can be provided with scenarios showing how various land-use combinations result in different levels of diversity and the efficiency of different ecosystem services. In so-doing it will be important to include aspects of temporal change as well as pattern on the landscape as both these factors influence the resilience of the landscapes which should be regarded as a factor of over-riding importance. These scenarios can then be used to identify policy interventions and institutional arrangements necessary to achieve the desired objective, whether it is one dominated by agricultural productivity targets or the maintenance of ecosystem services or the conservation of biodiversity, or a combination of all three.

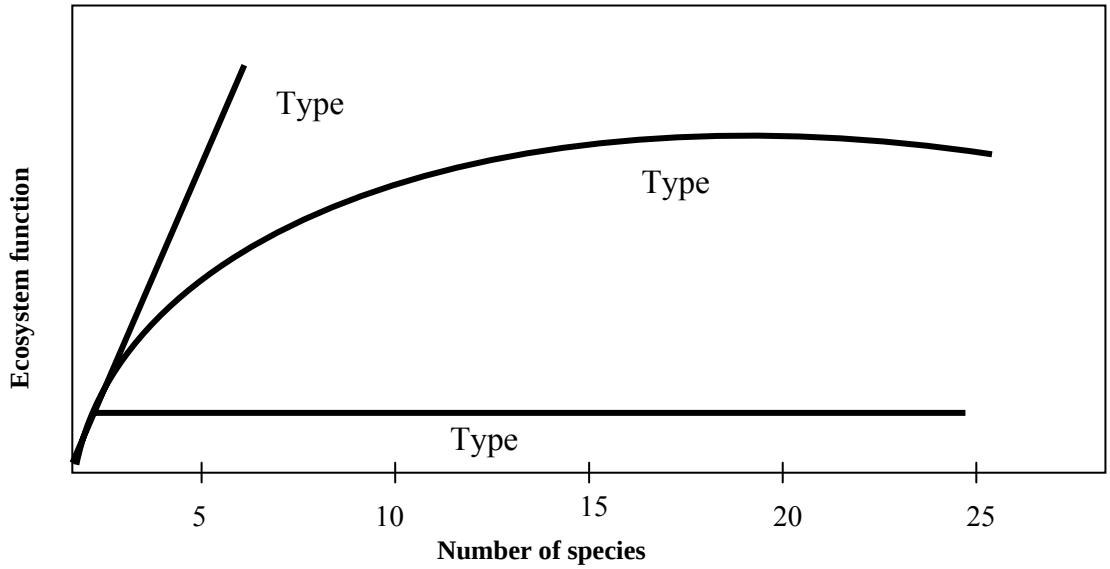


**Figure 1:** Possible relationships between biological diversity and ecosystem functions for the plant subsystem (from Vitousek and Hooper 1993). The authors hypothesised that curve 2 was the most probable of the three propositions.

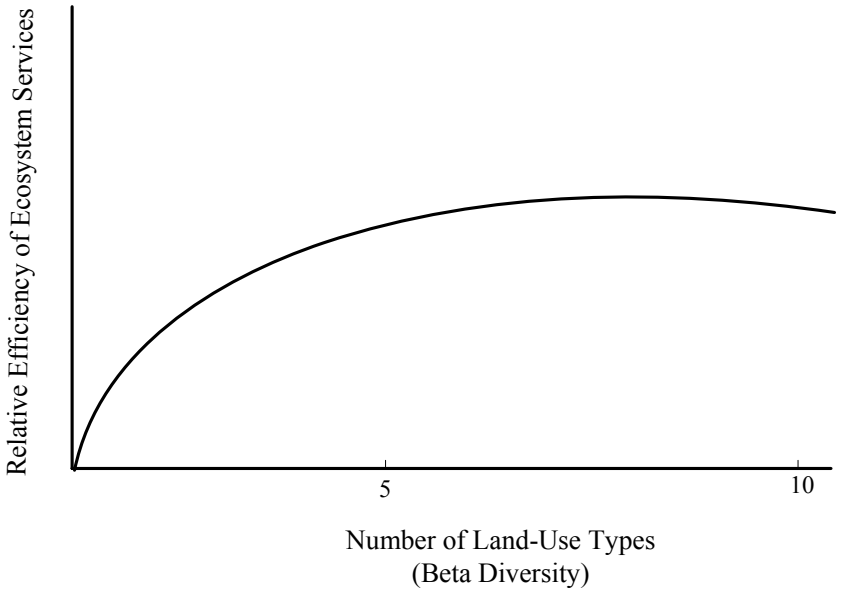


**Figure 2:** Hypothesised relationship between the diversity of ecosystem or land-use types and the efficiency of function of (the totality of) ecosystem services at the landscape scale.

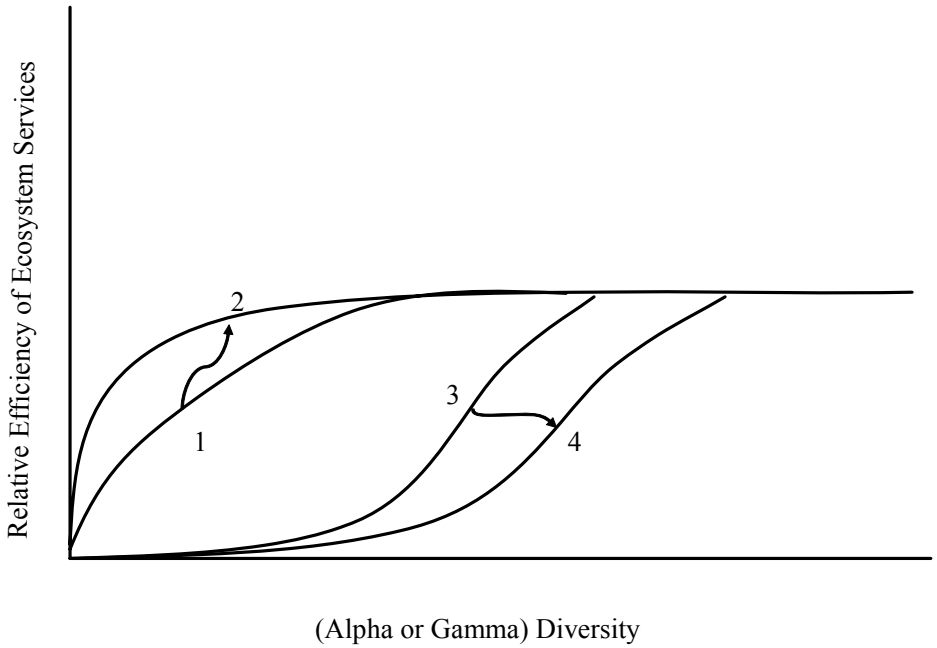


**Figure 3:** Hypothesised relationships between diversity (as measured by species richness) and the efficiency of function of ecosystem services at the patch-ecosystem (i.e. plot) scale (Curves 1 and 2) and the scale of the landscape (Curves 3 and 4). Curve 1 repeats hypothesis 2 of Figure 1: Curve 2 shows how in an intensively managed agricultural plot ecosystem services may be maintained by substitution of diversity by inputs derived from human and petro-chemical energy. Curve 3 shows, by comparison with curve 1, that the threshold of 'essential' diversity is greater as the land area increases. Curve 4 represents circumstances of high disturbance of the landscape by human intervention.

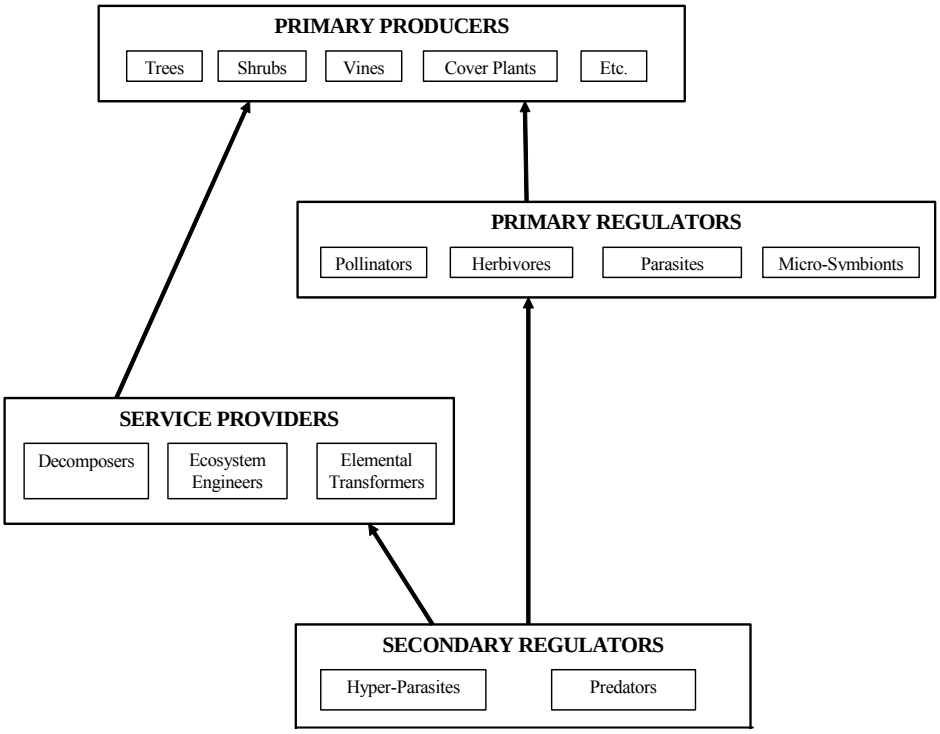


**Figure 4:** Hierarchical relationships between different categories of Functional Group – see Table 1 and Notes.

## Appendix

### Key functional groups: a preliminary classification

We have defined a Functional Group in text as ' a set of species that have similar effects on a specific ecosystem-level biogeochemical process'. There are many examples of classification of species in this way within specific taxonomic or trophic groups (e.g. for plants or pests). . There is no single classification to suit all purposes. In each case it is clear that the number of functional groups that is recognised, the criteria that are used to classify them and the degree of sub-division that is applied is a function of the question that is being addressed. We propose here a classification into the ten major groups that are briefly described below, together with such sub-division as may be necessary, for the purposes addressed in this paper, i.e. the relationships between biodiversity and function with particular respect to agriculture and ecosystem services. These Key Functional Groups are listed in Table 1 in relation to the ecosystem services they provide. The relationships between them are pictured in Figure 4. We suggest that this could provide a useful framework for investigating and testing key questions on this topic. A hierarchical structure is suggested (Figure 4). At the highest level are four major categories related to major trophic functions at the ecosystem scale i.e. Primary Production, Primary Regulation, Service Provision and Secondary Regulation. At the next level are the ten groups listed in Table 1 that perform distinct ecosystem functions; and at the third level are sub-divisions which it may be functionally and/or taxonomically useful to distinguish (e.g. vertebrate grazers versus invertebrate pests among the herbivores). Further levels of subdivision may also be useful or necessary in some cases.

**Table 1:** Relationship between key functional groups of organisms, the ecosystem level functions they perform and the ecosystem goods and services they provide

| ECOSYSTEM GOODS AND SERVICES | ECOSYSTEM FUNCTIONS | KEY FUNCTIONAL GROUPS |
|---|---|---|
| **Ecosystem goods including:** | | |
| Food | Primary and secondary (herbivore) production | Plants, Vertebrate herbivores |
| Fibre and Latex | Primary production and secondary metabolism | Plants |
| Pharmaceuticals and Agro-chemicals | Secondary metabolism | Plants, Bacteria and Fungi (Decomposers etc) |
| **Ecosystem services including:** | | |
| Nutrient cycling | Decomposition<br>Mineralisation and other elemental transformations | Decomposers<br>Elemental transformers |
| Regulation of water flow and storage | Soil Organic Matter synthesis<br>Soil structure regulation – aggregate and pore formation | Decomposers<br>Ecosystem Engineers |
| Regulation of soil and sediment movement | Soil protection<br>Soil Organic Matter synthesis<br>Soil structure maintenance | Plants<br>Decomposers<br>Ecosystem engineers |
| Regulation of biological populations including diseases and pests | Plant secondary metabolism<br>Pollination<br>Herbivory<br>Parasitism<br>Micro-Symbiosis<br><br>Predation | Plants<br>Pollinators[1]<br>Herbivores[1]<br>Parasites[1]<br>Micro-symbionts[1]<br>Hyper-parasites[2]<br>Predators[2] |
| De-toxification of chemical or biological hazards including water purification | Decomposition<br>Elemental transformation | Decomposers<br>Elemental transformers |
| Regulation of atmospheric composition and climate | Greenhouse gas emission | Decomposers<br>Elemental Transformers<br>Plants<br>Herbivores |

**Notes to Table 1.**

**Primary Production**
In some ecosystems photosynthetic micro-organisms may constitute as significant group eg. rice ecosystems). Here we deal only with plants.

Note 1.
*Plants.* There is a long history of classification of plants into functional groups. The groupings have been based on a variety of reproductive, architectural and physiological criteria. For the purposes of this paper the efficiency of resource capture is suggested as the main criterion. This will be determined by features of both architecture (eg. position and shape of the canopy and depth and pattern of the rooting system) and physiological efficiency. A very simple classification could for instance distinguish the roles trees, shrubs, vines and cover plants etc. and then subdivisions within each of these groups. Much more detailed consideration of these aspects is given by Smith et al (1997).

**Primary Regulation (Note 1).**
These are a set of functional groups which have a significant regulatory effect on primary production and therefore influence the goods and services provided by the plants.

*Pollinators.* See (ref) for discussion of functional groups of pollinators.[REFS BEING SOUGHT FOR THIS]

*Herbivores:* A great variety of organisms feed directly on primary producers. Vertebrate grazers and browsers are readily distinguished from invertebrate pests although their impacts on the plants may have similar functional significance at the ecosystem level. Each of these major groups are sub-divisible in terms of, for instance, feeding habits. The balance between different types of browser for instance can influence the structure of the canopy.

*Parasites:* Microbial infections of plants may limit primary production in analogous manner to herbivory. Parasitic associations can also influence the growth pattern of the plants and thence their architecture and physiological efficency.

*Micro-symbionts*: There is a wide range of microbial infections that are beneficial rather than destructive of which the most familiar are di-nitrogen fixing bacteria and mycorrhizal fungi.

Service Provision.
The functional groups within this category also strongly influence primary production but not in the directly destructive or stimulatory way of the primary regulators. They also provide a set of ecosystem services distinct to those deriving mainly from the primary producers.

*Decomposers*: This is group of great diversity which can be sub-divided taxonomically (bacteria, fungi, invertebrates etc) and in relation to size both of which correlate somewhat with functional roles in the breakdown (eg. detritivorous invertebrates) and mineralisation (fungi and bacteria) of organic materials of plant or animal origin (Swift et al 1979, Lavelle and Spain 2001).

*Ecosystem Engineers*: These are organisms that change the structure of soil by burrowing, transport of soil particles and formation of aggregate structures. The term is often confined to the macrofauna such as earthworms and termites but fungi and bacteria also play a key role in the binding of soil aggregates. Many of these organisms also contribute to the processes of decomposition.

*Elemental Transformers*: This may be the most diverse group of all and deserving of substantial subdivision. It includes a range of autotrophic bacteria that utilise sources of energy other than organic matter and therefore not classifiable as either decomposers but play key roles in nutrient cycles as transformers of C, N, S etc (eg ….). In addition there are heterotophs that thus have a decomposer function but also carry out elemental transformations beyond mineralisation (eg. free-living di-nitrogen fixers).

Secondary Regulators (Note 2)

*Hyper-Parasites and Predators*: This is diverse group of microbial parasites and vertebrate and invertebrate predators that feed on decomposers, herbivore, pollinators etc. They have particular significance in agriculture because of the service of biological control of pests and diseases that they play.

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## Integration of local soil knowledge for improved soil management strategies

Barrios Edmundo[(1)] , Delve Robert J. [(2,3)], Trejo Marco T.[(4)] And Thomas Richard J. [(1,5)]

[1]*Centro Internacional de Agricultura Tropical (CIAT), A.A. 6713, Cali, Colombia.*
[2]*Centro Internacional de Agricultura Tropical (CIAT), Kampala, Uganda*
[3]*Tropical Soil Biology and Fertility Programme, PO Box 30592, Nairobi, Kenya*
[4] *Centro Internacional de Agricultura Tropical (CIAT), Tegucigalpa, Honduras*
[5] *Tropical Soil Biology and Fertility Programme, PO Box 30592, Nairobi, Kenya,*

## Abstract

The increasing attention paid to local soil knowledge in recent years is the result of a greater recognition that the knowledge of people who have been interacting with their soils for a long time can offer many insights into the sustainable management of tropical soils. A participatory approach in the form of a methodological guide has been developed and used in Latin America and the Caribbean (Honduras, Nicaragua, Colombia, Peru, Venezuela, Dominican Republic) and Africa (Uganda, Tanzania) in order to identify and classify local indicators of soil quality related to permanent and modifiable soil properties. This methodological tool aims to empower local communities to better manage their soil resource through better decision making and local monitoring of their environment. It is also designed to steer soil management towards developing practical solutions to identified soil constrains, as well as, to monitor the impact of management strategies implemented to address such constraints. The methodological approach presented here constitutes one tool to capture local demands and perceptions of soil constraints as an essential guide to relevant research and development activities. A considerable component of this approach involves the improvement of the communication between the technical officers and farmers and *vice versa* by jointly constructing an effective communication channel. The participatory process used is shown to have considerable potential in facilitating farmer consensus about which soil related constraints should be tackled first. Consensus building is presented as an important step prior to collective action by farming communities resulting in the adoption of improved soil management strategies at the landscape scale.

**Keywords:** Africa, collective action, landscape, local knowledge systems, Latin America, participatory methodologies

## Introduction

A considerable proportion of soil degradation induced by human-related activities is a result of deforestation, overgrazing and improper agricultural practices. Eighty five percent (85%) of agricultural land is estimated to be degraded to some extent (Oldeman and van Lynden, 1997). The mounting evidence of land degradation induced by agriculture is resulting in a gradual shift from a high input agriculture paradigm, based on overcoming soil constraints to fit plant requirements by amending soils with fertilizers, lime, biocides and tillage, to a paradigm with more reliance on biological processes (Sanchez, 1994). This paradigm invokes a more ecological approach based on the adaptation of germplasm to adverse conditions, the enhancement of biological activity of the soil and the optimization of nutrient cycling to minimize external inputs and maximize the efficiency of their use. This new paradigm focuses on the need to improve agricultural production in more benign

ways compared with traditional agricultural improvement that is based on high inputs with subsequent detrimental environmental impacts that result in soil degradation. Nevertheless, while this paradigm shift is a good sign its beneficial impact, in terms of improved soil management options for healthier landscapes, will be limited if there is little adoption by local land managers.

The limited adoption of new technology and new cropping systems has been often attributed to local inertia rather than the failure to take into account the local experience and needs (Warren, 1991). According to Walker et al. (1995), increased application of indigenous knowledge to rural research and development can be attributed to the need to improve the targeting of research to address client needs and thus increase adoption of technological recommendations derived from research. The complementary role that indigenous knowledge plays to scientific knowledge in agriculture has been increasingly acknowledged (Sandor and Furbee, 1996). Experimental research is an important way to improve the information upon which farmers make decisions. It is questionable, however, if relying on experimental scientific methodology alone is the most efficient way to fill gaps in current understanding about the sustainable management of agroecosystems. There has been limited success of imported concepts and scientific interpretation of tropical soils in bringing desired changes in tropical agriculture. This has led an increasing recognition that local soil knowledge can offer many insights about managing tropical soils sustainably (Hecht, 1990).

Local knowledge related to agriculture can be defined as the indigenous skills, knowledge and technology accumulated by local people derived from their direct interaction with the environment (Altieri, 1990). Transfer of information from generation to generation undergoes successive refinement leading to a system of understanding of natural resources and relevant ecological processes (Pawluk et al., 1992). Nevertheless, although benefits of local knowledge include high local relevance and potential sensitivity to complex environmental interactions, without scientific input local definitions can sometimes be inaccurate and unable to cope with environmental change. It is thus argued that research efforts should further explore a suitable balance between scientific precision and local relevance resulting in an improved knowledge base as indicated by Barrios and Trejo (2001). Furthermore, this approach would overcome the limitations of site specificity and the empirical nature of local knowledge and would allow knowledge extrapolation through space and time as suggested by Cook et al. (1998).

**A participatory approach for integration of local and technical knowledge systems**

A common language is required to link local and technical knowledge about soils and their management so that acceptable, cost-effective strategies for improved soil management can be developed. For this purpose a methodological guide has been developed and used in Latin America and the Caribbean (Trejo et al., 1999) and Africa (Barrios et al., 2001) in order to help stakeholders identify and classify local indicators of soil quality (ISQ) related to permanent and modifiable soil properties as this is the first step in the development of local soil quality monitoring systems (Fig.1).

Selecting a suitable set of ISQ, and developing its use as a monitoring system (Soil Quality Monitoring System, SQMS), can be captured in the following figure (modified from Beare et al., 1997):

Suitable ISQ are identified from the local and technical knowledge base and critical levels defined. This phase is followed by the definition of guidelines to establish a Soil Quality Monitoring System (SQMS) along with interpretation information as well as reaching an agreement about the suitable ISQ for the relevant conditions. User feedback is very important at this stage as it will provide the grounds for acceptance of the SQMS for soil quality diagnosis and monitoring. Once the SQMS is fully accepted by users it becomes part of the Decision Support System for Natural Resource Management

This methodological guide is mainly focused on the first phase of this process; i.e.: identifying soil quality indicators that can be used by farmers, extension officers, NGO's, technicians, researchers and educators.

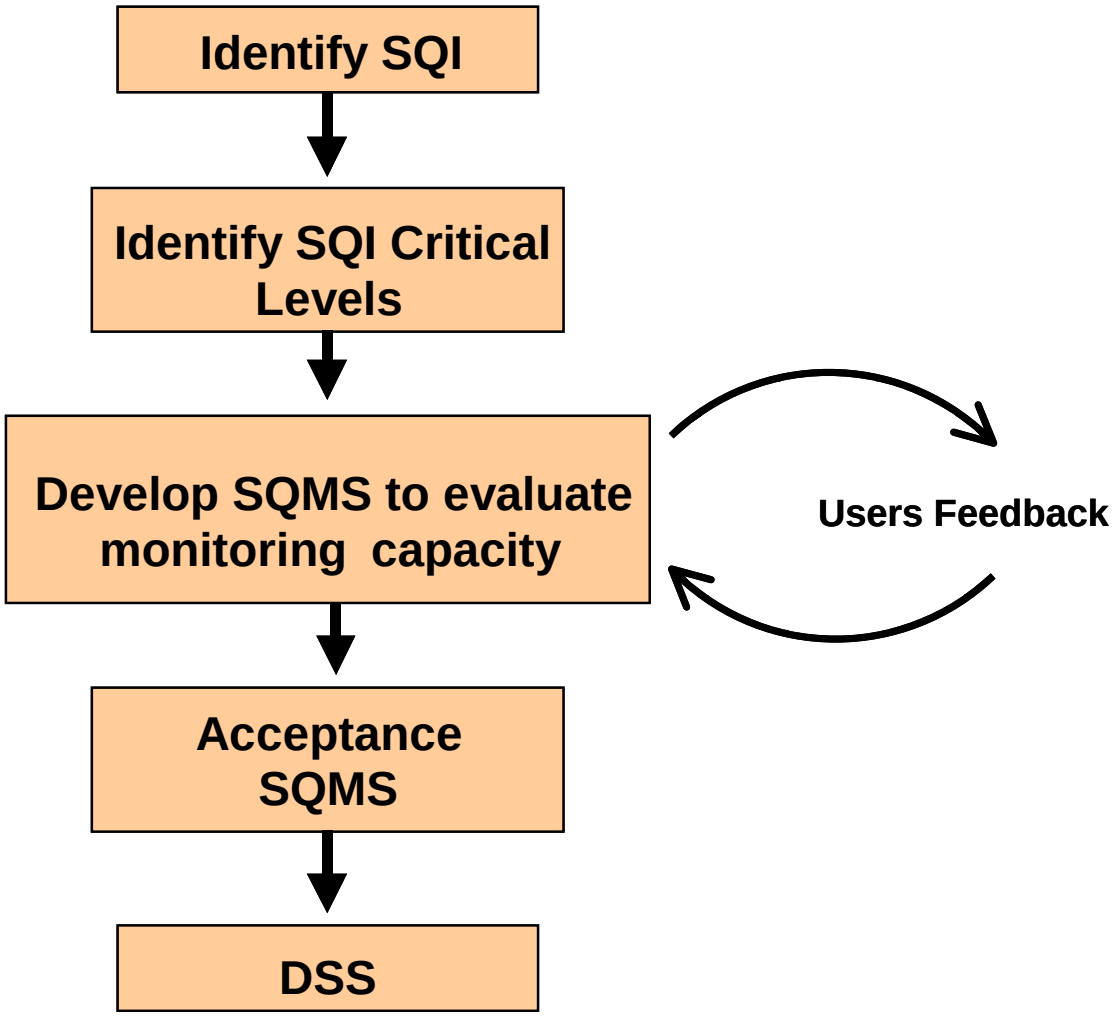


Fig. 1 Process leading to the development of Soil Quality Monitoring Systems

The ISQ will help in identifying the main soil biophysical limitations of the agricultural system under study. The most sensitive and robust ISQs selected for the soil constraints identified can then be incorporated into a Soil Quality Monitoring System (SQMS), and should include basic parameters such as bulk density, pH, effective rooting depth, water content, soil temperature, total C and electrical conductivity (Doran and Parkin, 1994). Since our objective is to develop a SQMS for the land users, local indicators of soil quality must be included in the monitoring system. The mix of native and scientific parameters varies according to the monitoring objectives; e.g.: if they are farmers, extension agents or policies makers. It is likely that integrative ISQ might be more useful to land users, than a measurement, for example, soil available P, since many indicators used by the farmers are also of the integrative type; for instance, soil color, soil structure, crop yield, presence of specific weed species. Attention should be paid to the inclusion of indicators that can be used while progressively increasing the scale at which results are applied (e.g. from plot to field and farm level, up to watershed, region and nation level). Some examples of such indicators might be crop yield and yield trends, land cover, land use intensity and nutrient balances (Pieri et al., 1995). More recently, Defoer and Budelman (2000) have proposed the use of resource and nutrient flows at farm scale to assess land use sustainability and local variation usually missed in studies at higher levels of aggregation (i.e. region, country).

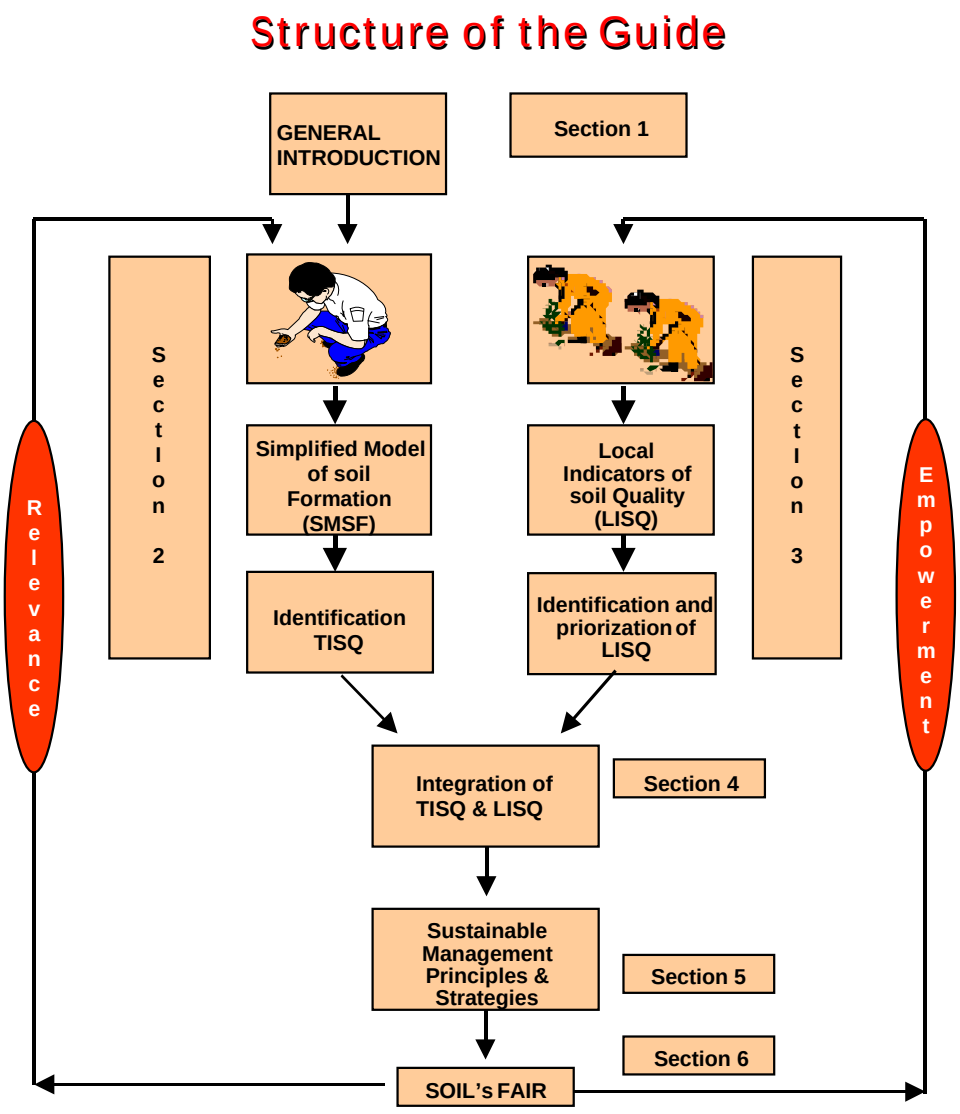


Fig. 2 Structure of the Methodological Guide

The methodological approach proposed by Trejo et al. (1999) and Barrios et al. (2001) rests on the belief that in order for sustainable management of the soil resource to take place, it has to be a result of improved capacities of the local communities to better understand agroecosystem functioning. Improved capacities by technical officers (extension agents, NGO's, researchers) to understand the importance of local knowledge is also part of the methodology. Therefore, after identifying if there is poor or a lack of adequate communication between the technical officers and the local farm community as a major constraint to capacity building, the methodology proposed deals with ways of jointly generating a common knowledge that is well understood by both interest groups. The structure of the guide is shown in Fig.2 shows the different sections of the methodological guide for Africa.

This methodological guide is made up of six sections: Section 1 provides a general introduction about the management of the soil resource in the African context and the ISQ. Section 2 presents a technical conception of the soil through a Simplified Model of Soil Formation (SMSF) based on Jenny's seminal work (Jenny, 1941; 1980) in order to bring participants to a common starting point.

Table 1. Integration of LISQ identified and ranked by farmers of Jalapa village, Yoro, Honduras with TISQ and their association with permanent or modifiable soil properties.

| Ranking[a/] | Knowledge integration | | Property | |
|---|---|---|---|---|
| | Technical | Local | P[b/] | M[c/] |
| 1 | Effective soil depth | Thick soil layer/thin soil layer | X | |
| 2 | Soil fertility | 'Opulento', no need of chemical fertilizer/ needs fertilization | | X |
| 3 | Biological activity | Presence of earthworms/ lack of earthworms | | X |
| 4 | Slope | Soils with gentle slopes, uniform/ soils with high slopes | X | |
| 5 | Structure | Soil macroaggregates can be broken into pieces, lose soil/ Macroaggregates can not be broken, tied soil | X | |
| 6 | Texture / water holding capacity | Soil keeps water for longer time/ soil does not keep water | X | |
| 7 | Soil burning | No burnings have occurred in the last 5 years/ Lands have been burned in the last 5 years | | X |
| 8 | Color | Black / various soil colors | X | |
| 9 | Texture / infiltration | Fast water absorption/ slow water absorption | X | |
| 10 | Texture | Loamy soils, little clay/ 'Barrialosa' or "muddy", sandy | X | |
| 11 | Indicator plants | 'Zaléa', 'Chichiguaste'/ 'Chichiguaste' does not grow, weeds do not develop, 'zacate de gallina' | | X |
| 12 | Physical barriers | Easy tillage/ difficult tillage, 'Tronconosa' | X | |
| 13 | Productivity | Greater yields/ Lower yields, more work to produce | | X |
| 14 | Stoniness | No stones present / 'Balastrosa', stony, gravely | X | |
| 15 | Drainage | Soil does not flood, no 'aguachina'/ 'aguachina', soil sweats | X | |
| 16 | Erosion | Non washed soils/ washed soils | X | |

a/ Degree of importance given by farmers
b/ P: permanent property
c/ M: modifiable property

It also introduces the technical indicators of soil quality (TISQ) with the participation of professionals from National Research and Extension Organizations (NARES), NGO's, universities and International Agricultural Research Centers. Section 3 deals with participatory techniques that help gather, organize and classify local indicators of soil quality (LISQ) through consensus building and this is conducted with local farming communities. The process to elicit information about local indicators of soil quality starts with a brainstorming session guided by trainers where local farmers explain, in their own words, how they define and classify the quality of their soils. Once local indicators have been collected a ranking session is initiated where the original group of farmers is split into smaller groups of 3 or 4 in

order to carry out several ranking exercises for the same information and thus obtain a more representative mean value. All results obtained from each group conducting the ranking exercise are put together in a ranking matrix where rows represent all local indicators identified during brainstorming and the columns represent the ranking assigned by different small groups of farmers.

Results to date indicate that biological indicators like native flora and soil macrofauna are important components of local indicators of soil quality. This is not surprising as biological indicators have the potential to capture subtle changes in soil quality because of their integrative nature. They simultaneously reflect changes in the physical, chemical and biological characteristics of the soil. There is considerable scope, therefore, to further explore the use of local knowledge about biological indicators of soil quality and as a tool guiding soil management decisions.

Section 4 provides a methodology to construct an effective channel of communication by finding correspondence between TISQ and LISQ which permit a better Extension/NGO officier, NGO – farmer communication. This is carried out in a plennary session exercise of integration where the most important local indicators of soil quality are analyzed in the context of technical knowledge and are classified into indicators of permanent or modifiable soil properties (Table 2). The classification of local indicators into permanent and modifiable factors provides a useful division that helps to focus on those where improved management could have the greatest impact. This strategy is particularly sound when there is considerable need to produce tangible results in a relatively short time in order to maintain farmer interest as well as to develop the credibility and trust needed for wider adoption of alternative soil management practices.

Although some local indicators can be rather general like fertility, slope, productivity and age under fallow, other local indicators are more specific. For instance, plant species growing in fallows, soil depth, color, water holding capacity and predominant soil particle sizes provide indicators that can be easily integrated with technical indicators of soil quality.

Section 5 is concerned with management principles behind potential strategies to address constraints modifiable in the short (< 2 yrs), medium (2-6 yrs) and long (> 6 yrs) term (Fig. 3).

Modifiable constraints are those that can be overcome through management. Examples include low nutrient and water availability, low and high pH, soil compaction and low soil organic matter content. The discrimination between short, medium and long term is necessary to enable ranking of management strategies, which is mainly dictated by resource endowment.

Section 6 is devoted to the Soils Fair which is designed to help farmers develop skills to characterize relevant physical, chemical and biological properties of their soils through simple methods that can then be related to their local knowledge about soil management. Here farmers and scientists communicate through a commonly developed language and simple demonstrations on how to measure soil quality *in situ* to solve local soil management and land degradation problems.

The result of this two-way exchange process is that it has a positive impact on the technical knowledge by nurturing it with local perceptions and demands. Positive impacts are also envisioned on the local knowledge base as it provides with a way for this tacit knowledge to be widely understood, assessed and utilized. Besides, local communities will be empowered by the joint ownership of the technical-local soil knowledge base constructed during this process.

The two-way improvement of communication channels will likely improve the communication of farmer's perceptions to extension agents and researchers as well as make recommendations by extension agents and NGOs better understood by the farmer community. Better communication opens opportunities for established and/or emerging local organizations to use this methodological approach for consensus building that precede collective actions resulting in the adoption of improved soil management strategies at the landscape scale.

This methodological guide aims to empower local communities to better manage their soil resource through better decision making and local monitoring of their environment. It is also designed to steer management towards solutions to the soil constrains identified as well as to monitor the impact of management strategies implemented to address such constraints.

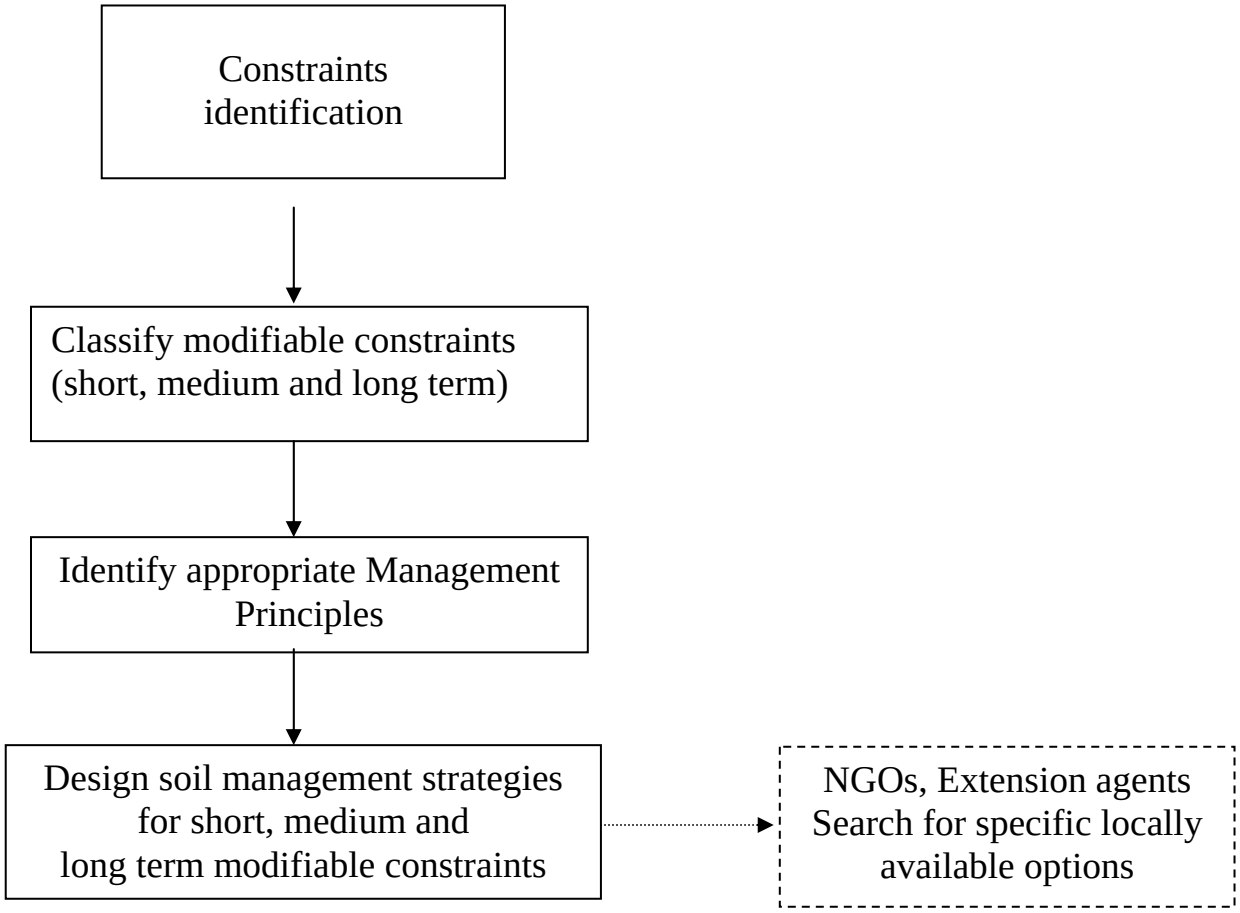


**Fig. 3 Process leading to improved soil management strategies**

The approach summarized in the preceeding sections provides the tools to conduct a technical-local classification of the soil, based on modifiable and permanent soil properties, which has the flexibility to work in the spatial scale continuum plot/farm/landscape (watershed) while also having the potential to take the stakeholder groups and gender issues dimensions into consideration. This guide then provides a valuable tool to evaluate the impact of the land use change across various spatial scales and social actors.

Finally, participants in the training event associated with the guide are encouraged to develop "action plans". These action plans show the institutional commitment made by participants to apply the guide and gained insights in their own work plans and environments. To date more than 23 action plans have been initiated in Latin America and Africa. Follow up of these action plans in the coming years will provide a measure of the impact of this participatory approach in better natural resource management through improved soil management strategies.

**Conclusions**

Current estimates of degradation of the soil resource indicate that we cannot afford to adopt a grow-now and-clean-up-later approach to development. Farmers need early warning signals and monitoring tools to help them assess the status of their soils, since by the time degradation is visible

because of unsuitable management, it is either too late of too expensive to revert it. The costs of preventing soil degradation are several times less than costs of remedial actions.

More often than not technical solutions to soil degradation abound but are often left on the scientist shelves because they are developed without the participation of the land user or do not build on local knowledge of soil management. Participatory approaches involving group dynamics and consensus building are likely to be key to adoption of improved soil management strategies beyond the farm-plot scale to the landscape scale through the required collective action process. Action plans developed by local actors as a result of consensus building and new insights derived from the training exercise become a vehicle by which profitable and resource conserving land management is locally promoted and widely adopted. Taking adavantage of the complementary nature of local and scientific knowledge is highlighted as an overall strategy for sustainable soil management.

The development of this methodological guide has been a good example of 'South – South' cooperation where experiences from Latin America were brought and adapted to the African context, and feedback from Africa has helped further improvement of the Latin American guide.

**Acknowledgement**

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**The TSBF African Network for Soil Biology and Fertility (AfNet)**

André Bationo (AfNet Coordinator)
TSBF-CIAT, Nairobi, Kenya

AfNet is the single most important implementing agency of TSBF in Africa. Its main goal is to strengthen and sustain stakeholder capacity to generate, share and apply soil fertility and biology management knowledge and skills to contribute to the welfare of farming communities. It is a mechanism to facilitate and promote collaboration in research and development among scientists in Africa for the purpose of developing innovative and practical resource management interventions for sustainable food production. AfNet has membership from National Agricultural Research and Extension Services (NARES) and Universities from various disciplines mainly soil science, social science, agronomy and technology exchange.

**Network collaborative trials in East and Southern Africa, 2002**

*Tanzania - NSS, Mlingano*

- Nitrogen fertilizer equivalencies based on organic input quality; NSS, Mlingano, Tanga managed by S. Ikerra and A. Marandu
- Optimum combinations of organic and inorganic N sources managed by S. Ikerra and A. Marandu

*Zimbabwe - University of Zimbabwe*

- Base nutrient dynamics and productivity of sandy soils under maize-pigeon pea rotational systems managed by P. Mapfumo and F. Mtambanengwe

*Zambia - Mt Makulu Research Station, Chilanga*

- Nitrogen fertilizer equivalencies based on organic input quality managed by M. Mwale
- Optimum combinations of organic and inorganic N sources managed by M Mwale

*Kenya*

- Nitrogen fertilizer equivalencies based on organic input quality managed by P. Mutuo and J.Kimetu in Maseno, Western Kenya and Central Kenya
- Maintenance of soil P with small applications of organic and inorganic sources managed by J Kinyangi and P Mutuo in Maseno, Western Kenya and Central Kenya
- Residual effects following different rates of phosphorus application managed by P Mutuo in Maseno, Western Kenya
- Hedgerow intercropping managed by D. Mugendi at KARI, Embu
- Assessment of the adoption potential of soil fertility improvement technologies managed by D. Mugendi and R. Kangai in Chuka, Embu
- Enhancement of soil productivity using low-cost inputs managed in Central Kenya by D. Mugendi and M. Mucheru
- Nutrient management by use of agroforestry trees for improved soil productivity managed by D. Mugendi and Kinyua in Central, Kenya.

**Network collaborative trials in West Africa, 2002**

*Burkina Faso*

Trials managed by Vincent Bado in various sites:

- Long-term cropping systems and integrated soil fertility management in Kouare and Farakoba.

- Fertilizer equivalency and optimum combination of low quality organic and inorganic plant nutrients in the Rice-based cropping systems at Kou Valley and also in the maize cropping system in Farakoba.

*Côte d'Ivoire*
Trials managed by Yao Tano in Lamto site:
- Fertilizer equivalency and optimum combination of low quality organic and inorganic plant nutrients
- Nutrient use efficiency in legume and cereal rotation systems.

*Ghana*
Trials managed by E. Yebaoh in Kumasi site:
- Fertilizer equivalency and optimum combination of low quality organic and inorganic plant nutrients
- Nutrient use efficiency in legume and cereal rotation systems.

*Mali*
- Fertilizer equivalency and optimum combination of low quality organic and inorganic plant nutrients managed by M. Bagoyoko at Niono site.
- Monitoring nutrient budget managed by R. Tabo and M. Bagoyoko in both Koulikoro and Fana sites.
- Biological nitrogen fixation managed by R. Tabo and M. Bagoyoko in both Koulikoro and Fana sites.
- Fertilizer equivalency and optimum combination of low quality organic and inorganic plant nutrients managed by R. Tabo and M. Bagoyoko in both Koulikoro and Fana sites.

*Niger*
Trials managed by Aboudoulaye and Manamane in various sites:
- Long-term operational scale research in Sadore site
- Long-term cropping system in Sadore site
- Long-term crop residue management in Sadore site.
- On-farm evaluation of soil fertility restoration technologies in Sadore, Karabedji, Gobery and Gaya sites.
- Methods of P and manure application in Sadore and Karabedji sites.
- Fertilizer equivalency and optimum combination of low quality organic and inorganic plant nutrients in Banizoumbou, Karabedji, Gobery and Gaya sites.
- Monitoring nutrient budget in Banizoumbou site.
- Biological nitrogen fixation in Banizoumbou site.
- Coral experiment in Sadore site.

*Nigeria*
- Fertilizer equivalency and optimum combination of low quality organic and inorganic plant nutrients managed by Emmanuel Iwuafo in Zaria site.
- Nutrient use efficiency in legume cereals rotation systems managed by Emmanuel Iwuafo in Zaria site.
- Biological nitrogen fixation managed by Abdou and Abdoulaye in Mirijibur IITA Research Station.
- Monitoring nutrient budget managed by Abdou and Abdoulaye in Mirijibur IITA Research Station.

*Togo*
- Fertilizer equivalency and optimum combination of low quality organic and inorganic plant nutrients managed by Tossah in Davie site.
- Nutrient use efficiency in legume cereals rotation systems managed by Tossah in Davie site.

**Results: Long-term soil fertility management trials**

*Long-term management of phosphorus, nitrogen, crop residue, soil tillage and crop rotation in the Sahel*
Since 1986 a long-term soil fertility management was established by ICRISAT Sahelian Center to study the sustainability of pearl millet based cropping systems in relation to management of N, P, and crop residue, rotation of cereal with cowpea and soil tillage. The traditional farmers' practices yields 146 kg/ha of pearl millet grain whereas with application of 13 kg P/ha, 30 kg N/ha and crop residue in pearl millet following cowpea yielded 1866 kg/ha of pearl millet grain. These results clearly indicate the high potential to increase the staple pearl millet yields in the very poor Sahelian soils.

*Maintenance of soil fertility under continuous cropping in maize–bean rotation*
The Kabete long-term trial was started by KARI at the National Agricultural Laboratories site, on a humic Nitisol in 1976. The objective of the trial was to find appropriate methods for maintaining and improving the productivity of soil through the use of inorganic N and P fertilizers, farmyard manures and crop residues under maize-bean rotation practices that are common to small-scale farmers. In 2001, samples were collected from key treatments to study P dynamics and to examine the effects of the different treatments on P pools and P availability. The results will be given in the next progress report.

*Long-term management of manure, crop residues and fertilizers in different cropping systems*
Since 1993 a factorial experiment was initiated at the research station of ICRISAT Sahelian Center at Sadore, Niger. The first factor was three levels of fertilizers (0, 4.4 kg P + 15 kg N/ha, 13kg P + 45 kg N/ha), the second factor was crop residue applied at (300, 900 and 2700 kg/ha) and the third factor was manure applied at (300, 900 and 2700 kg/ha). The cropping systems are continuous pearl millet, pearl millet in rotation with cowpea and pearl millet in association with cowpea. The analysis of variance data indicate that fertilizer; crop residue and manure application resulted in a highly significant effect of both pearl millet grain and total dry matter yields. Fertilizer alone account for 34% in the total variation of the dry matter whereas manure account for 18%. Although some interactions are significant they account for les than 3% in the total variation.

For pearl millet grain, the application fertilizer, manure, crop residue and cropping systems alone account for 66% of the total variation. The farmer's practices yield 236 kg/ha; the application of 13 kg P and 45 kg N/ha yielded 800 kg/ha but when these mineral fertilizers are combined with 2.7 t/ha of manure or crop residue in rotation with cowpea, yield of 1500 kg/ha can be achieved.

The N and P fertilizer value of manure and crop residue is 27 and 13 respectively and the N and P equivalency of manure is 113% and 153% for crop residue. The high values of fertilizers equivalency of manure and crop residue over 100% suggest that the organic amendment have beneficial roles other than the addition of plant nutrient such as addition of micronutrients and better water holding capacity. In addition, the release of nutrient with mineralization over time can match more the plant demand and this will result in higher nutrient use efficiency from the organic amendments. It is also well established that the application of organic amendments can reduce the capacity of the soil to fix P and then increase P availability to plant.

**Results: Optimum combination of organic and inorganic sources of nutrients**

Although the combined application of organic resources and mineral inputs forms the technical backbone of the Integrated Soil Fertility Management approach, procuring a sufficient amount of organic matter of a desired quality is very often a problem farmers are facing. While high quality organic resources (high %N, low %lignin and polyphenols) are known to behave as fertilizers through fast mineralization of their tissue N, lower quality organic resources are often more abundant on farmers' fields. Examples of such lower quality resources are crop residues or farmyard manure.

Sole application of low quality organic resources may lead to N immobilization and reduced crop growth. Consequently, mineral N is required to overcome the demand for N by the microbial decomposer

community and to supply N to the crop. While preliminary evidence shows that high quality resources rarely cause immobilization of mineral N, low quality organic resources may lead to immobilization of fertilizer N. Depending on whether this immobilization phase lasts or not, decreased or enhanced crop yields may be the result. In the case of long-term immobilization, residual effects may be more relevant rather than immediate N supply to the crop.

In 2002, network experiments were conducted at 7 benchmark locations across 7 countries to investigate the nitrogen and phosphorus contribution of different low quality organic materials that are available for direct use by farmers.

Soils in the Sahel are acidic and inherently low in nutrients with ECEC of less than 1 cmol/kg for all the sites except Gaya where the organic carbon is slightly higher and an ECEC of 1.3 cmol/kg. The data on phosphorus sorption isotherm clearly indicated that most of the soils have very low capacity to fix P due to their sandy nature.

As manure was used in most of the trials in combination with mineral fertilizer, a systematic chemical characterization of the manure used at the different sites was undertaken. These analysis will be used to determine the fertilizer equivalencies of different manure sources for nitrogen and phosphorus. The nitrogen and phosphorus levels in the manure were very low and varied from 0.47% to 0.71% and the P levels varied from 0.08% to 0.38%.

**Site 1: Banizoumbou, Niger**

*Interaction of N, P and manure.*

A factorial experiment of manure (0, 2 and 4 t/ha), nitrogen (0, 30 and 60 kg N/ha) and phosphorus (0, 6.5 and 13 kg P/ha) was established in Banizoumbou to assess the fertilizer equivalency of manure for N and P. The data show a very significant effect of N, P and manure on pearl millet yield. Whereas P alone accounted for 60% of the total variation, nitrogen accounted for less than 5% in the total variation indicating that P is the most limiting factors at this site. Manure account for 8% in the total variation.

*Biological nitrogen fixation.*

15N dilution technique was used to quantify the biological nitrogen fixation of three cowpea varieties (local, TN5-78 and Dan illa) under different soil fertility conditions. A non-fixing (NF) cowpea variety was used as non-fixing crop. The samples have been sent to the International Atomic Energy Agency in Vienna, Austria for mass spectrophotometer analysis of 15N in order to assess the biological nitrogen fixation.

*Combining organic and inorganic plant nutrients for cowpea production*

The data clearly indicate the comparative advantage to combine organic and inorganic plant nutrients for the low suffering soils in the Sahel. The use of only organic P sources yield 5000 t/ha of cowpea fodder whereas the application in the organic farm gave 5718 t/ha.

**Site 2: Maseno, Western Kenya.**

An integrated nutrient management experiment at maseno was established in the highlands of Western Kenya on a nitisol at an elevation of 1420 m ASL and receiving an annual rainfall of about 1800mm distributed over two growing seasons. Farmyard manure (quality parameters) was used as the low quality organic resource and was integrated with 0, 30, 60 and 90 kg N $ha^{-1}$. Since this was a poor season, the overall grain yield and subsequent response to N was poor. However at 0-30 N levels, treatments integrated with organics consistently yielded higher than urea-N. These differences declined beyond 30N. In contrast, these manures appeared to be effective in overcoming P deficiency that is widespread on farms in Western Kenya.

**Site 3: Kogoni, Mali**

The experiment was conducted in collaboration with the Institut d' Economic Rurale (IER), Mali at the research station in Niono. The site was located at Kogoni in the rice-growing region. Low quality manures

derived from livestock fed predominantly rice residues were used in combination with urea-N at 0, 30, 60, 90 and 120kg ha-1. The data show rice yield response to N in the presence or absence these manures. Application of 90-120 kg N gave the highest paddy yield (approx 7.5 t $ha^{-1}$) thereby doubling yield over the control. Integration with manure did not significantly increase the rice yields at any N levels; rather there was a slight additive effect of applying the low quality material.

**Site 4: Farakou Ba, Kou Valley, Burkina Faso**

In Burkina Faso, trials were conducted at the Kou valley research station in collaboration with the INERA. The low quality organic input was manure (<1.0%N). The test crop was irrigated rice. The manure applied at 1, 2, 3 and 4 tons dry matter per hectare was combined with urea-N at 0, 40, 80 and 120 Kg N $ha^{-1}$. The data show rice yield response to urea-N alone or in combination with organic matter at 4 levels. Applications of N alone doubled rice grain yield over the unfertilized control. There was an additive increase when organic matter was integrated with inorganic-N at all manure levels, however this increase was not significant.

**Site 5: Zaria, Nigeria**

The experiments at Zaria are conducted in collaboration with Ahmadou Bello University. The site is located adjacent to the Danayamaka village to the North of Zaria within the Guinean zone. Low quality manure that is typical of farmer organic resource input was used. The manure applied at 1, 2, 3 and 4 t dm ha-1 was combined with 0, 30, 60 and 90 kg N ha-1 in a split plot design arrangement where the main plots were treated with N at 4 levels and the sub-plots received manure inputs at 4 levels. The data show the yield obtained with sole applications of urea-N (response curve) or urea-N in combination with organic manure inputs. At this site, additive effects of manure and fertilizer combinations were not significant indicating that these manures contributed little to the N demand for the maize crop. In addition, the data show that these low quality manures can contribute significantly to overcome P deficiency to maize crop.

**Site 6: Kumasi, Ghana**

The Soils And Fertilizer Research Institute was the implementing partner for the network experiments in Ghana. The benchmark site was located within the humid forest zone north of Kumasi. The trial was arranged as a randomized block design on a uniform site that was recently cleared. Low quality maize stover and giant panicum grass were tested as possible organic resources that can be combined with mineral fertilizers for soil fertility improvements. However, the giant panicum treatments did not have sufficient replication to warrant being included in this report. In conclusion, the results for this site are not yet available.

**Site 7: Davie, Togo**

The site in Togo is located at Davie within the derived savannah zone. Partners from ITRA, Togo implemented the network experiments. For INM1, local organic resources used consisted of rice residues, which were obtained from an adjacent rice scheme. In order to achieve the required weight in dry matter equivalent for the materials added, not all residues could be incorporated and some of it remained as surface mulch for prolonged periods of time during the growing season. The response of maize to the application of rice residues. There was little or no response to N at this site, probably due to moisture stress resulting from drought during the first season

**Site 8: Kabete, Kenya**

In addition to the long-term trial that was earlier reported an adjacent experiment was established to investigate the optimum combination of organic and inorganic N sources. Three different materials of differing quality were applied at 60 kg N/ha equivalent. At this N rate, the fertilizer equivalency value of tithonia was 100% while for senna and calliandra it was 43% and 38% respectively. This indicated that tithonia was as good as urea in supplying N to maize crop.

**Results: Equivalency of fertilizer value of legume-cereal cropping**

Experiments were established at Maseno in Western Kenya, Zaria in Nigeria, Kumasi in Ghana and Davie in Togo

These experiments were to investigate Optimum N and P management in legume-cereal rotations. Although the combined application of organic resources and mineral inputs forms the technical backbone of the Integrated Soil Fertility Management approach, procuring a sufficient amount of organic matter of a desired quality is very often a problem farmers are facing. In-situ production of organic matter is an attractive alternative to technologies harvesting the organic resources from other sites within or outside the farm. Opting for legumes during the organic resource production phase has the potential to enrich the soil with N through biological $N_2$ fixation.

Herbaceous or green manure legumes usually leave substantial amounts of N in the soil although when left to grow to maturity, harvesting the seeds may substantially reduce the net N input into the soil. 'Traditional' grain legume germplasm has a large N harvest index indicating that although a significant part of the N taken up by the legume was certainly fixed from the atmosphere, more N was taken away during grain harvest resulting in a negative net N input. However, dual-purpose germplasm is now available for, e.g., cowpea and soybean, which produces substantial amounts of haulms besides grains and has a relatively low N harvest index. As such, a net N input into the soil can be expected. Besides fixing N, certain legumes are also known to access less available P pools, alter the soil pest spectrum or improve soil biological properties. These benefits are often summarized as non-N benefits. The effect of a legume on a following cereal crop is often expressed as its N equivalent. One needs to take into account that the processes mentioned above might also lead to a better utilization of legume or fertilizer N although the improved yields are not necessarily an improvement of N supply.

The current experiments aim at quantifying the contribution of herbaceous and grain legumes to N supply and, where relevant, at quantifying the impact of targeting P to certain phases of the rotation on the overall yield. No data is available for this report yet as we will be able to monitor the rotation effect only during the next cropping season.

**Results: Phosphorus (P) placement and P replenishment with Phosphate rock**

Single Superphosphate (SSP), Tahoua Phosphate Rock (TPR) and Kodjari Phosphate Rock (PRK) were broadcast (bc) and/or hill placed (HP). For pearl millet grain P use efficiency for broadcasting SSP at 13 kg P/ha was 18 kg/kg but hill placement of SSP at 4 kg P/ha gave a PUE of 83 kg/kg P. Whereas the PUE of TPR broadcast was 16 kg grain/kg P, the value increased to 34 kg/kg P when additional SSP was applied as hill placed at 4 kg P/ha. For cowpea fodder PUE for SSP broadcast was 96 kg/kg P but the hill placement of 4 kg P/ha gave a PUE of 461 kg/kg P. Those data clearly indicate that P placement can drastically increase P use efficiency and the placement of small quantities of water-soluble P fertilizers can also improve the effectiveness of phosphate rock .

**Results: Placement of phosphorus and manure**

A complete factorial experiment was carried out with three levels of manure (0, 3, 6t/ha) three level of P (0, 6.5 and 13 kg/P ha) using two methods of application (broadcast and hill placement).

The response of millet to P and manure for the two methods of application. For pearl millet grain the hill placement of manure performed better than broadcasting and with no application of P fertilizer, broadcasting 3 t/ha of manure resulted on pearl millet grain field of 700 kg/ha whereas the point placement of the same quantity of manure gave about 1000 kg/ha. Cowpea are showing also the same effect as for pearl millet.

A complete factorial experiment of three level of P (0, 13 and 26 kg P/ha), three levels of N (0, 30 and 60 kg N/ha), and three levels of manure (0, 2, 4 t/ha) was carried out. For pearl millet grain, the

optimum combination of organic and inorganic soil amendment gave yield of about 2 t/ha whereas the control yield was 450 kg/ha. The P and N fertilizer equivalency of manure range from 291 to 397%.

**Results: Farmer's evaluation of soil fertility restoration technologies**

*Karabedji site*

Past research results indicated a very attractive technology consisting of hill placement of small quantities of P fertilizers. With DAP containing 46% P2O5 and a compound NPK fertilizer (15-15-15) containing only 15% P2O5, fields trials were carried out by farmers on 56 plot per treatment to compare the economic advantage of the two sources of P for millet production. As hill placement can result in soil P mining another treatment was added consisting of application of phosphate rock at 13 kg P/ha plus hill placement of 4 kg P/ha as NPK compound fertilizers.

The data clearly shows that there was no difference between hill placement of DAP and 15-15-15 indicating that with the low cost per unit of P associated with DAP, this source of fertilizer should be recommended to farmers. The basal application of Tahoua Phosphate rock gave about additional 300 kg/ha of pearl millet grain. The combination of hill placement of water-soluble P fertilizer with phosphate rock seems a very attractive option for the resource poor farmers in this region. The data clearly show that the application of Tahoua PR with hill placement of water soluble P outperformed the other treatments in most instances.

*Sadore site*

**Low, medium and high inputs of mineral fertilizers evaluation**

Farmers' practices were compared to a low input system consistency on increasing crop planting density at recommended level, a medium input where Tahoua Phosphate rock was applied at 13 kg P/ha and SSP hill placed at 4 kg P/ha and high input as recommended by the extension services where SSP is broadcast at 13 kg P/ha with nitrogen applied at 30 kg N/ha as urea.

The data indicates that grain yield can be increased three fold with the medium input and higher economic returns can be anticipated with this treatment. The data show how the yield of the technologies evaluated fluctuated as compared to the farmers' practices with the high input systems dominating the other systems in most instances.

As for Karabedji, DAP, NPK and SSP were compared and there was any significant effect between the three sources and yield can be increased for more than two fold with this low input technology.

*African Academy of Sciences (in press)*

**Soil Fertility Management in Africa: A Regional Perspective**

Gichuru, M.P., Bationo, A., Bekunda, M.A., Goma, H.C., Kimani, S.K., Mafongoya, P.L., Mugendi, D.N., Murwira, H.M., Nandwa, S.M., Nyathi, P. and Swift, M.J. (Eds.)

**Preface**

In Sub-Saharan Africa (SSA) the economic growth and quality of life largely depends on the agricultural sector, which accounts for more than 25% of the Gross Domestic Product (GDP). Nonetheless, the region is characterised by declining per capita cereal production estimated at 150kg/person to 130 kg/person over the past 35 years. As a result recent estimates indicate that by year 2020, the SSA annual cereals imports will rise to more than 30 million metric tons.

Soil fertility degradation has been described as the single most important constraint to food security in SSA. A large proportion of soils in SSA have low inherent fertility but the major cause of soil fertility degradation is the imbalance caused by nutrients are not commonly replaced resulting to negative nutrient balances. Despite proposals for a diversity of solutions and the investment of time and resources by a wide range of institutions it continues to prove a substantially intransigent problem.

The effects of soil fertility degradation are not confined to the impact on agricultural production. The living system of the soil also provides a range of ecosystem services that are essential to the well being of farmers and society as a whole. Degradation of the soil resource also leads to:

- Reduced capacity to maintain vegetative cover;
- Decreased water quality;
- Lowered efficiency of use of water and management;
- Increased risk from pests and diseases because of lowered biological control capacity;
- Increased risk to human health for the same reason and because of lowered water quality;
- Increases in the emission of greenhouse gases with consequent effects on climate;
- Increased prevalence of catastrophic events such as landslides and floods.

In 1988, the Tropical Soil Biology and Fertility Programme (TSBF) established the African Network for Soil Biology and Fertility (AfNet) as the single most important implementing agent of TSBF programme. The network has the overall goal of strengthening and sustaining stakeholders capacity to generate, share and apply soil fertility management knowledge to contribute and to the welfare of farm communities. AfNet is a network of resource management scientists working in Africa whose objective is to promote research collaboration to develop sustainable soil management practices through the manipulation biological processes that control soil fertility. The network is unique in that research projects are developed primarily by scientists within national academic and research institutions so that research is conducted to meet national or regional priorities as well as personal and institutional goals. The purpose of this network research is to apply the principles of soil biology with emphasis on ways to increase food production in smallholder production systems. This book is a synthesis of results from AfNet and other sources and presents the views of African scientists on the critical issue of improving the fertility and productivity of the soils of the continent. The book incorporates both thematic and agroecological reviews. In the former case the main thrust lies in an integrated approach to soil fertility management - combining biological, physical and socio-economic scientific research with farmer's needs and opportunities. In the latter, the focus is to apply the lessons from the integrated analysis to the particular problems of different agroecological zones. This book represents the first step in disseminating AfNet results, concepts and recommendations to its clients. The writing of the book as a collaborative effort of scientists from several African countries has forced a synthesis of results and a sharing and distillation of ideas among network members from many countries and institutions. The book also attempts to compile the available information from the literature and from on-going work in soil biology. The target of such a book is the first level of clients - researchers and development personnel in Africa and

influential international agencies. However, the authors have also attempted to address the issues of dissemination of results to the ultimate client - the farmer.

The presentation is divided into three main sections. The first section (Chapters 1 and 2) introduces the principles of soil biology and fertility. The second section (Chapters 3 to 8) focuses on the major production systems in each of the main agroecological zones in Africa. The ecological zones and the main soil fertility constraints are defined followed by selected case studies of important production systems. Each chapter has a synthesis of strategies for integrated resource management for that agroecological zone. The final section (Chapter 9) integrates the concepts in the framework of integrated soil fertility management

We anticipate that the book will serve as a source book for university students, alongside the two previous TSBF texts (Laboratory Methods of Soil and Plant Analysis: A Working Manual, edited by JR Okalebo, K.W. Gathua and PL Woomer and The Biological Management of Tropical Soil Fertility, edited by P.L Woomer and M.J. Swift). Teachers of courses on soil biology and fertility in the region currently have only limited examples from the tropical setting. Students sometimes have difficulties relating examples from textbooks devoted almost exclusively to temperate region agriculture to production systems in tropics. The format of this book is however, aimed to serve as a source text for courses in soil biology and fertility as a reference for agricultural scientists and development workers interested in sustainable agriculture in the tropics.

We are grateful to DANIDA who provided funds to support the workshop where the initial ideas to write the book were developed as well as subsequent meetings of the Editorial Committee (Mwenja Gichuru, André Bationo, Mike Swift, Nairobi). Dr Mary Scholes, of the Department of Botany, University of the Witwatersrand, Johannesburg, Republic of South Africa, and a long time AfNet member, organised and provided the logistical support for the workshop. We are also grateful to the Technical Centre for Agricultural and Rural Cooperation (CTA) who provided the funds for the publication of this book. We also take this opportunity to thank the various donors who have funded the TSBF African Network research over the years.

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Chapter 8: Soil Fertility Management for Sustainable Land Use in the West African Sudano-Sahelian Zone. A Bationo, U Mokwunye, PLG Vlek, S Koala and BI Shapiro.
8.1 Introduction
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*AfNet 8 Proceedings (in press). African Academy of Sciences.*

**Soil fertility management for sustainable land use in the West African Sudano-Sahelian zone.**

**Bationo, A., Mokwunye, U., Vlek, P.L.G., Koala, S. and Shapiro, B.I. (Eds.)**

Arrangements to publish the AfNet 8- Arusha proceedings are in progress. The publishing will be done by the Africa Academy of Sciences. All the papers have already been submitted the publishers. The selection of the best papers of AfNet members for publishing in refereed journals has not yet been done.

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The use of pigeon pea (*Cajanus cajan*) for amelioration of Ultisols in Ghana
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Synthesis of the research in West Africa has been written. A book will be written and published with financial support from ICRISAT.

The network members have already started the layout of a book entitled **"Fighting Poverty in Sub-Saharan Africa: The Multiple roles of Legumes in Integrated Soil Fertility Management"** with the following outline:

Chapter 1: Agro-ecological distribution of legumes in farming systems and identification of biophysical niches for legume growth. (S Nandwa, S. Obanyi, J Kinyangi and P Mafongoya)
- Occurrence of various classes of legumes in the different agro-ecological zones
- Current and potential niches for legumes
- Potential for highland legumes

Chapter 2: Economic evaluation of the current and potential contribution of legumes to smallholder livelihoods. (M Odendo, V Manyong J. Ramisch, K. Acheampong and S Kimani)
- Current direct and indirect role of legumes in income generation for different agroecozones
- Nutritional value

Chapter 3: Inter and intra specific variation of legumes to access stable soil P and rock phosphate and adaptation to adverse soil conditions. (H Nwoko, B K Tossah, Susan Ikerra, N Sanginga, I.M. Rao, A. Bationo, and U. Mokwunye)
- Screening species and varieties for ability to access low soil P and RP
- Screening for adverse soil conditions (water logging, low soil pH, drought…)

Chapter 4: Legumes, soil biodiversity and soil-borne pest and disease dynamics. (M Bekunda, A Emechebe, K Ampofo, R Buruchara, S Schulz and M Swift)
- Role of legumes in altering soil biodiversity (positive and negative) for various classes of legumes
- Striga dynamics in rotations
- Pest and disease spectra dynamics in legume rotations for various classes of legumes

Chapter 5: Strategies to adapt, disseminate, and scale out legume based technologies. (D Mugendi, N Karanja, P Sanginga, P Soniia, E Mulugetta, Q Noordin and R Jones)
- Identification of socio-economic niches for growth of various classes of legumes
- Farmer participatory adaptation and evaluation of various classes of legumes

Chapter 6: Comparative analysis of the current and potential role of legumes in Integrated Soil Fertility Management in West and Central Africa
(A Bationo, V.Bado, B Vanlauwe, M Bagayoko, A Buerket and S Koala)
- Impact of various classes of legumes on soil fertility, emphasizing N contributions, soil physical properties, and soil C build-up in West/Central Africa

Chapter 7: Comparative analysis of the current and potential role of legumes in Integrated Soil Fertility Management in East Africa. (J Ojiem, C K K Gachene, J Mureithi, C Palm, R Delve, J Mureithi, B Jama, S Slim and G Odhiambo)
- Idem in East Africa

Chapter 8: Comparative analysis of the current and potential role of legumes in Integrated Soil Fertility Management in southern Africa. (P Mapfumo, W Sakala, S Slim, S Mpepereki, S Waddington, H Murwira, F. Mafongoya and K Giller)
- Idem in southern Africa

## List of Acronyms

| | |
|---|---|
| ACIAR | Ausralian Centre for International Agricultural Research, Australia |
| AUN | Agricultural University of Norway, Norway. |
| AHI | African Highlands Initiative |
| BMZ | Bundesministerium für Wirtschaftliche Zusammenarbeit und Entwicklung |
| CATIE | Centro Agronómico Tropical de Investigación y Enseñanza (para América Central), Costa Rica. |
| CENICAFE | Centro Nacional de Investigaciones en Café, Chinchiná, Colombia |
| CENIPALMA | Centro de Investigación en Palma de Aceite, Colombia |
| CIAT | Centro Internacional de Agricultura Tropical, Colombia |
| CIDIAT | Centro Internacional de Desarrollo Integral de Aguas y Tierras, Venezuela. |
| CIELAT | Centro de Investigaciones Ecológicas de los Andes Tropicales, Venezuela. |
| CIMMYT | Centro Internacional de Mejoramiento de Maiz y Trigo |
| CIP | Centro Internacional de la Papa |
| CIPASLA | Consorcio Interinstitucional para la Agricultura Sostenible en Laderas, Colombia. |
| CIRAD | Centre de Coopération Internationale en Recherche Agronomique poour le Depeloppement, France |
| CNPAB | Centro Nacional de Pesquisa de Agrobiologia, Brazil |
| COLCIENCIAS | Instituto Colombiano para el Desarrollo de la Ciencia y la Tecnología “Francisco José de Caldas”, Colombia |
| CORPOICA | Corporación Colombiana de Investigación Agropecuaria, Colombia. |
| CPAC | Centro de Pesquisa Agropecuaria dos Cerrados (of EMBRAPA) |
| CSIRO | Commonwealth Scientific and Industrial Research Organization, Australia |
| CVC | Corporación del Valle del Cauca, Cali, Colombia |
| DFID | Department for International Development |
| DRSS | Department of Research and Specialist Services, Zimbabwe |
| EC | European Comisión, Belgium |
| ENA | Escuela Nacional de Agricultura |
| EMBRAPA | Empresa Brasileira de Pesquisa Agropecuaria, Brazil |
| ETH | Institut for Plant Science, Zurich |
| FAO | Food and Agriculture Organization of the United Nations, Italy |
| FASID | Foundation for Advanced Studies in International Development, Japan |
| FEDEARROZ | Federación Nacional de Arroceros, Colombia |
| GTZ | Technical Cooperation, Germany |
| IAEA | International Atomic Energy Agency, Vienna, Austria |
| IBSRAM | International Board for Soil Research and Managment |
| ICRAF | International Centre for Research in Agroforestry, Nairobi, Kenya |
| ICRISAT | International Crops Research Insttitute for the Semi-Arid Tropics, India |
| IDRC | International Development Research Centre, Canada |
| IFDC | International Fertilizer Development, USA |
| IIAP | Instituto de Investigaciones Ambientales del Pacífico, Quibó (Chocó), Colombia |
| IITA | International Institute of Tropical Agriculture, Nigeria |
| IGAC | Instituto Geográfico “Agustín Codazzi”, Bogotá, Colombia |
| ILRI | International Livestock Research Centre, Kenya |
| IPF | Instituto de Fósforo y Potasio, Ecuador |
| IRD | Institut Français de Recherche sicentifique pour le Developpement et Coopération, France. |
| IRRI | International Research Institute |
| KARI | Kenya Agricultural Research Institute |

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| KWAP | Kenya Woodfuel and Agroforestry Project |
| LAC | Latin American and the Caribbean |
| MAS | Management of Acid Soils (of SWNM of the CGIAR), CIAT Colombia. |
| MIS | Integrated Soil Management (of SWNM of the CGIAR), CIAT Honduras |
| NARS | National Agricultural Research Systems |
| NAU | Norway Agricultural University |
| NGO | Non-Governmental Organization |
| PRONATTA | Programa Nacional de Transferencia de Tecnología, Colombia |
| SLU | Swedish Agricultural University |
| SOL | Supermercado de Opciones para Laderas |
| SWNM | Soil, Water and Nutrient Management (systemwide program of the CGIAR), CIAT Colombia. |
| UNA | Universidad Nacional Agraria, Nicaragua |