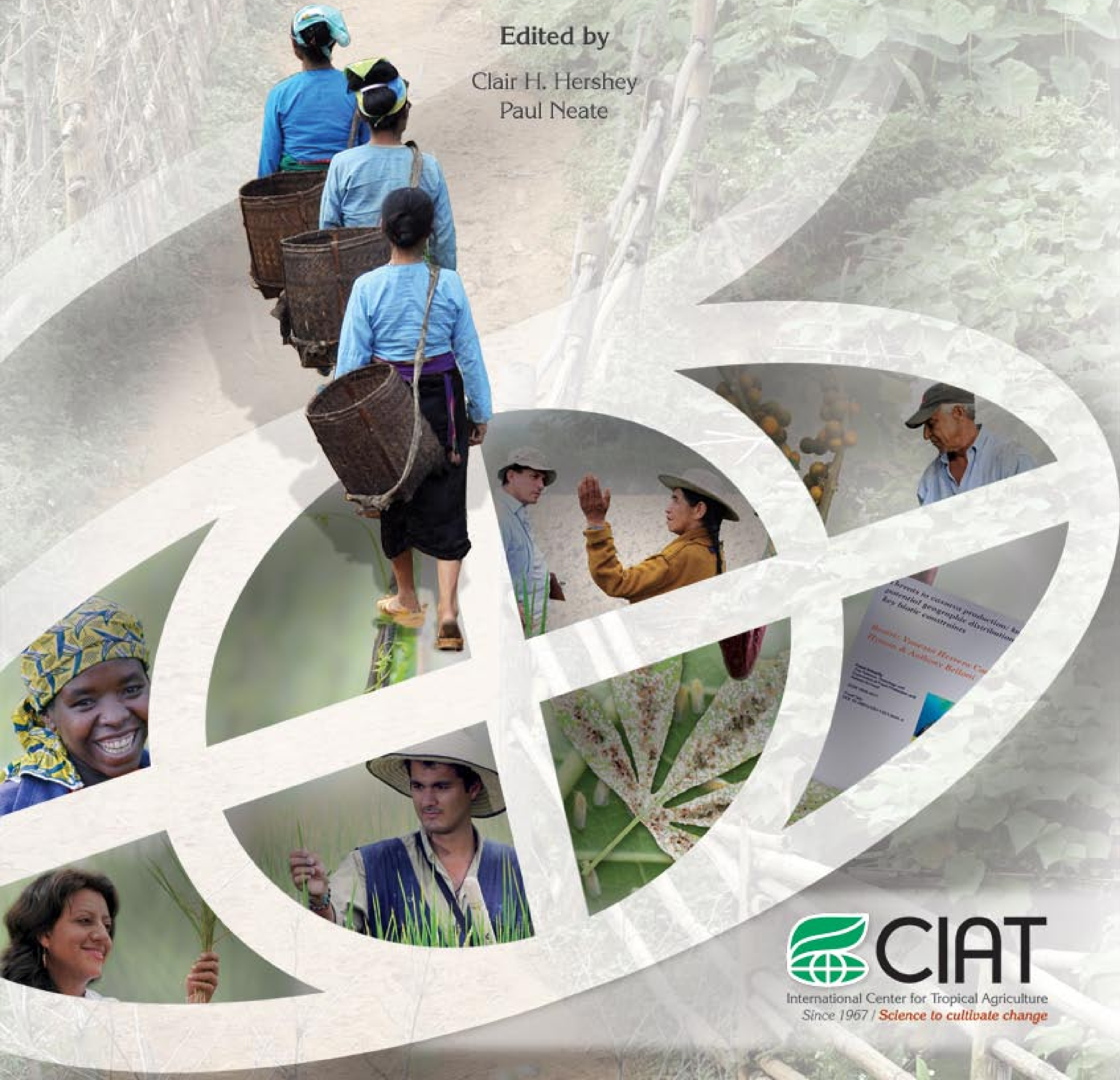
Eco-Efficiency: From Vision to Reality



Edited by

Clair H. Hershey
Paul Neate

CIAT
International Center for Tropical Agriculture
Since 1967 / **Science to cultivate change**

CIAT

The International Center for Tropical Agriculture (CIAT) – a member of the CGIAR Consortium – develops technologies, innovative methods, and new knowledge that better enable farmers, especially smallholders, to make agriculture eco-efficient – that is, competitive and profitable as well as sustainable and resilient. Eco-efficient agriculture reduces hunger and poverty, improves human nutrition, and offers solutions to environmental degradation and climate change in the tropics. Headquartered near Cali, Colombia, CIAT conducts research for development in tropical regions of Latin America, Africa, and Asia. www.ciat.cgiar.org

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1. Cropping systems. 2. Climatic change. 3. Mixed cropping. 4. Agroforestry. 5. Livestock. 6. Crops. 7. Cereals. 8. Manihot esculenta. 9. Oryza sativa. 10. Forages. 11. Sustainable agriculture. 12. Soil fertility. 13. Agroecology. 14. Farmers. 15. Developing countries.

Local Descriptors:
1. Eco-efficient agriculture. 2. Cassava. 3. Rice.

Descriptores AGROVOC:
1. Sistemas de cultivo. 2. Cambio climático. 3. Cultivo mixto. 4. Agroforestería. 5. Ganado. 6. Cultivos. 7. Cereales. 8. Manihot esculenta. 9. Oryza sativa. 10. Forrajes. 11. Agricultura sostenible. 12. Fertilidad del suelo. 13. Agroecología. 14. Agricultores. 15. Países en desarrollo.

Descriptores Locales:
1. Agricultura eco-eficiente. 2. Yuca. 3. Arroz.

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Dedicated to the memory of ***Anthony Bellotti*** *(1937–2013***)***,*
whose enormous professional accomplishments advanced the knowledge of cassava entomology from its infancy to maturity, opening the way for major contributions to improved livelihoods for cassava farmers.

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Foreword

CIAT is launching a new publication series titled *Issues in Tropical Agriculture*, and the first item in the series is *Eco-Efficiency: From Vision to Reality*. At first glance, the term "eco-efficiency" calls to mind the oft-repeated, simplistic idea of "producing more with less." But when viewed in relation to the challenge of what William Laurance and Jeff Sayer call the impending "agricultural bomb," the importance of the eco-efficiency theme becomes clear.

In fact, humanity is one drought away from massive famine. All it would take is an episode of dry weather, typical of past drought events, in the North China Plain, the US Corn Belt, or the Indo-Gangetic rice-wheat region. Indeed, the global food supply is on such a razor's edge that, as I was writing this foreword, a short heat wave without rain predicted for the US Corn Belt in the following week (24-30 June 2012) caused global maize prices to rise by 20% within just a few days. Since 2005, price spikes larger than this have occurred for rice and wheat, when drought or floods have occurred in a major crop production domain.

But the agricultural bomb is not just a warning about the need to increase production, because we live on a spaceship with finite resources. Land and water of adequate quantity and quality to support agricultural systems for a human population of 9 billion or more by 2050 are already in short supply. While there is some additional land suitable for agriculture in remnant rainforests, wetlands, and grassland savannas, bringing this land into food production would incur unacceptable costs in terms of greenhouse gas emissions and loss of climate regulation and biodiversity.

As a result, it is time to reach a global consensus on the explicit goal of meeting future food demand with the existing agricultural area—a goal that concedes conversion of an additional 100 million hectares of natural ecosystems to replace current crop land expected to be lost to urbanization and industrialization by 2050 (or about 7% of the current area used to produce annual crops).

Likewise, the manner in which crops and livestock are produced on existing farmland can have devastating negative impacts on the environment, human health, and greenhouse gas emissions. So, the challenge is not only to raise yields fast enough on existing farmland but also to do so using methods that reduce the environmental footprint of agriculture. And the scale of reduction in negative environmental externalities must be substantial: Nitrogen and water use efficiencies must increase by more than 50% in some of the world's major crop production systems; farming systems must be improved to reverse current trends of soil degradation and to maintain or increase organic matter levels; and net energy yields must double.

We are left with the realization that business as usual will not achieve a food-secure world on existing farmland without unacceptable loss of environmental services, because trajectories in crop yield advances and in the environmental impact of agriculture are simply not good enough. Hence, it can be argued that the single greatest scientific challenge facing humankind is generating the knowledge, technologies, and policies that can achieve the ecological intensification of agriculture that is required.

This brings us back to the concept of eco-efficient agriculture. As defined in CIAT's *Strategic Directions*, the concept focuses on increasing productivity while decreasing negative impacts on natural resources through approaches that meet the economic, social, and environmental needs of the rural poor. It seeks to integrate the economic, environmental, and social elements of development, and strives toward solutions that are competitive, profitable, sustainable, and resilient in the face of an uncertain climate. The concept also takes into account the fact that increasing crop yields is necessary, but not sufficient, to avoid conversion of natural ecosystems; effective policies and good governance are also needed. Eco-efficiency further assumes that there are no silver bullets and that dealing with tradeoffs and using integrative and interdisciplinary approaches are essential. Finally, it recognizes that almost every future climate scenario already exists somewhere in the world today, such that helping develop eco-efficient solutions for poor farmers who struggle to feed their families in those environments is among the best research investments for adaptation to future climate change.

The papers in this inaugural publication cover a number of promising technology packages and much exciting science aimed at making agricultural systems more eco-efficient. But it is also clear that a number of gaps and emerging issues remain.

There is a critical need for robust, low-cost, reproducible metrics to quantify the impact of agriculture on environmental quality and human well-being. A new area of "metrics research" must emerge to provide the scientific underpinning for applying to complex issues easily measured, integrative parameters for monitoring impact from the field to the watershed and global levels.

Likewise, there is a need for improved methods to anticipate and quantify tradeoffs at different spatial scales. For example, while organic agriculture may reduce the environmental footprint of agriculture locally, it may result in large negative impact at the global level. This could occur if organic systems are widely adopted and have lower yields per unit land area and time than conventional systems, which would encourage conversion of natural ecosystems and associated loss of environmental services and greenhouse gas emissions to meet future food demand.

Therefore, one of the grand challenges for CIAT, and indeed for CGIAR and its partners, is to conduct research and support development efforts that lead to quantum leaps in the eco-efficiency of agricultural systems of greatest importance to the poor in developing countries. We are in a race against time, and there is no time to lose.

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Preface

The term "eco-efficiency" was first put forward by the private sector around the time of the 1992 Earth Summit, held in Rio de Janeiro, Brazil. It first entered CIAT's vocabulary in 2008, as the Center charted new strategic directions for the coming years. Management foresaw the need to identify an overarching concept that would differentiate our work from that of others and help explain our unique contribution to the strategic global research of the CGIAR Consortium, of which CIAT is a member.

The eco-efficiency concept was chosen to serve that purpose, and it soon began to appear in CIAT documents and in discussions about our work. After a year or so, people began asking exactly what eco-efficiency meant for the Center's work. To some, it just sounded like another buzz word.

Then, during a visit to CIAT headquarters, Derek Byerlee, former chair of the Standing Panel on Impact Assessment of the CGIAR's Independent Science and Partnership Council (ISPC), suggested a way to explore the eco-efficiency vision. His idea was to create a "flagship" publication series, whose first volume would deal with the notion in depth.

We invited Derek and others – including Claudia Martínez, Rodomiro Ortiz, Nicolás Mateo, and Brian Keating – to form an editorial committee. Their efforts have resulted in this substantial scientific publication, which was first made available online (http://ciat.cgiar.org/new-publications/) and which we are now happy to see in print.

One especially noteworthy feature of this first volume in CIAT's new flagship publication series (named Issues in Tropical Agriculture) is that it involved authors from 18 other organizations, in addition to many CIAT scientists. So, eco-efficiency is not just CIAT's green paradigm but resonates with others as well.

One clear message of the publication for CIAT is that taking the eco-efficiency concept seriously does not mean that we have to completely rethink our research approaches and re-engineer our programs. Most of the Center's research already matches one of the six pathways to eco-efficient agriculture described by Brian Keating in his introductory chapter. That and other chapters also make it clear that eco-efficiency is highly relevant to climate change and other major challenges for agriculture.

This publication offers no simple solutions to those challenges but rather provides a set of guideposts for keeping research on track toward eco-efficient outcomes, which are important for CIAT's mission and that of CGIAR. Our challenge now is to apply the messages of this book earnestly in our work and to communicate them effectively with our partners and donors.

This publication marks the culmination of much hard work by dozens of scientists at CIAT and in partner organizations. To all of them we owe a very large debt of gratitude. We also thank Ken Cassman, Chair of the ISPC, for contributing the foreword.

Clair H. Hershey
Leader, Cassava Program, CIAT

CHAPTER

1

Resource Use Efficiency Revisited

Nicolás Mateo[1] *and Rodomiro Ortiz*[2]

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Abstract

The notion of "eco-efficiency" can provide a solid basis for developing a conceptual understanding of rational and effective use of resources in agriculture and a set of tools to move us toward these objectives. It will not, however, be the magic bullet to solve the overuse of resources in agriculture. A wide range of concepts and approaches need to come together if we are to succeed in solving this problem. Both high-input intensive agriculture and low-input agriculture need to evolve based on agroecological principles. In broad terms, high-input agriculture should aim at becoming more eco-efficient, and low-input agriculture needs to increase in productivity while retaining high efficiency of input use.

This chapter looks at eco-efficiency from a perspective of experiences and lessons in resource use, research for development, climate change adaptation and mitigation, policies and incentives, and social equity and gender. The narrative: (1) points out the key roles of research and potential research breakthroughs to alleviate food shortages in the future; (2) suggests following the path of "resource use efficiency" in terms of strategies and management practices; (3) suggests the need for changes in land use; and (4) indicates the importance of investing in gender equity as a means to improve food production and food security and achieve greater social equity.

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Background and Historical Perspective

> *In the long run the planet has the upper hand. In the short run humans act as if they do and as if this will continue to be the case (Hall, 2008)*

The concept of "eco-efficiency" originates from the field of natural resources research. However, in this chapter, while giving particular attention to natural resources, we adopt the more inclusive description used by CIAT and elaborated in its Medium-Term Plan 2010-2012, p.3. This states the following:

> "Eco-efficient agriculture increases productivity while reducing environmental impacts. Eco-efficient agriculture meets economic, social, and environmental needs of the rural poor by being profitable, competitive, sustainable, and resilient. It harmonizes the economic, environmental, and social elements of development, and strives toward solutions that are competitive and profitable, sustainable, and resilient, and generate benefits for the poor. Eco-efficient agriculture cannot effectively address the needs of the poor without taking into account the particular needs of women."

This definition follows suggestions of authors such as Park et al. (2010) to explicitly include social criteria as well as economic and environmental criteria in order to improve rates of uptake of eco-efficiency technologies, to promote practices that improve the effectiveness of hunger-reduction efforts, and to minimize environmental degradation. Chapter 2 of this volume goes into detail on conceptual foundations and frameworks for eco-efficiency.

The seminal work of Meadows et al. (1972)—*The limits to growth*—impacted academia and society at large, although perhaps not so much the political process. Using what was then an advanced model of interactions between human population, industrial growth, food production, and ecosystems—World3—the authors warned that growth without limits would have serious consequences on earth's finite resources. Twenty years later the authors followed up with another significant piece, *Beyond the limits* (Meadows et al., 1992), in which they argued that humans were overshooting the capacity and availability of earth's resources. This research sparked, and has become a cornerstone of, the intense debate on sustainable development. More recently, *Limits to growth: The 30-year update* (Meadows et al., 2004) attempted once more to provide data and make a compelling case for a significant debate and urgent actions to limit and to make rational use of scarce resources.

The experiences and lessons learned from the Green Revolution of the 1960s and beyond point to significant trade-offs in resource use. While there were ample benefits from targeted plant breeding and the application of external inputs in terms of increased productivity, income, and food production, this strategy placed significant pressures on natural resources and the environment.

During the last 4 decades recognition of unsustainable resource use and the increasing concerns expressed by producers, consumers, and civil society have prompted the development and testing of approaches to optimize resource use, such as minimum tillage, precision agriculture, plant breeding for input use efficiency (water, nitrogen), marker-assisted breeding, and transgenic crops and animals. This volume highlights a number of these accomplishments as well as related experiences and lessons learned.

Despite the advances in agricultural productivity, wasteful and contaminating systems continue to coexist with eco-efficiency-based approaches. Population growth, market forces, productivity levels, and incentives all impact on the balance between positive and negative forces driving agricultural innovation. Policies and incentives at the local, national, and international levels exert a strong influence on outputs and outcomes.

We need to consider eco-efficiency beyond the farm, crop, or animal enterprise level, and extend the concepts to include the whole food chain. This will include the full life cycle of inputs to the farm and products leaving the farm, i.e., nutrient and energy flows that include transport and processing.

While there are great opportunities for increasing eco-efficiency by adoption of mixed farming systems, particularly those involving both crops and livestock, the trend, particularly in developed countries, has been for increased specialization and separation of crop and livestock enterprises. Increasingly there may also be market opportunities based on consumer preferences for products from eco-efficient systems. Currently the proportion of food marketed as being from such systems is very small.

Several authors (Pimentel et al., 2005; Hobbs et al., 2008; Horrigan et al., 2002) have made the case for moving high-input agriculture toward greater sustainability. The arguments for this include the beneficial effects of high levels of soil organic matter, which help conserve soil and water resources and are particularly beneficial during drought years; the unsustainability of current levels of use of fossil fuels, water, and topsoil; and the documented benefits to both the environment and productivity of direct seeding, conservation tillage, integrated systems, bed planting, and mulching.

Ultimately, there will not be a simple, single solution to increasing the eco-efficiency of agriculture. There are practical advantages for intensive agriculture and low-input agriculture to each adapt and adopt the best practices of the other. High-input agriculture should aim at becoming more eco-efficient, and low-input agriculture needs to aim at higher productivity, often based on more intensive practices. To meet the growing demands for food, feed, fiber, and fuels from agriculture in the long term, this combination of higher productivity and sustainability through eco-efficient practices is imperative.

The Need for Eco-Efficiency in Agriculture

The question "why worry about producing more food?" needs to be considered from several angles.

First is how much we are currently producing. Despite constraints in water availability, land, and fertilizers (particularly nitrogen), the world should be able to feed itself. According to *The Economist* (2011), allowing for the staggering amounts of food wasted and all the food that could be eaten but is instead turned into biofuels, farmers are producing much more food than is required—more than twice the minimum nutritional needs of about 2100 calories a day.

The Food and Agriculture Organization of the United Nations (FAO) estimated that we need to increase food supplies by 70% by 2050 if we are to feed a population of 9 billion (FAO, 2009). This is a major challenge, and even more so with the constraints of available water, land, and fertilizer.

Currently, every 9 months we consume what the planet's ecology can provide sustainably in any given year (Global Footprint Network, 2011). From that point until the end of the year, we meet our ecological demand by liquidating resource stocks and accumulating CO_2 in the atmosphere. This cannot continue.

Another way to visualize this imbalance in resource use is humanity's ecological footprint. The *Living planet report 2010* (WWF, 2010) reveals that this footprint has more than doubled since 1966. In 2007, the most recent year for which data are available, humanity used the equivalent of 1.5 planet earths to support its activities. Even with modest United Nations (UN) projections for population growth, consumption patterns, and climate change, humanity will need the capacity of two earths by 2030 to absorb CO_2 waste and keep up with natural resource consumption. The report illustrates the scope of the challenges humanity faces, not only for preserving biodiversity, but also for halting climate change and meeting basic human development aspirations, such as reducing worldwide hunger and poverty.

The increased food insecurity and vulnerability of a large number of people worldwide point to a broken food production and distribution system. We need to look at the contribution agriculture should make not only to feed a growing population but also to impact less on the planet's resources. The future food supply equation needs to consider the current reality of lower growth rates for major crop yields in conventional agriculture, eco-efficient approaches to diminish impacts on natural resources, the climate change challenge, and the volatility of energy prices. Intensive, oil-dependent agriculture is reaching worrisome yield plateaus and water tables keep decreasing.

The world needs a new paradigm for the ways that we use natural resources—a new set of tools and policies. Should we eat less? Should we eat smarter (e.g., less protein of animal origin, with its high demands for energy, land, and water)? Should we create incentives to use fewer resources and implement legal directives to push for eco-efficiency? Should we put in place measures to control population growth? Pimentel et al. (2008) demonstrate that use of fossil energy in the United States' food system could be reduced by about 50% if appropriate technologies were adopted in food production, processing, packaging, transportation, and consumption.

Higher Productivity with Lower Negative Impact

Agricultural productivity must increase if we are to meet the increasing demands of a growing and more affluent population for food, feed, fiber, and fuels in the context of limited land available for expansion of agriculture (Hubert et al., 2010). Humans have always attempted to raise the efficiency of agroecosystems, aiming to harvest more per unit of input, mainly water, nutrients, energy, or agrobiodiversity (see Chapter 2 of this volume). Efforts to increase productivity should therefore consider crop breeding (particularly for maximizing input use efficiency and for host plant resistance for reducing pesticide use), eco-friendly husbandry, and the sustainable use of natural resources (especially agrobiodiversity), while enhancing ecosystem services. This volume explores many ways that this can be accomplished.

Sustainable intensification of agriculture should reduce the need to expand into environmentally vulnerable areas, thereby sparing some lands from further degradation by concentrating production in others. However, the result of this approach is not always clear cut. Rudel et al. (2009) analyzed trends in area planted to 10 major crops between 1970 and 2005, with particular emphasis on the 1990–2005 period. The data suggest that agricultural intensification was not often accompanied by decline or even stasis in cultivated area on a national scale, except in countries that imported grain and implemented conservation set-aside programs. Thus, policies and innovations aimed at increasing land use efficiency must be carefully designed and monitored to assure they have the desired impact, rather than leading to uncontrolled land use expansion (Lambin and Meyfroidt, 2011).

Humans face the challenge of managing trade-offs between immediate needs and maintaining the capacity of the biosphere to provide goods and services in the long term (Foley et al., 2005). Policy measures are needed that provide incentives for development and adoption of more diverse, eco-efficient farming; such measures include premium prices for products from eco-efficient systems, and price supports for the provision of their environmental services. Innovative education is needed on whole-system approaches that feature resource-use efficiency and resilient farming systems to train a new generation of practitioners whose main aim will be ensuring productivity, profitability, and security of food value chains (Francis et al., 2011).

There are numerous approaches for increasing agricultural productivity using eco-efficient production systems. For example, integrating livestock, crops, and forestry systems can lead to higher productivity and lower negative impact. In such integrated systems, livestock are reared mostly on grass, browse on nonfood biomass from maize, millets, rice, and sorghum and in turn supply manure and traction (Herrero et al., 2010). Wilkins (2008) argues that eco-efficiency can be increased either by altering the management of individual crop and livestock enterprises or by altering the land use system, for example by adopting mixed crop-livestock systems that incorporate biological nitrogen fixation and use of manure as fertilizer. Combining intensification, better integration of animal manure in crop production, and matching nitrogen and phosphorous supply to livestock requirements can effectively improve nutrient flows (Bouwman et al., 2011). Furthermore, a shift in human diets (e.g., poultry or pork replacing beef) can reduce nutrient use in countries with intensive ruminant production.

Implications of Major Land Use Changes, Scale of Production, Biofuels, and Global Farmland

Land use changes

Land use changes impact the quality and availability of soils, water, and biodiversity. Globally, croplands, pastures, plantations, and urban areas have expanded in recent decades, accompanied by large increases in energy, water, and fertilizer consumption, and significant losses of biodiversity (Foley et al., 2005). These changes can also lead to changes in atmospheric concentration of CO_2, and may therefore be a contributor to climate change (see discussion below).

As noted by Lambin and Meyfroidt (2011), Bhutan, Chile, China, Costa Rica, El Salvador, India, and Vietnam managed to increase both agricultural production and the area of forests in their territories. In doing this, they relied on various mixes of agricultural intensification, land use zoning, forest protection, increased reliance on imported food and wood products, creation of off-farm jobs, foreign capital investments, and remittances. The authors conclude that sound policies and innovations can, therefore, reconcile forest preservation with food production.

According to FAO (1993), there is an increasingly urgent need to match land types and land uses in the most rational way possible, so as to maximize sustainable production and satisfy the diverse needs of society while at the same time conserving fragile ecosystems and our genetic heritage. Land use planning is fundamental to this process. It is a basic component, whether we are considering mountain ecosystems, savannas, or coastal zones, and underlies the development and conservation of forestry, range, inland, and coastal resources (FAO, 1993). For example, land use allocation has contributed to protecting the Peruvian Amazon, in spite of recent increases in disturbance and deforestation rates (Oliveira et al., 2007). Likewise, protection of productive agricultural land has become a major priority in many regions of the world. Overgrazing and intensive agriculture on marginal lands are a major driver of land loss through degradation. Policies are in place in many countries to avoid this loss of production, but their effectiveness in the face of economic demand is often limited (Ellis and Pontious, 2010).

Scale of production

The assumption that large-scale mechanized agriculture is more productive and efficient than small, family farms may be influencing agricultural development policy around the world. In several continents, developing countries are moving toward large-scale, corporate farming as a way to boost production and jump-start agricultural development (Landesa, 2011).

In the case of Canada, Maynard and Nault (2005) propose to maintain both big and small farms, given the current situation where 2% of farms produce 35% of the food. The authors propose overall strategies to keep and expand the number of small enterprises, for example, maintaining vibrant rural communities, investing in research and extension, and implementing incentives, regulations, and indicators. Current regulations are not properly differentiated and tend to favor big farms. They also examine the term “sustainability” in the context of big and small farms and find that conclusions are difficult, as the term is open to multiple interpretations. The daily reality of farming asks the questions of tradeoffs between sustainability and profitability.

Biofuels

The debate about the costs and benefits of biofuels (economically and environmentally) now focuses squarely on whether their use causes too much conversion of natural lands into crop and livestock production around the world. According to Babcock (2009), "the worry is that the loss of carbon stocks on the converted land would more than offset the direct reduction in greenhouse gas emissions caused by lower gasoline use. The California Air Resources Board has concluded that corn ethanol causes such large amounts of land conversion that it does not qualify as a low-carbon fuel. In its recent analysis of greenhouse gas emissions from biofuels, the U.S. Environmental Protection Agency estimates that corn ethanol and biodiesel made from soybean oil cause enough land use changes to call into question whether these biofuels meet required greenhouse gas reductions."

New technology, crop management changes, and renewable energy are playing important roles in increasing the energy efficiency of agriculture and reducing its reliance of fossil resources (Woods et al., 2010). Alternative renewable energy sources also bring diverse opportunities and challenges, such as how to integrate potential biofuel markets, deal with impacts on food security, alleviate poverty, and manage crop and natural resources sustainably (FAO, 2010). The agricultural systems used to produce feedstock for biofuels must use biomass sustainably, and partition it among energy, feed, food, and CO_2 fixation demands (Tilman et al., 2009). Hill et al. (2006) indicate that biofuels produced from low-input biomass plants grown on marginal land or from waste biomass, could provide much greater supplies and environmental benefits than staple food-based biofuels. Appropriate life-cycle analysis will therefore be needed to determine the use of land resources and estimate net carbon emissions of each suggested renewable energy technology (Vonblottnitz and Curran, 2007).

Global farmland

There has been a dramatic rise in interest of investors in acquiring farmland, particularly in Africa, as a result of the escalating food prices at the end of the first decade of the 21st century. The focus of this interest has largely been on land with agricultural potential that is either uncultivated or producing less than its potential. This food crisis pointed to new players, challenges, and perhaps some opportunities associated with land use changes. This phenomenal development, if considered by the sheer size of the lands being acquired (some 56 million hectares in 2009), has prompted specific proposals on the ethics and principles that should be applied by all interested parties (Deininger et al., 2011). Three key principles that are closely related to the issue of land use change are:

- *Respecting land and resource rights.* Existing rights to land and associated natural resources should be recognized and respected.
- *Responsible agro-investing.* Investors should ensure that projects respect the rule of law, reflect industry best practice, are economically viable, and result in durable shared value.
- *Environmental sustainability.* Environmental impacts of a project should be quantified and measures taken to encourage sustainable resource use while minimizing and mitigating the risk and magnitude of negative impacts.

A recent report from the World Bank (2009) examines commercial agriculture in the Guinea savanna and elsewhere in Africa. The report claims that African agriculture continues to lag, as reflected in the decline in international competitiveness of many traditional African export crops during the past 30 years, as well as in the competitiveness of some food crops for which import dependence has increased. In contrast, over the same period two agricultural regions in the developing world have shown the way—the Cerrado region of Brazil (see Chapter 4 of this volume) and the Northeast Region of Thailand. Both have developed at a rapid pace and conquered important world markets. Their success defied the predictions of many skeptics, who had asserted that the two regions' challenging agroecological characteristics, remote locations, and high levels of poverty would prove impossible to overcome.

Two recent developments have led to a change in thinking about the potential of African agriculture (The World Bank, 2009). First, during the past decade, strong agricultural growth has been recorded in many African countries, suggesting that the sector can indeed be a driver of growth when the conditions are right. Second, the steep rise in prices of food and agricultural commodities that occurred in 2008 has led to a realization that new opportunities may be opening for countries that are endowed with the land, labor, and other resources needed to respond to the growing demand for food.

Climate Change Adaptation and Mitigation

Although there may be a large regional variability, models suggest that changes in temperature and precipitation patterns due to climate change and increasing concentrations of atmospheric CO_2 will significantly affect agroecosystems and yields (Battisti and Naylor, 2009; Lobell and Field, 2007), reducing food availability and thereby jeopardizing food security and farm incomes (Lobell et al. 2008) (see also Chapter 3 of this volume). There will be shifts of plant distributions because some species will expand into newly favorable areas and others will decline in increasingly adverse locations. Climate change may increase global timber production as a result of changes of forestry locations (shifting from low-latitude regions in the short term to high-latitude regions in the long term as climate changes), whereas demand for forest products will rise slightly (Kirilenko and Sedjo, 2007).

Agriculture contributes to carbon emissions through the direct use of fossil fuels in farming, the indirect use of energy in inputs that are energy-intensive to manufacture (e.g., fertilizers), and the cultivation of soils resulting in the loss of soil organic matter (Pretty and Ball, 2001). Agricultural management explains historic changes in regional soil carbon stocks. Agriculture is also a major contributor of atmospheric nitrous oxide (N_2O), a potent greenhouse gas (GHG) commonly generated by the use of manure or nitrogen (N) fertilizers. In intensive wheat-cropping systems, common N fertilizer practices may lead to high fluxes of N_2O and NO (nitric oxide). Several groups of heterotrophic bacteria use NO_3^- as a source of energy by converting it to the gaseous forms N_2, NO, and NO_2. N_2O is therefore often unavailable for crop uptake or utilization.

Land use change contributes considerably to increases in atmospheric CO_2. The IPCC (2007) estimates the land use change (e.g., conversion of forest to agricultural land) contributes 1.6 ± 0.8 gigatons of carbon per year to the atmosphere, compared with 6.3 ± 0.6 gigatons of carbon from fossil fuel combustion and cement production.

The total biomass carbon stock of tropical forests is estimated to be 247 gigatons, with 193 gigatons stored above ground and 54 gigatons stored below ground in roots. Latin American, sub-Saharan African, and Southeast Asian forests account for 49, 25, and 26% of the total stock, respectively (Saatchi et al., 2011). Deforestation and degradation of tropical forests accounted for 12 to 20% of global anthropogenic GHG emissions in the 1990s and early 2000s. Reducing deforestation and forest degradation would thus both reduce GHG emissions and increase the potential of forests to remove additional carbon from the atmosphere.

Expansion of cattle ranching has been identified as a major cause of deforestation and a major contributor to CO_2 emissions (see Chapter 10 of this volume). The carbon footprint of beef produced on newly deforested land in the Amazon exceeds 700 kg CO_2 equivalents per kilogram of carcass weight if direct land use emissions are annualized over 20 years (Cederberg et al., 2011). Enteric fermentation is also a major contributor to GHG emissions, particularly in the developing world, which accounts for almost three-quarters of such emissions (Thorpe, 2009). Intensive ruminant-based meat production systems consume large amounts of high-value feed but suffer from low feed conversion rates and long reproductive intervals, making them inefficient users of resources. Changing from ruminants to monogastrics could significantly reduce the contribution of livestock to GHG production (Steinfeld and Gerber, 2010).

Eco-Efficient Practices to Resolve Land Use and Climate Change Challenges

Adoption of eco-efficient practices would contribute immensely to solving land use and climate change challenges noted in the previous sections. Agriculture can sequester carbon when organic matter is built up in the soil or when above-ground woody biomass acts either as a permanent sink or is used as an energy source that substitutes fossil fuels. The mitigation effects of adoption of improved pastures, intensifying ruminant diets, changes in land use practices, and changing breeds of large ruminants could account for 4 to 7% of the global agricultural mitigation potential to 2030, or US$1.3 billion per year at a price of US$20/t of CO_2 equivalents (Thornton and Herrero, 2010).

Expanding cropland onto areas under natural ecosystems reduces carbon stocks in natural vegetation and soils, with the amount of carbon released and crop yields differing markedly between temperate regions and the tropics (West et al., 2010): for each unit of land cleared, land in the tropics releases nearly twice as much carbon (~120 t/ha vs. ~63 t/ha) and produces less than half the annual crop yield as land in temperate regions (1.71 t/ha per year vs. 3.84 t/ha per year). However, high-input industrialized agriculture uses far more energy, in the form of nitrogen fertilizers, pumped irrigation, and mechanical power, than does low-input, sustainable agriculture, making it less energy efficient. Production of 1 ton of cereals or vegetables from high-input farming consumes 3000–10,000 MJ of energy, compared with only 500–1000 MJ using sustainable farming practices (Pretty and Ball, 2001).

Van Wesemael et al. (2010) studied changes in soil organic carbon (SOC) stocks in soils in Belgium between 1960 and 2006, and found a large reduction in SOC in grassland soils that had been drained after 1960, and large gains in croplands in sandy lowland soils due to manure additions.

Cassman (1999) indicates that precise management and improvements in soil quality are needed to achieve high yields without causing environmental damage. Conservation agriculture, green manures, and cover crops contribute to organic matter and carbon accumulation in the soil, physically protect the soil from the action of sun, rain, and wind, and help feed soil biota. No-tillage systems result in accumulation of 0.3–0.6 t C/ha per year, but no-tillage combined with rotations and cover crops may double the amount of carbon accumulated, to 0.66–1.3 t C/ha per year (Pretty and Ball, 2001).

No-tillage has revolutionized agricultural systems because it allows individual producers to manage larger amounts of land with fewer inputs of energy, labor, and machinery (Tripplet and Dick, 2008). Lal (2010) points out that not all conservation agriculture practices and other resource conservation technologies are applicable across all farming systems. However, he reports that increasing SOC in the root zone can increase grain yields (kg/ha per ton of C) of bean (30–60), maize (200–300), rice (20–50), soybean (20–50), and wheat (20–40). Such increases in SOC also improve soil quality, increase eco-efficiency, and enhance ecosystem services. Such soil sinks must become permanent if they are to contribute to mitigating climate change; if lands under conservation agriculture are ploughed all the gains in soil carbon and organic matter would be lost.

Using the correct amount and timing of N application can halve NO_2 emissions in intensive irrigated agroecosystems without significantly affecting crop yields (Ruan and Johnson, 1999). Using a handheld optical sensor that calculates the normalized differential vegetation index (NDVI), thereby assessing yield potential as plants grow, can reduce unnecessary N-fertilizer inputs, saving farmers money and protecting the environment by reducing trace gas emissions.

Some plants produce chemicals that inhibit nitrification in the soil, reducing loss of fertilizer N (Fillery, 2007). This ability, which is referred to as biological nitrification inhibition or BNI (Subbarao et al., 2006), seems to vary widely among and within species, and appears likely to be a widespread phenomenon in tropical pasture grasses (Subbarao et al., 2007).

Nitrification inhibition enhances agroecosystem fertility in a sustainable way, especially under high nitrate leaching and denitrification fluxes, which may account for the ecological advantage of African grasses over indigenous grasses in South American pastures (Boudsocq et al., 2009). These deep-rooted grasses (e.g., *Brachiaria humidicola*) also sequester significant amounts of organic carbon deep in the soil and help offset anthropogenic CO_2 emissions (Fisher et al., 1994). *Brachiaria humidicola,* an African forage grass found from southern Sudan and Ethiopia in the north to South Africa and Namibia in the south, shows particularly high BNI capacity (Ishikawa et al., 2003; Subbarao et al., 2009).

Local agrobiodiversity will be an important coping mechanism for climate change, especially for the most vulnerable people (Ortiz, 2011a). Agro-silvo-pastoral systems can also be designed to optimize agrobiodiversity and attain production benefits without adding pressure to convert natural habitat to farmland (Ortiz, 2011b; see also Chapter 4 of this volume). However, in some areas locally available agrobiodiversity may not able to adapt quickly to changing conditions, and therefore new crop cultivars, livestock breeds, or other species better suited to the new environments will be needed to cope with climate change.

Nitrogen use efficiency (NUE) of agricultural systems can be increased by growing plant species or genotypes with high N uptake and utilization abilities (Fageria and Baligar, 2005). Whole-plant physiology, quantitative genetics, and forward- and reverse-genetics approaches are providing a better understanding of the physiological and molecular controls of N assimilation in crops under varying environments (Hirel et al., 2007). Crops are being bred for NUE because this trait will be a key factor in reducing N fertilizer pollution and increasing yields in N-limiting environments.

Besides sophisticated approaches to make photosynthesis more efficient, a number of already well-developed biotechnologies such as plant micropropagation, virus-free planting materials, molecular diagnostics of plant and livestock diseases, and molecular markers to identify superior lines and populations in conventional breeding operations must continue to be improved and disseminated, particularly in those countries with limited research infrastructure and low rates of adoption. Production of genetically modified organisms (GMOs), undoubtedly the most controversial approach of the new biotechnologies, holds significant promise for contributing to eco-efficient agriculture, but there is an urgent need to focus investment on the needs of the poor (The World Bank, 2008). This is likely to require increased public investment in these technologies. It will also be necessary to increase the capacity to evaluate the risks and regulate these technologies in ways that are cost effective and inspire public confidence in them.

However, conventional breeding, benefitting from techniques such as marker-assisted selection, is likely to be at the center of agricultural developments in the immediate future. Unfortunately, the number of plant and livestock breeders continues to decline. This will affect our capacity to improve crops and animals in the future, and urgent measures are needed to reverse this trend.

Policies, Capacity Building, and Capitalizing on Market Forces

Eco-efficient agriculture will only be adopted and implemented if conducive policies and incentives are in place. This will require that lessons be learned from prior experiences, alignment with market forces, clear communication and engagement with public opinion, development of public-private partnerships, and strong leadership.

Any eco-efficiency approach must recognize and exploit the impact of multidimensional economic, environmental, and social interactions on the four components of the food system, i.e., availability, utilization, accessibility, and stability (Park et al., 2009). Failing to do so will impede uptake of adaptation and efficiency strategies.

There is an urgent need to intensify, diversify, and integrate production systems to achieve eco-efficiency, but this will require more than just technical solutions. A new vision, combined with policies and incentives, needs to be part of the mix. Reverting to mixed farming will not be easy (Wilkins, 2008). Persuading farmers to do so will require evidence of clear economic advantages from linking crop and livestock systems, cost-effective ways of handling and incorporating animal manures, and systems that are managerially simple to operate. It may also require conducive policies and support payments. For example, the European Union's Nitrate Directive and the Water Framework Directive, by limiting inputs, have provided a very direct incentive for the adoption of eco-efficient practices, while support payments have promoted conversion of land to organic farming and maintenance of organic systems (Wilkins, 2008).

The food requirements of the expected population levels in 2050 cannot be met exclusively by the intensive agriculture of today, simply because the natural resource base would either collapse or be placed under very severe stress. Likewise, less input-intensive, agroecological approaches—in particular integrated livestock, crop, and tree systems—could not be utilized everywhere due to limitations in labor, land, water, markets, and infrastructure. Technology, innovation, and policies are essential components of the mix in order to reach acceptable social, economic, and environmental outputs and outcomes in the future. Consumers exert significant pressure on the market and are ultimately one of the main drivers of the agricultural agenda (Gopalan, 2001).

Policies and subsidies are sensitive and controversial issues. Developed-country agricultural policies cost developing countries about US$17 billion per year, a cost equivalent to about five times the current levels of overseas development assistance to agriculture, while subsidies in developing countries divert funds from high-return investments in public goods (The World Bank, 2008). Investment in infrastructure (irrigation, roads, transport, power, and telecommunications), markets, rural finance, and research would boost agricultural productivity in developing countries while being less distorting than price subsidies and incentives.

How best to promote products from eco-efficient systems is an area that requires further research and more systematic analyses in order to guide both producers and consumers on food grown using eco-efficient approaches. For example, there are learning opportunities from the experiences of the organic markets and locally produced foodstuffs, as well as consideration of non-price incentives and the power of consumers to guide production towards a more eco-efficient path.

Meeting Challenges to Social Equity

Eco-efficient agriculture can deliver quality products that meet consumers' needs with a low ecological impact. However, to ensure that it does so equitably and sustainably it is imperative that assessments address social and economic performance as well as ecological criteria (Park et al., 2010).

Research on and implementation of the concept and practices of eco-efficiency must be sensitive to gender issues. Women play a major role in agriculture, accounting for about 70 to 80% of household food production in sub-Saharan Africa, 65% in Asia, and 45% in Latin America, cultivating food crops and commonly contributing to production of commercial crops (The World Bank et al., 2009). Women are generally responsible for food selection and preparation and for the care and feeding of children. They are thus key to food security for their households (Quisumbing et al., 1995).

Women also commonly play active roles as traders, processors, laborers, and entrepreneurs. However, many development policies and projects continue to assume that farmers and rural workers are mainly men (The World Bank et al., 2009). According to Deere and Leon (2003), about 70 to 90% of formal owners of farmland are men in many Latin American locations.

A World Bank water and sanitation study (Fong et al., 1996) concluded that gender is an issue not only of equity but of efficiency, because involving both women and men enhances project results, increases cost recovery, and improves sustainability. A review of 121 rural water supply projects found that women's participation was among the variables strongly associated with project effectiveness in the sector. Women's participation serves both practical and strategic gender needs. The practical gender needs of women are needs based on existing divisions of labor and authority, whereas the strategic gender needs are those that require redress of gender inequalities and redistributing power more equitably.

A closer look at women's roles in agricultural production (Table 1-1) illustrates the important part they play in every aspect of agriculture and food production, the significant challenges they face, and why gender-neutral strategies alone will not be sufficient to meet future needs and expectations.

Both men and women play critical and often complementary roles, both at the farm-level in smallholder agricultural systems and downstream in more intensive production systems, where processing, packaging, and overall value-adding require the complementary abilities and knowledge of women and men. Interventions must address the specific needs and opportunities of both women and men, particularly the poorest, if they are to reduce inequalities, stimulate growth, and contribute to reducing environmental degradation (The World Bank et al., 2009). To achieve this it is vital to understand and change natural resource tenure and governance and address gender-based inequalities in access to and control over natural resources.

The World Bank (2006) sums up the importance of addressing gender issues, stating that "Gains in women's economic opportunities lag behind those on women's capabilities. This is inefficient, since increased women's labor force participation and earnings are associated with reduced poverty and faster growth. In sum, the business case for expanding women's economic opportunities is becoming increasingly evident; this is nothing more than smart economics and appropriate social policy."

Monitoring and Evaluation

Eco-efficiency monitoring requires disciplined record-keeping and managed conservation to ensure long-term environmental improvement (Reith and Guidry, 2003).

Life-cycle analysis (LCA) helps to assess potential environmental impacts along the value chain (McGregor et al., 2003). LCA quantifies inputs (e.g., water, nutrients, energy, and agrochemicals) and outputs (e.g., grain, stubble, flour, oil, waste), assesses the environmental performance relative to input use and outputs, analyzes and explains the environmental performance of the supply chain, and suggests where and what measures can improve performance. LCA helps the individual actors (farmers, food processors, farm suppliers, retailers, and end users) to manage their environment along the value chain, to set their own environmental performance goals and indicators, and to identify practical, cost-effective measures to improve environmental performance. It can also be used to improve the quality of extension services, increase the profitability of farms by green marketing, and support the regional transition to sustainable agricultural systems (Hayashi et al., 2007).

In agriculture, water, energy, and land use intensity are used as resource intensity indicators, whereas NO_x pollution, CO_2, and CH_4 intensity are used to measure environmental impacts (United Nations, 2009). Wießner et al. (2010) introduced a set of practical indicators reflecting ecological and agronomic performance to describe the current eco-efficiency of sugar-beet cultivation,

Table 1-1. Roles, needs, and challenges faced by women in agriculture.

Activities	Key characteristics
Agricultural production	Rural women are the main producers of the world's staple crops—rice, wheat, and maize—which provide up to 90% of the food consumed by the rural poor. Women sow, weed, apply fertilizer and pesticides, and harvest and thresh crops. Their contribution to growing secondary crops such as legumes and vegetables is even greater. Grown mainly in home gardens, these crops provide essential nutrients and are often the only food available when major crops fail.
Water ownership and tenure	Women have much less access to water than men. The distribution of water and land is a major determinant of poverty, and inheritance laws that deprive women of access are often the cause of women's poverty.
Selection, improvement, and adaptation of local cultivars	Women are typically involved in the selection, improvement, and adaptation of local cultivars, as well as seed exchange, management, and saving. They often keep home gardens where they grow traditional cultivars of vegetables, herbs, and spices selected for their nutritional, medicinal, and culinary benefits. Women, therefore, play an important role in maintaining biodiversity. Women are also the primary collectors of wild foods that provide important micronutrients in diets and that are vital for the survival of households during food shortages.
Climate change	Least-developed countries are more reliant on rainfed agriculture and natural resources than more developed countries, and are therefore the most vulnerable to climate change. These countries generally lack the necessary adaptive capacities to cope with climate change. Poor people tend to live on marginal lands that are subject to frequent droughts or floods and are most likely to be affected by even small changes in climate variability. Because of gender-based inequalities in accessing critical livelihood assets (such as land, credit, technology, information, markets, and organizations), women are more exposed to these risks.
Biomass and fuelwood	Over one-third of the world's population (2.4 billion people) relies on fuelwood, agricultural residues, and animal wastes for their primary energy needs. Many women spend up to 3 to 4 hours a day collecting fuel for household use, sometimes traveling 5 to 10 km a day. In many African, Asian, and Latin American countries, rural women carry approximately 20 kg of fuelwood every day. This work burden limits time available for food production and preparation, household-related duties, and women's participation in income-generating activities and educational opportunities.
Weeds, pests, and diseases	Some 20–40% of the world's potential crop production is lost annually because of the effects of weeds, pests, and diseases. Attempts to control agricultural pests have been dominated by chemical control strategies, but the overuse of chemicals has adversely affected human health, the environment, international trade, and farm budgets. It is broadly estimated that between 1 million and 5 million cases of pesticide poisoning occur each year, resulting in several thousand fatalities. Pesticide fatalities are overwhelmingly a developing-country phenomenon and children and women are especially at risk.

SOURCE: Summarized and adapted from The World Bank et al. (2009).

and showed that eco-efficiency could be enhanced by reducing input levels. Recently, BASF (2010) announced its first eco-efficiency analysis for maize grown with or without a fungicide. The analysis compared both economic and environmental aspects of products and processes, and took the product's entire life cycle into account, from sourcing raw materials to product manufacture, use, and disposal. They found that using the fungicide reduced costs and energy and resource use and delivered high yields, i.e., farmers could both earn more by using this fungicide and protect the environment.

Conclusions

Those agricultural systems and practices that release less C to the atmosphere, conserve organic matter, utilize biological methods for disease and pest control, use clever rotations, pursue recycling opportunities by means of crop, tree and animal components and interactions, and use water rationally tend to be inherently eco-efficient. Humankind—given prospective demands and socio-economic, political and environmental challenges—will not be able to sustain and survive based solely on low-input agricultural systems. Intensive and high-input agriculture also has a key present and future role to play; however, it must attempt to do more with less and, as argued by several authors, it should aim at being more sustainable (Pimentel et al., 2005; Hobbs et al., 2008; Horrigan et al., 2002).

In summary:

- In view of the challenge to enhance productivity and counteract current yield plateaus in key crop and animal systems by means of eco-efficient methods, technology must be at the forefront of political, strategic, and investment priorities.
- Policies and incentives should be also of high priority, in order to tilt the balance towards eco-efficiency, food security, food safety, and reduced waste.
- Researchers and policy-makers need to consider the more-from-less, the more-from-more, and even the same-from-less scenarios to define priorities and goals at the national, regional, and local levels. In this context, eco-efficiency needs to be considered at wider scales than the farm or individual crop or animal production system.
- The widely assumed notion that developed countries are the ones that tend to specialize in few intensive production systems no longer holds. A growing number of large and intensive crop and animal enterprises (in particular fruits, vegetables, poultry, and beef for the export markets) are nowadays commonly found in the tropical belt.
- Generation and dissemination of eco-efficiency knowledge and adoption will greatly benefit from active participation of farmers in research and development, enhanced extension methods (including the new information technologies), and producer and consumer education.
- The current and potential impact of climate change on achieving a higher degree of eco-efficiency needs to be better researched and understood. There are both challenges and opportunities that must be worked out, particularly in relation to how eco-efficiency may or may not impact diversification and systems adaptability.
- Research and implementation of the concepts and practices of eco-efficiency cannot and should not be made with a gender-neutral approach. Lessons learned all over the world and abundant literature clearly show the advantages—smart economics as depicted by the World Bank (2006)—of considering and designing research and implementation of eco-efficient systems based on gender roles and inherent advantages.

In the lines of thought outlined above the best possible outcome is for high-input intensive agriculture and low-input agriculture to come closer to each other. High-input agriculture should certainly aim at becoming more environmentally friendly and low-input agriculture should adopt, whenever possible, a more intensive approach leading to higher productivity.

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CHAPTER 2

Eco-Efficient Agriculture and Climate Change: Conceptual Foundations and Frameworks

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Contents

Abstract

The concept of eco-efficiency is explored, in terms of its history of use, its bio-physical meaning, and its utility, as a concept in the pursuit of enhanced productivity, profitability, and sustainability of agricultural practice. Eco-efficiency is a multi-dimensional concept relating the efficiency with which a bundle of desired outputs is produced from a bundle of inputs, with minimal generation of undesired outputs. An analysis framework based on efficiency frontiers relating outputs to inputs (or where relevant, outputs to risk) is presented and this framework is used to identify six pathways for system improvement—all addressing some dimension of eco-efficiency. The paper concludes with an analysis of how climate change impacts and adaptation can be factored into this eco-efficiency framework.

Introduction

The notion of "efficiency" has always been a force shaping the world's food and fiber systems. Hunter-gatherer societies sought efficiencies in labor by changing their location, diet, and hunting and gathering practices to match seasonal and spatial patterns in food supply. Early cultivation practices evolved in ways that made the most efficient use of labor, enabling human society to

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direct time and energy into creative and practical activities beyond securing a sufficient food supply. As settled agriculture evolved, seeds were selected, land was cultivated, and crops were managed to further enhance the efficiency with which limiting resources were deployed. Human labor has been a dominant limiting resource for much of agriculture's history. Animal traction and, more recently, mechanization off the back of fossil fuels relieved the human labor constraint and the efficiency focus has shifted to the efficiency by which a complex set of land, labor, capital, energy, nutrients, and water resources are combined to produce economic products in a sustainable way.

This paper proposes a conceptual and analytical framework to support the desired goals of enhanced eco-efficiency in agricultural systems and of economic and ecological drivers considered at a range of decision scales. While the challenges and opportunities to improve eco-efficiencies under the threat of climate change are considered, particularly for smallholder production systems, the paper focuses on the bio-physical dimensions of eco-efficiency. Social and political drivers strongly influence agricultural decision-making and so will influence the eco-efficiencies that can be attained in each agricultural system.

The Eco-Efficiency Concept

Eco-efficiency in the context of agriculture grows out of the deep historical pursuit of efficiency in the world's food and fiber systems, but places particular focus on economic (productivity and profitability) and ecological (environmental sustainability) drivers of efficiency.

The World Business Council for Sustainable Development claims first use of the term "eco-efficiency" in the lead-up to the 1992 Rio Earth Summit (WBCSD, 2000). In that setting, the intent was to develop synergies between the private sector or business world's focus on efficiency with wider concepts of sustainable development and ecological integrity. In simple terms, the focus was on "creating more goods and services with ever less use of resources, waste, and pollution" (WBCSD, 2000). The World Business Council saw eco-efficiency as a management philosophy that encouraged business to search for environmental improvements that yielded parallel economic benefits. They acknowledged that the term and concept did not capture all the issues relevant to sustainable development.

An early application of eco-efficiency in an agricultural research context comes from CIAT in setting their research and development goals in terms of eco-efficient agriculture for the rural poor. CIAT's Medium-Term Plan (CIAT, 2009) states:

> "Eco-efficient agriculture increases productivity while reducing negative environmental impacts. Eco-efficient agriculture meets economic, social, and environmental needs of the rural poor by being profitable, competitive, sustainable, and resilient. It harmonizes the economic, environmental, and social elements of development, and strives toward solutions that are competitive and profitable, sustainable, and resilient, and generate benefits for the poor. Eco-efficient agriculture cannot effectively address the needs of the poor without taking into account the particular needs of women."

Keating et al. (2010) noted that eco-efficiency was not a tightly defined concept—instead it was highly multidimensional. As such, there is unlikely to be a single measure that characterizes the eco-efficiency performance of an agricultural system. Instead, a set of measures is likely to be relevant in particular circumstances and these are likely to change in relation to differences in the most limiting set of biophysical, economic, or human resources (Park et al., 2010).

Eco-Efficiency Metrics

Any measure of eco-efficiency involves some measure of outputs (desired or undesired) related to some measure of inputs or alternative independent variables against which outputs are assessed. Figure 2-1 presents a set of output–input relationships, nominally representing crop and environmental responses to increasing nitrogen supply. The shape of these response functions, their intercept, and scale will depend on the measures being used and the responses observed under the spatial and temporal drivers of variability (e.g., climate).

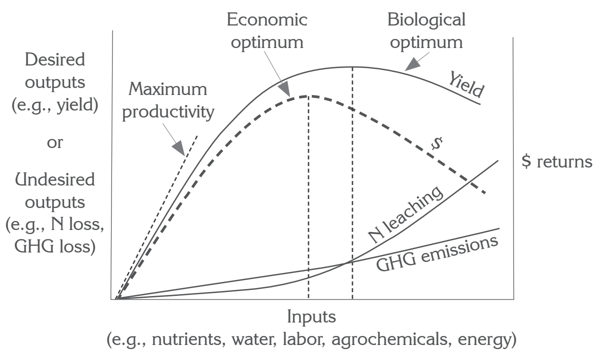

Figure 2-1. Output–input relationships relating desired and undesired agricultural outputs to the level of resource supply of soil nitrogen (N).

Desired-output measures might typically include some measure of harvested product, some measure of profit or return on investment, or some measure of the security of a food system. Measures could extend beyond food quantity and include measures of quality in meeting nutritional needs. A broader suite of "ecosystem services" can also be considered as desired outputs, such as services around biodiversity conservation, carbon sequestration, freshwater flows, pest management, or pollination services (Costanza et al., 1997). Markets are emerging for some such ecosystem services whereby they would represent direct opportunities for economic return (Herzog, 2005). This is most developed in the carbon-sequestration domain (Hamilton et al., 2007). Other services are encouraged through non-market policies such as agri-environmental stewardship payments (Hajkowicz, 2009), while yet other services remain outside an institutional mechanism.

Input measures typically involve a unit of land but equally importantly could be expressed in terms of nutrients, water, energy, labor, or capital investments (Figure 2-1). Production functions relate agricultural outputs to the level of resource and other inputs (Dillon, 1977) and, at one level, are a measure of eco-efficiency. In analyzing production response curves to multiple inputs, de Wit (1992) argued that the resources are utilized most efficiently when their supplies are all close to yield-optimizing levels.

Importantly, while eco-efficiency carries the notion of "more with less" (Keating et al., 2010), there is the risk of this being misinterpreted to mean only higher outputs with lower inputs. This is too narrow an interpretation, as at least four different scenarios can be envisaged for raising eco-efficiency (Table 2-1).

Table 2-1. Eco-efficiency scenarios expressed in input/output terms.

Input/output descriptor	Explanation and example(s)
More desired outputs and/or less undesired outputs with less inputs	Reducing over-fertilization, such as N-fertilizer use on cereals in China (Ju et al., 2009), or over-irrigation such as with irrigation volumes on sugarcane in north-west Australia (Smith, 2008)
A lot more with a little more	Raising production levels through careful targeting of production inputs such as "micro-dosing" maize or sorghum with N fertilizer in southern Africa (Twomlow et al., 2008)
More with the smarter use of the same	Raising the effectiveness of current agricultural inputs through better targeting these inputs in space, such as via precision agriculture (Bramley, 2009), or time, for example with a seasonal climate forecast (Ash et al., 2007)
Less with much less	Lowering production in those regions or systems where inputs are not efficiently used (e.g., for climatic or soil reasons) and redirecting resources to areas of greater eco-efficiency (Oliver et al., 2010)

Agriculture produces a range of products (food, fiber, bioenergy, medicines, etc.) but not without broad and, at times, unsought consequences for land and society. Thus, alongside the desired outputs from agriculture are possible undesired outputs such as biodiversity loss, greenhouse gas (GHG) emissions, nutrient or soil loss, and other forms of land degradation. These undesired outputs often are also a function of relevant input levels (Figure 2-1).

The range of outputs from agriculture, both desired and undesired, can be assessed in trade-off relationships (Groot et al., 2007), often where production outputs are counterbalanced against the state of a system in environmental or social terms (Kelly et al., 1996). When represented graphically (Figure 2-2), an outer efficiency frontier can be drawn to represent the outermost desirable system outputs for the range of known (undesired) system states. Any point under the efficiency frontier represents room to move, with resultant wins and/or losses for both production and environmental outputs (Figure 2-2).

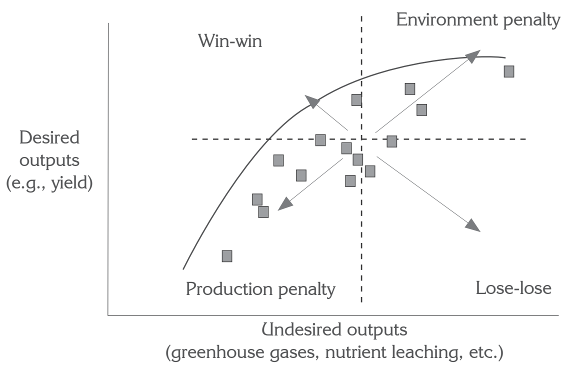

Figure 2-2. Example of a trade-off relationship between a desired output and an undesired output (points) resulting in an efficiency frontier of outermost points (line).

An Eco-Efficiency Framework

Keating et al. (2010) introduced an eco-efficiency diagnosis framework drawing on the types of relationships represented by production functions and trade-off relationships. A return–risk space formed the supporting analytical structure to assess system performance—mean economic returns are plotted against their associated variance, used as a measure of riskiness. An efficiency frontier of outermost points was envisaged where mean returns are maximized for any given level of variance in returns. This eco-efficiency diagnosis framework is represented in Figure 2-3. Keating et al. (2010) and Carberry et al. (2010) used the stylized return–risk framework to propose four pathways to improve system performance; two more are added here in Figure 2-3.

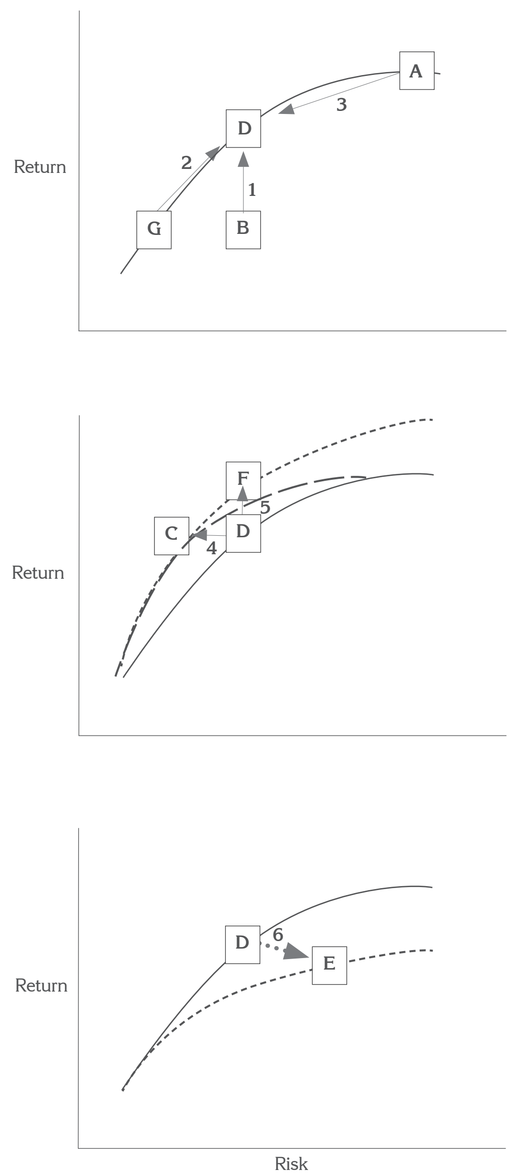

Figure 2-3. A stylized return–risk framework demonstrating six pathways to improve system performance relative to a measure of risk.

SOURCE: After Keating et al. (2010).

At the field and farm scale, the position of individual farmers relative to the efficiency frontier is largely determined by their attitude to risk and operational performance. To achieve the environmental potential or maximum possible output from a farm (Point A, Figure 2-3) necessitates acceptance of maximum risk, and thus a preference for risk-taking, as well as exemplary management. More likely, a region's best farmers choose acceptable-risk investments that return less than the potential (Point D). If farmers are operating close to the efficiency frontier, at their chosen level of production risk, they are achieving the expected level of return for the technologies deployed and the environmental conditions experienced. However, many farmers in a region would operate at positions below the efficiency frontier (Point B). These farmers invest as much in their production systems as the better farmers but achieve poorer returns by falling short in their agronomy and operational management.

A first and most important pathway to improve system performance is to increase the number of farmers performing close to attainable best practices (Pathway 1: B→D). Their transition to performing on a par with the better farmers will likely require both evidence of such inefficiencies and access to better agronomic advice. A second pathway is to encourage farmers to move along the current efficiency frontier to higher returns while acknowledging and addressing the added risks (Pathway 2: G→D). This pathway largely consists of good farmers adopting the practices of those farmers operating further up the efficiency curve. Such farmers need to be convinced that the increased investment needed to achieve the returns of the best farmers justifies their higher risk exposure. In a case study of Australian wheat crops, Hochman et al. (2011) reported that 36% of crops failed to achieve close to their attainable yield at the rate of nitrogen fertilizer applied and a further 21% of crops were under-fertilized—opportunities for efficiency improvements along pathways 1 and 2, respectively.

Under existing production systems and relevant efficiency frontiers, the third pathway for improved system efficiencies is to encourage farmers to reduce their investment in inputs where they are overinvesting (Pathway 3: beyond A→D). Although uncommon, excess use of fertilizers is evident in some agricultural systems, as in nitrogen fertilizer use in China (Ju et al., 2009).

Increasingly, more efficient resource use has been a mainstay of agriculture's response to the cost–price squeeze. For a region's better farmers, who currently operate on existing production frontiers, a real and ongoing requirement is to create new efficiency frontiers that generate similar returns for less investment and risk (Pathway 4: D→C). Such technologies generally enable cost savings and have no impact on production potential. On this pathway, technologies are sought to increase productivity from the existing resource base by reducing biotic constraints or to improve efficiencies in nutrient, water, or labor use. Such technologies can be developed through both agronomic (Bramley, 2009) and breeding approaches (Fageria et al., 2008).

A key role for agricultural research is to help discover the practices that will result in the next step-change in productivity and profitability. Thus, the fifth pathway is to create new efficiency frontiers by increasing the production potential and by helping farmers take this productivity step (Pathway 5: D→F). Most see this pathway as the hope for genetically modified crops (Phillips, 2010). In reality, furthering the frontiers of productivity will likely evolve from the synergies between novel plant genetics and innovative management technologies. Moving farmers to new efficiency frontiers will require research into and delivery of new technologies that increase production for much the same level of investment.

Maintaining current levels of productivity for a desired level of investment requires ongoing effort to prevent situations that could substantially limit productivity. The sixth and last pathway for investment in research, development, and extension is to protect against any loss of current production systems (Pathway 6: D ≠ E). Indeed, significant current effort is targeted either at preventing any breakdown in existing disease, weed, or pest management strategies, or at maintaining facilities to rapidly respond to future outbreaks of exotic diseases, weeds, or pests. Either threat could dramatically dampen the efficiency frontier prospects of farmers. Likewise, practices that threaten the natural resource base for agriculture will result in an unavoidable loss of productivity. Issues such as soil salinity, acidification, and nutrient rundown require research investment to ensure productivity levels are maintained.

Eco-Efficiency and Climate Change

Keating and Carberry (2010) projected food demand out to 2050 and estimated likely increases in the order of 64–81%, with the variation dependent on assumptions of population growth, consumption increases, food wastage along the value chain, and food diversion to biofuels. The Food and Agriculture Organization of the United Nations (FAO) estimated that food demand will increase by 70% between 2000 and 2050 (FAO, 2009). These increases will need to be achieved in the face of increasingly constrained and contested land, water, nutrient, and energy resources. The threat of dangerous climate change also means the food security challenge has to be met while reducing the GHG load on the atmosphere and in the face of uncertainties generated by the climate change that is already happening. These intertwined challenges necessitate an eco-efficiency imperative for global agriculture, where more food and fiber are produced with more efficient use of natural resources and less impact on the environment.

The climate change challenge facing agricultural land use encompasses both adaptation to current and predicted new climates and the mitigation of GHG through both reductions in direct emissions and biosequestration of carbon. Globally, agriculture, including fertilizer production, directly contributes 10–12% of GHG emissions; and this figure rises to 30% or more when land conversion and emissions beyond the farm gate are added (Smith et al., 2007). The consensus on the climate science is that global GHG emissions would need to peak before 2015 and be reduced by something in the order of 50–85% (on 2000 levels) by 2050 if dangerous climate change (i.e., temperature rise > 2.4 °C) is to be avoided (IPCC, 2007). The relationship given as an example in Figure 2-2 depicts a trade-off between agricultural production and GHG emissions. A win–win outcome for agriculture and its emissions will require eco-efficient solutions that create new efficiency frontiers of reduced GHG intensities of food production. These new efficiency frontiers are required to generate similar outputs for less emissions risk (Pathway 4, Figure 2-3) or to increase production potential without emissions growth (Pathway 5).

Agricultural production may have to intensify efficiently on a smaller land area in order to free up land, water, and other resources for carbon biosequestration and environmental services (Pretty et al., 2011). Nevertheless, there are indeed win–win outcomes through the synergies between agricultural productivity and GHG mitigation by increasing soil carbon (Lal, 2004), reducing livestock methane (Beauchemin et al., 2008), or better managing livestock and manure (Monteny et al., 2006). That said, Campbell (2009) points out that win–win outcomes will not be feasible in all cases and so winners and losers are likely in programs such as the United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+).

The challenge of adaptation to climate change has largely focused on ameliorating the negative impacts of climate that is likely to be drier and hotter, although the benefits of CO_2 fertilization and improved agroclimatic environments will be evident in some locations (Howden et al., 2007). Simple (negative) impacts of climate change are depicted in the production response functions shown in Figure 2-4 together with an indication of the likely effect of adaptation options identified by Howden et al. (2007) and others. Such adaptation actions aim to maintain current production outputs through management changes that better respond to the new environments (Pathway 6, Figure 2-3). However, in reality, all six pathways identified for efficiently increasing agricultural returns will contribute to the adaptation options for climate change—i.e., the long-held imperatives for increasing agricultural productivity through both incremental and transformational research and uptake will likely lead to appropriate responses to a future probable change in the climate risk. Thus, the imperative for research to help farmers to better deal with current seasonal climate variability will likely enable them to adapt to future climate change (Howden et al., 2007).

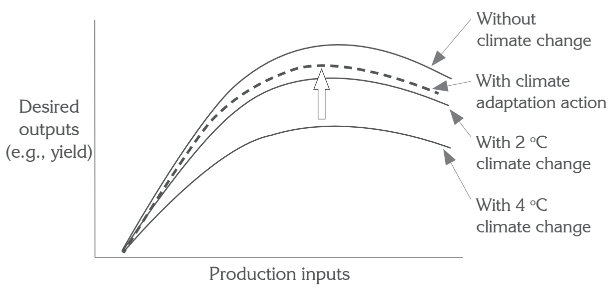

Figure 2-4. Production functions under two climate change scenarios and an adaptation response.

The need for targeting transformational research specifically to adaptation to future climate change must pass the test of additionality; the notion that such added investment should be additional to what is already being done. Changes in frequency and magnitude of climate extremes, and thus agricultural systems crossing thresholds (Tubiello et al., 2007), may be the driver for such additional and specific response.

Explicit treatment of uncertainties in a decision-making context is needed to ensure that adaptation action now does not get ahead of our confidence in locally specific expectations for the future. In smallholder tropical environments with large numbers of biophysical and institutional factors constraining development, it would be unwise to focus on adaptation to an uncertain future climate if it meant that certain current constraints to agricultural development were ignored. Building a longer-term climate change perspective into current efforts to raise agricultural productivity, sustain the natural resource base, and overcome rural poverty is, however, a wise counter to the risk of development proceeding down maladaptive pathways (Stafford Smith et al., 2011).

Eco-Efficiency and Smallholder Farmers in the Tropics

In the generally low-input, low-output situations of smallholder farmers in the tropics, natural resources are co-opted to meet food production needs. Thus, while nutrient inputs may be used most efficiently for the first unit of addition in these systems (Twomlow et al., 2008), the coincident inputs of land, water, and labor are used inefficiently in many smallholder systems. Eco-efficiency needs to be an integrating concept, extending beyond single-factor production functions to a measure of the efficiency with which food production needs are met with the least environmental impacts.

The six pathways for enhanced eco-efficiency (Figure 2-3) are relevant to smallholder farmers in the tropics. The large yield gaps identified in tropical systems (Neumann et al., 2010) testify to the prospects for moving overall farmer performance closer to the attainable efficiency frontiers (Pathway 1). However, given that smallholder systems are often low input, especially in sub-Saharan Africa, there is likely much to gain from encouraging farmers to move along currently attainable efficiency frontiers in order to increase returns to individual farmers and aggregate production from smallholder farming systems (Pathway 2) (Keating et al., 1991; Tittonell et al., 2008). Addressing farmer perception and management of the added risks from such practices is a critical endeavor for success in this pathway. Similarly, encouraging farmers to reduce their investment in unnecessary inputs (Pathway 3), as in nitrogen fertilizer use in China (Ju et al., 2009), will require comparable persuasive communication of the benefits of a significant change to established practices.

Creating new efficiency frontiers that improve returns, lower risks, or both (Pathways 4 and 5) can benefit smallholder farmers by enhancing the incentives for adoption—the Green Revolution is the exemplar case of the impacts of these pathways for improved productivity (Evenson and Gollin, 2003). Certainly the needs of Green Revolution smallholder farmers in tropical Asia and Latin America now mirror the demands for productivity innovations from large-scale commercial farmers in developed countries. Agricultural productivity in the past can be pinned to the development and adoption of specific technologies and practices and it is critical today that new technologies continue to be identified, developed, and adopted over the coming years (Carberry et al., 2010).

In contrast to Asia and Latin America, sub-Saharan Africa has not gained the same benefits from the Green Revolution. Despite the arguments for significant returns from Green-Revolution-type investments to improve smallholder productivity and infrastructure in Africa (Diao et al., 2008), it is difficult to see traction for such pathways (4 and 5) without prior priority given to improving basic agronomic performance and to changing perceptions of investment risk (Pathways 1 and 2). Here, the increasing role of the private sector and input/output markets in Africa may hold hope for progress (Gabre-Madhin and Haggblade, 2004).

Finally, the mitigation and adaptation challenges of climate change and their relation to the food security imperatives in tropical landscapes are a mix of synergies and trade-offs (DeFries and Rosenzweig, 2010). As argued previously, an eco-efficiency imperative utilizing all available pathways will need to be brought to bear.

Conclusions

We have focused on biophysical issues around the efficiency with which natural and human inputs are transformed into desired food and fiber outputs and environmental services, with a minimum of undesired outputs such as natural resource degradation or GHG loads on the atmosphere. In the context of global or regional food security in the face of climate change mitigation and adaptation challenges, this serves as a useful framing for a key global challenge. However, social and economic circumstances are going to shape decision-making in a particular farming situation and efficiency optima are often going to be different for production, productivity, profitability, or risk tolerance criteria.

In a broader view of eco-efficiency, spatial and temporal scales become important. In terms of spatial scale, what might be an eco-efficient solution at a local level may be ecologically inefficient at national or global scale if the production activity is less productive and more environmentally demanding at other locations. In terms of temporal scale, short-term efficiency in resource use that leads to longer-term natural-resource degradation will end as up ecologically inefficient due to the longer-term negative feedbacks to productive capacity.

The proposed eco-efficiency diagnosis framework (Figure 2-3) allows these different perspectives to be contemplated in terms of pathways for change. The challenge for smallholder farmers in the tropics (and for this CIAT publication) is to turn these concepts into practice.

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CHAPTER

3

Are Climate Change Adaptation and Mitigation Options Eco-Efficient?

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Contents

Abstract

This chapter provides an overview of predicted global climate change, placing special emphasis on the implications for agriculture. The power of modelling for understanding both impacts on productivity and adaptation options is demonstrated. The models on agricultural production for 50 crops predict significant impacts, with both winners and losers. The resultant need for systems reconstruction in highly vulnerable areas demonstrates a possible entry point for eco-efficient agriculture, in parallel with demands for adaptation measures that are climate smart and deliver on mitigation co-benefits. The chapter then focuses on Colombia and provides an end-to-end analysis of projected climatic changes for 2050, the impacts this may have on agriculture, and mitigation and adaptation options in the country's rice sector. Priority options include managing the methane emissions of flooded rice, eliminating crop residue burning, irrigation, genetic modification for heat tolerance, and increasing efficiency of nitrogen fertilizer application. The relevance of eco-efficient agriculture in adapting to and mitigating climate change is discussed, with special emphasis on synergies between eco-efficiency and climate change adaptation or mitigation.

Introduction

Climate change is widely considered one of the major drivers of societal change in this century, and agriculture has been identified as particularly exposed and vulnerable to its impacts (Lobell et al., 2008; Roudier et al., 2011; Thornton et al., 2011). In addition to crop losses from the increased incidence of natural disasters (floods, droughts, fires, etc.) (Sivakumar et al., 2005; Tao

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et al., 2009), agricultural systems will have to cope with changing rainfall regimes, geographical shifts in the occurrence of pests and diseases (Garrett et al., 2012; Jarvis et al., 2012), shorter growing seasons (Jones and Thornton, 2009), temperature stress (Challinor et al., 2007) and loss of climatic suitability (Jarvis et al., 2012). Global climate models[4] (GCMs) predict that while climatic variability is certain to produce both winners and losers, the losses will far outweigh the gains in many cases. The tropics, in particular, are expected to experience crop yield decreases in the order of 10–30% (Moorhead, 2009). Likewise, South Asia might well be too heat stressed to grow wheat by 2050 (Ortiz et al., 2008; Lobell et al., 2012). Both of these regions depend heavily on agriculture for rural livelihoods, making them especially susceptible to climate-change-induced pressures.

Agriculture's position in the climate change equation is perhaps unique; it is simultaneously a highly vulnerable sector as the numbers above indicate, a highly culpable sector with regard to its significant contribution to anthropogenic emissions (Key and Tallard, 2012), and also a sector with enormous potential for mitigating anthropogenic climate change (Hutchinson et al., 2007; Tubiello and Fischer, 2007). Indeed, agriculture produces a disproportionate share of emissions of the high-impact gases methane (CH_4) (47% of global total) and nitrous oxide (N_2O) (58% of global total) (Pye-Smith, 2011). It is responsible for 30% of all greenhouse gas emissions when taking into account land use change and deforestation for agricultural expansion, fuel, fiber, and food (IPCC, 2007). On the other hand, carbon sequestration in agricultural soils could potentially offset 5–15% of global fossil fuel emissions (Lal, 2004), not to mention the mitigation power of deforestation reduction and fertilizer and irrigation optimization through sustainable intensification practices.

These considerations make climate-smart agriculture a critical topic for discussion and rapid action. Changing conditions require transformations in agricultural systems towards higher productivity, but on a lower-emissions trajectory (FAO, 2010a). Climate-smart agriculture aims to achieve food security for a world of 9 billion people and successful adaptation to an increasingly variable climate, while reducing emissions and sequestering carbon. It includes practices such as agroforestry, mulching, water management, intercropping, and silvopastoralism, as well as technologies for climate risk management, such as more accurate weather forecasts and the development of improved food crop varieties (Cooper et al., 2012; Smith et al., 2011; The World Bank, 2011). Specific definitions for climate-smart agriculture can vary widely depending on the source. For the purposes of this chapter we will use the following definition for climate-smart agriculture: an agricultural system employing practices which (a) contribute to farmer adaptation to climate change by bolstering the security of food systems, or (b) help to mitigate climate change by sequestering or preventing the release of carbon emissions, while (c) ideally increasing agricultural productivity.

Although climate-smart agricultural practices have been shown to be effective in matters of adaptation and mitigation, there remains the question of whether a climate-smart practice is necessarily an eco-efficient practice. When applied to agriculture, eco-efficiency describes a system that produces the most possible output with the least possible input, harmonizing economic, social, and environmental needs (see Mateo and Ortiz, Chapter 1 of this publication). But to what extent do eco-efficient practices overlap with climate-smart practices? Although climate-smart farming practices may be able to reduce emissions from agriculture, do they also constitute a system that uses resources effectively and efficiently for maximum yields?

This chapter shows how climate and crop models can be used to anticipate future scenarios for agricultural development and support decision making for priority adaptation and mitigation interventions. Future projections are presented, which are then used to evaluate impacts on agricultural production and systems. The chapter

[4] Global climate models, the term that we use here, are also called "global circulation models" and "general circulation models" by other authors.

then presents a case study of Colombia, where likely climate changes are quantified, impacts on agricultural systems are assessed, and the efficacy of different adaptation and mitigation options for the country is evaluated. This example is then used to discuss whether climate change presents a challenge or an opportunity for eco-efficient agriculture, looking at the impacts and potential responses in a broader political economy. Using the example, we address the following question: are the high-priority adaptation and mitigation options identified for Colombia necessarily eco-efficient as well?

Aspects of global climate change relevant to agriculture

Predicted changes in the climate system

While GCMs are all based on the same underlying principles, they vary in their implementation. We rely on the comprehensive collection of GCM climate change data and statistics of the Intergovernmental Panel on Climate Change (IPCC) for the scenarios presented here.

The IPCC used 24 GCMs in its Fourth Assessment Report (AR4) (IPCC, 2007) to show changes in climatic variables at various times in the future. The predictions depend on which of the various scenarios of economic and environmental development is assumed to occur, analyzed in detail in the IPCC's Special Report on Emissions Scenarios (SRES) (IPCC, 2000). Overall, annual mean temperatures are predicted to increase by 1–3° C by 2050 (depending on the SRES scenario), with mid- to high latitudes likely to warm at higher rates than the tropics. Changes in rainfall are varied and complex, ranging from -10 to +20% (again depending on the SRES scenario), with very high likelihood of increases along the Pacific coast of South America and in Eastern Africa, and decreases over South Asia (IPCC, 2007). More specifically, under the SRES A2 scenario ("business as usual"), global mean temperatures are predicted to rise by 1.6–8.4 °C by 2050, with winter temperatures at northern latitudes increasing most, while global average rainfall is predicted to increase as much as 1.9% by 2020 and 22.8% by 2050 (IPCC, 2007). Again under the SRES A2 scenario, the Mediterranean area of North Africa extending towards the Sahara is predicted to be drier throughout the year. Changes in rainfall in Asia are spatially variable, while in the Middle East, predictions show a decrease in overall rainfall [although with low certainty (IPCC, 2007)]. Changes in rainfall in the Amazon are highly uncertain, ranging from -10 to +15% by 2050.

All of these changes are expected to have profound implications for world agriculture, but the impact will depend on: the crop grown, farmer adaptability to climate change, type and severity of the expected change, and the current system vulnerability. Coping with these changes requires reliable predictions of future climate, coupled with reliable impact models and knowledge of adaptation options that can be implemented at the individual farm level (Jarvis et al., 2011; Thornton et al., 2011).

Uncertainties in climate modelling

We cannot measure the response of the climate to natural or anthropogenic forcings in absolute terms, but we can represent it in GCMs. GCMs themselves, however, are based on imperfect approximations that cause inaccuracies and uncertainties. Inaccuracies occur when we do not reproduce observed climate patterns at the scales that they appear (i.e., predicted climates differ from observations). In contrast, uncertainties reflect the variability (i.e., spread) of GCM predictions and can arise from:

- Disagreement on the future socio-economic behavior of the world's nations, leading to disagreement over which SRES scenarios to use
- Lack of understanding of the response of the climate system to anthropogenic forcing
- Inability to understand properly, and hence model, the different forcings in the climate system, which are then parameterized differently in the GCMs
- Disagreement over GCMs' initial conditions (i.e., the fact that climate change experiments are initialized arbitrarily on the basis of a quasi-equilibrium control run) (Challinor et al., 2009).

Often the conditions necessary to initialize GCMs in climate change experiments must be selected randomly (Gleckler et al., 2008; Taylor et al., 2012), which contributes to model spread. Uncertainties, therefore, are a range of predictions for any future time giving us a plausible range under which the impact of potential adaptation- or mitigation-oriented decisions can be analyzed (Moss et al., 2010; Webster et al., 2012). Quantifying these uncertainties is critical to understanding the future changes in climate and how agricultural systems will respond to them (Challinor et al., 2009; Moss et al., 2010).

Given enough observed data, we can assess the predictive skill for any climatic variable prediction by the GCMs, but a variable that performs well in one instance (i.e., present-day climate) may not perform well in others (i.e., future scenarios) (Challinor and Wheeler, 2008). In addition, the uncertainty determined for one variable does not necessarily represent the uncertainty of all the others. That is, one variable's estimate of "high uncertainty" does not signify that the projection is highly uncertain in absolute terms. Quantification of uncertainty is critical for decisions regarding adaptation of agricultural systems to climate change (Smith and Stern, 2011; Smith et al., 2011). These decisions directly impact farmers' livelihoods and therefore need comprehensive analysis of current vulnerabilities and future uncertainties to avoid the risk of making faulty recommendations (Jarvis et al., 2011).

Decision making under uncertainty

Despite the inherent uncertainties in climate change projections, there can be no excuse for inaction on the policy front. On the contrary, decisions on adaptation strategies should be anticipatory, putting into place as much effective policy and infrastructure as possible in the near term to avoid possibly irreversible repercussions. Moreover, anticipatory adaptation has the additional benefit of reducing the potential costs that may result from maladaptation, particularly for decisions regarding long-lived and costly infrastructure or sector-level planning (Ranger et al., 2010).

Climate change adaptation is by no means without risk. Decision makers may fail to appreciate the magnitude of a climate-related risk and not deliver a crucial adaptation, or there is the possibility of overestimation of risk and thus "over-adaptation" and waste of resources (Willows and Connell, 2003). Although we cannot predict with complete certainty how the climate will be in the future, it is possible to take steps to buffer negative effects with minimum levels of risk. That is to say, adaptation does not necessarily require a perfectly accurate prediction. A framework developed by Willows and Connell (2003) emphasizes the necessity of keeping open or increasing the options that could allow adaptation measures to be implemented in the future, when the situation may be less uncertain.

According to Willows and Connell (2003), risk assessments should aim to identify "no-regrets" alternatives or immediately actionable options that should deliver adaptation benefits under any circumstances regardless of actual climate outcomes. For example, an early-warning system for natural disasters would be a suitable adaptation for any foreseeable future; it would constitute a "no-regrets" option (Ranger et al., 2010). Other plausible approaches include building flexibility into the adaptability measure, e.g., constructing infrastructure that could be modified in the future, if necessary, rather than rebuilt, or building flexibility into the decision-making process itself by taking no-regrets actions first and delaying more high-stakes actions until better information is available (Ranger et al., 2010). Doing so could help to avoid decisions that may become maladapted with time or limit further flexibility. Planned adaptation options may be the most appropriate in the face of low uncertainty, while generating adaptive capacity in a system might be a more appropriate strategy if there is high uncertainty of climate impacts. In any case, while uncertainty may complicate the decision-making process, it should not hinder it altogether.

Global impacts of climate change on agricultural production

We ranked the area harvested of the 50 most important crops reported by FAOSTAT (FAO, 2010b) and assessed their patterns of crop suitability using the EcoCrop model, following the procedure described by Ramírez-Villegas et al. (2011). The areas of each crop ranged from 26,290 to 2,161,000 km^2, and each had a wide range of physiological responses to climate, for example, growing seasons (40–365 days), rainfall (200–8,000 mm/yr), and temperatures (2–48 °C). Within their environmental ranges (as indicated by EcoCrop), adaptation for a particular crop ranged from very marginal to highly suitable. We expected, therefore, to show the range of climatic response of each crop and estimate the likely effects of climate change on crop distribution.

We found that if crops were assumed to migrate without limit, global crop suitability increased by 0.84%, with buckwheat increasing most (+9.7%) and wheat decreasing most (-15.1%). At the global scale, 16 crops were less suitable, with wheat, sugar beet, white clover, and coffee becoming more than 10% less suitable, and no crop becoming more than 10% more suitable. Over half (26) of the crops were relatively insensitive to climate change (suitability changing less than 5%). Global changes in suitability may, however, vary from one region to another and 37 crops lost more than 50% of the area currently classified as suitable (Figure 3-1).

Trends in crop suitability also differed geographically. North Africa lost an average of 80% crop suitability, while Europe made the most important gains with no crop losing more than 5% suitability on average. Latin America, the Pacific, the Caribbean, and sub-Saharan Africa lost about 35–40% suitability overall, even allowing the crop area to migrate. Important issues of food security arise when crop suitability decreases significantly, especially in subtropics of the Mediterranean and India (Challinor et al., 2007).

Overall, the tropics become less suitable because critical thresholds of adaptability are exceeded in most marginally suitable areas (Figure 3-1). Predicted losses of more than 20% climate suitability will occur over 10, 15, 50, and 75% of the area currently growing cassava (Ceballos et al., 2011; Jarvis et al., 2012),

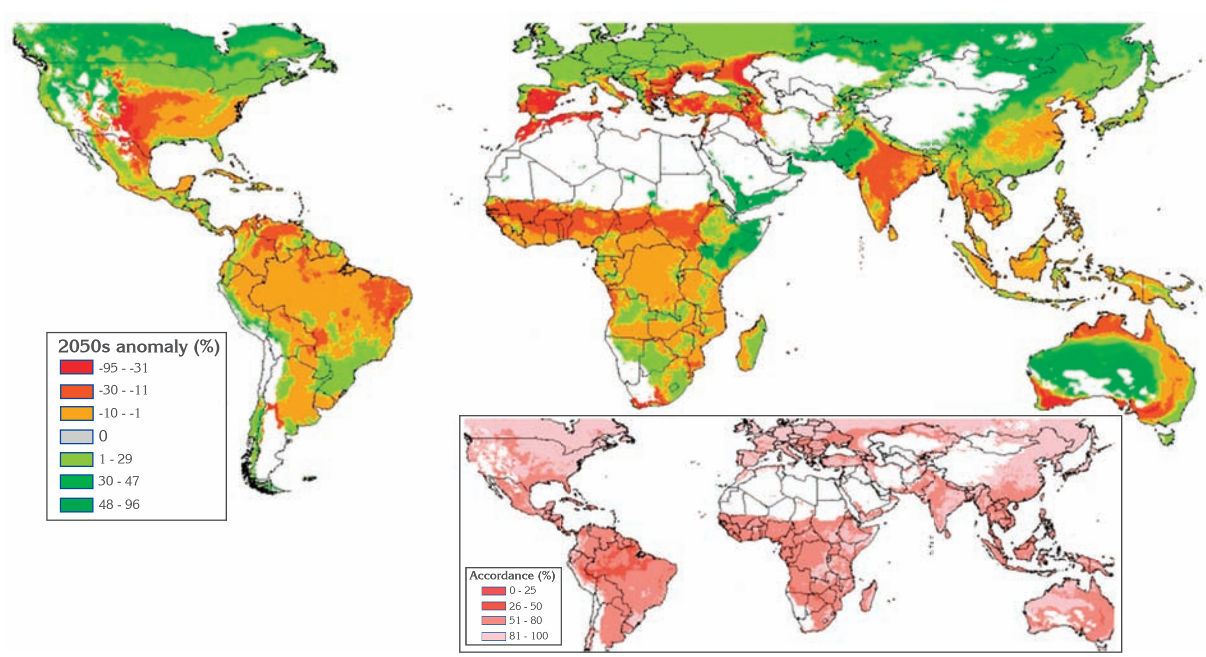

Figure 3-1. Average changes (main map) in climatic suitability by 2050s of the 50 most important crops globally (area basis), and accordance % (inset) of 18 global climate models.

bananas (Ramírez et al., 2011; Van den Bergh et al., 2012), potatoes (Schafleitner et al., 2011), and beans (Beebe et al., 2011), respectively. In contrast, black leaf streak, a major disease in bananas, is predicted to decrease by 3–7% in most banana-growing areas (Ramírez et al., 2011). Crop traits that the model flagged as important were: cold/waterlogging tolerance for cassava (Ceballos et al., 2011; Jarvis et al., 2012), cold/heat tolerance for bananas (Ramírez et al., 2011), heat/cold/drought tolerance for potatoes (Schafleitner et al., 2011), and heat/drought tolerance for beans (Beebe et al., 2011). Although cold tolerance may seem an odd trait when climate change predicts higher temperatures, at least some tropical crops may extend into the subtropics where cold snaps can damage sensitive crops (e.g., citrus in Florida).

In the past, farmers have adapted their cropping systems to tackle adverse climates and to respond to other environmental pressures. It is likely that they will continue to adapt their systems as the climate changes by adopting new varieties – or even new crops altogether – and by changing agronomic practices such as time of sowing (IPCC, 2007; Krishnan et al., 2007; Srivastava et al., 2010). There is a clear need to develop strategies to alleviate the negative impacts and capitalize on the positive impacts of climate change, particularly in the most vulnerable regions such as the tropics and subtropics. Adaptation strategies to overcome reduced crop suitability include:

- Changes in management to temporarily buffer negative climate change impacts
- Changes in infrastructure and timing, including modification of irrigation and drainage amounts, frequencies, and system types
- Modification of varieties in a well-defined regional breeding strategy, using both conserved genetic resources and molecular biotechnology to respond quickly to adaptation needs as they appear
- Changes in the intercropping, e.g., crop migration, taking into account economic and environmental sustainability

Another possibility is changing one or more of the components of the cropping system. Changing crops might be the only option available to poor smallholders, who are the most vulnerable, least able to adapt to rapid change, and most limited in access to new technology. Crop substitution therefore appears to be a key issue when addressing adaptation pathways for negatively impacted areas. It will be a challenge to produce well-adapted varieties that also comply with the many entrenched socio-cultural traditions that might prevent their adoption, such as regional preferences for size and color of beans in Mesoamerica (Thornton et al., 2011), or fruit characteristics in commercial bananas (Ramírez et al., 2011; Van den Bergh et al., 2012). Substitution of completely new crops will be even harder to bring about.

Given the significant shifts in the geographic suitability of crops, a considerable turnover in agricultural technologies and practices is likely to take place. The result could be more opportunities for piggy-backing change, both through appropriate deployment of technologies/practices and the creation of suitable incentive mechanisms that ensure that new agricultural systems deliver greater eco-efficiency. However, this poses the question: are climate change adaptation and mitigation measures always going to be eco-efficient?

Case study: End-to-end analysis of climate impacts and eco-efficient responses in Colombia

This section develops a concrete example of a climate change challenge and the possible response mechanisms to put to the test the hypothesis that eco-efficient agriculture is synonymous with climate change adaptation and on-farm mitigation interventions specific to the case of Colombia. First, climate impacts are assessed and the effects these have on crop suitability are quantified. Possible response mechanisms in the rice sector are then developed and tested economically and biophysically for their likely effectiveness in adapting to the various challenges.

Climate change scenarios for Colombia

Predicted climate changes

We extracted annual rainfall and mean annual temperature data for Colombia for two time slices – 2030 and 2050 (Figure 3-2) – from 19 global climate models (GCMs) forced with IPCC SRES scenario A2 (IPCC, 2007). SRES A2 is one of the less optimistic, "business-as-usual" scenarios based on continued regionally oriented economic and industrial intensification. Atmospheric concentrations of greenhouse gases (GHGs) over the 10 years since the SRES was

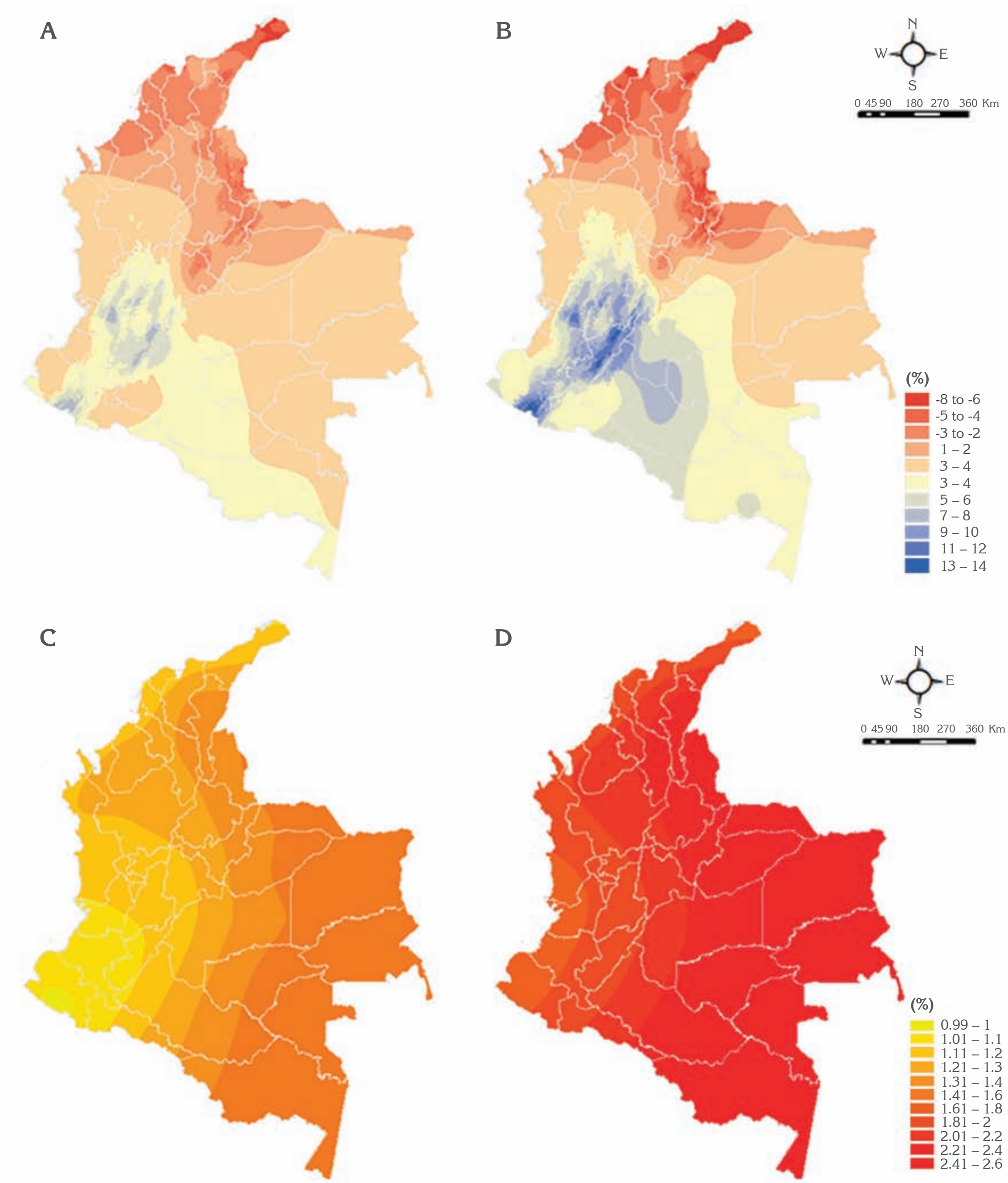

Figure 3-2. Changes in annual precipitation by (A) 2030 and (B) 2050, and in mean annual temperature by (C) 2030 and (D) 2050, predicted for Colombia under IPCC SRES emissions scenario A2. Average data based on 19 global climate models.

published broadly match the scenario's prediction. We emphasize that the predictions in the text that follows are derived from the GCMs and should be treated as such.

Precipitation in Colombia will likely decrease in some areas and increase in others for both time slices [Figures 3-2(A) and 3-2(B)]. In general, precipitation could decrease in the north by 40 mm/yr by 2030 and 90 mm/yr by 2050, while elsewhere it could increase by as much as 80 mm/yr by 2030 and 180 mm/yr by 2050.

The largest predicted decreases in annual precipitation are in the departments of Atlántico, Norte de Santander, Cesar, Sucre, Arauca, and Magdalena, and the largest increases will likely be in Valle del Cauca, Amazonas, Cauca, Quindío, Nariño, Tolima, Huila, and Caquetá. Precipitation patterns in 2030 and 2050 may be very similar to current patterns, though differing in magnitude, with ranges of -3 to +3% in 2030, and -6 to +5% in 2050.

Overall, mean annual temperatures are predicted to increase by 1.0–1.4 °C by 2030 and by 1.8–2.4 °C by 2050 (Table 3-1). Although mean annual temperatures will probably increase in all departments, the increase is likely to be greatest in Vaupés, Guainía, and Vichada for both 2030 and 2050 [Figures 3-2(C) and 3-2(D)].

Colombia is projected to warm 1.4–2.5 °C by 2050, while precipitation is likely to vary between -6% and +5% in the current values. Distribution of precipitation is also likely to change, again varying by region. Temperature-sensitive crops may be affected by the higher temperatures and have to move to higher altitudes to avoid suffering significant losses of yield and quality. There will likely be trade-offs, e.g., with areas at or under 1,200 m altitude becoming less suitable for coffee than at present, while areas above 1,800 m become more suitable.

Uncertainty assessment

Although the GCMs are based on current understanding of the atmospheric processes, they do not implement that understanding in exactly the same way, causing their outputs to differ. The global climate change community deals with this by expressing the variation (i.e., spread) in the output as "uncertainty".[5] Uncertainty is a property of the external world, not the model itself, and as such it arises from a lack of data and/or knowledge about the initial conditions of the system, including the impossibility of modelling at a very high resolution (Challinor and Wheeler, 2008; Hawkins and Sutton, 2009; Majda and Gershgorin, 2010).

The uncertainties of the 19 GCMs for annual precipitation and annual mean temperature are shown in Figure 3-3. The dispersion between models for precipitation is high (Figure 3-3), especially along the Colombian Andes. This outcome is probably due to the complex topographic gradients of the Andean region, which cannot be resolved with such coarse models. Hence, some models project large increases and decreases in precipitation in highland areas, but only small changes in the country's lowlands, such as the Eastern Plains and the Caribbean regions. The result is high uncertainty for regions in the center of the country (Table 3-1).

The largest decreases in precipitation – up to 60 mm/yr by 2050 – are projected for the Caribbean region. The most pronounced increases are for the Amazon region and the coffee-growing zone: up to 130 mm/yr, although with relatively high uncertainty.

Although the scales are different, the uncertainty for mean annual temperature is relatively low when compared with the uncertainty for annual precipitation (see also Hawkins and Sutton, 2009; 2011 for a global analysis of

[5] Although we are unable to represent exactly in a mathematical model how nature works, in this case the complex interactions of atmospheric circulation, there a number of different models that mimic the processes tolerably well. The results of these models can be expressed as a comparison between models (see e.g., Knutti et al., 2009; Meehl et al., 2007). There is an implicit understanding that the models used are approximations to what might be obtained from a thorough analysis if a fully adequate model of real-world processes were available.

Table 3-1. Changes in annual precipitation and mean annual temperature by 2030 and 2050 under IPCC SRES emissions scenario A2 for departments in Colombia.

		Precipitation (mm)					Temperature (°C)				
Region	Department	Current	Percent Change 2030	Range 2030	Percent Change 2050	Range 2050	Current	Change 2030	Range 2030	Change 2050	Range 2050
Amazon	Amazonas	4273.2	1.46%	305.4	2.45%	468.2	26.9	1.4	5.0	2.4	3.7
	Caquetá	3651.2	1.88%	716.2	3.55%	1196.8	24.9	1.3	3.9	2.2	2.8
	Guainía	2916.8	0.81%	363.8	1.45%	597.1	26.2	1.4	5.0	2.5	3.7
	Guaviare	3651.2	1.02%	457.2	2.30%	769.1	24.9	1.4	4.7	2.4	3.4
	Putumayo	3651.2	1.71%	986.1	3.29%	1701.7	24.9	1.1	3.0	2.0	1.9
	Vaupés	4273.2	0.74%	322.3	1.63%	470.7	26.9	1.4	5.0	2.5	3.6
Andean	Antioquia	4333.1	0.34%	424.9	0.64%	689.6	24.9	1.2	3.8	2.1	3.0
	Boyacá	5456.1	-0.38%	1095.7	-0.43%	1864.2	22.2	1.3	5.0	2.3	3.8
	Cundinamarca	5456.1	0.07%	1407.0	0.62%	2400.6	22.2	1.2	4.1	2.1	3.0
	Huila	5456.1	1.35%	863.7	2.53%	1370.6	22.2	1.1	2.7	1.9	1.8
	N. Santander	4333.1	-1.03%	698.7	-1.44%	1124.1	21.6	1.4	5.4	2.4	4.2
	Santander	4333.1	-0.43%	784.5	-0.64%	1369.9	24.9	1.3	5.3	2.3	4.0
	Tolima	5456.1	1.23%	678.4	2.15%	1232.7	22.2	1.1	3.1	1.9	2.4
Caribbean	Atlántico	971.7	-3.55%	335.3	-6.75%	613.5	26.5	1.1	2.5	1.8	2.2
	Bolívar	4333.1	-0.66%	323.1	-0.88%	539.7	24.9	1.3	4.3	2.2	3.4
	Cesar	4333.1	-0.89%	354.5	-1.28%	570.6	24.9	1.3	4.5	2.3	3.5
	Córdoba	4333.1	-0.60%	418.5	-0.85%	538.6	24.9	1.2	3.6	2.1	2.8
	La Guajira	971.7	-3.28%	286.7	-5.14%	446.5	26.5	1.2	3.0	1.9	2.6
	Magdalena	971.7	-3.70%	308.6	-6.23%	549.4	26.5	1.2	3.5	2.1	2.8
	Sucre	4333.1	-0.88%	355.8	-1.26%	502.3	24.9	1.2	3.9	2.1	3.0
Coffee-growing Zone	Caldas	5456.1	0.95%	629.6	1.61%	1028.0	22.2	1.2	3.6	2.0	2.9
	Quindío	5456.1	1.21%	492.5	1.87%	797.7	22.2	1.1	2.9	1.9	2.5
	Risaralda	5369.7	0.97%	493.6	1.52%	766.8	25.5	1.1	2.9	1.9	2.5
Eastern Plains	Arauca	2501.2	-1.25%	812.3	-2.17%	1394.6	26.0	1.4	5.6	2.5	4.5
	Casanare	5456.1	-0.14%	735.9	-0.08%	1233.5	22.2	1.4	5.2	2.4	4.0
	Meta	5456.1	0.72%	760.7	1.72%	1391.0	22.2	1.3	4.3	2.2	3.1
	Vichada	2916.8	0.39%	381.3	0.58%	553.4	26.2	1.4	5.0	2.5	3.9
Pacific	Chocó	5369.7	0.70%	466.6	1.04%	805.3	25.5	1.2	2.2	1.9	2.0
Southwest	Cauca	5369.7	1.15%	857.7	2.13%	1274.8	25.5	1.1	1.8	1.8	1.3
	Nariño	5265.0	1.25%	649.5	2.32%	1090.2	24.9	1.0	1.4	1.8	1.0
	Valle del Cauca	5369.7	1.15%	601.1	1.78%	1024.5	25.5	1.1	2.0	1.8	1.7

uncertainty). Both the differences between models and the standard deviation of their outputs vary longitudinally, increasing towards the east of the country, particularly in the Eastern Plains and the Amazon. The uncertainty in these two areas is also higher than elsewhere. The GCMs differ considerably – by up to 5 °C – in their projections for 2030 and 2050, although the mean of all models shows an increase of only half that by 2050. Differences between the GCMs, and thus their uncertainty, are relatively low in the southwest of the country.

GCM performance across Colombia

We cannot be certain which of the GCMs best represents the future climates. However, we can evaluate how well their output matches the baseline climates (1961–1990), i.e., present-day climates for which we have observational data. A simple way to evaluate the performance of

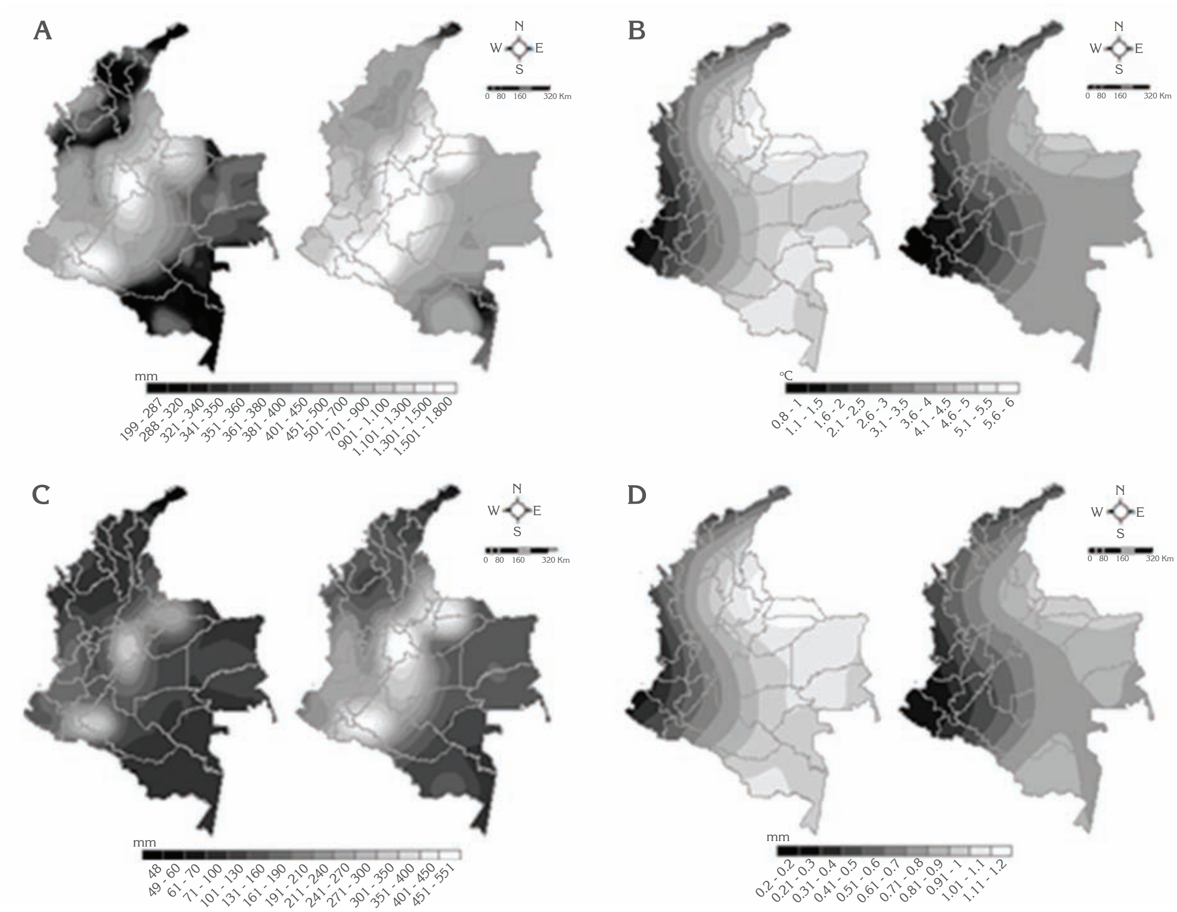

Figure 3-3. Uncertainty between global climate models for IPCC SRES scenario A2 for annual precipitation (A and C) and mean annual temperature (B and D). In each subfigure, the map on the left is for 2030 and the map on the right is for 2050. Subfigures A and B are the range between the global climate models and subfigures C and D are the standard deviations.

climate models is to compare their results against observations.

We compared the results of each GCM with the readily-available climate databases WorldClim (Hijmans et al., 2005), Global Surface Summary of Day (GSOD) (Lott, 1998), Global Historical Climatology Network (GHCN) (Peterson and Vose, 1997; Lott, 1998), and Climate Research Unit (CRU) (Mitchell and Jones, 2005) following the methodology of Ramírez-Villegas et al. (2012) and Ramírez-Villegas and Challinor (2012) (Figure 3-4). We analyzed total rainfall and mean temperature over four seasons (Dec–Feb, Mar–May, June–Aug, Sept–Nov) and the whole year (ANN). For each model, the mean of all stations (GHCN and GSOD) or grid cells (WorldClim and CRU) was computed, GCM grid cells grouped, and the spatial consistency of the mean climate prediction assessed by calculating the coefficient of determination (R^2) between the observed data and the GCMs. This coefficient defines the skill of each climate model to represent the climate of the baseline period.

The coefficient of determination (R^2) for the baseline of annual precipitation is medium-high for the majority of the GCMs, especially for the interpolated surfaces (WorldClim and CRU), but is lower for the station data (GSOD and GHCN) because of their geographic distribution and relative scarcity (Figure 3-4). The GCMs perform slightly better for annual data, but less well for seasonal data, especially in the second semester (JJA–SON). At least 40% of the seasons and GCMs perform poorly ($R^2<0.6$) for precipitation,

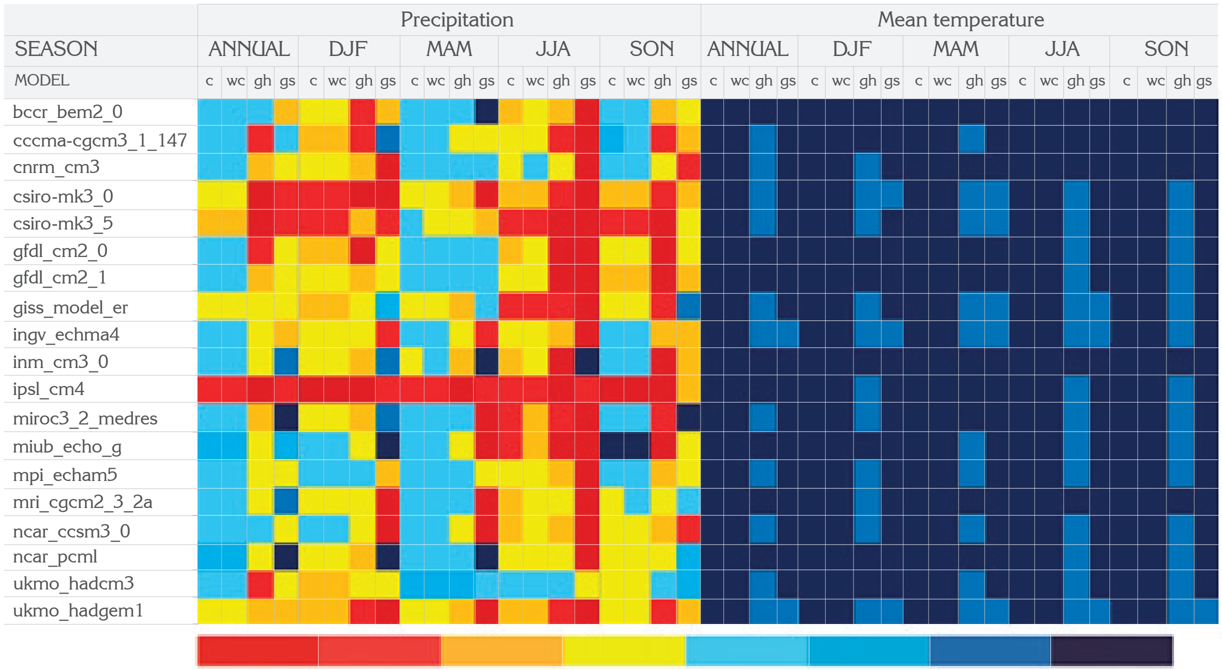

Figure 3-4. R^2 values for Climate Research Unit (CRU) interpolated surfaces (c), WorldClim interpolated surfaces (wc), Global Historical Climatology Network (GHCN) weather station data (gh), and Global Surface Summary of Day (GSOD) weather station data (gs) in relation to each global climate model over the 1961–1990 period.

and only 20% perform well (R^2>0.8). In contrast, R^2 for mean temperature is greater than 0.95 for all the models, both for the annual cycle and for seasons of the year (see also Ramírez-Villegas et al., 2012). We conclude that GCMs can generate data of mean future climates with moderately high precision for temperature and low precision for precipitation, although models still have a long way to go before they can predict Colombian climate variations accurately.

Climate change impacts on crops

We calculated the average change in climatic suitability for 25 crops selected for their importance in harvested area (ha) and production (t) in Colombia (Table 3-2), calculated averages for each department, and grouped them by region. We estimated the change in climate suitability using EcoCrop (Hijmans et al., 2001; Ramírez-Villegas et al., 2011) and applied the SRES A2 scenario for 2050 using data from 19 GCMs (Ramírez-Villegas and Jarvis, 2010). Current climate data were from WorldClim (Hijmans et al., 2005).

Overall, and using ±50% as the cutoff, losses in climate suitability between now and 2050 were greater than the gains. Losses could be seen in up to 82.7%, or about 945,930 km^2, of the country's total area (1,143,640 km^2), while the remaining 17.3% (197,710 km^2) should continue to have suitable climatic conditions for growing crops. The most critical regions are the Amazon, Caribbean, Pacific, and the Eastern Plains, where all departments are projected to have negative changes, although changes in several departments may be less than 15%. Changes will likely be positive in five of the seven Andean departments and all three of the coffee-growing region's departments: Caldas (3.8%), Risaralda (4.9%), and Quindío (12%).

It is useful for planning purposes to determine how many of the 25 crops analyzed are likely to become more suitable for the climate (winners), and how many are likely to become less suitable (losers) (Figure 3-5). In this case, the threshold of climate suitability – that is, a crop's climatic aptitude (CA) – for a winner or loser is ±5%.

Table 3-2. Climatic suitability changes in potential agricultural area for each department in Colombia, excluding San Andrés and Providencia Islands.

Region	Department	Change (%)	Potential area affected km²	Potential area affected %
Amazon	Amazonas	-24.8	108,780	9.5
	Caquetá	-23.6	90,620	7.9
	Guainía	-27.8	70,680	6.2
	Guaviare	-19.6	55,830	4.9
	Putumayo	-23.8	25,460	2.2
	Vaupés	-28.4	53,100	4.6
Andean	Antioquia	-5.7	63,700	5.6
	Boyacá	12.2	22,140	1.9
	Cundinamarca	3.6	22,550	2.0
	Huila	3.3	18,320	1.6
	Norte de Santander	0.5	21,980	1.9
	Santander	-0.1	30,470	2.7
	Tolima	2.0	23,610	2.1
Caribbean	Atlántico	-24.6	3,420	0.3
	Bolívar	-14.8	27,150	2.4
	Cesar	-12.9	22,880	2.0
	Córdoba	-15.8	25,300	2.2
	La Guajira	-34.7	20,840	1.8
	Magdalena	-17.1	23,000	2.0
	Sucre	-15.3	10,890	1.9
Coffee-growing Zone	Caldas	3.8	7,390	0.6
	Quindío	12.0	1,930	0.2
	Risaralda	4.9	3,470	0.3
Eastern Plains	Arauca	-19.2	23,670	2.1
	Casanare	-16.7	44,670	3.9
	Meta	-16.3	85,960	7.5
	Vichada	-15.5	100,100	8.8
Pacific	Chocó	-9.6	28,940	2.5
Southwest	Cauca	6.3	26,650	2.3
	Nariño	-3.4	30,470	2.7
	Valle del Cauca	1.8	17,370	1.5

Note: Total percentage of area likely to be adversely affected would be 97.3% (1,112,800 km²).

In some departments in the Andean and Pacific regions (Antioquia, Boyacá, Cauca, Cundinamarca, Nariño, and Valle del Cauca), 7–10 crops covering 1.6 million ha could gain in CA. In the departments of La Guajira, Cesar, and Bolívar in the country's Caribbean region, 9–13 crops covering 440,000 ha could decrease in CA. About 72 million ha show uncertainty (coefficient of variability between models) less than 30%, mostly in the Andean and Eastern Plains regions, which represent most of the country's agricultural activity.

Climate-smart adaptation and mitigation options for rice systems in Colombia

Colombian rice systems

Rice ranks first among short-cycle crops in terms of its importance to Colombia's economy.

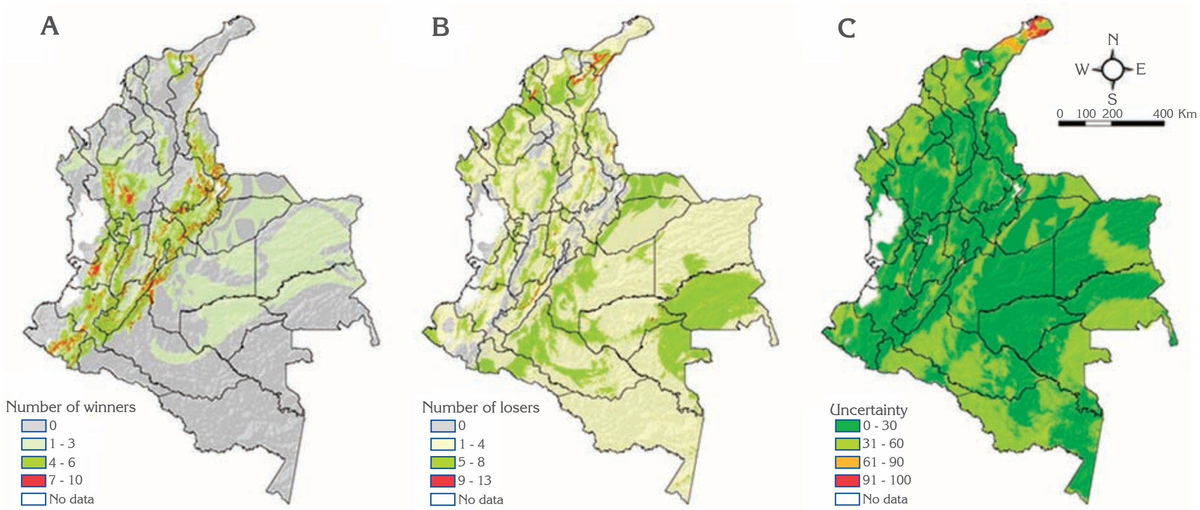

Figure 3-5. Changes in the suitability of 25 crops in Colombia estimated with EcoCrop: (A) climate more suitable; (B) climate less suitable; and (C) estimates of uncertainty (Coefficient of Variation, CV).

The country is the second largest rice producer in Latin America, and even so is a net rice importer. Rice is the primary source of calories for the low-income group, which accounts for over 37% of Colombia's population (The World Bank, 2012). The two predominant systems of rice production in Colombia are mechanized – which includes both irrigated and rainfed systems – and manual, with all production activities being undertaken with hand labor. In 2007, Colombia produced 2,471,545 tons of rice on over 400,000 ha of land (Fedearroz, 2007).

An expert workshop on climate change at the International Center for Tropical Agriculture (CIAT) identified two potential climate-smart adaptation pathways for rice in Colombia: irrigation of traditional dryland rice and genetic modification for high-temperature tolerance. We also considered three mitigation measures for rice in Colombia: managing flooded rice to minimize CH_4 emissions, eliminating burning of crop residues, and optimizing the amount of applied fertilizer.

Types of economic analyses

Two important tools for selecting and prioritizing "no-regrets" adaptation or mitigation options are cost–benefit analysis (CBA) and cost-efficiency analysis (CEA). For adaptation purposes, the most relevant analysis is usually the CBA, which asks whether the returns (benefits, such as avoided damage/losses or extra developmental benefits compared with "business as usual") are greater than the costs (extra investment compared with "business as usual"), and by how much. CBA quantifies all costs and benefits of an intervention with monetary values, making it appropriate when economic efficiency is the only decision-making criterion (UNFCCC, 2011).

The impact of climate change on crops can be quantified with modelling, as can the extent to which impacts can be avoided through one or more adaptation options. Thus the most effective adaptation option can be chosen based on a discrete comparison of the cost of implementing the adaptation measure and its resulting benefits (improvement in crop production, avoidance of economic losses). Elements of climate change mitigation, on the other hand, are not always so easy to express in monetary terms. For example, the benefits of reduced GHG emissions are not restricted to the site of the emissions but are global in their effects, making them difficult to estimate (it is not yet possible to estimate GHG emission damages by modelling at the specific local level and then extrapolating globally). Positive environment-, health-, or livelihood-related outcomes cannot be valued in a strictly monetary sense because they are not localized in the way that adaptation benefits are.

CEA is useful for situations in which there is a concrete objective and where impacts are measurable but benefits are not (UNFCCC 2011), as is the case with many mitigation measures. The costs in a CEA can be valued in monetary terms, but the benefits must be expressed in "physical" units. It is then possible to construct a cost-efficiency curve that can be used to identify and prioritize those mitigation measures that are economically viable for achieving a well-defined physical target.

Cost–benefit analysis of adaptation options

Out of the area under rice production in Colombia, 256,295 ha (64%) are irrigated and 29,556 ha (36%) are dryland/rainfed (Fedearroz, 2007). The potential area for irrigation based on water availability and climate is estimated to be 6.6 million ha (AQUASTAT, 2010). Dryland rice will be vulnerable to yield losses from water stress caused by climate change, i.e., increased evapotranspiration due to higher temperatures and compounded by lower overall rainfall. Furthermore, the introduction of modern seed varieties has seen dryland rice lose competitiveness with irrigated systems; the average yield gap between irrigated and dryland systems can be more than 4 t/ha (Lang, 1996).

We simulated the effects of climate change for dryland rice with the Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al., 2003), using the variety and agronomy currently recommended by the National Federation of Rice Growers (Fedearroz, its Spanish acronym). We first simulated the effect of climate change without irrigation and subsequently its effect with irrigation. We estimated the costs of providing irrigation in terms of the initial investment required and the costs of operation and maintenance with a life span of 20 years. We calculated the benefits of the irrigation project as the difference between rice production with and without irrigation under the SRES scenario A2. We calculated operation and maintenance costs and estimated an increase of 1% annually, using an annual social discount rate of 12%.

Analysis of the financial flow shows that building an irrigation system in the Colombia's Caribbean and Eastern Plains regions gives positive net present values (Figure 3-6), and in each case the development would be financially viable.

The second adaptation measure that we tested was a research program to seek and develop, by 2030, new rice varieties tolerant of higher temperatures. The rising temperatures expected from climate change pose a threat to rice production by increasing the risk for spikelet sterility during development. However, rice germplasms exhibit great variability in their response to heat stress. Heat-tolerant cultivars have been shown to respond well to increased

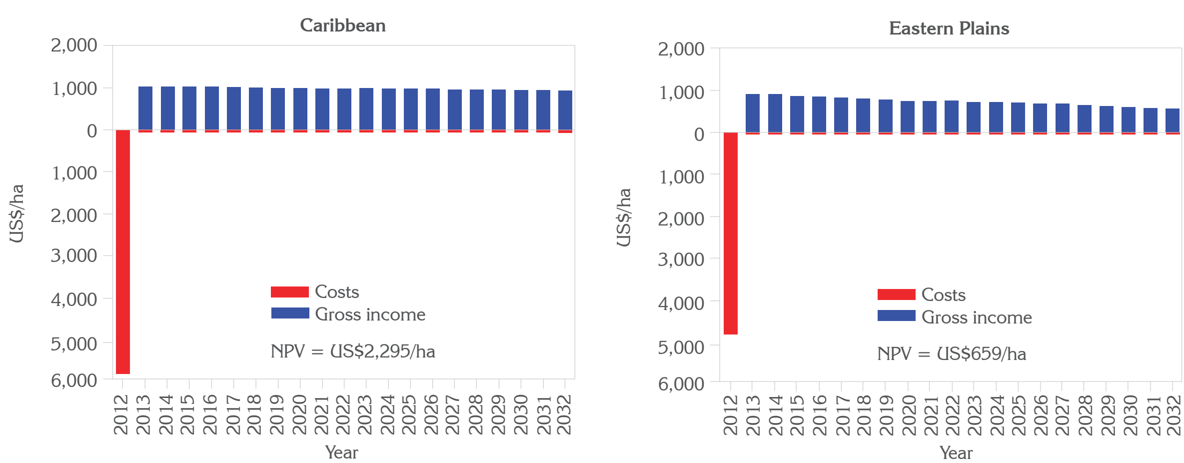

Figure 3-6. Costs and benefits year by year for an irrigation system project in Colombia's Caribbean and Eastern Plains regions, and net present value (NPV) with a social discount rate of 12%.

temperatures while still producing economic yield (Shah et al., 2011). Furthermore, improved cultivars could potentially offset stress from increased evapotranspiration by exhibiting better water use efficiency, greater harvest indices, and deeper/faster-growing roots.

We used the costs of a 26-year research program (including researchers, assistants, field workers, materials, infrastructure, and operational and administrative costs) and simulated the yields in 2050 of the currently recommended variety and a synthetic variety less sensitive to temperature using DSSAT.[6] We calculated the benefit as the economic value of the difference in production between the current and the synthetic varieties. We assumed a progressively decreasing rate of adoption with a final level of adoption of 15% for the whole country and a discount rate of 12% annually.

The cost–benefit analysis shows that it is highly desirable to mount a research program to improve the resistance of rice to high temperatures, giving a large net present value (Figure 3-7).

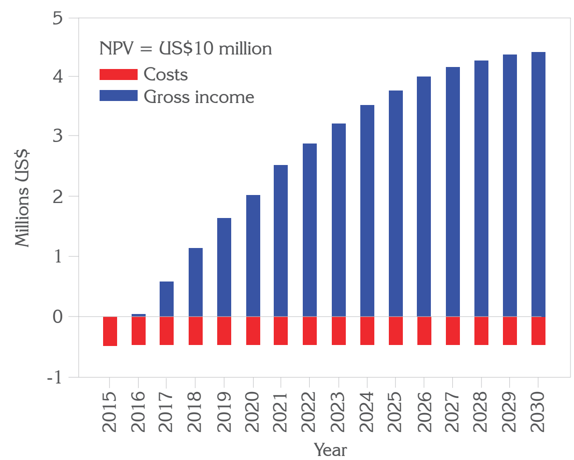

Figure 3-7. Costs and benefits year by year for a research program to increase the resistance of rice to high temperatures, and net present value (NPV) with a social discount rate of 12%.

Cost-efficiency analysis of mitigation options

CEA assesses the economic costs and the technical efficiency of different options to achieve some predetermined level of environmental quality. The analysis assists the decision-making process by allowing feedback from those affected by a proposed program or plan of action to revise the objectives as part of the process. CEA allows the construction of curves of marginal cost, which are obtained by ordering all possible alternative actions according to their cost and their effect on the environmental factor under consideration. In the case of the reduction of GHG emissions in agriculture, the options can be modelled using the *Cool Farm Tool* (www.coolfarmtool.org/Home), a tool originally developed by Unilever and researchers at the University of Aberdeen to help growers measure and understand on-farm GHG emissions.

Calculations of methane emissions reduction are based on empirical evidence collected from Colombian literature. Calculations of nitrogen/yield relationships are based on modelling of potential yield under different treatments using the DSSAT CERES-Rice model. Quantifications of on-farm production in the different regions of Colombia are drawn from Fedearroz survey data.

Data from the field have shown that flooded rice generates greater emissions of CH_4 than rice grown with intermittent irrigation (or irrigation interspersed with dry periods), which allows soil aeration and is unfavorable for the anaerobes that produce CH_4. Flooded rice in Colombia is typically grown in the municipalities of Jamundí (Valle del Cauca) and Cúcuta (Santander). Substituting of intermittent irrigation for continuous flooding requires the following: (1) implementation of a

[6] DSSAT largely represents the effects of temperature on rice as its effect on the development rate, in which higher temperatures shorten the duration of the various growth stages. We arbitrarily altered the genetic coefficients in DSSAT to make a synthetic variety that was less sensitive to temperature by increasing the genetic coefficients P1 and P5 by 15%. Coefficient P1 is the time period [expressed as growing degree days (GDD) above a base temperature of 9 °C] from seedling emergence during which the rice plant is not responsive to changes in photoperiod. This period is also referred to as the basic vegetative phase of the plant. Coefficient P5 is the time period in GDD from the beginning of grain filling (3 to 4 days after flowering) to physiological maturity with a base temperature of 9 °C.

system of monitoring and water use control at the level of the individual field; (2) training and field demonstrations of land preparation and the use of water budgeting balance; and (3) land preparation for more efficient water use. The cost to implement these measures is US$107/ha per year, which will reduce GHG emissions by 11.65 t CO_2 eq/ha per year in Cúcuta and 13.06 t CO_2 eq/ha per year in Jamundí. The estimated cost efficiency is $9.20/t CO_2 eq per ha per year in Cúcuta and $8.21/t CO_2 eq per ha per year in Jamundí. The maximum potential reduction of emissions is 197,050 t CO_2 eq/yr for Cúcuta and 66,810 t CO_2 eq/yr for Jamundí.

Harvest residues are typically burned in the municipalities of Espinal (Tolima), Valledupar (Cesar), and Yopal (Casanare). Instead of burning, residues can be managed using minimum tillage and decomposition accelerators, which, including training, costs US$112 for Espinal and Valledupar, and $57 for Yopal. The reductions of GHG emissions are 0.95, 0.53, and 0.47 t CO_2 eq/ha per year for Espinal, Valledupar, and Yopal, respectively, with estimated cost efficiencies of $59, $104, and $120/t CO_2 eq per ha per year. The potential reduction of GHG emissions is 26,270 t CO_2 eq/yr for Espinal, 3,280 t CO_2 eq/yr for Valledupar, and 3,300 t CO_2 eq/yr for Yopal.

There are many factors that affect rice's nitrogen use efficiency (NUE), or its ability to absorb and use nitrogen inputs. The result is often that more fertilizer is applied than can be used by the plant, or that not enough is applied to get maximum yields and economic returns. There are three possible approaches for increasing the efficiency of nitrogen fertilizer application to rice in Colombia, thereby reducing unnecessary inputs and decreasing emissions from crop fertilization (Figure 3-8). The first involves reducing overall nitrogen application, which increases NUE but entails reduction in rice yields (scenario A). The second requires no reduction or increase in nitrogen application, but requires more-effective management techniques so that what does get applied is used effectively by the plant (scenario B). The final approach involves both increasing nitrogen inputs and NUE through better management to arrive at optimum economic returns from the system (scenario C). All three scenarios are climate smart – they result in fewer emissions per ton of rice produced due to optimal N uptake – however we will only be analyzing scenario A for economic viability and relative eco-efficiency.

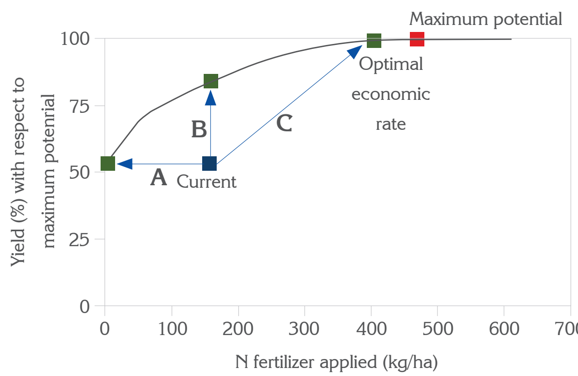

Figure 3-8. Potential yield achieved under different application levels of nitrogen, based on modelling crop response with the DSSAT CERES-Rice model. The arrows represent different approaches for increasing efficiency of nitrogen fertilizer application in rice systems: A) Decreased N input but increased use efficiency maintains a stable yield, B) Same N input, with increased NUE and reduction of yield gap through optimal management, and C) increased N input to economic optimal levels, with associated increased NUE and increased management.

It is possible to halve the rates of fertilizer applied to rice in two regions of Colombia: the Andean and Caribbean regions. The cost of this option is estimated using the following equation:

$$C_r = \sum_{s=1}^{2} (\nabla R_{rs} * \bar{P}s - \nabla F_r * Z_r)$$

where:

C_r = annual cost of measure C in region r (US$/ha);

∇F_r = reduction of 50% of the mean fertilizer of the region in each cropping cycle (kg/ha);

∇R_{rs} = change in yield of the crop in region r in semester s as simulated in DSSAT due to the 50% reduction in fertilizer (t/ha);

Z_r = mean price of fertilizer in 2010 (US$/ton);

$\bar{P}s$ = mean value of rice in semester *s* (during the last 10 yr in constant 2010 US$/ton).

The estimated costs of this option in terms of foregone production are: Andean, US$113/ha per year, and Caribbean, $183/ha per year. The expected reduction of GHG emissions are: Andean, 1.0 t CO_2 eq/ha per year, and Caribbean, 0.2 t CO_2 eq/ha per year. Nevertheless, the estimates of cost efficiency are $109 and $170/t CO_2 eq reduced for the Andean and Caribbean regions, respectively. The maximum potential reduction of GHG emissions is 76,170 and 2,920 t CO_2 eq/yr for the Andean and Caribbean regions, respectively.

It is important to keep in mind that the yield reductions caused by decreased nitrogen inputs have further repercussions for global food security. There is a possibility that reducing N application in one region or country could simply displace GHG emissions to another, which would have to produce more to make up for the decrease in yield, a factor which was not taken into account in this analysis.

The data for the three mitigation options in various departments in Colombia are summarized in Figure 3-9.

The priority adaptation and mitigation interventions identified for the rice sector all involve optimization of resource inputs and outputs, be it fertilizers or water, or improved use of "waste" products. The economic analysis demonstrates the cost-benefit ratios of these interventions from a climate change mitigation perspective, but equally could consider these from a competitiveness perspective, or prioritize them based on eco-efficiency principles.

Eco-efficiency of climate-smart practices

Although the practices described above are already considered climate smart, our definition of the term leaves room for the possibility that, though a strategy may be climate smart, it may not necessarily be economically viable, environmentally sustainable, or make good use of resources. As noted by Keating et al. in Chapter 2 of this publication, eco-efficiency is a multifaceted

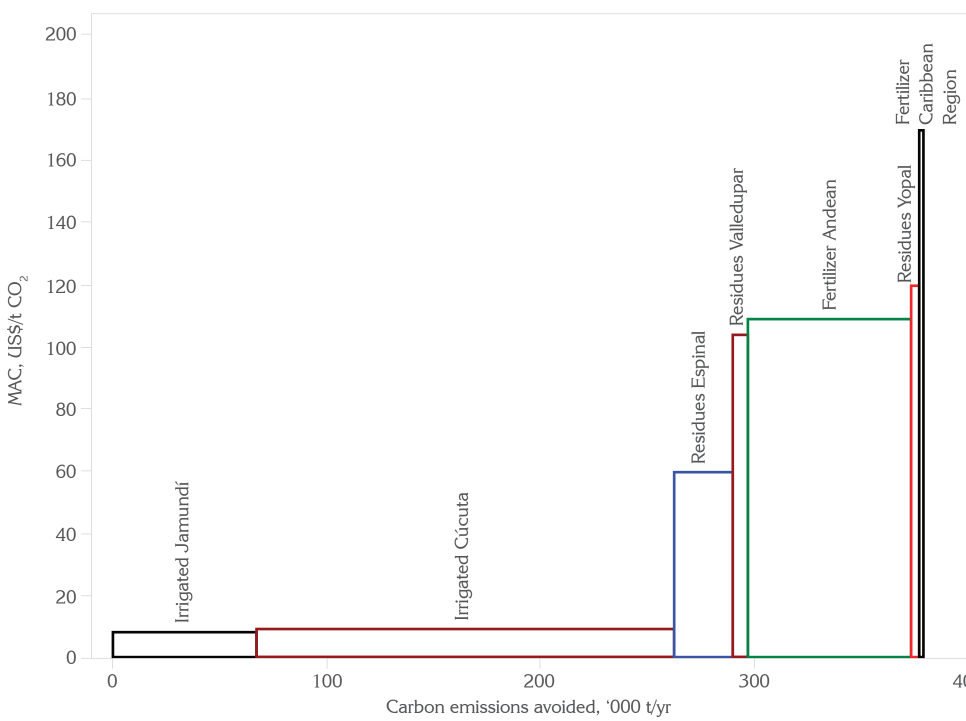

Figure 3-9. Marginal abatement curves (MAC) (US$/t CO_2 eq) for various interventions in rice culture in Colombia.

concept that is characterized by a variety of potential measures. Thus, while an eco-efficient practice is highly likely to also be climate smart, some climate-smart practices are probably more eco-efficient than others if a number of such measures are taken into account.

Making use of some of the explicit measures noted by Keating et al. (Chapter 2 of this publication), we attempted to qualitatively evaluate the climate-smart adaptation and mitigation measures chosen for Colombia based on their relative eco-efficiency. A measure of eco-efficiency must be made with regard to the relation of inputs, such as labor, capital, nutrients, and water; with desired outputs, such as harvested product or economic profit. Table 3-3 gives a positive or negative value for the eco-efficiency measures to each of the 5 climate-smart practices; a negative value (red) is assigned when a practice requires more inputs (+) or results in less of the desired outputs (-), whereas a positive value (green) is assigned for a reduction in inputs (-) or increase in desired outputs (+).

Table 3-3 shows that not all of the climate-smart strategies chosen for Colombia are highly eco-efficient, though some are more so than others. For example, the composting of crop residues in the field instead of burning appears to be highly eco-efficient – as it both reduces the amount of input required in terms of labor, water, and soil nutrients, and increases outputs in the form of ecosystem services. This inference is confirmed by the cost-efficiency analysis, which shows that eliminating residue burning it is capable of greatly reducing GHG emissions at a very reasonable cost to the farmer.

Conclusions

Despite the built-in uncertainties of global climate models, there is a reasonable amount of evidence to support the prediction that global temperatures could rise anywhere from 1 to 8 °C by 2050. Precipitation patterns are less predictable, though certain scenarios can predict with high certainty a global average increase of almost 23% by 2050, along with major changes in spatio-temporal distribution. Circumstances at the country level are similar, with Colombia predicted to undergo temperature increases between 1.4 and 2.5 °C by 2050, shifting distributions of rainfall, and a range of regional precipitation changes (-6 to +5%).

Table 3-3. Eco-efficiency ratings for adaptation/mitigation strategies in Colombian rice systems.

Eco-efficiency measure		Irrigation of dryland rice	Heat-tolerant variety	Intermittent irrigation	Residue re-use	Nitrogen efficiency
Inputs	Land area	-	-	0	0	+
	Soil nutrients	+	0	0	-	-
	Water	+	0	+	-	0
	Energy	-	0	0	0	-
	Labor	+	0	+	0	0
	Capital	+	+	0/+	0	-
Outputs	Production (rice yield)	+	+	+	0	-
	Profit or return on investment	+	+	0/+	0/+	0
	Security of food system	+	+	0	0	
	Nutritional quality	0	0	0	0	0
	Ecosystem services	0/-	0	+	+	+
	Eco-efficiency rating	0.5	3	0	3.5	1

Desirable	1
	0.5
	0
	-0.5
Undesirable	-1

The implications of these changes for world agriculture could be profound, with some 37 of the most important crops predicted to lose more than 50% of area currently classified as suitable for their cultivation. Colombia could experience losses in crop suitability in up to 83% of the country's total area, especially in the Amazon, Pacific, Caribbean, and Eastern Plains regions. In these regions, adaptation strategies will undoubtedly be necessary to cope with the impacts of decreased crop suitability.

Economic analyses of preferred adaptation and mitigation strategies for Colombian agriculture give encouraging results. Both the adoption of an irrigation system and the development of a research program for heat-resistant rice are economically viable, and, in the latter case, highly profitable in the mid-term. Mitigation strategies offer a more mixed bag: replacing flooded rice with intermittent irrigation reduces emissions at a relatively low cost. Using minimum tillage and decomposition accelerators instead of burning residues greatly reduces emissions, but at a higher cost.

Climate change necessitates the implementation of adaptation/mitigation measures to ensure food security. The critical question is whether these climate-smart strategies and measures that meet the standards of eco-efficiency are mutually inclusive. To be sure, many of the resources that eco-efficiency aims to manage prudently (water, nutrients, labor, finances, etc.) are the same resources that must be managed for adaptation/mitigation purposes. For example, using minimum tillage and decomposers in Colombian rice fields instead of burning crop residues after harvest is eco-efficient because it greatly reduces the inputs of water and labor required for conventional puddled transplanting systems while leaving yields virtually unaffected (Bhushan et al., 2007). The practice advances mitigation goals at the same time; omitting tillage and burning considerably reduces carbon emissions.

Qualitatively evaluating the eco-efficiency of the climate-smart strategies chosen for Colombia in terms of the balance of inputs and outputs indicates that, while most eco-efficient practices are by default climate smart, not all climate-smart practices are necessarily highly eco-efficient. Instead, climate-smart practices display a range of compatibility with eco-efficient measures. While some, like the more precise application of nitrogen fertilizer, could result in significant reduction of inputs (soil nutrients, capital, labor, etc.) while augmenting desirable outputs, others may imply more labor, greater financial risk, or even unexpected environmental costs. Accordingly, those options which are a win for both system types should be emphasized in climate change planning to avoid the possibility of adaptation/mitigation coming at the price of efficiency and food security. Furthermore, climate financing could provide a boost to eco-efficient agriculture, thus opening the door for economic incentives to transform low-efficiency systems.

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CHAPTER

4

Integration of Crops, Livestock, and Forestry: A System of Production for the Brazilian Cerrados

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Contents

Abstract

Some of the most promising and at the same time some of the most challenging areas of future food production are found in the savannas of South America. Integrating cropping, livestock, and forestry in these regions can increase the eco-efficiency of agricultural production. This chapter presents a case study of an integrated crop, livestock, and forestry system in Brazil. The study area is in Goiás State in the Cerrado region, a vast savanna covering almost one quarter of Brazil's land area. About half of the area suited to agriculture in the Cerrrado is under cultivated pasture, but much of this is degraded as a result of overgrazing. The systems studied in this report include different arrangements to test productivity, profitability and sustainability of eucalyptus, crops, and pastures. Findings demonstrated that integrated crop, livestock, and forestry systems are economically and technically feasible in the Cerrados. In addition to producing food of high biological value (meat and milk), cultivated pasture provides other important environmental benefits, including long-term ground cover, carbon fixation, increases in soil organic matter content, and reduction in the emission of greenhouse gases.

Background and System Description

Demand for food is expected to continue to increase for at least the next 40 years (Godfray et al., 2010), and food production will need to increase by 70 to 100% by 2050 (The World Bank, 2008). However, this has to be done in the face of growing competition for land, water, and energy, and without harming the environment. The objective must therefore be sustainable intensification of agricultural production (The Royal Society, 2009).

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Brazil is one of the countries with the highest potential of farmland expansion to meet the growing demand for food and biofuel (Brown, 2004), especially in the Cerrado region. The Cerrado is characterized by a savanna-like native vegetation of low trees, scrub brush, and grasses. It covers approximately 204 million hectares (Mha), or 23% of Brazil's land area (Bustamante et al., 2006). About 62% of this area (127 Mha) is suitable for agriculture (Lilienfein and Wilcke, 2003). Cultivated pastures in the Cerrado region cover about 66 Mha (Sano et al., 2000). An estimated 50 Mha are subjected to a process of degradation by excessive grazing (Silva et al., 2004; Klink et al., 2008).

The Cerrado biome is the second largest vegetation formation after the Amazon, and also the world's richest in biodiversity (Mistry, 2000). The climate is characterized by two well-defined seasons: dry winters and rainy summers. Average temperature of the coldest month is about 18 ºC. The dry season extends from April to September; the relative humidity is low, enabling the occurrence of fires. Even in the rainy season from October to March, drought spells often occur, varying from 1 to 2 weeks and sometimes causing considerable losses to agricultural production. Latosols predominate, with good soil physical characteristics (high water infiltration, moderate water retention, and easy mechanization). The majority of the soils are acid, with high aluminum saturation, strong phosphorus retention, and poor nutrient contents. Those characteristics inhibited the development of the Cerrado for agriculture until modern times.

The Cerrado became the leading edge of the expansion of the agricultural frontier in Brazil in the 1970s. Before that, only a small portion of dusky red latosols and structured “terra roxa” were considered suitable for agriculture—a little more than 5% of the total. However, from 1975 a federal government development program known as “Polocentro” allocated resources to develop technologies for profitable and productive agriculture in the Cerrado soils (Bittar, 2011).

Traditionally, beef cattle production is a major source of income for many farmers in the Cerrado region (Klink and Moreira, 2002; Diniz-Filho et al., 2009). However, poor herd management, overgrazing, and lack of adequate nutrient replacement to the soil have led to declining productivity and reduced profitability of the system (Landers, 2007).

There have been many challenges to developing sustainable agricultural systems in the Cerrados, chief among them the soil constraints. Natural low soil fertility and aluminum toxicity limit root development and mineral nutrition. Further, limited root systems turn plants more susceptible to short drought periods during the summer wet season. Liming and organic matter incorporation were key input to alleviate aluminum saturation, raise water retention capacity, stabilize soil aggregates, and increase soil macro biota activity. Research also advanced in developing new varieties adapted to these environmental characteristics. These varieties typically possess deep root systems, have high tolerance to aluminum toxicity, respond well to fertilization, are adapted to mechanization; besides having high resistance to insect pests, diseases, and hydric stress.

In recent years the increasing demand for ethanol biofuel resulted in leasing land for sugarcane production being more profitable than raising beef cattle or even growing crops such as soybean and maize (Koh, 2007; Koh and Ghazoul, 2008). Although profitable in the short term this monoculture brings with it risks such as increasing incidence of pests and diseases, degradation of soil and natural resources, and declining yields. It also exposes farmers to dependence on a single income source: the ethanol processing plant.

With those technological advancements, the region became the principal growing agricultural pole. Today Cerrado agriculture broadly employs modern technologies, and system productivity continues to climb.

Agriculture and livestock production in the Cerrado region generates 42% of the agribusiness share of GDP in Brazil. Currently agribusiness contributes about 30% of the country's GDP, employs around 40% of the economically active population, and accounts for a large portion of the country's balance of trade surplus. One third of the country's grain production (soybeans, maize, sorghum, rice, wheat, coffee, etc.), half of the meat and most of the cotton output come from the Cerrados. A big share of that production is for export.

Nonetheless, managing agriculture in the Cerrado biome is an ongoing learning process. When the stabilizing effects of diversity were replaced by simple systems such as monoculture, destabilizing factors showed their destructive potential. Intensive cultivation without crop rotation resulted in low yields, due mainly to destabilization of soil physical quality, and pest and disease infestations.

According to Cunha et al. (2008), soil degradation is the main ambient threat to sustainability of agriculture in the Cerrado region. A large portion of the soils is compacted and susceptible to erosion when facing strong rainfall. Under these conditions, traditional techniques such as contour planting may be inadequate.

This challenge led to the adoption of no-till systems, which increased soil cover and brought additional environmental benefits. In the early 1990s, the area under no till in the Brazilian Cerrado represented just 9% of the total; by the 1995/96 cropping season that percentage rose to 33%. In the same period, the total no-till area in Brazil grew 3.5 times, but in the Cerrados it increased 17 times (Marouelli, 2003).

In spite of huge advances in productivity of agriculture and our understanding of the environmental risks, Brazil has a long way to go to transform the Cerrados into a biome that will sustainably support crop, animal, and forest production, with acceptable levels of profit to producers and safe, economic food supplies for urban consumers. Research on eco-efficient systems will drive that transformation.

The Ministry of Agriculture, Livestock and Food Supply is promoting low-carbon agriculture as a means of reducing agricultural emissions of greenhouse gases, especially carbon dioxide (CO_2). Besides offering financial support for farmers, the government promotes agricultural research through the Brazilian Agricultural Research Corporation (Embrapa), and provides professional training to facilitate the diffusion of modern practices such as no till, use of biological nitrogen fixation, and technologies to revive degraded pastures.

It is also promoting the Crop–Livestock–Forestry Integration System (CLFIS). CLFIS combines cropping, livestock, and forestry activities through approaches such as crop rotation, succession, double cropping, and intercropping, searching for synergistic effects among the components of the agroecosystems. One approach is to grow commercial crops such as soybeans, maize, or beans between rows of forest trees for the first 2 or 3 years after the trees have been planted. Thereafter, the area is planted with forages for livestock, in association with maize or sorghum. Once the pasture is established between the tree rows, it is grazed by livestock until the trees are ready for harvest. This diversification of economic activities minimizes the impact of climate or market changes on farm income.

Integration of the system components minimizes use of agrochemicals, reduces the opening of new areas for crop or livestock production, and reduces environmental impacts, increasing biodiversity, reducing soil erosion, and improving soil structure and fertility, particularly in combination with conservation agriculture practices such as zero-tillage (Vilrla et al., 2003; Landers, 2007).

Integrated crop, livestock, and forestry systems show particular promise in increasing the eco-efficiency of agricultural production (Wilkins, 2008), i.e., maximizing production while minimizing inputs such as land, water, nutrients, and energy (Keating et al., 2010).

Integrating Crops, Livestock, and Forestry through CLFIS

Overview

CLFIS is focused in the so called "green agriculture". This system combines cropping, livestock, and forestry activities to promote the recovery of degraded pastures. Each farm will have a varied production system, such as grains, fibers, meat, and milk and agro-energy. It also aims to improve soil fertility with the use of adequate cropping systems and techniques to optimize and intensify its use. Therefore, it allows the diversification of economic activities on farm, and minimizes income risks due to climate and/or market changes. The system consists in growing forest species simultaneously with commercial crops like soybeans, maize, or beans added for the first 2 or 3 years. After crop harvest, the area is planted with forages for livestock, associated with maize or sorghum. After grain harvesting, the pasture is already established between the tree rows, enabling grazing, until wood is harvested.

Integration of different system components minimizes use of agrochemicals, reduces the opening of new areas for crop-livestock, and prevents environmental liabilities. It enables increases in biodiversity, and allows a better control of erosion through soil coverage. Integration, together with soil conservation practices such as no till, is an economic and sustainable alternative to raise yields in degraded areas. Other attributes of CLFIS are related to environmental compliance of the farm, maintenance and/or recovery of permanent preservation areas, and of 'legal reserves' (percentage of a forested property that needs to be set aside). The introduction of new technologies is aimed at eco-efficiency—minimizing environmental impact while improving production and profitability.

A major challenge facing CLFIS is its dissemination and incorporation into the production chain and extension of benefits at the national level. It is necessary to invest in training, as well as to publish results for widespread knowledge dissemination.

CLFIS should be: (1) technically efficient, using adequate management and inputs, and taking into account local conditions of the farms; (2) economically viable with a better use of land and other natural resources; (3) diversified; (4) socially acceptable, i.e., adaptable to any farm size, providing more consistent and higher income and improved agricultural competitiveness; and (5) environmentally fit through the use of soil conservation practices, and better land use.

Enhancing eco-efficiency

Intensification of production should not be synonymous for indiscriminate use of inputs; it should mean rational and efficient use of technologies to maximize profits, using natural resources rationally. For a certain level of production, resources (land, water, inputs) should be used with a minimal impact on the environment without sacrificing the bio-economic productive potential of the cropping-livestock activity. The efficient use of nutrients, agrochemicals, and energy along with the reduction of greenhouse gas (GHG) emission are key factors to enhance eco-efficiency of the system.

A feasible alternative to effectively implement the CLFIS can be a partnership between grain producers and ranchers. Farmers who use sorghum and maize intercropped with *Brachiaria* spp. to obtain crop residues for no-till soil preparation could harvest that forage collected in the off season. To minimize capital costs in the purchase of animals, those farmers could establish partnerships with ranchers. Harvested grain residues could be used as feed supplement during the dry season, either in grazing or in confinement, besides using the forage obtained in the intercropping system.

A common problem of intercropping forages and grains is competition for water and nutrients. Losses in crop yield and failures in pasture establishment may occur. There are alternatives to minimize that competition, such as delayed sowing of the pasture component and use of low doses of herbicides, as well as plant arrangement, to minimize the competition of the forage with the grain crop (Kluthcouski et al., 2003).

Farms adopting the CLFIS may benefit from a better stability of forage production to feed the herd year around. During the wet season, pastures are more productive due to the higher soil fertility developed during the crop phase. During the dry season, crop residues and harvest byproducts, as well as the newly green established pastures are in adequate amounts and of good quality to provide weight gains. Weight loss is very common in the dry season on most farms of the Cerrado region.

Good soil and ecosystems management practices are potentially capable of mitigating greenhouse anthropogenic gas emissions. In this sense the Cerrado region is capable of playing an important role in the carbon cycle equilibrium (see also Chapter 11 of this volume).

A Case Study of CLFIS

Study area and experimental design

Faced with this scenario, farmers are seeking alternative production systems that maximize the economic productivity of their land while minimizing risks. One such alternative is integrated crop, livestock, and forest production. This section presents a case study that evaluates and compares three different spatial arrangements of crops, livestock, and forestry.

The study was located at Boa Vereda Farm, Cachoeira Dourada County, in the south of the State of Goiás (latitude 18°29'30", longitude 49°28'30") and average altitude of 459 m. The climate is typical of the tropical savanna type (Aw, according to Köppen classification), with well-defined wet and dry seasons. Annual average temperature is 24 °C, with an average annual rainfall of 1,340 mm, distributed from October to March. Soils are classified as dark red latosol, highly weathered, with low natural fertility.

Much of Boa Vereda Farm consists of degraded pastures with low carrying capacity that are used to raise beef cattle. Income from livestock sales has been insufficient to invest in reclaiming the pastures.

CLFIS demonstration plots were established on 17 ha in the 2008/09 cropping season and a further 27 ha in the 2009/10 cropping season. The land was cultivated twice using a disc harrow to incorporate lime and was then leveled, again using a disk harrow. Fertilizer was applied according to recommendations based on soil analyses. Weeds were controlled using herbicide and hoeing between tree rows up to the 12th month after planting. Pests were controlled using integrated pest management.

In the establishment year (year 0), eucalyptus was planted in rows, and soybean was planted in the plots between the tree stands. In the following year (year 1), plots were sown with a maize/*Brachiaria* grass intercrop, in accordance with the Santa Fe System (Kluthcouski et al., 2003). Cattle were introduced to the pasture 70 days after the maize was harvested. At this time (18 months after the plots were established), the eucalyptus was about 6 m tall with trunks 10 cm in diameter at chest height, allowing the entry of cattle without risk of damage to the trees. From this point on, the pasture was used for animal husbandry, particularly fattening beef cattle, until the eucalyptus was cut, which in this study was modeled as being between the fourth and the sixth year after planting.

Three different planting arrangements were tested. Scenario 1 consisted of three rows of eucalyptus (stands), with 3 m between rows and 3 m between plants; the stands were spaced 14 m apart to allow for crops and pasture to be established between them. Thus, 62.5% of the land under scenario 1 was allocated to crop/pasture and 37.5% to forest, with a tree density of 500 trees/ha. Scenario 2 consisted of four rows of eucalyptus spaced 3 m between rows and 3 m between trees, with 22 m between stands, giving 68% of the land allocated to crop/livestock and 32% to forest and a tree density of 430 trees/ha. Scenario 3 consisted of single rows of eucalyptus, with 1.5 m between trees within the row and 14 m between rows, giving 89% of the area allocated to crops/livestock and 11% to forest, with 476 trees/ha.

The soybean cultivar used was BRS-GO 8360; maize cultivars were BRS 1030 and BRS 1035; and for the pasture *Brachiaria brizantha* cultivar

'Marandu' was used. Six clones of the *Eucalyptus urograndis* were used. Eucalyptus yield was estimated based on tree development in November 2010.

The crossbred cattle used in the trial weighed an average of 242 kg when introduced to the plots. Supplementary concentrate feed was provided at a rate of 250 g/head per day in the dry season and 350 g/head per day in the wet season. Average carrying capacity was estimated at 2.1 animals/ha. With adequate management and fertilization, this stocking rate was assumed to be maintained until the eucalyptus was cut and the system reestablished.

Prices for calves were set 10% higher than the price paid for adult animals, because the market pays more for young animals.

The cost for pasture maintenance was based on the price paid locally for pasture rental (R$10.00/head per month; approximately US$18.40, February 2010 exchange rate). Other livestock production costs were purchase of supplementary feed and R$3.00/head per month for vaccines, labor, and veterinary supplies.

Production costs were calculated up to harvest, including freight from the farm to the store.

The opportunity cost for land was set at the value of ten 60 kg bags of soybean per hectare (US$168.48/ha), equal to the price paid by ethanol processing plants to lease land for sugarcane production.

Data on farm operations and prices were collected in 2008/09 and 2009/10 cropping seasons from farmers and companies associated with agriculture. Net present value (NPV), internal rate of return (IRR), and equivalent uniform annual net value (NUV) were calculated using an interest rate of 5.75%, the rate applied by banks run by the federal government.

Results and conclusions

Production costs for scenario 1 are shown in Tables 4-1, 4-2, and 4-3, while Table 4-4 shows the yields achieved in all three scenarios.

Table 4-1. Production costs in the establishment year (year 0) for one hectare of eucalyptus intercropped with soybean (scenario 1).[a]

Specification	Unit	Amount	Value (US$)		OEC*
			Unit value	Total	(%)
Soybean					
Inputs					
Lime	t	1.25	37.50	46.88	4.47
Fertilizer NPK(02-20-20)+(0.3 B+0.5 Zn)	t	0.25	527.17	131.79	12.56
Seeds BRS-GO 8360	kg	31.00	1.03	32.27	3.08
Inoculants	liter	0.25	4.18	1.05	0.10
Seed treatment	liter	0.06	206.52	12.91	1.23
Formicide	g	6.30	0.54	3.40	0.32
Pre-emergence herbicide	kg	0.02	592.17	13.32	1.27
Pre-emergence herbicide	liter	0.50	25.22	12.61	1.20
Postemergence herbicide	liter	0.25	32.61	8.15	0.78
Mineral oil – 3 applications	liter	1.88	3.26	6.11	0.58
Fungicide – 3 applications	liter	0.56	86.41	48.61	4.63
Insecticide	liter	0.16	29.35	4.59	0.44
Insecticide – 2 applications	liter	1.88	6.25	11.72	1.12
Subtotal inputs soybean				333.40	31.78

(Continued)

Table 4-1. (Continued).

Specification	Unit	Amount	Value (US$)		OEC*
			Unit value	Total	(%)
Labor					
Lime distribution	ha	0.63	13.32	8.32	0.79
Lime incorp. (heavy disc harrow × 2)	ha	0.63	95.65	59.78	5.70
Soil preparation (leveling × 2)	ha	0.63	71.74	44.84	4.27
Formicide application	day	0.16	21.74	3.40	0.32
Sowing	ha	0.63	27.17	16.98	1.62
Pre-emergence herbicide application	ha	0.63	4.18	2.62	0.25
Postemergence herbicide application	ha	0.63	4.18	2.62	0.25
Fungicide application (× 3)	ha	0.63	12.55	7.85	0.75
Insecticide application (× 3)	ha	0.63	12.55	7.85	0.75
Harvest (6% of income)	%	6.00	302.16	18.13	1.73
Freight (farm to storage house)	bag	33.00	0.33	10.76	1.03
Subtotal labor soybean				183.14	17.46
Soybean cost				516.54	49.24
Eucalyptus – establishment					
Inputs					
Lime	t	0.75	37.50	28.13	2.68
Fertilizer – NPK(06-30-06)+(0.3 B+0.5 Zn)	kg	75.00	0.41	30.57	2.91
Fertilizer – single super phosphate (SSP)	kg	100.00	0.23	23.37	2.23
Seedlings	thousand	0.50	206.52	103.26	9.84
Seedlings (replanting)	thousand	0.05	206.52	10.33	0.98
Formicide	g	3.80	0.54	2.04	0.19
Preemergence herbicide	g	15.00	0.54	8.15	0.78
Subtotal inputs eucalyptus				205.84	19.62
Labor					
Liming	ha	0.38	13.32	4.99	0.48
Lime incorp. (heavy disc harrow × 2)	ha	0.38	95.65	35.87	3.42
Soil preparation (leveling × 2)	ha	0.38	71.74	26.90	2.56
Formicide application	day	0.09	21.74	2.04	0.19
Pit preparation	ha	0.38	79.35	29.76	2.84
Planting	ha	0.38	32.61	12.23	1.17
Fertilizer application – NPK	ha	0.38	43.48	16.30	1.55
Fertilizer application – SSP	ha	0.38	76.09	28.53	2.72
Preemergence herbicide application	ha	0.38	4.18	1.57	0.15
Subtotal labor eucalyptus				158.19	15.08
Eucalyptus cost				364.04	34.70
Land opportunity cost				168.48	16.06
Total operational cost				1049.05	100.00

a. Scenario 1 consists of three rows of eucalyptus (stands), with 3 m between rows and 3 m between plants; the stands were spaced 14 m apart to allow for crops and pasture to be established between them.

* Operational effective costs.

Table 4-2. Production cost (year 1) of one hectare of eucalyptus intercropped with maize and *Brachiaria* grass (scenario 1).[a]

Specification	Unit	Amount	Value (US$)		OEC*
			Unit value	Total	(%)
Maize and *Brachiaria*					
Inputs					
Fertilizer – NPK(02-20-20)+(0.3 B+0.5 Zn)	t	0.19	527.17	98.85	15.62
Urea	t	0.13	516.30	64.54	10.20
Maize seed	kg	11.00	5.16	58.08	9.18
Brachiaria brizantha seed	kg	6.30	2.99	18.68	2.95
Pre-emergence herbicide	liter	0.06	28.26	1.77	0.28
Postemergence herbicide	liter	1.88	4.35	8.15	1.29
Mineral oil	liter	0.31	3.26	1.02	0.16
Insecticide	liter	0.38	38.04	14.27	2.26
Subtotal inputs				265.35	41.94
Labor					
Incorporation (heavy disc harrow × 1)	ha	0.63	47.83	29.89	4.72
Soil preparation (leveling × 1)	ha	0.63	35.87	22.42	3.54
Brachiaria sowing	ha	0.63	13.32	8.32	1.32
Maize sowing	ha	0.63	27.17	16.98	2.68
Top dressing	ha	0.63	13.32	8.32	1.32
Postemergence herbicide application	ha	0.63	4.18	2.62	0.41
Insecticide application (× 1)	ha	0.63	4.18	2.62	0.41
Harvest	%	5.00	277.06	13.85	2.19
Freight	bag	67.00	0.33	21.85	3.45
Subtotal labor				126.87	20.05
Maize cost				392.22	62.00
Eucalyptus – maintenance					
Inputs					
Fertilizer – single super phosphate (SSP)	kg	100.00	0.23	23.37	3.69
Fertilizer – boric acid	kg	10.00	1.30	13.04	2.06
Formicide	kg	0.015	543.48	8.15	1.29
Herbicide	liter	1.00	5.43	5.43	0.86
Subtotal inputs				50.00	7.90
Labor					
Fertilizer application	ha	0.38	43.48	16.30	2.58
Herbicide application	ha	0.38	4.18	1.57	0.25
Formicide application	day	0.19	21.74	4.08	0.64
Subtotal labor				21.95	3.47
Eucalyptus cost				71.95	11.37
Land opportunity cost				168.48	26.63
Total operational cost				632.65	100.00

a. Scenario 1 consists of three rows of eucalyptus (stands), with 3 m between rows and 3 m between plants; the stands were spaced 14 m apart to allow for crops and pasture to be established between them.

* Operational effective costs.

Table 4-3. Production cost (year 2) of one hectare of eucalyptus intercropped with pasture grazed by cattle (scenario 1).[a]

Specification	Unit	Amount	Value (US$)		OEC*
			Unit	Total	(%)
Livestock					
Animal purchase	head	3	306.52	919.57	57.90
Vaccine + labor + medicine	head	3	19.57	58.70	3.70
Feeding (dry season)	head	3	24.46	73.37	4.62
Feeding (wet season)	head	3	34.24	102.72	6.47
Pasture maintenance (leasing value)	head	3	65.22	195.65	12.32
Livestock cost				1350.00	85.00
Eucalyptus – maintenance					
Inputs					
Fertilizer – boric acid	kg	10.00	2.40	24.00	0.51
Formicide	kg	0.015	543.48	8.15	1.51
Subtotal inputs				32.15	2.02
Labor					
Fertilizer application	ha	0.38	80.00	30.00	0.48
Formicide application	day	0.35	21.74	7.61	1.89
Subtotal labor				37.61	2.37
Eucalyptus cost				69.76	4.39
Land opportunity cost				168.48	10.61
Total operational cost				1588.24	100.00

a. Scenario 1 consists of three rows of eucalyptus (stands), with 3 m between rows and 3 m between plants; the stands were spaced 14 m apart to allow for crops and pasture to be established between them.
* Operational effective costs.

Table 4-4. Prices and yields of soybean, maize, livestock, and eucalyptus used to calculate economic performance of integrated crop, livestock, and forestry system in Cachoeira Dourada County, Goiás, Brazil.[a]

Product	Unit	Price	Yield (unit/ha)		
		(US$/unit)	Scenario 1	Scenario 2	Scenario 3
Soybean	60 kg bag	16.85	33	34	47
Maize	60 kg bag	7.61	67	70	95
Livestock	kg live wt.	1.40	540	570	690
Eucalyptus	cubic meter	24.46	28	24	26

a. Scenario 1 consisted of three rows of eucalyptus (stands), with 3 m between rows and 3 m between plants; the stands were spaced 14 m apart to allow for crops and pasture to be established between them. Scenario 2 consisted of four rows of eucalyptus spaced 3 m between rows and 3 m between trees, with 22 m between stands. Scenario 3 consisted of single rows of eucalyptus, with 1.5 m between trees within the row and 14 m between rows.

Table 4-5 shows cash flow for scenario 1, including the value of lumber for energy from the trees cut in the sixth year. In years 1 and 2 the annual cash flow balance was negative: costs exceeded income due to the high cost of establishing the eucalyptus. From year 3 onwards cash flow was positive as a result of income from the cattle and low maintenance costs for the eucalyptus.

Scenario 3, with one row of eucalyptus with 14 m between rows and 1.5 m between trees,

Table 4-5. Cash flow per hectare for integrated crop, livestock, and forestry production in Cachoeira Dourada County, Goiás, Brazil, under scenario 1.[a]

Year	Costs (US$)[b]	Income (US$)	Net income (US$)
0	1049.05	555.98	-493.07
1	632.65	509.78	-122.87
2	1588.24	1672.83	84.59
3	1588.24	1672.83	84.59
4	1588.24	1672.83	84.59
5	1588.24	1672.83	84.59
6	1588.24	5781.52	4193.28

a. Scenario 1 consisted of three rows of eucalyptus (stands), with 3 m between rows and 3 m between plants; the stands were spaced 14 m apart to allow for crops and pasture to be established between them.
b. February 2010 prices and exchange rate.

gave the best economic performance (Table 4-6), with the highest NUV being achieved if the trees were harvested in year 5. In scenarios 1 and 2, NUV was highest when the trees were harvested in year 6.

These findings are in keeping with reports of similar studies elsewhere in Brazil (Dube et al., 2002; Yamada and Gholz, 2002), and demonstrate that integrated crop, livestock, and forestry systems are economically and technically feasible in the Cerrado. The system is flexible enough to be adapted to meet local environmental, social, and economic circumstances, and offers the prospect of sustainable, eco-efficient agricultural production.

Much of the Cerrado is underutilized or degraded, and integrated crop, livestock, and forestry production offers an opportunity for raising productivity without harming the environment. In addition to producing food of high biological value (meat and milk), cultivated pasture provides other important environmental benefits, including long-term ground cover, which reduces erosion and promotes water infiltration; carbon fixation; increases in the soil organic matter content; and reduction in the emission of greenhouse gases.

Table 4-6. Net present value (NPV), internal rate of return (IRR), and equivalent uniform annual net value (NUV) per hectare for integrated crop, livestock, and forestry production in Cachoeira Dourada County, Goiás, Brazil, as affected by the age at which eucalyptus was harvested.

	NPV (US$)	IRR (%)	NUV (US$)
Scenario 1[a]			
Year 4	1,710.04	53	502.01
Year 5	2,131.67	48	516.42
Year 6	2,495.40	44	519.49
Scenario 2[b]			
Year 4	1,498.58	52	439.93
Year 5	1,882.57	48	456.07
Year 6	2,215.49	44	461.22
Scenario 3[c]			
Year 4	1,911.47	75	561.14
Year 5	2,337.33	66	566.24
Year 6	2,707.26	60	563.60

a. Scenario 1 consisted of three rows of eucalyptus (stands), with 3 m between rows and 3 m between plants; the stands were spaced 14 m apart to allow for crops and pasture to be established between them.
b. Scenario 2 consisted of four rows of eucalyptus spaced 3 m between rows and 3 m between trees, with 22 m between stands.
c. Scenario 3 consisted of single rows of eucalyptus, with 1.5 m between trees within the row and 14 m between rows.

In the search to produce more food and energy within the constraints of available water, land, and other inputs; eco-efficient, climate-smart systems like integrated crop, livestock, and forestry systems have a vital role to play.

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CHAPTER

5

Intensive Cereal–Legume–Livestock Systems in West African Dry Savannas

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Contents

Abstract

The dry savannas of West Africa are undergoing rapid transformation of agricultural practices owing to the rapid human and livestock population growth, increase in agricultural intensification and accelerated climate change which has increased the incidence and severity of diseases, pests and drought. The major constraints to agricultural production in the savanna include poor soil fertility, pests and diseases of crops and livestock, parasitic weeds such as *Striga hermonthica*, drought, and competition between crops and livestock for resources. Inadequate policies, weak institutional mechanisms, and poor linkages among farmers, and researchers prevent adoption of improved agricultural technologies that can combat these constraints. The risk of continuous cultivation on these poor and fragile soils is huge. Integrating crop and livestock production offers ways to increase production while protecting the environment. Over the years, research and development institutions have generated several agricultural technologies to alleviate the majority of the production constraints in the West African savannas. However, most development organizations use traditional extension methods that result in poor adoption of the improved technologies. The integration of crop and livestock production is particularly desirable in intensively farmed and densely populated areas with access to urban markets. Proper integration of these practices will diversify smallholder income and increase food security. Integrated genetic and natural resource management provides the keys to improved eco-efficiency. This includes integrating pesticide use with cultural practices such as modified planting date and disease control; rotating/intercropping cereals and legumes; use of pest resistant\tolerant cultivars to increase the effectiveness of pest control and reduce the need for pesticides; and improving soil fertility restoration/maintenance. Government and national institutions in West Africa are encouraged to scale out these technologies to wider areas for increased benefit to farmers through the use of proven extension methods.

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Introduction

The lowland savannas of West Africa are characterized by elevation of less than 800 m, a growing period sufficient for most cereal and grain-legume crops, and a relatively high potential for livestock production. Agricultural production systems are intensifying across the region in response to increases in population pressure, demand, and opportunities for product marketing. In the dry savanna, defined as the area with a growing period of between 4 and 6 months, cereal and legume cropping systems are being intensified and traditional crops—sorghum [*Sorghum bicolor* (L.) Moench subsp. *Bicolor*], finger millet [*Eleusine coracana* (L.) Gaertn.], cowpea [*Vigna unguiculata* (L.) Walp.], and groundnut (*Arachis hypogaea* L.)—are being replaced by new crops such as maize (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] (Sanginga et al., 2003). Throughout the Guinea and dry savannas of West Africa, farmers increasingly combine crop farming with livestock production (Tiffen, 2004). The integration of crop and livestock production is particularly noted in intensively farmed and densely populated areas with access to urban markets (Franke et al., 2010).

Alongside the increase in cropping intensity, livestock numbers are also increasing in response to an increased demand for meat, milk, and other products. Delgado et al. (2001) estimated that demand for animal products in sub-Saharan Africa would increase by more than 250% between 2001 and 2020, with much of the increase being in West Africa. Intensification of crop–livestock systems in the region has resulted in shorter fallows than in traditional farming systems, and fallow periods are becoming too short to restore soil fertility and reduce pest pressure. Consequently, cropping and grazing have expanded onto marginal lands, increasing competition between cropping and livestock production and increasing demand for crop residues as livestock feed.

Addressing Major Constraints to Agricultural Production in the Dry Savanna

The major constraints to agricultural production in the savanna include poor soil fertility (including low soil organic matter (SOM) content in intensified cropping systems), pests and diseases of crops and livestock, parasitic weeds such as *Striga hermonthica* (Delile) Benth. (purple witchweed), drought, and competition between crops and livestock for resources. Inadequate policies, weak institutional mechanisms, and poor linkages among farmers, development agencies, and researchers prevent adoption of improved agricultural technologies that can combat these constraints. Most development organizations use traditional extension methods that result in poor adoption of improved technologies.

Poor soil fertility

Crop production in the West African dry savanna is limited by the inherently low fertility of most of the soils. In the past, farmers depended on fallow periods to restore soil fertility, but current fallow periods are not long enough to replace exported nutrients (Bado et al., 2012). Stoorvogel et al. (1993) estimated annual nutrient loss from sub-Saharan African soils is at 22 kg N, 2.5 kg P, and 15 kg K/ha in 1982–84, and 26 kg N, 3 kg P, and 19 kg K/ha in 2000. This underscores the extent of nutrient mining and the need to mobilize strategies to conserve soil fertility.

SOM plays an important role in sustaining soil fertility by contributing to several soil properties, including cation exchange capacity, water-holding capacity, buffer capacity, and soil structure. Higher levels of SOM could also raise the efficiency with which mineral fertilizer is used by plants. However, SOM is very low in most savanna soils, averaging 6.8 g/kg (Jones, 1973), compared with 20–100 g/kg for most soils (Bot and Benites, 2005). Increasing SOM contents is therefore considered a prerequisite for increased crop production in the savanna. This can be achieved by growing crop varieties that produce large amounts of above-ground biomass, incorporating residues in the soil where the crop was grown, concentrating plant residues on a limited cropped area, and corralling livestock on crop fields so that they deposit urine and manure on the cropland (Bationo and Mokwunye, 1991; Powell et al., 2004; Valbuena et al., 2012).

Nitrogen (N) is the most limiting nutrient in soil. In the savannas, considerable amounts of soil-available N are released with the onset of rains but its uptake by crops is insignificant due to the low N requirements of plants at early growth stages (Kamara et al., 2005). As a result, much of this N is lost through leaching. Phosphorus (P) is the second most limiting nutrient in the savanna soils of West Africa, and in some areas, plant-available P may be as low as 2 mg P/kg (Bray 1) (equivalent to approximately 4 kg P/ha) (Kwari et al., 1999). Most of these savanna soils also contain large amounts of iron and aluminum oxides, which contribute to the removal of P from the soil solution. Because P is not a renewable resource, the soil P pools can be replenished only through external P inputs. In addition, the acidity that is generated through crop removal and leaching can lead to the loss of calcium (Ca), magnesium, and potassium (K), and toxic levels of soluble manganese and aluminum.

Although mineral fertilizers can be used to replace nutrient losses, socio-economic constraints such as high prices and lack of credit limit their use. Smallholder farmers commonly apply too little fertilizer, either because they cannot afford more or because fertilizers are not readily available. Moreover, most fertilizers applied contain N, P, and K, albeit in inadequate quantities. Applying these fertilizers initially increases yields, but this accelerates depletion of other soil nutrients such as sulfur, copper, and zinc, ultimately reducing response to NPK fertilizer and reducing crop productivity (Kwari et al., 2009). Thus, both mineral fertilizers and organic inputs are required to improve soil fertility (Vanlauwe et al., 2002; Powell et al., 2004).

Other problems include physical deterioration of soils, such as crusting (Oldeman, 1994), which reduces water infiltration, increases runoff, reduces oxygen diffusion to seedlings, inhibits plant growth, and reduces soil biological activity, and the breakdown of soil aggregates, which increases soil erosion. There is thus a great challenge to protect and manage land and soil resources to maintain their productivity and to contribute to food security.

Increased use of organic and inorganic fertilizers, together with diversification of cropping to include legumes are important tools in restoring or sustaining soil fertility of the intensifying cropping systems of the dry savannas of West Africa (Vanlauwe et al., 2001; Sanginga et al., 2003; Franke et al., 2004). These so-called “balanced nutrient management systems” can be further enhanced through the use of improved cultivars that are drought tolerant and use available nutrients efficiently, such as maize cultivars developed at the International Institute of Tropical Agriculture (IITA), Nigeria (Kamara et al., 2005). This approach has come to be known as integrated soil fertility management (ISFM). ISFM is not characterized by unique field practices, but is rather a fresh approach to combining available technologies in ways that preserve soil quality while promoting its productivity (Sanginga and Woomer, 2009).

Pests and diseases

Plants

Insect pests are a major constraint to legume production, particularly cowpea in the dry savannas of West Africa (ICIPE, 1980; Singh and Allen, 1980; Singh et al., 1990; Rusoke and Rubaihayo, 1994). Indeed, Jackai et al. (1985) assert that it is not feasible to grow cowpea commercially in the West African savanna without using insecticide. In a recent study, Kamara et al. (2007) reported that flower thrips [*Megalurothrips sjostedti* (Trybom)], the legume pod borer (*Maruca vitrata*), and a range of pod-feeding bugs were the major insect pests of cowpea in the dry savannas of West Africa. Thrips start to attack at flower initiation, causing flower bud abortion (Akingbohungbe, 1982). Pod borer larvae damage flower buds, flowers, green pods, and seeds (Singh and Jackai, 1985). Adults and nymphs of pod bugs remove sap from green pods, causing abnormal pod and seed formation (Singh and Jackai, 1985). High levels of insect resistance are not available in current cultivars (Oghiakhe et al., 1995), hence integrated insect pest management is key to successful cowpea production (Ajeigbe and Singh, 2006; Kamara et al., 2010).

The most important diseases of cowpea in the dry savannas of West Africa are bacterial blight (*Xanthomonas* sp.), leaf spot (*Septoria* spp.), and scab (*Sphaceloma* sp.) (Emechebe and Florini, 1997; Hampton et al., 1997).

In West Africa, groundnut yields are traditionally low, due to several constraints including pests and diseases. Aphids (*Aphis craccivora*) are a serious pest as well as a vector of virus diseases, such as the rosette, a major constraint to groundnut production, particularly in the dry regions. Groundnut rosette disease (GRD), early leaf spot (ELS), late leaf spot (LLS), and rust are the major biotic constraints responsible for low yield of groundnut in West Africa (Ntare et al., 2008). Groundnut rosette is one of the most important diseases that wiped out more than half of the groundnut cropped area in Nigeria in the mid 1970s. From 1992, ICRISAT and national partners in Nigeria embarked on a large hybridization program to develop early maturing rosette-resistant varieties that would fit into the Sudano-Sahelina savanna zones of Nigeria. From this program, a total of 44 new varieties with resistance to groundnut rosette were tested (Mayeux et al., 2003). Three varieties SAMNUT 21, SAMNUT 22, and ICGV-IS 96894 (SAMNUT 23) were formally released in 2001 and ICIAR 19BT (SAMNUT 24) was released in 2011.

Infection by *Aspergillus flavus* on groundnut (and its products) is the main food safety concern. Aflatoxin contamination causes cancer to humans and animals and has thus adversely affected international trade in groundnuts in many producing countries (Ntare et al., 2008). Resistant cultivars provide the most appropriate means of control of diseases, especially for smallholder farmers. Therefore, development of rosette-and/or ELS resistant, high-yielding groundnut varieties with appropriate duration is important to enhance and stabilize productivity. Early planting and dense close spacing are effective cultural practices. Early planting allows plants to start flowering before aphids appear. Dense planting provides a barrier to aphids penetrating in from field edges, discourages population build-up of aphids and reduces incidence of "rosette" disease. Other diseases of groundnut include: bacterial wilt (*Ralstonia solanacearum*) and damping-off diseases (*Pythium spp*., *Rhizoctonia solani*). In some locations, termites are serious field and storage pests. Species of *Microtermes* and *Odontotermes* are the most damaging, while *Macrotermes* cause occasional damage. The small-sized *Microtermes* spp., in particular, attack and invade growing groundnut plants through the roots and stem near ground level, hollowing them out and causing the plants to wilt and die with a consequent reduction in crop stand. Stored groundnuts are attacked by moths (*Ephestia cautella, Plodia interpunctella*, *Cadra cautella*), and beetles (*Caryedon serratus, Tribolium castaneum, Trogoderma granarium*). The larvae of moths and the grubs and adult beetles bore into and damage seeds. Moths cause extensive webbing. The bruchid beetle *Caryedon serratus* is the major pest of groundnut in pod shell in West Africa. A good postharvest pest management program based on good storage practices is very important.

Insect pests constitute an important factor limiting grain sorghum production in West Africa. Several species of insect pests attack sorghum at the different stages of its development. Several lepidopterous stem borers inflict considerable losses in sorghum. Intercropping cereals with legumes has shown to reduce stem borer attack and damage in sorghum (Amoako-Atta et al., 1983; Ampong-Nyarko et al., 1994) and has been recommended as a component of integrated pest management for small-scale resource limited farmers. Insect pests attacking panicles of sorghum and millet are especially damaging as they affect crop development at a late stage and have direct harmful quantitative and qualitative effects on grain yields. At this late stage of crop development, the main production inputs would have already been made, which maximizes economic losses and there is also little scope for the crop to compensate for damage done close to harvest. Sorghum midge (*Contarinia sorghicola*) is the most wide spread and damaging insect species attacking sorghum. It occurs almost everywhere that the crop is grown. Sharma (1993) reported that substantial progress has been made in utilizing resistance to midge. Millet head miner (*Heliocheilus albipunctella)* is the most important pest in West Africa. Nwanze and Sivakumar (1990) reported crop losses on farmers fields up to 41% with a mean of 20% based on field surveys in Burkina Faso, Niger, and northern Nigeria. Other important insect pests include shoot fly and aphids.

Several fungi and viral diseases also attack sorghum and millet crops in West Africa. Grain mold caused by several fungal pathogens can reduce grain quality or destroy seeds. Stem rot and leaf diseases caused by an array of fungal and bacterial diseases cause spots or stripes on leaves which can result in death of the leaf (House, 1987). Downy mildew (DM) caused by an obligate parasite *Sclerospora graminicola* is quite widespread and economically the most important disease of pearl millet (*Pennisetum glaucum*) in India and several countries in Africa (Thakur et al., 2008). Severely infected plants are generally stunted and do not produce ear heads. Resistant varieties and other cultural practices are the most important control measures under smallholder farming systems of West Africa.

The major insect pest problems on maize in the West African savannas are the stem borers, (*Busseola fusca* and *Sesemia calamistis*); and army worms (*Spodoptera exempta* and *Helicoverpa armigera*). The stem borer attack is usually more serious in late-maturing maize than the early cultivars. They cause two types of damage to the plants. First is mechanical damage due to consistent feeding in the stem, weakening it, and thus rendering the stems susceptible to lodging and withering (dead-heart). Secondly, stem borers may cause characteristic perforations or windows on leaves called ‘fenestrations’ seen when the sheath opens, exposing the perforations (Bosque-Pérez and Schulthess, 1998). This type of damage reduces the photosynthetic area of the leaves resulting in poor cereal yield, especially during high infestation.

In a survey for incidence and severity of diseases in both the northern and southern Guinea savannas of Nigeria, Adeoti (1992) reported the occurrence of common foliar diseases such as the rust induced by *Puccinia* spp, *Turcicum* blight, *Curvularia* leaf spot, and *Maydis* blight. Other important maize diseases occurring in the savanna ecological zones include smut (*Ustilago maydis*), downy mildews, maize leaf fleck, and maize streak.

Integrated pest management—integrating biological control, cultural practices such as modified planting date, disease- and pest-tolerant cultivars, and pesticides where necessary—can increase the effectiveness of pest control and reduce overuse of pesticides. Manipulation of planting date with a judicious use of insecticides has been found to be profitable (Kamara et al., 2010). Efforts are being made to develop biological control methods to control insect pests (e.g., Wajnberg et al., 2001; Neuenschwander et al., 2003; van Driesche et al., 2008). However, further efforts are needed to develop crop cultivars that are resistant to or tolerant of the major pests and diseases of the West African savannas in order to promote sustainable, eco-efficient agriculture in the region.

Animals

The major pests and diseases affecting livestock in the West African savanna region include anthrax, black leg, contagious bovine and caprine pleuropneumonias, dermatophilosis, ectoparasites, gastrointestinal parasites, heartwater, liverfluke, respiratory complexes, and trypanosomiasis (Perry et al., 2002). High prevalence of diseases and parasites causes high mortality in sheep and goats, especially in kids and lambs. Preweaning mortality of up to 40% has been recorded with kids and lambs in Nigeria, but levels may be higher under extensive systems (Ademosun, 1994). Parasites may aggravate other conditions, such as nutritional stress, and increase susceptibility to disease, especially in young animals.

Livestock health can be improved in smallholder systems by application of simple, low-cost, and well-proven techniques. These include control of pests, parasites, and diseases using traditional or modern veterinary medicines or husbandry practices (see, for example, Okoli et al., 2010), tolerant breeds of livestock, improved feeding, and hygienic housing and handling facilities. The improvements in productivity achieved by implementing such approaches can be dramatic. Van Vlaenderen (1985; 1989), for example, demonstrated increases in ewe productivity of nearly 300% (from 7.2 kg lamb/ewe per year to 28.7 kg lamb/ewe per year) through improved flock management, simple health control, mineral supplementation, and strategic supplementation at the end of the rainy season. However, encouraging widespread adoption of these improved husbandry practices will require investment in policies, markets, and extension services (McDermott et al., 2010).

Parasitic weeds

Parasitic flowering plants (*Striga* and *Alectra* spp.) pose a serious threat to cereal and legume production in the dry savannas. It is estimated that 40 million hectares of land are severely infested by *Striga* spp., while nearly 70 million hectares have moderate levels of infestation (Lagoke et al., 1991).

Striga hermonthica (Delile) Benth. (purple witchweed) is one of the most severe constraints to cereal production in the dry savannas of West Africa (Oswald and Ransom, 2004), attacking millet, sorghum, maize, and upland rice (*Oryza sativa* L.) (Kim et al., 1997; Showemimo et al., 2002). In northeast Nigeria, over 85% of fields planted to maize and sorghum were infested with purple witchweed (Dugje et al., 2006). *Striga* infestation can result in total loss of the crop (Lagoke et al., 1991; Oikeh et al., 1996) and may force farmers to abandon their cereal fields. The increasing incidence of *Striga* has been attributed to poor soil fertility and structure, intensification of land use through continuous cultivation and an expansion of cereal production (Vogt et al., 1991; Rodenburg et al., 2005; van Ast et al., 2005).

Striga gesnerioides (Willd.) Vatke (cowpea witchweed) and *Alectra vogelii* (Benth.) (yellow witchweed) cause substantial yield reduction in cowpea in the dry savannas of sub-Saharan Africa (Emechebe et al., 1991). In a survey of 153 cowpea fields in six countries in West Africa, 40% were found to be infested with *Striga* (Cardwell and Lane, 1995), while in northeast Nigeria, where cowpea is the most important cash crop, Dugje et al. (2006) found 81% of cowpea fields surveyed to be infested with *Striga*, leading to serious crop losses. Cowpea yield losses associated with cowpea witchweed has been reported to range between 83 to 100% (Emechebe et al., 1991; Cardwell and Lane, 1995). Both parasites are difficult to control because they produce large numbers of seeds and up to 75% of the crop damage is done before they emerge from the ground.

The abandonment of long-term fallows as a result of increasing cropping intensity has removed one of the key traditional practices used to control parasitic weeds. The primary approaches to management of parasitic weeds now available are the use of tolerant or resistant cultivars, and agronomic practices such as crop rotation.

Striga damage in cereal crops can be reduced by growing varieties of maize (*Zea mays*), sorghum (*Sorghum bicolor*), and pearl millet (*Pennisetum glaucum*) that are tolerant of or resistant to *Striga* or by planting trap crops such as varieties of groundnut (*Arachis hypogaea*), soybean (*Glycine max*), cowpea (*Vigna unguiculata*), and sesame (*Sesamum indicum*) that stimulate *Striga* seed to germinate without providing a viable host (Carsky et al., 2000). Some studies have shown that applying N fertilizer reduces *Striga* emergence and population and boosts cereal grain yield (Kim et al., 1997; Showemimo et al., 2002; Oswald and Ransom, 2004; Kamara et al., 2009). Applying N fertilizer may not be feasible as a stand-alone solution to managing purple witchweed in cereals because of the high cost of fertilizer, but the combined use of N fertilizer and *Striga*-tolerant/resistant maize and sorghum varieties has shown promise in the West African savannas (Showemimo et al., 2002; Kamara et al., 2009). In addition, farmers have developed a range of coping strategies including hand-roguing, application of inorganic fertilizer, manures and composts, and crop rotations (Emechebe et al., 2004).

However, control is most effective if a range of practices are combined into a program of integrated *Striga* control (ISC) that can provide sustainable control over a wide range of biophysical and socio-economic environments (Berner et al., 1997; Ellis-Jones et al., 2004; Franke et al., 2006; Kamara et al., 2008). Ellis-Jones et al. (2004) showed that growing *Striga*-resistant maize after a soybean trap crop more than doubled economic return compared with continuous cropping with local (nonresistant) maize. Franke et al. (2006) found that ISC that combined rotation of *Striga*-resistant maize, trap crops, and fertilizer application reduced the *Striga* soil seed bank by 46% and increased crop productivity by 88%, while Kamara et al. (2008) showed that these practices reduced *Striga* infestation and damage on farmers fields and increased productivity by more than 200%. The latter also found that the use of a participatory research and extension approach improved community and group cohesion and relationships between farmers and extension agents, resulting in farmer-to-farmer transfer of knowledge and widespread adoption of ISC.

A range of technologies have been tested for controlling *Striga* and yellow witchweed in cowpea, including cultural practices, chemical control, biological control, and host plant resistance (Singh and Emechebe, 1997). Among these, the use of resistant varieties is the most feasible, sustainable, and appropriate solution. Several cowpea varieties resistant to *Striga* and yellow witchweed have been released to farmers in Africa, including IT89KD-374 (Sangaraka) and IT89KD-245 (Korobalen) in Mali; IT90K-76, IT90K-82-2, and IT97K-499-35 in Nigeria; and IT90K-59 in South Africa (Singh, 2002).

Drought

There is a clear trend of decreasing rainfall and increasing temperatures in the dry savannas of West Africa (Dai et al., 2004). According to projections by van den Born et al. (2000), by 2050 temperature in West Africa will be 1.5 to 2.5 °C higher than at present and precipitation 100 to 400 mm/yr lower. Current vegetation zones will shift towards the South, as will aridity. Jagtap (1995) showed that annual rainfall in Nigeria declined between 1961–70 and 1981–90, with delays in the onset of the rainy season and reduction in early rainfall, which shortened the growing season by nearly one month. There were fewer wet days and higher rainfall intensities in most of the country. The rainfall series showed prolonged dry periods, especially since 1970. The rainfall decline is unprecedented in duration, spatial, temporal character, and seasonal expression.

Some 21% of the maize area in sub-Saharan Africa often suffers from drought stress (Heisey and Edmeades, 1999). Drought is also the main abiotic constraint responsible for low and unstable yields in groundnut. Drought also increases the probability of aflatoxin contamination on groundnut and its products. In the dry savanna zone of West Africa, the probability of drought is highest at the start and end of the growing season, but the timing of deficits is unpredictable. Because of this, the effects of drought cannot be avoided by either genotype maturity or planting date. Decreasing the susceptibility of a crop to drought, while maintaining or increasing yield in good rainfall years, would increase and stabilize rural incomes, reduce the chronic food shortages that plague these areas prior to harvest, and lessen the risk of farming.

There is growing consensus that restoration of soil fertility and conservation of soil and water resources are the starting points for agricultural transformation and development in West Africa (Rockström et al., 2010; Vanlauwe et al., 2010; Bationo et al., 2011; Oduol et al., 2011). Several strategies have been developed for the conservation of soil and water to maintain productivity in West Africa, including rainwater harvesting, live barriers, supplementary irrigation, minimum tillage, mulching, bunded basins, and tree planting (Drechsel et al., 2004).

A central approach to increasing crop production in the dry savanna is planting well-adapted cultivars at the optimum date. The short growing season and frequent droughts in the dry savanna require early- and extra-early-maturing crop cultivars with drought tolerance. Breeders at the International Institute of Tropical Agriculture (IITA) and partner institutions have developed maize, cowpea, and soybean cultivars that are early maturing; tolerant to drought, high temperatures, and low soil nutrient contents; and are resistant to pests and diseases (see, for example, Badu-Apraku et al., 2005; Kamara et al., 2005; Menkir et al., 2009).

Competition between crops and livestock for resources

Among the tremendous challenges facing agriculture in the dry savannas of West Africa, is the need to generate enough food for people and feed for animals without destroying the natural resource base. Traditional farming systems are breaking down under human and livestock population pressure. Competition is increasing between crops and livestock, particularly for land and labor (Okoruwa et al., 1996). In subhumid ecological zones, rangelands are rapidly being converted to cropland (McIntire et al., 1992) with consequent shrinkage of traditional livestock grazing areas. As a result, livestock increasingly depend on crop residue for feed. Also, as savanna zones are progressively transformed from the traditional extensive fallow systems to continuous cropping, yields of crops and land productivity are declining and sustainability is threatened. Integration of crop and livestock offers a viable approach to sustainable intensification of land use (Ajeigbe et al., 2001), since cultivated areas can support more livestock during the dry season than non-cultivated areas if the crop residues are judiciously used. Van Raay (1975) reported that in the semi-arid areas of northern Nigeria, cattle resident in farming areas are better able to meet their protein requirement than transhumant cattle. However, as shown in Table 5-1, the use of crop residues as fodder removes soil nutrients (Powell and Williams, 1995), as does the harvesting and removal of grain and fodder (Mortimore et al., 1997).

Livestock have a vital role to play in maintaining or increasing the yields of cereals and certain cash crops in the dry savannas of West Africa, through provision of animal traction and organic fertilizer and diversification of production systems (Harrison, 1991; CIRAD, 1996; Smith et al., 1997; Brock et al., 2002; Williams et al., 2004; Franke et al., 2010). CIRAD (1996) noted that a farmer who works his or her land by hand can cultivate only 0.4 ha, but can cultivate 5 ha

Table 5-1. Nutrient (%) removal by 100 kg of grain and fodder in harvest.

Nutrient	Cowpea grain (100 kg)[1]	Cowpea fodder (100 kg)
Nitrogen	2.37	1.19
Phosphorus	0.15	0.13
Potassium	2.02	1.38
Magnesium	0.58	0.33
Calcium	0.50	0.89

1. Equivalent to 128 kg unthreshed.

SOURCE: Mortimore et al. (1997).

with the help of two oxen. Dual-purpose (food and feed) cowpeas, groundnuts, and other leguminous crops can provide food for humans, feed for livestock, and supply of nitrogen to the soil (Singh et al., 2003). Singh and Ajeigbe (2007) and Ajeigbe et al. (2010) documented the benefits of an improved cereal–legume–livestock system adopted by 20,000 farmers in the savanna zone in Nigeria and Niger. Stall-feeding sheep and goats with cereal and legume stover during the dry season increased liveweight gains and animal fertility, increased the quality of manure that the farmers could collect and return to their fields, and allowed closer monitoring of animal health, increasing the overall productivity of the system. The system also resulted in positive residual soil N contributions to following crops, boosting crop yields (Sanginga et al., 2003).

In the past decade, it has been recognized that farmers in mixed crop–livestock systems sometimes value the crop residues as much as the grain owing to their importance as a feed for livestock, particularly in the dry season (Blümmel et al., 2003; Blümmel and Rao, 2006). Breeding programs for these crops are increasingly being adapted to include breeding for residue quality without compromising grain yield.

Utilization of crop residues as livestock feed is, however, not without implications for crop production (Giller et al., 2009; Valbuena et al., 2012). For example, Kang (1993) showed that crop-residue management could affect cowpea grain yield. Use of crop residue as mulch together with application of fertilizer gave significantly higher grain yield than fertilizer without crop residue. Where crop residue and weeds are collected and used as fodder, the resulting animal manure should be returned and used as fertilizer. Singh and Ajeigbe (2000) showed that row planting of two rows of cereal interspersed with four rows of cowpea produced more grain and better-quality fodder than the traditional system of alternating rows of cereal and legume. This so-called “strip cropping” allows the two crops to be cultivated independently but provides for them to interact agronomically (Ajeigbe et al., 2005).

Clearly, there is a continuing need to develop improved integrated crop–livestock systems that minimize competition for scarce resources (particularly land and labor) and maximize the synergies between the components (Figure 5-1).

Weak extension services

Many technologies have been developed that have the potential to increase agricultural production in West Africa, but their adoption by farmers remains limited (Bationo and Baidu-Forson, 1997; Diouf et al., 1998; Ndjeunga and Bantilan, 2005). Researchers have identified a range of technical, socio-economic, institutional, and policy constraints to technology uptake, including weak extension services, weak markets for both inputs and outputs, and poor infrastructure. For instance, extension recommendations are sometimes inappropriate or ineffective. The promotion of manure application without warning that it may reduce yields under limited rainfall is a case in point (Affholder, 1994). Likewise, use of mineral fertilizers is widely promoted by research and development organizations as a blanket recommendation irrespective of zonal, climatic, and geological diversity (Diouf et al., 1998). Often a technology that worked well on station has not been adapted to farmers’ conditions.

Poor communications among farmers, extension agents, and researchers has often led to poorly targeted research or to the poor adoption of promising options generated by research. Extension workers are expected to disseminate agricultural knowledge and technologies to rural communities, which include production, postharvest, and livestock issues, yet they do not possess adequate knowledge in all these areas. The lack of continuing education opportunities is a drawback to extension workers’ performance. This poor performance of extension efforts calls for fresh approaches (Mercoiret et al., 2003). For example, farmer-participatory research and participatory learning have been adopted to make research results more understandable and useful to target groups (Farrington and Martin, 1988; Chambers et al., 1989; van de Fliert and Braun, 2002).

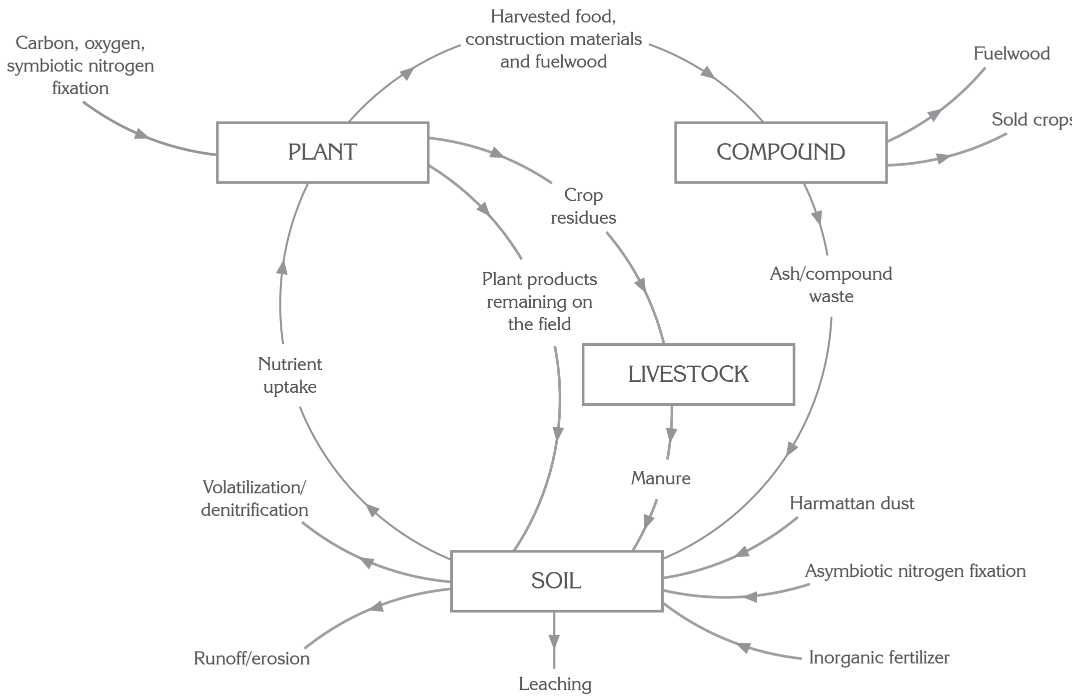

Figure 5-1. An example of a nutrient cycle in a mixed crop–livestock farming system.
SOURCE: Mortimore et al. (1997).

Participatory extension models, such as farmer field schools and local agricultural research committees, make agricultural technologies quickly available and easily accessible in farming communities and enable participating organizations to gain experience in developing researcher–farmer–extension partnership (Braun et al., 2000).

Conclusions

Crop–livestock systems are intensifying in the dry savannas of West Africa because of increasing population pressure. Despite the high potential for crop and livestock production, the intensification of land use systems faces increasing biotic and abiotic constraints. Poor soil fertility, parasitic weed infestation, drought, pests, and diseases are major constraints to food and feed production in the dry savannas. Over the years, research institutions have developed and disseminated component technologies that can improve system productivity when deployed in an integrated manner. Government and national institutions in West Africa are encouraged to scale out these technologies to wider areas for increased benefit to farmers.

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CHAPTER

6

Integrated Soil Fertility Management in Central Africa: Experiences of the Consortium for Improving Agriculture-based Livelihoods in Central Africa (CIALCA)

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Contents

Abstract

Agricultural intensification is a necessity in the densely populated areas of sub-Saharan Africa and certainly so in the Great Lakes region of Central Africa, the operational domain of the Consortium for Improving Agriculture-based Livelihoods in Central Africa (CIALCA). The integrated soil fertility management (ISFM) paradigm has been accepted by the research and development community, including the Alliance for a Green Revolution in Africa (AGRA), as a viable set of principles to foster agricultural intensification. In this paper we first describe the production environment of CIALCA's mandate areas and its impact on livelihood characteristics and constraints on enhanced productivity. We then develop the definition of ISFM and evaluate its relation with eco-efficiency principles. ISFM components are illustrated with data from various cropping systems in the mandate areas and specific reference is made to issues of dissemination and the creation of an enabling environment for the uptake of ISFM technologies. We found that ISFM principles are relevant for increasing system productivity within the Great Lakes region but that unfavorable conditions for their uptake are a major impediment to their potential impact. CIALCA and future initiatives should simultaneously invest in the development and evaluation of ISFM practices and the creation of an environment that favors their uptake.

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Introduction

The Consortium for Improving Agriculture-based Livelihoods in Central Africa

The Consortium for Improving Agriculture-based Livelihoods in Central Africa (CIALCA; www.cialca.org) is a research-for-development consortium led by the Tropical Soil Biology and Fertility Research Area of the International Center for Tropical Agriculture (TSBF-CIAT), the International Institute of Tropical Agriculture (IITA), and Bioversity International. It involves a diverse range of partners across the research-to-development continuum. Its major goal is to improve the livelihoods of rural households in Central Africa through the identification, evaluation, and promotion of technological options to enhance the productivity of banana-, maize-, cassava-, and legume-based systems and creation of an enabling environment for their adoption. CIALCA has been operating since late 2005 in 10 mandate areas in Burundi, the Democratic Republic of the Congo (DR Congo), and Rwanda. This paper focuses on the seven areas located in the highlands of Burundi, Rwanda, and South Kivu Province in eastern DR Congo (Figure 6-1A). These areas lie at altitudes varying between about 850 meters above sea level (masl) in the Rusizi Plains near Lake Tanganyika to over 2000 masl in some of the higher parts of Gitega (Burundi) and South Kivu (DR Congo). These areas have some of the highest population densities in Africa, with the average ranging between 238 people/km^2 in Kigali-Kibungo (Rwanda) and 514 people/km^2 in Gitarama (Rwanda) (Figure 6-1B).

Environmental and farming system characteristics of the mandate areas

All mandate areas contain highland perennial systems following the farming systems classification of the Food and Agriculture Organization of the United Nations (FAO) (Dixon et al., 2001). More than half of the farmers in the mandate areas grow banana, maize, cassava, and bush or climbing beans (Ouma and Birachi, 2011). The length of growing period varies

(A) Mandate areas of CIALCA **(B)** Population density within mandate areas of CIALCA

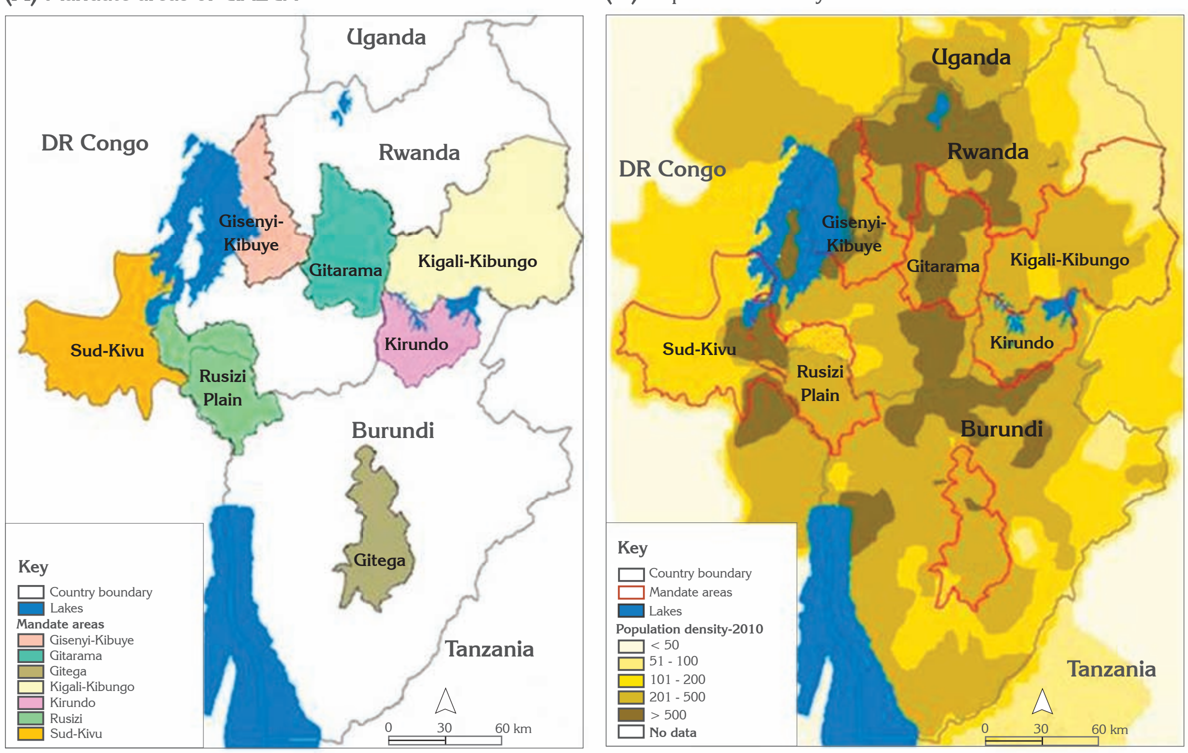


Figure 6-1. **(A)** The seven CIALCA mandate areas in Burundi, eastern Democratic Republic of the Congo, and Rwanda and **(B)** population densities in these areas.

between 240 and 365 days (Figure 6-2A), with a clear gradient from east to west. Most areas have two growing seasons: February–August and September–January. The reliability of these seasons varies between the mandate areas. Greater climate variability has been observed in recent years, especially in terms of variability in the onset of the rainy season and increasing frequency of mid-season drought events. The main soil types are Ferralsols and Acrisols according to the World Reference Base for Soil Resources classification (IUSS Working Group WRB, 2006) (Figure 6-2B). These have inherently good physical properties but poor chemical properties and low nutrient stocks due to long-term leaching. Average slopes are steep and vary between 11% (Kigali-Kibungo) and 24% (Rusizi Plain) (Figure 6-2C). This and the lack of a dense network of primary and rural feeder roads results in an average travel time to major markets varying from 2 hours (Gitega) to nearly 7 hours (Rusizi Plain) (Figure 6-2D).

As a result of these biophysical features, farms in the mandate areas are relatively small, contain a diverse range of crops, are labor limited, have varying but low numbers of livestock, and use very few external inputs such as improved varieties, fertilizer, or pesticides (Table 6-1). Only in Gitega does a considerable proportion of households use fertilizer (Table 6-1). Utilization of improved crop varieties is limited, with improved banana varieties used by 0–19% of households, improved groundnut and soybean varieties by 0–6% of households, improved cassava varieties by 0–16% of households, and improved maize varieties by 0–24% of households (Ouma and Birachi, 2011). The only exception is improved bean varieties, which are used by 5–91% of households in the mandate areas. Most households (50–85%) sell their agricultural produce at the farm gate or in local markets (Ouma and Birachi, 2011). Only in South Kivu do 20% of the households visit a regional market. Between 60 and 90% of the households sell fresh food products, while 10–25% of households sell processed products (Ouma and Birachi, 2011).

In many densely populated areas of sub-Saharan Africa (SSA), fallow periods are no longer an option and organic resources are scarce. This has commonly resulted in large variability in soil fertility between fields within a single farm. These “soil fertility gradients” are created by the position of specific fields within a soil-scape (Deckers, 2002), by the selective allocation of available nutrient inputs to specific crops and fields, and by improved management (e.g., time of planting, weeding, etc.) of plots with higher fertility (Tittonell et al., 2005b). In the CIALCA mandate areas, large differences in crop productivity over relatively short distances can be observed. For instance, in East Province of Rwanda, bean yields without inputs varied between less than 50 kg/ha and more than 2000 kg/ha (Figure 6-3A).

Livelihood characteristics of the mandate areas

An important consequence of the production environment and its many constraints, as described above, is substantial food insecurity. Between 38% and 72% of all households often have too little to eat and more than 80% of the households consume a maximum of two meals per day (Table 6-2). Over 70% of the households consume vegetable protein on a daily basis, over 80% of households consume animal protein only once a week or less often (Ouma and Birachi, 2011). Since agricultural outputs are limited, 29% to 73% of the adult population is involved part time or full time in off-farm activities, resulting in substantial off-farm income for most households. Literacy levels are relatively high, with between 52 and 84% of the household heads having completed at least primary education (Table 6-2).

In terms of gender relationships, women contribute significantly to agricultural activities (Table 6-2). Both men and women are involved in crop management, though dominance of one gender is evident in certain enterprises in some mandate areas. In most cases, women dominate management of staple crops such as beans and cassava that are largely targeted for home consumption. Gender dominance in banana management is not evident, except in South Kivu where it is male dominated. In some of the mandate areas, banana cultivation is largely male dominated while harvest activities are dominated by women.

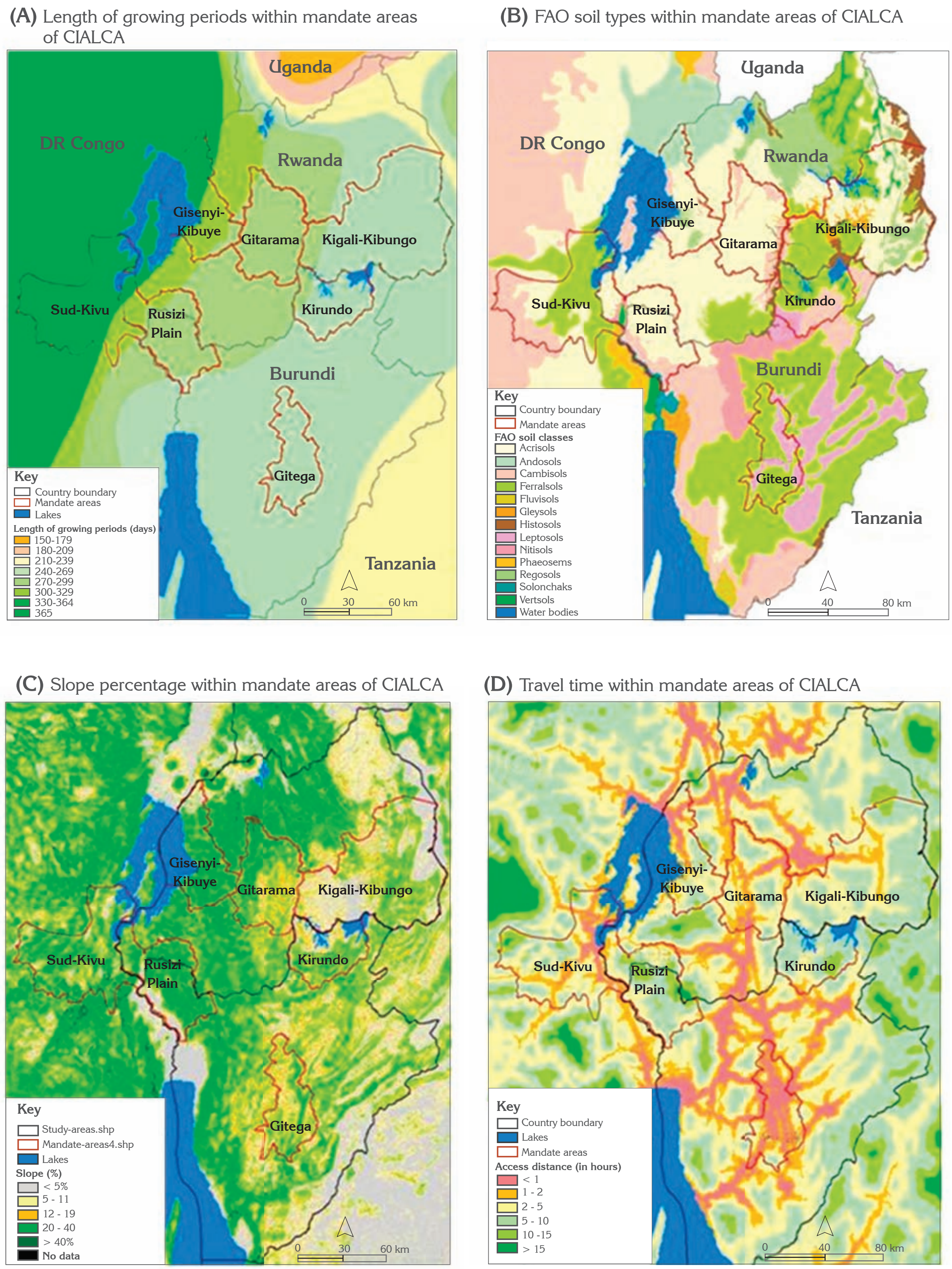


Figure 6-2. **(A)** Length of growing period, **(B)** main soil types, **(C)** slopes, and **(D)** distance to markets for the CIALCA mandate areas in Burundi, eastern Democratic Republic of the Congo, and Rwanda
SOURCE: World Agroforestry Centre Geographical Information Systems Group.

Table 6-1. Characteristics of farming systems in seven CIALCA mandate areas in the African Great Lakes region.

Mandate area	Average farm size (ha)	Household size (no. of members)	Household members engaged full time in farm activities (no./ household)	Ruminant livestock ownership (TLU[a]/farm)	Proportion of households using fertilizer (%)	Proportion of households using organic inputs (%)
Gitega	1.0	6.0	2.1	0.3	49	66
Kirundo	1.1	6.2	2.4	0.5	3	44
Rusizi Plain	2.0	5.9	2.2	0.4	13	29
South Kivu	0.7	7.0	2.1	0.4	0	19
Kigali-Kibungo	1.8	5.7	2.7	0.8	6	43
Gisenyi-Kibuye	1.8	6.4	2.6	0.9	4	39
Gitarama	2.4	6.6	2.9	1.5	20	36

a. TLU: tropical livestock unit = 250 kg body weight.

SOURCE: Adapted from Ouma and Birachi (2011).

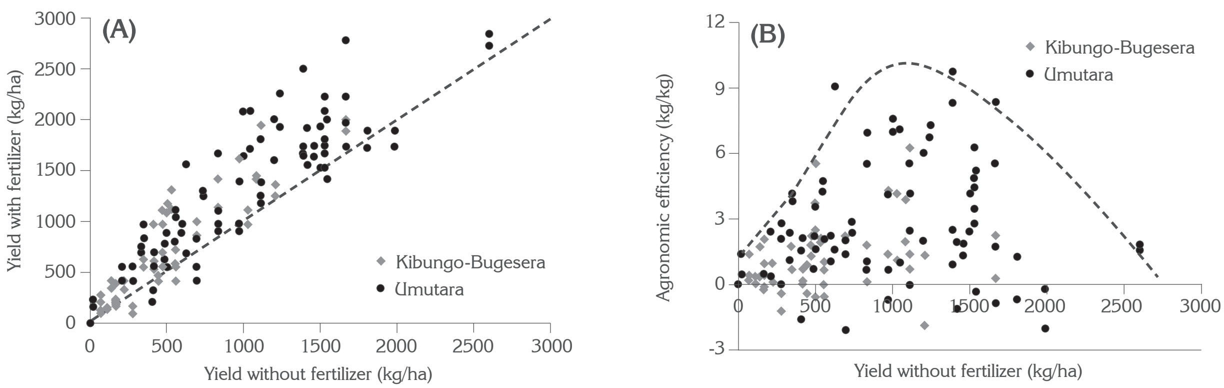


Figure 6-3. Grain yield of common beans with diammonium phosphate fertilizer and agronomic efficiency as a function of grain yield without fertilizer as observed in farmers fields in two mandate areas in the Eastern Province of Rwanda. Bugesera and Kibungo belong to the Kigali-Kibungo mandate area while Umutara is in the North-East of Rwanda.

SOURCE: Adapted from Pypers et al. (in preparation).

The poor security environment and inefficient government structures during the past few decades have forced farmers to support one another, and this is reflected in substantial levels of social capital as illustrated by household membership of a farmer group (14–45%) or a credit and savings group (3–46%) (Table 6-2).

In most communities in SSA, access to resources is not homogeneous, with some households having greater access to, for instance, land, labor, livestock, and capital, than others (Tittonell et al., 2005a). This is also the case for the farming households within the CIALCA mandate areas (Ouma and Birachi, 2011). Households with greater resource endowment commonly have a wider range of options to improve productivity and are less risk averse (Shepherd and Soule, 1998). This needs to be considered when identifying best soil management practices.

Table 6-2. Livelihood indicators of farming households in the CIALCA mandate areas.

Mandate area	Proportion of households experiencing food insecurity often or sometimes[a] (%)	Proportion of households consuming two or fewer meals per day (%)	Proportion of household heads that have completed primary education (%)	Proportion of household members involved part time or full time in off-farm activities (%)	Involvement of women in agricultural activities (%)[b]	Proportion of households belonging to a farmer group (%)	Proportion of households belonging to a credit and savings group (%)
Gitega	63	96	54	44	67	31	3
Kirundo	72	100	52	57	59	45	7
Rusizi Plain	40	97	64	29	60	14	18
South Kivu	61	80	62	73	71	40	40
Kigali-Kibungo	38	96	70	39	75	30	26
Gisenyi-Kibuye	39	90	84	39	77	24	24
Gitarama	44	90	81	39	83	35	46

a. "Often" means that the households do not have enough food to eat for most of the year; "sometimes" means that households do not have enough food to eat occasionally.

b. Refers to decision-making on management of banana, cassava, bean, groundnut, and cowpea enterprises based on gender and includes all cases where the woman or both the man and the woman were involved.

SOURCE: Adapted from Ouma and Birachi (2011).

Major constraints to increased and eco-efficient productivity

Major constraints to eco-efficient intensification can be identified for various system goals:

- *Enhanced production:* Low use of external nutrient inputs, or agriculture that is mainly based on nutrient mining, combined with the low inherent soil nutrient stocks results in low crop productivity. Few crop residues are incorporated into the soil, and this is compounded by a lack of farmyard manure. This results in declining soil organic matter stocks and impairs various functions that enhance the efficiency with which water and nutrients are used by crops. The widely used unimproved germplasm has low demand for nutrients and the efficiency of conversion of nutrients and water to yield is also low. The relatively steep slopes and minimal use of erosion control measures result in substantial soil losses.
- *Enhanced profit and competition:* Low overall production, limited processing of produce, and the lack of market infrastructure results in local produce being unable to compete with imported food. As a consequence, farm incomes and profits are low. Moreover, due to the recent civil strife in the area, food and emergency aid systems have only been recently phased out, leaving behind a rural population that has become accustomed to free inputs.
- *Enhanced sustainability:* The low use of external inputs and the lack of investment capacity of the farmers results in declining crop productivity and worsening environmental, economic, and social sustainability. This has been exacerbated over the recent decades with the drastic decline in livestock numbers in all mandate areas. Livestock was very likely one of the most important factors sustaining agricultural production in the past.
- *Enhanced resilience:* Climate change is resulting in greater climate variability, particularly more variable onset of rains to begin the growing seasons and more frequently mid-season droughts. This is causing yield losses. Farmers have little say in setting the price for agricultural products, reducing their ability to raise their income and profits.

- *Enhanced equity:* Women manage most of the household food security crops, while men most often manage cash crops. Men take most decisions on investments in agriculture and control income from sales, while women implement most labor-intensive field activities.

These constraints are exacerbated by the lack of effective extension systems, the lack of a conducive policy environment, and the lack of conditions that enable farmers to move from subsistence to commercial agriculture. The main exception is Rwanda where, over the past 15 years, institutional and policy-related changes have created a production environment that is well-placed to tackle constraints through investments in input value chains for improved seeds and fertilizer, provision of access to credit, initiatives to increase cattle ownership and to empower women, and the creation of an effective extension system.

Integrated Soil Fertility Management: Definition and Relationship with Eco-Efficiency

Context for system intensification

The Green Revolution in South Asia and Latin America boosted crop productivity through the deployment of improved varieties, water, and fertilizer. However, efforts to achieve similar results in SSA largely failed (Okigbo, 1987). The need for sustainable intensification of agriculture in SSA has gained support in recent years, especially in densely populated areas where natural fallows are no longer an option, as is the case in the African Great Lakes region. There is a growing recognition that farm productivity is a major entry point to overcoming rural poverty. A recent landmark event was the launching of the Alliance for a Green Revolution in Africa (AGRA) (Annan, 2008). Since fertilizer is an expensive commodity, AGRA has adopted integrated soil fertility management (ISFM) as a framework for boosting crop productivity through reliance on soil fertility management technologies, with emphasis on increased availability and use of mineral fertilizer.

Operational definition of ISFM

We define ISFM as “a set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions, aiming at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity. All inputs need to be managed following sound agronomic principles” (Vanlauwe et al., 2011). The goal of ISFM is optimized crop productivity through maximizing interactions that occur when fertilizers, organic inputs, and improved germplasm and the required associated knowledge are integrated by farmers (Figure 6-4).

Focus on agronomic use efficiency

The definition focuses on maximizing the efficiency with which fertilizer and organic inputs are used since these are both scarce resources in the areas where agricultural intensification is needed. Agronomic efficiency (AE) is defined as incremental return to applied inputs:

$$AE \text{ (kg return/kg input)} = (Y_F - Y_C) / (F_{appl})$$

where Y_F and Y_C refer to yields (kg/ha) in the treatment where nutrients have been applied and in the control plot, respectively, and F_{appl} is the amount of fertilizer and/or organic nutrients applied (kg/ha).

Note that maximal AE also leads to maximal value:cost ratios since both indicators are linearly related for specific input and output prices.

Fertilizer and improved germplasm

In terms of response to management, two general classes of soils are distinguished: (1) soils that show acceptable responses to fertilizer, or “responsive soils” (Path A, Figure 6-4) and (2) soils that show little or no response to fertilizer due to other constraints besides the nutrients contained in the fertilizer, or “less-responsive soils” (Path B, Figure 6-4). In some cases, where land is newly cleared or where fields are close to homesteads and receive large amounts of organic inputs each year, a third class of soil exists where

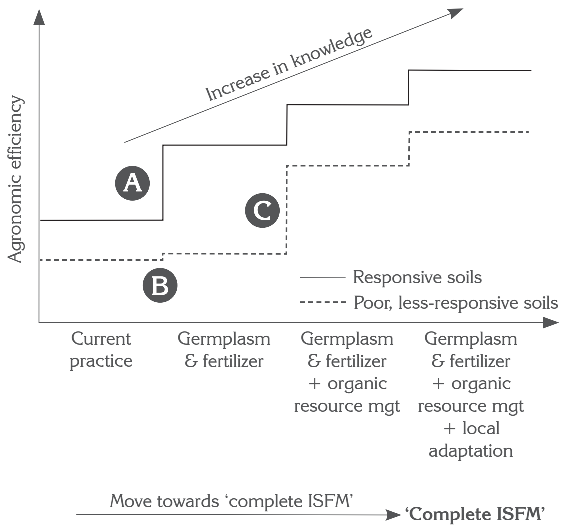


Figure 6-4. Conceptual relationship between the agronomic efficiency of fertilizers and organic resources and the implementation of various components of integrated soil fertility management (ISFM). "Current practice" assumes the use of the current average fertilizer application rate in sub-Saharan Africa of 8 kg of fertilizer nutrients per hectare.

SOURCE: Adapted from Vanlauwe et al. (2011).

crops respond little to fertilizer as the soils are fertile. The ISFM definition proposes that application of fertilizer to improved germplasm on responsive soils will boost crop yield and improve AE relative to current farmer practice, which is characterized by traditional varieties receiving too little and poorly managed nutrient inputs (Path A, Figure 6-4). Major requirements for achieving production gains on responsive fields within Path A (Figure 6-4) include the use of disease-resistant and improved germplasm; crop and water management practices; and application of the "4R" Nutrient Stewardship Framework—a science-based framework that focuses on applying the right fertilizer source, at the right rate, at the right time during the growing season, and in the right place (IFA, 2009).

Combined application of organic and mineral inputs

Organic inputs contain nutrients that are released at a rate determined in part by their chemical characteristics or organic resource quality. However, organic inputs applied at realistic levels seldom release sufficient nutrients for acceptable crop yield. Combining organic and mineral inputs has been advocated for smallholder farming in the tropics because neither input is usually available in sufficient quantities to maximize yields and because both are needed in the long term to sustain soil fertility and crop production. An important question arises within the context of ISFM: Can organic resources be used to rehabilitate less-responsive soils and make these responsive to fertilizer (Path C in Figure 6-4)? In Zimbabwe, applying farmyard manure to sandy soils at relatively high rates for 3 years resulted in a clear response to fertilizer where there was no such response before rehabilitation (Zingore et al., 2007). In southwestern Nigeria, integration of residues from Siamese senna (*Senna siamea*), a leguminous tree, reduced topsoil acidification resulting from repeated application of urea fertilizer (Vanlauwe et al., 2005).

Adaptation to local conditions

As previously stated, soil fertility status can vary considerably within short distances with substantial impacts on fertilizer use efficiency. Three broad classes of fields can be distinguished that occur across a range of agroecologies: (1) fertile, less-responsive fields, (2) responsive fields in which a strong response to fertilizers is found, and (3) poor, less-responsive fields. Figure 6-4 illustrates examples 2 and 3, above. In addition to fertilizer and organic input management, other measures for adaptation to local conditions include application of lime on acid soils, water harvesting techniques on soils susceptible to crusting under semi-arid conditions, or soil erosion control on hillsides. Lastly, adaptation also includes considering the farming resources available to a specific farming household, often referred to as farmer resource endowment. The status is related to a specific set of farm typologies. In other words, ISFM options available to a specific household will depend on the resource endowment of that household.

A move towards complete ISFM

Complete ISFM comprises the use of improved germplasm, fertilizer, appropriate organic resource management, and local adaptation. Several intermediary phases have been identified that assist the practitioner's move towards complete ISFM, starting from the current average practice of applying 8 kg/ha fertilizer nutrients (NPK) to local varieties. Each step is expected to provide the management skills that result in yield and improvements in AE (Figure 6-4). Figure 6-4 is not intended to prioritize interventions but rather suggests a stepwise adoption of the elements of complete ISFM. It does, however, depict key components that lead to better soil fertility management. In areas, for instance, where farmyard manure is targeted towards specific fields within a farm, local adaptation is already taking place, even if no fertilizer is used, as is the case in much of Central Africa.

Integrated soil fertility management and eco-efficiency

CIAT equates eco-efficient agriculture to more productive, profitable, competitive, sustainable, resilient, and equitable agriculture. Although this definition is primarily quantitative, it also allows qualitative assessment of the ISFM paradigm relative to current agricultural practices.

ISFM aims at eco-efficiency in various ways. The definition of ISFM itself embeds the concept of eco-efficiency through its focus on maximizing the agronomic efficiency of inputs, with enhanced productivity and profitability and minimized losses to the environment as direct consequences. Intensifying agricultural production can also reduce the pressure to open up new land that is often poorly suited to crop production but valuable in the context of other ecosystem functions. The concept of local adaptation embedded in the definition requires consideration of not only soil fertility gradients but also resource endowment of farming families, thus promoting increased equity among households.

The rehabilitation of less-responsive sites is a special case, as immediate returns to investment are not expected to be high. Implementing ISFM options restores productivity through a gradual increase in soil fertility resulting from more-effective use of improved germplasm, fertilizers, organic inputs (crop residues, farmyard manure), or even biofertilizers. Rehabilitating such soils enhances eco-efficiency at the farm level since more of the land area will be using agricultural inputs more efficiently.

A main issue related to sustainability is whether applying fertilizer can generate the required crop residues and other organic inputs that are needed to optimize the AE of fertilizer and sustain the soil-based ecosystem functions and services, governed by the soil organic-matter pool. There are indications that it can. Bationo et al. (1998) found that where fertilizer was applied to millet, sufficient residue was produced to meet both farm household demands for feed and food and the management needs of the soil in terms of organic-matter inputs and protection of the soil from wind erosion.

Integrated Soil Fertility Management: Application of Principles Applied in Systems Relevant to the African Great Lakes Region

Principles embedded within the definition of ISFM need to be applied within existing farming systems. Based on the main principles underlying ISFM and the specific production environment of the African Great Lakes region, specific entry points have been identified covering the various dimensions of ISFM (Table 6-3). Rehabilitation of non-responsive soils is not included in the table because it is unlikely to be a major short-term entry point towards ISFM. Some of these potential entry points are further developed in the following sections, based on results obtained within the CIALCA mandate areas and following the ISFM stepwise approach.

Step 1: Fertilizer and varieties

For a significant improvement in eco-efficient crop productivity, an enhanced supply of nutrients has to go hand in hand with a greater demand by the crop. Applying fertilizer to germplasm that is unresponsive, not adapted to the environment, or that is affected by pests and diseases will result in low AE values. In South Kivu, DR Congo, for example, improved, open-pollinated maize varieties yielded more than local varieties without

Table 6-3. Potential entry points toward ISFM[a] in the context of the CIALCA[b] mandate areas of the Great Lakes region of Africa.

ISFM step	Potential ISFM interventions	Comments
Fertilizer and varieties	Use of improved varieties of cassava, legumes, maize, and banana	Requires effective seed systems; the private seed sector is still at best nascent in the African Great Lakes countries
	Enhanced use of fertilizer adapted to specific crops	Requires input value chains, including agro-dealer networks for last-mile delivery
	Appropriate fertilizer management practices (4 Rs: right source, right rate, right time, right place)	Requires specific training on the appropriate use of fertilizer
	Appropriate agronomic practices (e.g., planting in lines, appropriate planting densities, and intercropping arrangements)	Usually requires additional labor; shortage of labor is a major constraint in the mandate areas
Organic matter x fertilizer interact	Appropriate utilization and management of available manure and compost	Little farmyard manure is available because farmers have few cattle
	Integration of dual-purpose legumes (food and feed) in cassava, maize, and banana-based systems	Enhanced production of grain legumes requires markets for these products, which is a major issue for soybean
	Targeted application of organic inputs on crops with relatively wide spacing, in combination with fertilizer	Spot placement of inputs requires substantially more labor (a major constraint in the mandate areas) and is usually only practicable on small areas
	Inclusion of organic mulches for moisture conservation in banana plantations	Mulch is a major constraint in newly established banana plantations before self-mulching is initiated
Local adaptation	Target most responsive soils with microdoses of fertilizer	Capacity to diagnose soil fertility constraints to enable identification of appropriate fertilizer types and rates is very limited
	Application of lime in areas with high soil acidity and high exchangeable aluminum	Lime of adequate quality is in short supply in the mandate areas
	Erosion control measures on steep slopes	Investments in erosion control require substantial effort and finances and often collective action

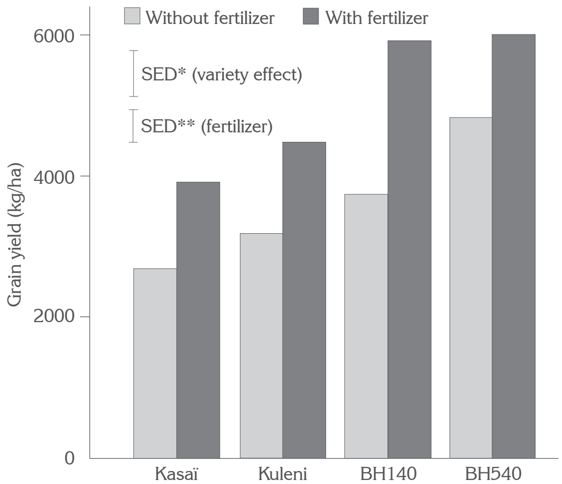
a. ISFM: integrated soil fertility management.

b. CIALCA: Consortium for Improving Agriculture-based Livelihoods in Central Africa.

fertilizer but some varieties also had a higher response to fertilizer application, resulting in higher AE values (Figure 6-5). Similarly, replacing mosaic-virus-susceptible cassava varieties with tolerant varieties resulted in a substantial increase in cassava response to fertilizer (unpublished data from authors).

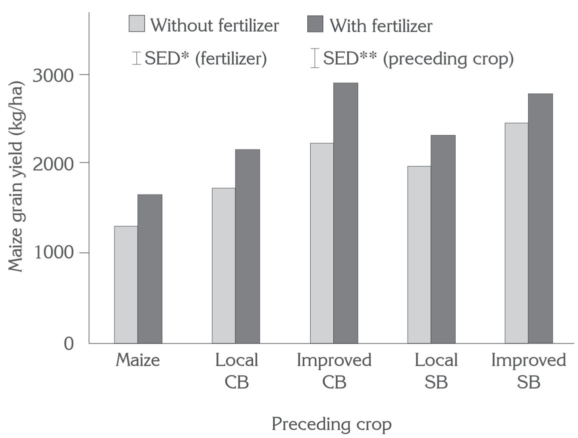
Step 2: Organic matter x fertilizer interactions

Pypers et al. (in preparation) observed a significant effect of previous cropping on maize yields both with and without fertilizer in field demonstrations in South Kivu, DR Congo (Figure 6-6). Yields of maize following soybean or climbing beans (*Phaseolus vulgaris)* were 27–57% higher than that of maize following maize. Rotational benefits were also greater when improved, dual-purpose legume varieties with a low harvest index were grown. These legumes gave similar grain yields to local varieties (not shown), but grain yields following maize crops were 20–34% higher than those of maize following local legume varieties. These yield improvements were related to greater biological nitrogen (N) fixation in the improved legumes, which derived a



SED: standard error of difference; *=significant at P<0.05; **=significant at P<0.01. There was no significant fertilizer × variety interaction.

Figure 6-5. Grain yield of two local maize varieties (Kasaï and Kuleni) and two improved, open-pollinated maize varieties (BH140 and BH540) as affected by application of 13 kg phosphorus, 60 kg nitrogen, and 25 kg potassium per hectare across four sites in South Kivu, Democratic Republic of the Congo.



SED: standard error of difference; *=significant at P<0.05; **=significant at P<0.01. There was no significant fertilizer × preceding crop interaction. CB: climbing bean (*Phaseolus vulgaris*); SB: soybean.

Figure 6-6. Maize grain yield as affected by application of compound fertilizer (NPK, 17:17:17) at 100 kg/ha and the crop grown in the preceding season (maize, climbing beans [CB] or soybean [SB]) in South Kivu, Democratic Republic of the Congo

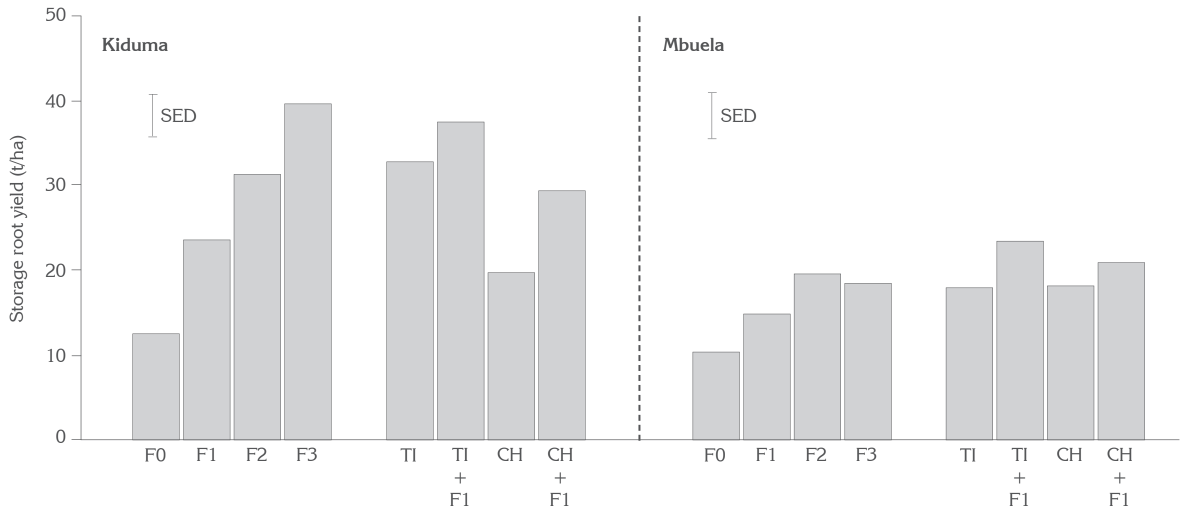
SOURCE: Adapted from Pypers et al. (in preparation).

greater proportion of N from the atmosphere (due to their longer growing period relative to local varieties) and gave a higher biomass yield. Independently, application of compound fertilizer (nitrogen [N] : phosphorus [P] : potassium [K], 17:17:17) increased maize yields by 22–39%. Combining crop rotation and fertilizer application resulted in yield increases up to 120% relative to the unfertilized maize-maize rotation, and a mean fertilizer value:cost ratio of 2.7 (Pypers et al., in preparation).

Fertilizer response and the effect of combining inorganic and organic nutrient resources were also evaluated in cassava systems. The most common fertilizer, NPK 17:17:17, was applied with or without green manure made from *Tithonia* sp. or *Chromolaena* sp., and effects on storage root yield evaluated in two locations with differing soil fertility status (Figure 6-7) (Pypers et al., 2012). Control yields were similar at the two sites (12 t/ha fresh roots), but response to fertilizer differed between the sites: storage root yields reached 40 t/ha at Kiduma but only 20 t/ha at Mbuela. A much larger response to *Tithonia* sp. green manure was also observed at Kiduma, which was likely related to the higher quality and nutrient contents of the green manure grown at that site. Combining organic and inorganic nutrient resources did not result in positive interactions. No significant differences in yield were observed comparing sole application of fertilizer or green manure added to the control, relative to yields obtained with combined application of both nutrient sources (Figure 6-8) (Pypers et al., 2012). In maize-based systems, positive interactions between organic and inorganic fertilizers often arise from better synchrony in N release and N uptake by the crop. In cassava systems, where K is more often the most limiting nutrient, such a mechanism is likely to be less relevant. Potassium is mostly retained on the exchange complex, and has little affinity for organic matter.

Step 3: Local adaptation

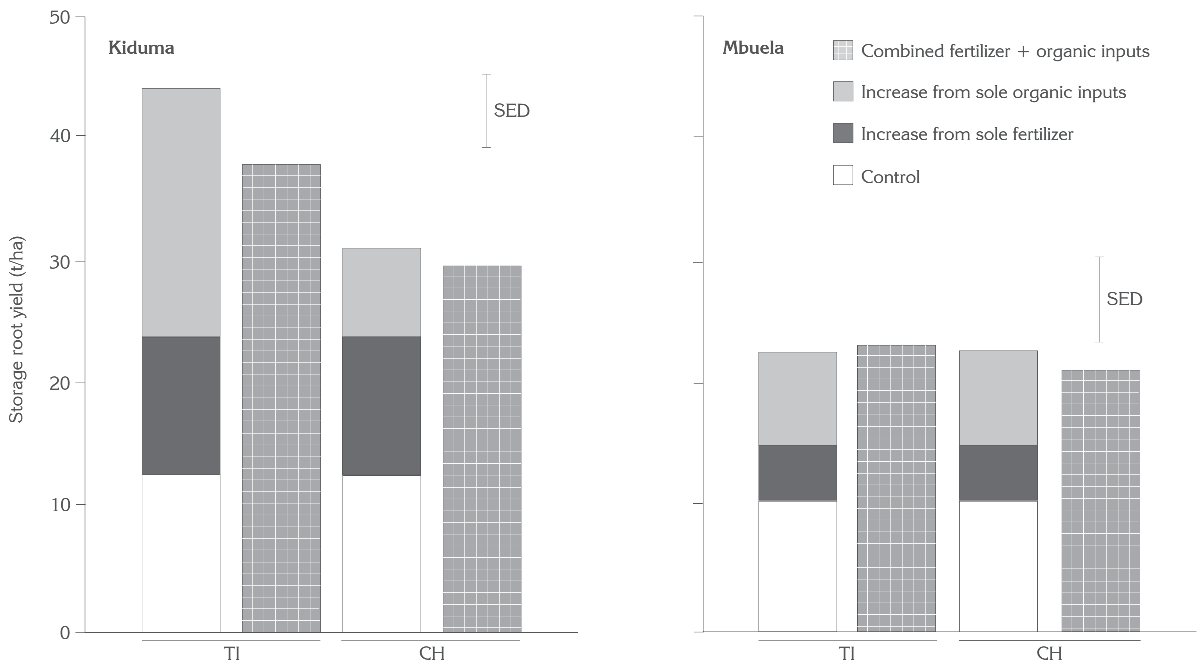
Response to fertilizer also varies according to specific local conditions. For example, bean yields increased between 0 and 1 t/ha (Figure 3A). AE averaged 2 kg of grain per kilogram of diammonium phosphate fertilizer applied, but



SED: standard error of difference at P<0.05.

Figure 6-7. Cassava storage root yields as affected by applying compound fertilizer (17 nitrogen:17 phosphorus: 17 potassium) at rates of 0 (F0), 283 (F1), 850 (F2), and 1417 (F3) kg/ha, and green manure (TI = *Tithonia* sp.; CH = *Chromolaena* sp.) at 2.5 t dry matter/ha alone or together with compound fertilizer at 283 kg/ha in two trial locations in Bas-Congo, Democratic Republic of the Congo.

SOURCE: Adapted from Pypers et al. (2012).



SED: standard error of difference at P<0.05.

Figure 6-8. Comparison of cassava storage root yields obtained by combining fertilizer inputs with organic inputs (TI = *Tithonia* sp.; CH = *Chromolaena* sp.) with incremental yield increases obtained from sole fertilizer or organic input application in two trial locations in Bas-Congo, Democratic Republic of the Congo

SOURCE: Adapted from Pypers et al. (2012).

varied between -2 kg return/kg input and 10 kg return/kg input (Figure 6-3B). This variability is related to both management and soil factors. Late planting and poor crop management reduce crop yield and agronomic efficiency. Fields far from homesteads commonly have poor, degraded soils and respond poorly to fertilizer. Fertile homestead fields, where nutrients from household waste are accumulated, also often respond poorly to fertilizer because control yields are already high. Soils with intermediate soil fertility levels that are deficient in N and P but have a moderate soil organic-matter content and a good soil structure are often the most responsive to fertilizer. As a result, maximal values of AE follow a dome-shaped curve when plotted as a function of control yields (Figure 6-3B) (Pypers et al., in preparation). AE can be maximized by targeting fertilizer to the most-responsive soils.

On sloping land, anti-erosion measures are necessary to conserve the fertile topsoil and sustain long-term crop productivity. Without such measures, soils will degrade and become unproductive. One technique often promoted is progressive terracing using *Calliandra calothyrsus* hedgerows combined with earth embankments whereby the soil is deposited above a furrow dug along the contour (*fanya juu* in Kiswahili). However, these measures often have few short-term benefits and reduce the area available for cropping. In addition, hedgerows may compete with the crops, and earth embankments may bring up less fertile subsoil. A trial was conducted in South Kivu to evaluate the trade-offs between crop production and soil conservation in these systems. Yields were highest on plots without any anti-erosion measures (Figure 6-9) (Pypers et al., in preparation). Plots with both *fanya juu* and *Calliandra* hedgerows yielded only half as much as the control plots in the first year. In the fourth year, yields in the systems with anti-erosion measures were only 17–33% lower than from the control plots. After 4 years, more than 30 kg of soil had been lost per square meter of the control plots, which implies that about 3 cm of topsoil had eroded away. *Fanya juu* embankments were more effective in protecting the soil than were *Calliandra* hedgerows, and the two measures combined resulted in a five-fold reduction in soil loss. While anti-erosion measures are obviously necessary to maintain soil fertility, there are few short- or medium-term benefits for farmers. Application of fertilizer and large quantities of organic matter to the terraces may accelerate soil fertility restoration, but an external incentive and communal action may be required if these measures are to be implemented (Pypers et al., in preparation).

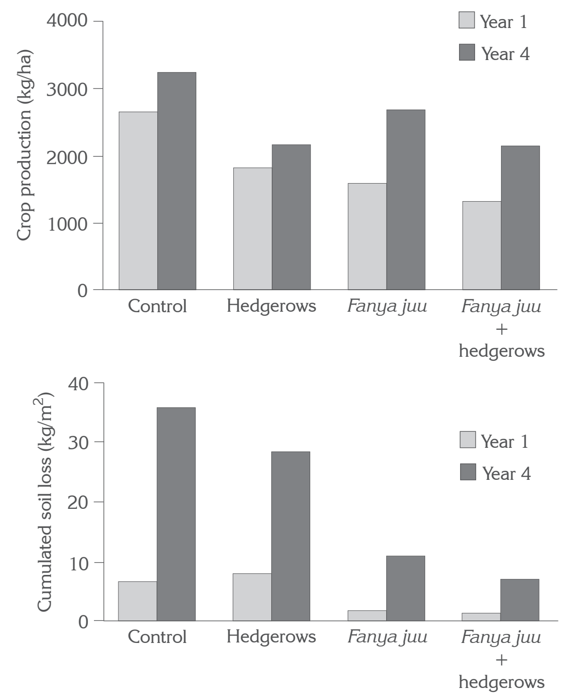


Figure 6-9. Average crop production for a soybean–maize rotation system and cumulated soil loss during the first and fourth year after establishment of anti-erosion measures: *Calliandra calothyrsus* hedgerows, terraces established using *fanya juu* embankments, or both in South Kivu Province, Democratic Republic of the Congo.

SOURCE: Adapted from Pypers et al. (in preparation).

Dissemination of ISFM within the CIALCA Mandate Areas

Complexity and dissemination

The gradual increase in complexity of knowledge as one moves towards complete ISFM (Figure 6-4) has implications on the strategies used to promote widespread dissemination. The operations of each farm are strongly influenced by the wider rural community, policies, supporting institutions, and markets. Not only are farms linked to the off-farm economy through commodity and labor markets, but the rural and urban economies are also strongly interdependent. Farming households are also linked to rural communities and social and information networks, which provide feedback that influences farmer decision-making. Because ISFM is a set of principles and practices to intensify land use, uptake of ISFM is facilitated in areas with greater pressure on land resources.

The first step towards ISFM requires fertilizer and improved varieties. An essential condition for their adoption is access to farm inputs, produce markets, and financial resources. To a large extent, adoption is market driven as commodity sales provide incentives and cash to invest in soil fertility management technologies, providing opportunities for community-based savings and credit schemes. Dissemination strategies should include ways to facilitate access to the required inputs, simple information flyers, spread through extension networks, and knowledge on how to avoid less-responsive soils. Such knowledge can be based on farmers' experiences since most local indicators of soil fertility status are linked to the production history of particular fields (Mairura et al., 2008). A good example of where the seeds and fertilizer strategy has made substantial impact is the Malawi fertilizer subsidy program. Malawi became a net food exporter through the widespread deployment of seeds and fertilizer, although the aggregated AE was only 14 kg of grain per kilogram of N applied (Chinsinga, 2007). Such AE is low and application of ISFM could at least double this, with all consequent economic benefits to farmers.

As efforts to promote the seed and fertilizer strategy are under way, activities such as farmer field schools or development of site-specific decision guides that enable more-complex issues to be tackled can be initiated to guide farming communities towards complete ISFM. This may require improved management of organic matter and local adaptation of technologies. The latter will obviously require more intense interactions between farmers and extension services and will take a longer time to achieve its goals. Farmer adoption of ISFM may be further accelerated by implementing campaigns that address all of these aspects by offering farmers information, technology demonstrations, product exhibits, financial incentives, and opportunities to develop their skills within their own farms.

CIALCA's experience shows that the need for intensive farmer facilitation and training increases rapidly with increasing complexity of knowledge. This demands considerable investment in farmer training and knowledge-support resources. The CIALCA Knowledge Resource Centre was established in the African Great Lakes region to identify and leverage new impact pathways for ISFM technologies. By working closely with extension agents and outreach partners, targeted information tools can be developed to support adoption of practices by farmers in specific settings. A particular challenge is to develop innovative knowledge products that take into account the low rates of adult literacy and formal education prevalent in the region. Rural radio is one tool that offers a wide reach, and is very useful for raising awareness around a particular issue. However, it is less suitable as a training tool, particularly as knowledge complexity increases. It is therefore important to stress the need for integrated, multipronged communications approaches using a mix of tools when attempting to achieve impact of ISFM at a large scale.

Policies towards sustainable land use intensification, and the necessary institutions and mechanisms to implement and evaluate these, also facilitate the uptake of ISFM. Policies favoring the importation of fertilizer, its blending and packaging, or smart subsidies are needed to stimulate the supply of fertilizer. Specific policies addressing the rehabilitation of degraded, non-responsive soils may also be required since investments to achieve this may be too large to be supported by farm families alone. In recent years, several initiatives have been set up in the CIALCA area to facilitate access to fertilizer. In

Rwanda, for example, the Crop Intensification Program has invested in training agro-dealers (small-scale agricultural supplies traders), the development of specific fertilizer recommendations for the major crops, and smart subsidy schemes. In DR Congo, the CATALIST (Catalyze Accelerated Agricultural Intensification for Social and Environmental Stability) project successfully lobbied for the removal of import duties on fertilizer and persuaded private-sector partners to invest in fertilizer supply, resulting in 60 t of fertilizer being imported during the February 2011 planting season, a first for eastern DR Congo.

An enabling environment

A set of enabling conditions can favor the uptake of ISFM. One factor that is expected to catalyze uptake of productivity-enhancing technologies in CIALCA is linkage to defined markets.

CIALCA's market intervention seeks to achieve three objectives: (1) improve the economic livelihoods of men and women in rural areas; (2) create sustainable market linkages and relations for actors; and (3) enhance adoption and raise scale of production. CIALCA has intervened in markets by working with farmers' organizations to achieve a marketable production scale. Capacity building on collaborative action, marketing and business planning skills, and management of credit and finances has ensured that farmers are now able to bulk their produce, wait for better prices, and earn higher incomes from their produce. Besides the farmers, training also targets the institutions and organizations that support the farmers' organizations, such as non-governmental organizations (NGOs) and national research staff, to ensure post-project sustainability. For instance, farmers in South Kivu were able to raise their sales revenues by 50% through strategic storage facilitated by inventory credit schemes (*warrantage* in French): farmers did not have to sell immediately after harvest but were able to store their produce collectively, awaiting better prices for their products. Through group efforts, farmers were also able to acquire credit for their ISFM-based farming activities and, because they had targeted production to key markets, were able for the first time to borrow funds without collateral. In addition, farmers working in groups have been able to initiate mutual savings schemes that supplement other sources of finance, particularly for investment in new technologies. Farmers' production projections (captured in business plans) are based on the expected application of specific ISFM technologies to achieve projected yields. This creates a direct link between the ISFM technologies and the intended livelihood improvement through incomes expected to be generated.

Another factor that may facilitate the dissemination of ISFM involves the promotion of improved nutrition. CIALCA's baseline studies indicate that the primary underlying cause of malnutrition in the mandate areas is poor-quality diets, characterized by high intakes of food staples but low consumption of animal and fish products, fruits, and vegetables. Staple foods (overwhelmingly cassava, maize, and banana in this example) account for 80% of total per capita energy intake. As such, most of the malnourished are those who cannot afford to purchase highly nutritious foods and also lack access to agricultural technologies and knowledge to grow these foods. By incorporating legume-based products into local diets and demonstrating impact of improved dietary intake on nutrition, CIALCA is encouraging communities to adopt ISFM technologies. While dissemination and adoption of complete ISFM is the ultimate goal, substantial improvements in production can be made by promoting the greater use of farm inputs and improved germplasm within market-oriented farm enterprises. To minimize conflict between food security and income generation, an interdisciplinary approach is used to integrate expertise in farming systems analysis and agronomy, human nutrition, and development economics. Strategic partnerships are forged with a wide range of development partners including health-based NGOs, farmers' groups and community-based organizations to facilitate technology dissemination and uptake.

Conclusions: Key Lessons for Research, Development, and Policy

The main principles underlying ISFM have been shown to be applicable to maize- and cassava-based cropping systems in the African Great Lakes region. Combinations of different ISFM components have resulted in substantial added benefits through higher resource-use efficiencies. Nonetheless, responses to ISFM interventions were variable, highlighting the need for local adaptation and identification of interventions best suited for a particular production environment and household resource endowment.

The seed and fertilizer approach is providing substantial increases in productivity in Central Africa, and initial efforts should be directed towards increasing farmers' access to these inputs and associated information on how best to utilize them (e.g., avoidance of non-responsive soils). As productivity increases, approaches can gradually shift towards more complex interventions, but this will certainly require more intensive interaction with farming communities. Investment in input supply chains and engagement of farming households in output value chains are crucial to large-scale impact. Such investments are best underpinned by activities aimed at strengthening the ability of farmers' associations to work collectively in purchasing inputs and marketing their produce, increasing access to credit, and strengthening the abilities of farmers to manage financial and other resources.

Policy has a crucial role to play in delivering ISFM practices by facilitating access to agricultural inputs and credit, establishing an effective extension system, upgrading rural infrastructure (including feeder roads and local storage facilities), empowering women farmers or female-led households, and investing in national agricultural research capacity. Governments also have a role to play in ensuring that development organizations do not spread contradictory messages within farming communities; a number of such organizations are still advocating against the use of fertilizer and strongly promoting organic agriculture, which, based on ISFM research, is less likely to raise productivity following eco-efficient principles.

Lastly, monitoring and evaluating the performance of specific interventions under farmer-managed conditions is crucial to better understanding the relevance of these interventions and eventual adaptation of the processes of technology identification and dissemination. This can only be achieved in a meaningful way through investments in capacity building and community participation.

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CHAPTER 7

Enhancing Eco-Efficiency in the Intensive Cereal-Based Systems of the Indo-Gangetic Plains

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Contents

Abstract

The northwest and central parts of the Indo-Gangetic Plain (IGP) of South Asia are among the most productive agricultural regions of the world. But production is becoming unsustainable due to depletion or degradation of soil and water resources, rising production costs, decreasing input use efficiency, and increasing environmental pollution. In contrast, cereal production systems in the eastern IGP are largely traditional, with low yields and farm income. Eco-efficient farming can be used to enhance productivity throughout the IGP. Eco-efficient agriculture can borrow technologies or packages of practices from intensive agriculture and couple them with practices that reduce environmental impacts, such as laser-aided land leveling, reduced or zero tillage and direct/drill seeding, precise water management, crop diversification, and improved plant nutrient management. Such eco-efficient practices are expected to raise land and water productivity, improve resource use efficiency, reduce risks and vulnerability of cropping systems to climate change, diversify farm income, and improve family nutrition and livelihood. A comprehensive understanding of scientific, technical, environmental, economical, and societal issues, including farmers' re-education, are prerequisite to effectively promote eco-efficient farming practices.

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The Indo-Gangetic Plains

The Indo-Gangetic Plains cover some 700,000 km^2 in Bangladesh, India, Nepal, and Pakistan and are home to nearly one billion people.

Narang and Virmani (2001) divided the IGP into five subregions, based on physiographic, climatic, and vegetation patterns (Figure 7-1).

Subregions 1 and 2 (northwestern IGP) have a semi-arid climate with 400–800 mm annual rainfall. The land is gently sloping or flat. The topography is dotted with saucer-shaped depressions with poor drainage, locally named as *chaurs*. These create flood-plain lakes or wetlands with 50 to 400 cm water depth during the peak rainy season. They are more abundant in the eastern than in the western part of the IGP. In coastal areas, these depressions form the marshy/swampy lands. They are used as community fishing ground in the wet season, and for winter (*boro*) rice, maize and vegetable crops after the water recedes. Soils are alluvial and calcareous with some alkaline soils in pockets. The groundwater is mostly depleted or of marginal quality. Mean farm size is 3.55 ha, mostly irrigated and mechanized (Table 7-1). Some parts are intensively cultivated, with liberal application of chemical inputs, while agriculture in other areas is rainfed with limited use of inputs (Singh et al., 2009). Surface water and groundwater are used for irrigation and many farmers take full advantage of improved technologies to enhance crop yields and profit (Erenstein et al., 2007; Erenstein and Laxmi, 2008; Singh et al., 2009). Wheat and basmati and non-basmati long-grain rice are the main crops in subregion 1, while the main crops in subregion 2 are basmati and long-grain rice, wheat, maize, black gram (*Phaseolus mungo* L.), green gram or mung bean [*Vigna radiata* (L.) R. Wilczek], sunflower, potato, sugarcane, cowpea, and dhaincha (*Sesbania aculeata* Pers.) grown for green manure in rice-based systems (Gupta et al., 2005). The annual land use intensity (LUI) is relatively low (182%) (Singh et al., 2009).

In the central IGP (subregion 3), the climate is hot subhumid, with 650–970 mm of annual rainfall. The topography is mostly saucer-shaped (see description above for subregions 1 and 2). Soils are alluvial with pockets of alkaline soils on the plains and acidic soils on the hills. Major crops cultivated include rice, sugarcane, wheat, maize, soybean, cotton, potato, and pigeon pea in rice- or maize-based systems, with an annual LUI of 191%. Mean farm size is 0.94 ha (Table 7-1), with limited farm mechanization and adoption of resource-conserving technologies (RCTs) (Singh et al., 2009).

Figure 7-1. Five sub-regions of the Indo-Gangetic Plains (IGP) in South Asia.
SOURCE: Narang and Virmani (2001).

Table 7-1. Selected indicators of farmers' resource endowments and farm characteristics in the Indo-Gangetic Plains (IGP).

Particulars	Northwest IGP	Central IGP	Eastern IGP
Mean farm size (ha/household)	3.55	0.94	0.59
Share of operational land owned (%)	91	85	86
Irrigated land (%)	100	60	90
Rainfed land (%)	0	40	10
Depth to water table, 1997/98 (m)	11	8	32
Depth to water table, 2007/08 (m)	19	14	39
Annual land use intensity (% of cultivated area)	182	191	233
Crops			
Monsoon season	Rice, sugarcane, fodder, pearl millet	Rice, maize, pulses	Rice, maize, fiber crops, vegetables
Winter season	Wheat, sugarcane, fodder, vegetables	Wheat, vegetables, pulses, mustard	*Boro* rice, maize, vegetables, wheat
Livestock (per household)			
Cattle	4.3	1.4	1.9
Goats/sheep	0.7	1.1	1.9
Chickens	14.1	5.2	6.9
Agricultural implements			
Tractors (per 1,000 households)	260.6	36.3	2.0
Power tillers (per 1,000 households)	0.0	7.0	33.6
Zero-till seed drills (per 1,000 households)	35.2	10.9	0.0
Rotovators (per 1,000 households)	7.8	0.8	0.0
Reapers (per 10,000 households)	8.9	0.0	0.0
Combine harvesters (per 10,000 households)	5.1	0.0	0.0
Laser levelers (per 100,000 households)	2.5	0.0	0.0

SOURCE: Singh et al. (2009).

Eastern IGP (subregions 4 and 5) has a hot subhumid climate with a mild winter (5.4 °C in January) and higher rainfall (1000–1800 mm per year) than other regions. The land is gently sloping with alluvial, calcareous/alkaline, and acidic soils that are poorly drained. Flooding is a serious problem in this area. The rich groundwater resource is contaminated with fluoride and arsenic in some pockets. Half of the irrigated area is supplied with surface water and half using groundwater. Rice is the dominant crop, followed by potato, wheat, maize, sunflower, onion, jute, and lentil in rice-based cropping systems. Cropping intensity is quite high (LUI of 233%) (Singh et al., 2009) and mean farm size is only 0.59 ha (Table 7-1). Farmers are relatively poor, and use power tillers for land preparation and seeding (Singh et al., 2009). Farmers supplement their income with other activities such as working as laborers on other farms or in local industries, services, and businesses (Erenstein, 2009). Migration for off-farm employment is also common in other subregions.

Two or more crops are grown each year in most parts of the IGP. Rice followed by wheat (R–W) is the predominant cropping system in the IGP in India and Nepal, while double-cropping with rice (R–R) is the predominant cropping system in the IGP in Bangladesh, and cotton–wheat (Cot–W) is predominant in Pakistan (Table 7-2). Maize cultivation has increased in recent times both in terms of area and production in the eastern IGP because winter maize is more productive and profitable and requires less water than winter (*boro*) rice (Timsina et al., 2011).

Table 7-2. Major cereal cropping systems (area in m ha and % of total area) in four South Asian countries.

Cereal cropping	Bangladesh		India		Nepal		Pakistan		Total	
systems	m ha	%	m ha	%	m ha	%	m ha	%	m ha	%
R–W	0.60	5.05	9.20	11.81	0.57	18.15	2.20	17.09	12.57	11.88
R–R	4.50	37.88	4.70	6.03	0.30	9.55	–	–	9.50	8.98
R–R–R	0.30	2.53	0.04	0.05	–	–	–	–	0.34	0.32
R–M	0.35	2.95	0.53	0.68	0.43	13.69	–	–	1.31	1.24
R–Pulses	–	–	3.50	4.49	–	–	–	–	3.50	3.31
R–Veg	–	–	1.40	1.80	–	–	–	–	1.40	1.32
R–Potato	0.30	2.53	–	–	–	–	–	–	0.30	0.28
Cot–W	–	–	1.39	1.78	–	–	3.10	24.09	4.49	4.24
M–W	–	–	1.80	–	0.04	1.27	1.00	7.77	2.84	2.68
Millet–W	–	–	2.44	3.13	–	–	–	–	2.44	2.31

R = Rice; W = Wheat; M = Maize; Veg = Vegetables; Cot = Cotton;
– = refers to either data not available or negligible area.

SOURCE: Jat et al. (2011).

Cereals may also be alternated with other crops, such as potato, lentil, chickpea, mustard, or sunflower in winter; and jute, fodder maize, rice, mung bean, or cowpea during the spring season.

The area under R–W on the IGP trebled and production increased fivefold from 1960 to 2000 (Saharawat et al., 2009). Now, however, the cereal systems in subregions 1–3 are becoming more and more unprofitable and less sustainable due to yield stagnation, a 50% decline in total factor productivity, increasing production costs (high cost of land, labor, and chemical inputs), and declining returns from additional inputs (Ladha et al., 2003; Singh et al., 2009). Despite this, farmers continue to intensify R–W systems and are reluctant to diversify to crops with lower water requirements, mainly because of high subsidies for power, fertilizer, and irrigation water, and well-developed production and marketing systems for rice and wheat in the region (Erenstein, 2009; Saharawat et al., 2009). In the eastern IGP (subregions 4 and 5), rice and wheat are produced in traditional, labor-intensive systems on small (average 0.59 ha) farms. Frequent droughts, flooding in the monsoon season, late rice harvests which delay planting of wheat, and limited use of inputs are common and lead to low productivity and returns (Gupta and Seth, 2007). However, LUI is high (233%) because of year-round cropping (Erenstein, 2009; Singh et al., 2009).

The problems of both regions of the IGP can be addressed through adoption of eco-efficient agriculture that enhances and sustains productivity and profitability of the rice-, wheat-, and maize-based systems while minimizing the adverse impact on the environment.

Rising Demand, Declining Yields: The Need for Eco-Efficient Agriculture

It is estimated that demand for food and non-food commodities is likely to increase by 75–100% globally between 2010 and 2050 (Keating et al., 2010; Tilman et al., 2011). The increase in demand in South Asia is expected to be at least as much. As there is little scope for expanding the area under cultivation in South Asia, there is thus an urgent need to further intensify land use and increase productivity of cereal systems to meet the growing demand. Projections indicate that production of rice, wheat, and maize will have to increase by about 1.1%, 1.7%, and 2.9% per year, respectively, over the next four decades to ensure food security in South Asia (O. Erenstein, pers. comm.). National mean yields of all three cereals in South Asia are below global averages (except for maize in Bangladesh) and yield gaps of 50% or more exist in all the three crops (Table 7-3) (Aggarwal et al., 2008; Lobel et al., 2009). Thus, there is a

Table 7-3. Yields (t/ha) and yield gaps (t/ha) for rice, wheat, and maize in sub-regions of the Indo-Gangetic Plains (IGP).

Yield and	Northwest			Central	Eastern	
yield gaps	Pak. Punjab	Indian Punjab	Haryana	Uttar Pradesh	Bihar	Bangladesh
Rice (Paddy)						
Potential yield	5.2(M); 3.8(F)	8.8(M); 6.5(E)	6.6(E); 5.9(F)	6.1(M); 6.6(E)	5.5(M); 6.1(E)	5.4(E); 7.1(E)
Average yield	3.6(M); 1.6(F)	5.0(M); 5.0(E)	5.0(E); 4.7(F)	3.1(M); 2.9(E)	2.0(M); 1.8(E)	4.6(E); 6.3(E)
Yield gap	1.6(M); 2.2(F)	3.8(M); 1.5(E)	1.6(E); 1.2(F)	3.0(M); 3.7(E)	3.5(M); 4.3(E)	0.8 (E); 0.8(E)
Wheat						
Potential yield	6.8(M); 4.6(F)	5.5(M); 4.6(E)	4.0(M); 5.4(E)	5.0(M); 3.8(E)	3.8(M)	4.2(F); 3.4(E)
Average yield	2.7(M); 2.5(F)	4.1(M); 4.1(E)	3.8(M); 4.2(E)	2.5(M); 2.5(E)	2.2(M)	2.9(F); 2.5(E)
Yield gap	4.1(M); 2.1(F)	1.4(M); 0.5(E)	0.2(M); 1.2(E)	2.5(M); 1.3(E)	1.6(M)	1.3(F); 0.9(E)
Maize						
Potential yield	9.2(M); 6.9(F)	5.1(M)	–	3.0(E)	5.7(E)	9.0(M)
Average yield	3.5(M); 1.9(F)	2.6(M)	–	1.3(E)	1.7(E)	5.7(M)
Yield gap	5.7(M); 5.0(F)	2.5(M)	–	1.7(E)	4.0(E)	3.3(M)

(M): Model-based; (E): Experimental on-station or on-farm; (F): Farmers' best yield.

great potential to increase the yields of major cereals in South Asia (Ladha et al., 2009; Timsina et al., 2011).

Economic and environmental concerns

Energy use is generally high in intensive cereal production systems. Of the total energy used for crop production, fertilizer and chemical energy inputs comprise 47% for wheat, 43% for rice (Khan et al., 2009b), and 45% for maize (Kraatz et al., 2008). About 60% of this is due to nitrogen (N) fertilizers alone. In the R–W system in northwest IGP, most of the energy is used for land preparation—wet tillage and puddling for rice and preparatory tillage operations for wheat, pump irrigation, and combine harvesting. Conventional tillage is not only fuel- and cost-inefficient, it also contributes to a larger carbon footprint through increased emission of CO_2 (Grace et al., 2003).

The liberal or excessive use of natural resources and external inputs such as N fertilizers and other agrochemicals in the western and central regions of IGP has caused environmental and ecological degradation—soil degradation (salinity and alkalinity, soil erosion), depletion of soil organic matter due to oxidation of soil carbon under conventional tillage, depletion of groundwater in large areas, pollution of surface and groundwater, and leakage of reactive N into the environment (Bijay-Singh et al., 2008).

Power subsidy to farms leads to inefficient use of electricity, particularly for pumping water. For example, in 2007, 7.5 billion units of electricity (28% of total power consumed in the state) were used for tube-wells in Punjab alone, in addition to the diesel consumed (Anonymous, 2008).

As a result of excessive exploitation of groundwater, the depth to water table has increased steadily in many areas (Hira and Khera, 2000; Hira, 2009; Rodell et al., 2009), for example, by 0.2 m/year between 1973 and 2001 and by 1 m/year between 2000 and 2006 in Punjab (Humphreys et al., 2010). The rates of groundwater depletion were greatest in the northwest Indian IGP: in 2009, groundwater was overexploited in 103 out of 138 administrative blocks in Punjab and 55 out of 108 in Haryana (Humphreys et al., 2010). With the continued decline in water table, power consumption for tube-well irrigation will double by 2023 and the cost to farmers of maintaining pump infrastructure and replacing failed pumps will escalate. Moreover, saline groundwater is intruding into fresh groundwater aquifers (Humphreys et al., 2010). Fluoride and arsenic contamination of groundwater is also a problem in some areas of the IGP. Fluoride in groundwater above the safe limit of 1.5 mg/liter has been recorded in five districts of Bihar, two districts of Chhattisgarh, four districts of Jharkhand, and seven districts each of Uttar Pradesh and West Bengal. Similarly, occurrence of arsenic above the safe limit of 0.01 mg/liter in groundwater from the intermediate aquifer at a depth of 20 to 100 m has been observed in 12 districts of Bihar, five districts of Uttar Pradesh, and one district each of Chhattisgarh and Assam (Anonymous, 2008; Hira, 2009).

Agricultural systems in northwest and central IGP also produce large amounts of greenhouse gases (GHGs), particularly from flooded rice fields (Pathak et al., 2002; Pathak et al., 2003; Bhatia et al., 2010; Pathak et al., 2011). While emission of methane (CH_4) from flooded rice systems can be reduced by adopting different water and crop management strategies (Adhya et al., 2009; Gupta-Vandana et al., 2009), such changes, plus increased N fertilizer use, in intensive cereal systems would be likely to increase production of nitrous oxide (N_2O), another GHG (Pathak et al., 2007; Wassmann et al., 2009). This trade-off between CH_4 and N_2O emissions is a major limitation in devising an effective strategy for mitigating GHG emissions from the R–W system (Ladha et al., 2009). Burning of rice residues to clear the land for wheat also releases large amounts of CO_2 into the atmosphere (Ladha et al., 2003). Farm machinery, including the pumps used for irrigation, emitted 283–437 kg CO_2-C/ha of rice and 33–58 kg CO_2-C/ha of wheat in a R–W system (Pathak et al., 2011).

Clearly, new approaches are needed to develop agricultural production systems that are productive and sustainable, both economically and ecologically. Eco-efficient agriculture offers such an approach.

Eco-Efficient Agriculture

Eco-efficiency is concerned with the efficient and sustainable use of resources in farm production and land management. It can be increased either by altering the management of individual crop and livestock enterprises or by altering the land use system. Conceptually the eco-efficiency seems to be similar to the concepts of ecological intensification (Cassman, 1999; Dobermann et al., 2008) and conservation agriculture (CA) (Hobbs et al., 2008), while encompassing both the ecological and economic dimensions of sustainable agriculture. In addition to the economic aspect, evolving social, institutional, market-, and policy-related pressures will determine the extent of development of eco-efficient agriculture (Keating et al., 2010).

At the farm level, eco-efficiency might be represented in terms as diverse as food output per unit labor, the biodiversity benefits provided by retention of natural habitat per unit food production, or the aggregate food output per unit water or fertilizer applied (Keating et al., 2010). Production increases of the last 50 years were achieved at significant cost to the natural resource base (degraded soils and ecosystem impacts, including habitat fragmentation threatening biodiversity) as well as the global environment. Future production increases must come from stabilizing yields in areas where yields are already high and increases in production in areas where yields are currently low, while promoting ecological sustainability. The agricultural revolution over the next 40 years has to be the eco-efficiency revolution, with 50 to 100% increases in the efficiency with which scarce resources of land, water, nutrients, and energy are used. Importantly, this greater output and efficiency has to be achieved while maintaining or restoring land, water, biodiversity, and agroecosystems.

Practices that have been shown to increase the productivity and eco-efficiency of agriculture at the farm level include resource-conserving technologies (RCTs) such as laser land leveling and direct seeding (Hobbs and Gupta, 2003; Ladha et al., 2003; Sharma et al., 2005; Gupta and Seth, 2007; Harrington and Hobbs, 2009; Ladha et al., 2009), integrated crop management (ICM) (Nguyen, 2002; Balasubramanian et al., 2005), integrated crop and resource management (Ladha et al., 2009), integrated farming systems (Hesterman and Thorburn, 1994), and integrated soil–crop system management (Chen et al., 2011).

These and other components of eco-efficient agriculture are discussed in more detail below.

Key Components of Eco-Efficient Agriculture in the IGP

Laser leveling and land preparation

Integrating laser leveling with other best management practices has been shown to increase productivity of R–W systems by 7–19% and reduce water consumption for irrigation by 12–30% in on-station and farmer-participatory trials in India, increasing net returns by US$113–US$300/ha per year (Jat et al., 2009). This has been reflected in a rapid increase in the number of laser units employed in the northwest Indian IGP between 2001 and 2008, from zero to 925 and in the laser-leveled area from zero to 0.2 m ha (Jat et al., 2009; Ladha et al., 2009). The laser-leveled area in Pakistan increased from zero to 0.18 m ha during the same period (Harrington and Hobbs, 2009; M. Ahmed, pers. comm.).

Reduced/zero tillage and direct/drill seeding

Zero-tillage (ZT) wheat has been the most successful technology for reducing resource use in R–W systems, particularly in the Indian IGP. The prevailing ZT technology in the IGP uses a tractor-drawn zero-till seed drill to drill wheat directly into unplowed fields with a single pass of the tractor. The ZT drills are made domestically at a cost of around US$400 (Thakur, 2005). Alternatively, wheat seed can be broadcast on a saturated soil surface before or after the rice harvest (Erenstein and Laxmi, 2008). This is ideal for poor farmers, requiring no land preparation or machinery, but its use is still largely confined to low-lying fields that remain too moist for tractors to enter, particularly in the eastern IGP.

ZT as applied to the R–W systems in the IGP has three characteristic features that separate it from related systems elsewhere (Erenstein, 2003). First, ZT is typically applied only to the wheat crop in the double-cropped system, with the subsequent rice crop still intensively tilled. Second, ZT wheat after rice does not necessarily entail an increased reliance on herbicide, as the paddy rice fields are relatively weed free at harvest time. Third, ZT wheat does not necessarily imply the retention of crop residues as mulch. In fact, the prevailing Indian ZT seed drills are relatively poor in trash handling, but this has not been a major issue in view of the limited biomass remaining in R–W systems after the rice crop (Erenstein et al., 2007).

Combining precision land leveling, ZT, and drill seeding wheat with leaving crop residues on the soil surface quadrupled farmer income compared with reduced-till or conventional-till wheat, mainly due to higher yields resulting from timely planting and reduced tillage cost (Gupta and Seth, 2007; Jat et al., 2011). Smallholders in the eastern IGP have also increased yields and reduced costs by adopting ZT for broadcast seeding of wheat (Gupta et al., 2003). It is estimated that 20–25% of the wheat area in northwest IGP is now under zero or reduced tillage, with or without crop residues left on the soil surface (Erenstein, 2009).

Similarly, direct seeding of rice has the potential to provide several benefits to farmers and the environment over conventional practices of land preparation such as puddling and transplanting. Recently, Kumar and Ladha (2011) reviewed the benefits of direct seeding compared with transplanting into puddled soil, which typically include reduction in irrigation water use (12–35%), labor (0–46%), and cultivation costs (2–32%); higher net economic returns, and reduced methane emissions. However, yields are lower in some cases, especially with dry seeding combined with reduced/zero tillage, as a result of uneven and poor crop stand, poor weed control, higher spikelet sterility, crop lodging, and poor knowledge of water and nutrient management. Most rice varieties are bred and selected for transplantation into puddled land. Risks associated with a shift from puddle transplanting to direct seeding include a shift toward hard-to-control weed flora; development of herbicide resistance in weeds; evolution of weedy rice; increases in soil-borne pathogens and pests such as nematodes; higher emissions of nitrous oxide—a potent GHG; and nutrient disorders, especially N and micronutrients. Grain yields and net income were lower from reduced-till and zero-till direct-seeded or bed-planted rice than from conventional rice, despite significant savings in water use (Ladha et al., 2009; Gathala et al., 2011; Jat et al., 2011). This was because of increased weed infestation. Further research is needed to develop suitable weed control technologies for direct seeded rice systems (Kumar and Ladha, 2011).

Thus, direct seeding of rice will be adopted only once an integrated package of technologies has been developed, including improved weed control and cultivars that perform well under these conditions.

Water management

As already noted, water consumption can be significantly reduced by directly seeding rice into dry soil instead of transplanting into puddled soil (Bhuiyan et al., 1995; Bouman, 2001; Cabangon et al., 2002; Sharma et al., 2002), and by growing rice on raised beds (Borrel et al., 1997). However, yields on raised beds may be reduced by 15% or more compared with traditionally-grown rice (Sharma et al., 2002; Vories et al., 2002; Gathala et al., 2011). Similarly, other water conservation techniques, such as crop-need-based water application, alternate wetting and drying (AWD), aerobic rice culture. Would both increase water use efficiency and irrigated crop area (Cabangon et al., 2002; Bouman et al., 2005; Bhushan et al., 2007; Gathala et al., 2011). For example, AWD irrigation of rice transplanted into puddled soil reduced water use by 25% with little impact on yield (7-year average of 7.8 t/ha compared with 8.1 t/ha) (Gathala et al., 2011).

Some of the water conservation technologies have positive impacts on resource use and the environment, such as increased water infiltration leading to groundwater recharge, lower energy use due to less pumping of water, enhanced soil quality, reduced methane emissions, and short-term carbon sequestration in soil due to retention of crop residues instead of burning (Jat et al., 2011).

Crop diversification

Farmers in the IGP are being encouraged to grow high-value crops, such as vegetables, fruits, and cut flowers, and to expand production of fodder crops and livestock/dairy farming for both local and export markets. In the central and eastern IGP, farmers following the R–W system leave land fallow for about 60–70 days in the pre-monsoon (pre-*kharif*) season, after the wheat harvest. Growing short-season pulses, such as mung bean (green gram), black gram; green manure crops, such as *Sesbania*, vegetables, or other high-value crops during this period would diversify the R–W cropping system, improve soil quality, and increase farmers' income (Gupta and Seth, 2007; Singh et al., 2007).

Integrated crop–fish/poultry/duck/livestock systems also would diversify farm income, improve food and nutritional security, enhance land and water productivity, and preserve ecosystems (Ayyappan et al., 2009).

Plant nutrition management

Nitrogen sources and nitrogen use efficiency in eco-efficient farming

Efficient N use is central to eco-efficiency in agriculture (Keating et al., 2010). The term nitrogen use efficiency (NUE) relates only to applied fertilizer N, although crops absorb N from other sources. Four agronomic indices are commonly used to measure NUE in crops and cropping systems: (a) partial factor productivity (PFP_N), expressed as the total grain yield per unit of N applied; (b) agronomic efficiency (AE_N), expressed as the increase in grain yield over that of the zero-N control per unit of N applied; (c) apparent recovery efficiency (RE_N), defined as the percentage of applied N absorbed by the crop in aboveground biomass; and (d) internal or physiological efficiency (PE_N), defined as the increase in grain yield over that of the zero-N control per unit of N acquired by the crop (Novoa and Loomis, 1981; Ladha et al., 2005).

Two key factors that influence crop yields and RE_N in cereal cropping systems are the spatial and temporal synchronization of applied N with crop demand and use of N-efficient crop cultivars (Tilman, 1998; Balasubramanian et al., 2004; Ladha et al., 2005; Balasubramanian, 2010). For example, application of N in transplanted rice in the IGP (551 farms) based on need indicated by a leaf-color chart (LCC) increased grain yield by 0.24 to 0.75 t/ha and net income by US$41 to US$49/ha (Regmi and Ladha, 2005; Varinderpal-Singh et al., 2007; Ladha et al., 2009). Takebe et al. (2006) demonstrated that applying the correct N dose at full heading stage increased the wheat protein content to more than 120 g/kg.

Balanced fertilizer use is also critical. For example, Norse (2003) has shown that application of fertilizer with unbalanced N–P_2O_5–K_2O ratios (e.g., 100–36–19 in China, 100–37–12 in India, and 100–35–45 in USA) may diminish plant utilization of applied N and thus reduce NUE. Deficiency of calcium, magnesium, sulfur, and micronutrients reduce plant response to N and hence reduce NUE (Aulakh and Bahl, 2001; Aulakh and Malhi, 2004; Mosier, 2002). Thus, deficiency of nutrients other than N must be corrected to get an optimal response to N (Ladha et al., 2005).

Soil and soil organic matter

Soil organic matter (SOM) is a key component of soil health and acts as a temporary storehouse of nutrients. It is reported that more than 50% of crop N is obtained from SOM in most soils except coarse textured sandy soils (Dourado-Neto et al., 2010). Crops use applied N more efficiently in organic-matter-rich soils than in organic-matter-poor soils.

Maintenance of SOM is critical for increasing eco-efficiency in farming, especially in tropical soils. Fertilizer N added to soil plays both a constructive and a destructive role in the maintenance of SOM (Ladha et al., 2011). Application of fertilizer N increases production of biomass, part of which is added to soil to enrich SOM (Sisti et al., 2004). However, fertilizer N also increases mineralization of SOM. Oxidization of SOM is also promoted by conventional tillage, removal of vegetation cover, and exposure of the soil to the sun's radiation (Khan et al., 2007; Powlson et al., 2010).

Overall, practices such as ZT, maintenance of permanent groundcover, and crop rotation help increase SOM levels and thus maintain soil health and crop productivity (Ladha et al., 2009; Jat et al., 2011).

SOM levels can also be increased by applying organic materials, including crop residues, green manure, and animal manure, and biowaste, such as byproducts from food processing and city/municipal biowastes (Yadvinder-Singh et al., 2005; Sidhu et al., 2008), as can crop productivity and fertilizer use efficiency (Ladha et al., 2011). However, organic materials such as crop residues and animal manures have competing uses (fodder, fuel, roofing material) and thus their availability for use as a soil amendment is limited (Erenstein, 2009). Also, conventional practices of organic amendment, such as incorporation and composting, are labor intensive. Therefore, in-field cycling of available crop residues is likely to be the most effective and least expensive option for the farmers (Yadvinder-Singh et al., 2011).

Integrated nutrient management

The ideal approach for eco-efficient agriculture is integrated nutrient management (INM), or optimum use of all available nutrient sources—SOM, BNF, crop residues, manures, and mineral fertilizers. The integrated soil fertility management in Africa (Vanlauwe et al., 2004), site-specific nutrient management in Asia (Dobermann and White, 1999; Dobermann et al., 2004; Buresh, 2010), and integrated plant nutrient systems (Bruinsma, 2003) are some of the efforts to promote the efficient use of various nutrient sources. INM can save 5–30% of fertilizer N and increase grain yield by 10–15% (Vanlauwe et al., 2002; Balasubramanian et al., 2004; Dobermann and Cassman, 2004; Ladha et al., 2005; Bijay-Singh et al., 2008; Buresh, 2010). Stress-tolerant crop varieties, when combined with INM systems and ICM, increase grain yields and NUE even under stressful conditions (Havlin, 2004; Ortiz et al., 2008; Ribaut et al., 2009; Ali-Jauhar and Santlaguel, 2011).

Intensive Eco-Efficient Agricultural Systems

Globally, the demand for food and agricultural products is projected to double by 2050 (Keating et al., 2010). Given that only 7 to 12% of the projected increase in food production between 2010 and 2050 is likely to come from expansion of arable land area (Fischer et al., 2005), most of the increase will have to come from intensification of existing production systems —13–15% from increased cropping intensity and 75–76% from increased yields (Fischer et al., 2005, 2007). This can be achieved sustainably only through eco-efficient agriculture. Here we present three examples of eco-efficient agricultural systems operating successfully in the IGP that could be replicated in other similar agroecological zones.

Intensive eco-efficient cereal production systems in the northwest and central IGP

Intensive irrigated cereal production systems of the northwest and central IGP combine CA practices with efficient water, nutrient, and pest management. Land management, crop establishment, and crop management practices employed include land leveling, ZT, direct/drill seeding, deep placement of fertilizer N, residue mulch, and diverse crop sequences/rotations. The systems achieve land productivity of 70–90% of site yield potential for major crops; water productivity of 0.8 to 1.0 kg grain/m^3 water for rice and 2.0–2.5 kg grain/m^3 water for maize and wheat; agronomic N use efficiency of 20–25 kg additional grain/kg N applied for rice and wheat and 25–30 kg additional grain/kg N applied for maize; crop N recovery efficiency of significantly more than 50%; reduce farm energy use by 40–50%; reduce methane and N_2O emission by 40–50%; and increase soil organic matter to 2–3% in most soils except in sandy soils. The systems are thus highly productive and profitable, efficient in resource use and conservation, enhance ecological efficiency and climatic resilience, improve soil quality, preserve biodiversity, and have minimal environmental footprints (Gupta et al., 2003; Gupta and Seth, 2007; Harrington and Hobbs, 2009; Ladha et al., 2009). Such systems currently occupy some 4 million hectares of land in the IGP.

Integrated farming systems for rainfed lowlands

Integrated farming systems (IFSs) are a natural resource management strategy advocated by the Central Rice Research Institute (CRRI), Cuttack, India. The objective is to achieve economic and sustainable production of diverse products to meet farm families' needs and to cater to local market demands, while preserving the resource base and maintaining environmental quality (Hesterman and Thorburn, 1994). Generic IFS models developed by CRRI integrate cropping with horticulture, fish, poultry, ducks, pigs, sericulture, mushroom culture, bee-keeping, farm woodlots, depending on agroclimatic and socio-economic conditions (Table 7-4). A micro watershed (15–18% of the farm area) is used to drain excess water from rice fields during floods in deepwater ecosystems, and to provide one or two supplementary irrigations for field crops during periods of drought. All crop residues and other farm wastes, including animal droppings, are recycled or composted and returned to the land. Initial cost of earth works for land shaping ranges between US$2900 and US$3300/ha.

IFSs have been shown to stabilize crop production (especially in rainfed ecosystems); enhance resource recycling; ensure efficient use of all inputs; generate year-round employment; improve farm income, cash flow, and family nutrition; and maintain healthy ecosystem services in the face of biotic, abiotic, and environmental stresses and climate-change-induced extreme weather events in the lowlands (Srivastava et al., 2004; Mangala, 2008). The benefit/cost ratio increased from 1.89 for rice alone to 2.27 for rice plus horticultural crops, 2.80 for rice plus horticultural crops and fish, and to more than 3.00 if ducks were added to the system (Srivastava et al., 2004). The IFS model for rainfed medium lowland has been adopted on 100 ha of land in Orissa State, India, and the model for deepwater areas on 40 ha. These IFSs could be expanded to the eastern IGP, but this would require financial assistance to help with the costs of initial land shaping, training of and technical support to farmers during the first year of adaptation and adoption, and development of market access for the multiple products produced in the IFS.

Integrating grain legumes in the rice–wheat system in Bangladesh

Incorporating grain legumes in the R–W system has the potential to increase farm income,

Table 7-4. Characteristics, land-shaping cost, productivity, employment generation and income of integrated farming systems (IFSs) developed for irrigated, rainfed medium lowland, and deepwater areas.

Rice–fish–multicrop IFS model for irrigated lowland	Rice–fish–horticulture–farm animals IFS model for rainfed medium lowland	Multi-storey rice–fish–farm animals–agroforestry IFS model for deepwater ecology
		
Upland (15% of area) + 2–3-m-wide bunds (20% of area): perennial & seasonal fruit crops & trees; tubers, vegetables, ducks, poultry, mushroom, bee-keeping Irrigated lowland rice (50% of area): rice–pulse/oil seed/vegetable crops Micro watershed (15% of area): fish refuge, aquaculture, irrigation during droughts	Upland (15% of area) + 2–3-m-wide bunds (20% of area): perennial & seasonal fruit crops & trees; tubers, vegetables, goats tethered, rabbits in cages, ducks, poultry Rainfed lowland rice (40% of area): rice–pulse/oil seed/vegetable crops Micro watershed (18% of area): fish refuge, aquaculture, irrigation during droughts Fish nursery (7% of area): fingerlings	Upland (15% of area) + 2–3-m-wide bunds (20% of area): perennial & seasonal fruit crops & trees; tubers, vegetables, goats tethered, rabbits in cages, ducks, poultry Rainfed lowland rice (20% of area): rice–pulse/oil seed/vegetable crops Deep-water rice (20% of area): Deep-water rice–summer/*boro* rice Micro watershed (18% of area): fish refuge, aquaculture, irrigation during droughts Fish nursery (7% of area): fingerlings
Initial investment: US$2900 to 3300/ha		
Productivity in t/ha per year: Food crops: 16–18 Fish + prawns: 0.4–0.5 Bird meat: 0.5–0.7 Animal fodder/feed: 5–6 Flowers, fuel wood, etc.	Productivity in t/ha per year: Food crops: 16–18 Fish + prawns: 0.5–0.6 Meat: 0.5–0.8 Animal fodder/feed: 5–6 Eggs (number): 8,000 Pearl, flowers, wood, etc.	Productivity in t/ha per year: Food crops: 14–15 Fish + prawns: 1 Meat: 0.5–0.8 Animal fodder/feed: 3–5 Fuel wood: 10–12
Additional employment: 250–300 person days/ha per year	Additional employment: 400–450 person days/ha per year	Additional employment: 400–500 person days/ha per year
Income per ha per year: US$1300–US$1600	Income per ha per year: US$1800–US$2900	Income/ha per year: US$2200–US$3300
Teak trees on bunds can be sold at maturity (30+ years) to meet large family expenses		

SOURCE: Central Rice Research Institute, Cuttack, India.

improve soil fertility, and thus enhance the sustainability of the farming system. For example, farmers in Bangladesh planting mung bean, during the short fallow period between winter wheat and monsoon rice, earned more than US$600/ha more than those who left the land fallow (A. Sarkar, pers. comm.). Improved short-duration, salt-tolerant crop varieties (e.g., BARI mung-6 in Bangladesh, hybrid pigeonpea in India) could intensify or diversify crop production in the IGP (Dahiya et al., 2002; Khan et al., 2009a).

Summary and Conclusions

Intensive eco-efficient farming has an important role to play in addressing existing and emerging problems of intensive cereal production systems in the IGP.

In the water-poor northwest IGP, changes envisaged include enhancing eco-efficiency in intensive cereal production systems and replacing rice with crops with lower water requirements. In the rainfall- and groundwater-rich eastern IGP, viable options include integration of irrigated *boro* rice, maize, and annual crops, such as sugarcane and banana, inclusion of grain or green manure legumes in the R–W cropping system, and intensification of rice-based cropping systems and crop–livestock systems. Generic IFS models have been developed that employ land leveling and micro watershed to grow rice, upland crops, fruit trees, timber trees, produce fish and poultry, and support bee-keeping and sericulture. However, although the system has been shown to stabilize crop production, enhance resource use efficiency and recycling, generate year-round employment, improve income, cash flow and family nutrition, and maintain healthy environment, farmer adoption is still limited.

Improving the productivity of farm-scale eco-efficient agriculture to the level achieved on research plots will be a challenge as it requires transfer of complex and knowledge-intensive principles and practices to millions of smallholder farmers. This will require massive concerted efforts in six areas:

- Large-scale training or technical mentoring programs in eco-efficient agriculture for agricultural scientists, extension workers, and farmers.
- Development of appropriate machinery and farm machinery rental services to allow farmers to adopt conservation agriculture practices and integrated soil, water, and crop management technologies.
- Research and development based on farmers' feedback to solve practical problems in the adoption of CA and related integrated crop management technologies.
- Development of local champions to showcase and promote the best management practices and other technologies to farmers in their respective areas.
- Development of price support and markets for new agricultural products produced in integrated farming systems.
- Focused institutional and policy support, including appropriate incentives and crop insurance to reduce risks for the widespread dissemination and adoption by farmers of intensive eco-efficient agricultural practices in the IGP of South Asia.

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CHAPTER

8

Improving Resource Use Efficiency and Reducing Risk of Common Bean Production in Africa, Latin America, and the Caribbean

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Contents

Abstract

Common bean (*Phaseolus vulgaris* L.) is the most important food legume in tropical Latin America and East and Southern Africa. Beans originated in the mid-altitude neotropics with moderate soil fertility conditions. Typically, they are not well adapted to extreme climatic and edaphic environments. Climate change will alter distribution and intensity of biotic constraints to bean production, and more intense droughts will adversely affect important production regions in Mexico, Central America, the Caribbean, and Southern Africa. In the tropics, the crop is cultivated largely by poor farmers, often on soils that are deficient in nitrogen and phosphorus. Both climatic and edaphic constraints cause severe yield losses. They are widespread, often intense, and occur every year in the case of heat and soil problems. Developing the right root system to cope with root rots, drought, and soil problems in each production environment will be a major research challenge. Genetic improvement for resistance to major biotic and abiotic constraints will have significant and wide impact. Fertilizers that improve plant vigor, root growth, and access to soil moisture, or irrigation to counter drought, are seldom viable options for small-scale farmers. While programs to subsidize such inputs merit consideration, crop improvement through plant breeding will probably be the cornerstone of adapting beans to climate-smart production systems in the tropics. The secondary and tertiary gene pools of common bean cover a range of environments from cool moist highlands to hot semi-arid regions, and will be important resources for the genetic improvement of common bean as it must increasingly confront extremes of heat, drought, and excess moisture.

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Background Information and System Description

Common bean (*Phaseolus vulgaris* L.) is a traditional crop of the neotropics, where it was domesticated several thousand years ago (Freytag and Debouck, 2002; Chacón et al., 2005). In Central America it formed an essential part of the diet as one of the "three sisters"—maize, beans, and squash. Its central role in the livelihoods of the original inhabitants of the American continent is illustrated by its frequent representation in artwork. It continues to be an essential part of the diet in tropical America, as well as in East and Southern Africa, where it was introduced about 400 years ago (Greenway, 1945), and many other parts of the world.

Wild beans

Many of the issues of adaptation of the modern cultivated bean can be traced to its wild ancestor. Knowledge of this wild ancestor and its native environments can elucidate patterns of adaptation of the cultivated bean and identify some of the challenges that breeders and agronomists face in confronting environmental stress.

The wild bean is a vigorous annual liana of 6 to 10 months duration that depends on its vegetative vigor to outcompete surrounding vegetation. It originated in a subhumid premontane forest, typically at mid-altitudes of 1200 to 1800 meters above sea level (masl) and with moderate temperatures (Toro et al., 1990). Soils in this environment typically are organic with reasonable drainage and moderate fertility. Weather patterns are characterized by well-defined wet and dry seasons and abundant total rainfall, but often with a dry period of 2 to 4 weeks or longer in midseason between peaks of bimodal rainfall. Thus, with the possible exception of the dry highlands of Mexico where drought is endemic and occasionally intense, the wild ancestor was not often exposed to extreme environments of soil, temperature, or drought. This fact influences the adaptation range of the species and of cultivated beans, and represents a particular challenge to efforts to adapt the crop to more challenging environments, especially as these evolve under the influence of climate change.

Cultivated beans and genetic diversity

The cultivated bean was domesticated in its mid-altitude environment both in the southern Andes and in Mesoamerica, resulting in two contrasting gene pools that have been subdivided into races (Blair et al., 2009). The Mesoamerican gene pool has been subdivided into four genetic groups or races (Beebe et al., 2000), while three races have been defined in the Andean gene pool based on plant morphology and adaptation range (Singh et al., 1991). From these regions, beans were carried into environments with stresses that were different from what they likely confronted in their wild state. The cultivated bean has thus been adapted to wider environments, either by empirical selection by plant domesticators and farmers or through systematic selection by plant breeders (Beebe et al., 2011a).

Beans in cropping systems

Primitive bean varieties in Mexico, Central America, and the Andes were vigorous climbers and were planted with maize for physical support in altitudes from 1200 to 3000 masl. Semidomesticated types might have been collected from the wild with little or no human intervention during the growth cycle (Beebe et al., 1997b). Subsequently, less aggressive plant habits were selected for cultivation as semi-climbing beans in a relay system with mature maize stalks as support, or between rows of maize, cassava or other crops, or as a sole crop.

As beans were moved into still-lower altitudes, they confronted less favorable environments. In Central America and Brazil, they are frequently cultivated between 400 and 1000 masl with much higher temperatures than the wild ancestor experienced. In Brazil, currently the largest single bean producer in the world, bean is grown on the drought-prone sandy soils of the northeast and acid infertile soils of the Cerrados (Thung and Rao, 1999).

The crop was probably introduced to Africa by Portuguese traders early in the 17th century, where it met with great success in the Great Lakes region. Highland Africa is now regarded as a secondary center of diversity for the common bean and the crop is an important contributor to food security in the region (Asfaw et al., 2009). In Africa bean has found its niche in a similar mid-altitude environment as it occupies in the Americas, occasionally interplanted with maize or other crops such as cassava, banana, and pigeon pea (Wortmann et al., 1998). Bush bean varieties are adaptable to various cropping systems due to their short growing cycle, while climbing varieties have been cultivated in the highlands of East Africa for many years at elevations of 2000 masl or higher. In the mid-1980s, CIAT introduced Mesoamerican climbing beans with adaptation to altitudes of 1500–1800 masl. Beans have now been pushed into the dry eastern hills of Kenya and northern Tanzania, into environments that represent frontiers of adaptation for the common bean and a challenge for breeders and agronomists to improve adaptability.

In modern times in Latin America, it is more common to find beans planted as a sole crop than as an intercrop. Even in the traditional systems with maize in Central America, most farmers prefer to plant varieties with bush growth habits that require less labor to harvest than the traditional association or relay systems where the bean must be untangled from the maize stalk. In Argentina, Brazil, on the Pacific coast of Mexico, and in the USA, beans have become a commercial crop with high inputs and mechanization. Modern varieties have upright plant habit with an eye to direct mechanical harvest. In these commercial systems, bean cultivation responds to market demand and competes with other commercial crops, especially soybean and maize. In Africa, beans are gaining an important place on the export market and are considered an important source of household income.

Major Constraints for Target Production System

Table 8-1 lists the major production constraints to common bean production, including biotic (fungal, bacterial, and viral diseases; insect pests) and abiotic (drought, heat, nitrogen [N] and phosphorus [P] deficiency; acid soil) stress factors. This topic has been reviewed by Singh (1999), Rao (2001), Miklas et al. (2006), and Beaver and Osorno (2009).

Diseases and pests

Diseases and pests are universal constraints to bean production, especially fungal pathogens (Schwartz and Pastor-Corrales, 1989; Wortmann et al., 1998). Diseases may cause 80–100% yield loss while pest damage, especially during the early seedling stage and pod formation, also causes severe yield losses. Anthracnose, rust, and angular leaf spot are widely distributed, while rhizoctonia web blight and ascochyta blight can be locally intense in warm-moist and cool-moist environments, respectively. In the past few decades, root rots have emerged as a greater problem (Abawi and Pastor-Corrales, 1990), especially those caused by *Pythium* spp. and *Fusarium* spp. Intense cultivation under increasing population pressure, without fallow periods or adequate crop rotations, results in declining soil fertility or soil compaction, or both, and in build-up of pathogen inoculum in the soil (Wortmann et al., 1998). Reduced soil quality inhibits root growth and the potential for plant recovery after infection. *Fusarium* spp. are a major constraint in Mexico (Navarrete-Maya et al., 2002) and Rwanda, and *Pythium* spp. in the moist highlands of Uganda (CIAT, 2007). Several species of *Pythium* have been isolated from infected beans in Uganda, some of which also infect sorghum. While rotation with cereals is a widely accepted practice to reduce inocula in the soil, this practice may not be as effective with pathogens that infect both beans and cereals.

Common bacterial blight is the most important bacterial disease, while halo blight can occur occasionally in cool climates. Although yield losses of up to 40% have been recorded in managed trials, and common blight can be intense in production systems in Argentina and Brazil, in most small-scale farming systems, losses seldom reach this level. Rather, common blight is more of a threat in seed production, since the pathogen is seed borne and results in rejection of seed lots. Infection of pods will discolor grain, especially of white seeded types, and reduces commercial quality.

Table 8-1. Major production constraints of common bean.

Constraint[a]	Regional importance	
	Latin America and Caribbean	East, West, and Southern Africa
Abiotic constraints		
Drought	+++	+++
Heat	+++	++
N deficiency	++	+++
P deficiency	+++	+++
Acid soil toxicities (Al, Mn)	++	+
Viral diseases		
BCMV/BCMNV	+	++
BGMV/BGYMV	+++	
Fungal diseases		
Angular leaf spot	++	+++
Anthracnose	++	++
Pythium	+	+++
Fusarium	+	++
Rust	++	++
Bacterial diseases		
Common bacterial blight	+	+
Insect pests		
Bruchids	++	++
Bean stem maggot		+++
Ootheca		+
Whiteflies	+	
Apion sp.	+	

a. Al = aluminum; Mn = manganese; BCMV = bean common mosaic virus; BCMNV = bean common mosaic necrotic virus; BGMV = bean golden mosaic virus; BGYMV = bean golden yellow mosaic virus.

Severity of constraint: += low; ++= moderate; +++= high.

SOURCE: Adapted from Beebe et al. (2011a).

Viruses can be especially devastating. In lowland Americas gemini viruses are almost universally present (Anderson and Morales, 2005). Bean common mosaic virus (BCMV) is a seed-borne potyvirus and is distributed throughout the bean-growing world. Its close relative, bean common mosaic necrotic virus, is prevalent in parts of Africa and appears locally in the Americas.

Insects are occasional problems. In Central America the bean pod weevil, *Apion godmani* and *A. aurichalceum*, is the most important pest (Schwartz and Pastor-Corrales, 1989), while in East Africa the bean stem maggot (*Ophiomyia* spp.) is a serious limitation (Wortmann et al., 1998), as are aphids and pod borers. In Mexico the bean beetle causes serious damage. Leafhoppers (spp.) cause serious damage in drier climates.

Climate change will undoubtedly alter patterns of disease and insect incidence and intensity. Equatorial regions of the northern Andes and the East African highlands are expected to receive more rainfall on average as a result of climate change, although extreme rainfall events induced by the La Niña phenomenon will be the major problem (Yadav et al., 2011). Excess rainfall will exacerbate existing problems with many of the fungal pathogens, particularly soil-borne pathogens and foliar pathogens such as angular leaf spot and anthracnose (Beebe et al., 2011a). Excess rainfall and medium to high temperature will increase the incidence of web blight and angular leaf spot at elevations between 50 and

1400 masl. On the other hand, disease caused by *Fusarium oxysporum* and *Macrophomina phaseoli* can be more severe on drought-stressed crops, and could also become more limiting in Mexico and other countries. Most root-rot pathogens need some soil moisture to support infection. However, once disease has been established in a drought-stressed plant, the damage may be much greater than in plants in a non-drought situation. *Macrophomina* is a major problem under conditions of terminal drought (Frahm et al., 2004), whereas *Rhizoctonia solani* and *Fusarium* spp. are major root pathogens in regions where intermittent drought occurs (Navarrete-Maya et al., 2002).

Drought conditions will affect disease by making the environment more or less favorable for infection, disease development, and/or disease spread. Although droughts occur when there is a lack of rainfall, humidity may not be lacking and dew is likely to form if the air is humid and night temperatures fall below the dew point. Dew on leaves creates a favorable environment for some pathogens, and damage from some leaf diseases may be extreme in drought-stressed plants. Dew on leaves often provides enough moisture for the rust pathogen (*Uromyces appendiculatus*) to infect plants. High humidity provides a favorable environment for the infection and development of powdery mildew as well.

Pests such as the bean stem maggot, whiteflies (*Bemisia tabaci*) that transmit bean golden mosaic virus, and aphids that transmit BCMV (*Aphis fabae* and *Aphis craccivora*) are very important in drought conditions. High incidence of BCMV is expected at elevations between 50 and 1400 masl and during drought periods and at high temperatures. Rising temperatures will likely broaden the geographic range of *Bemisia* spp. and will carry the viruses into higher elevations (Beebe et al., 2011a).

Soil constraints

Soil constraints per se are probably the biggest single cause of a persistent yield gap between potential and realized productivity, particularly in developing countries in the tropics (Wortmann et al., 1998; Thung and Rao, 1999). General symptoms of mineral deficiency or toxicity include poor emergence; slow growth; seedling and adult plant stunting; leaf yellowing, chlorosis, and bronzing; reduced overall growth and dry-matter production; delayed and prolonged flowering and maturity; excessive flower and pod abortion; low harvest index; reduced seed weight; deformed and discolored seeds and severe yield loss (Singh et al., 2003). Root growth may also be adversely affected (Fawole et al., 1982; Cumming et al., 1992).

The wild ancestor of the common bean originated in soils that were typically high in organic matter and that were seldom critically deficient in nutrients. The wild bean is more sensitive to low soil P availability than its cultivated counterparts, suggesting that domestication and selection have actually improved adaptation to P-deficient soils (Beebe et al., 1997a). However, adapting bean to nutrient-poor soils continues to be a challenge.

P and N are the elements most often limiting in tropical soils. Legumes are especially limited by poor P availability; K is limiting only occasionally. Often fertilizer is not applied to the bean crop, but rather to the companion cereal crop, either in association or rotation, and the bean crop benefits from residual fertility. Micronutrients are constraining in some soils, especially those with alkaline pH. In Iran, for example, iron and manganese can be critically limiting.

Low soil fertility is particularly a constraint for bean production in Africa. In Central and Eastern Africa, the major soil fertility-related problems include low N and P availability, low availability of exchangeable bases, and soil acidity (Wortmann et al., 1998). In this area, P is deficient in 65–80% of the cultivated area and N in 60% of the area. Although beans are produced primarily in areas where median soil pH is between 5.0 and 6.0, over 23% of the production in Eastern Africa occurs in areas where soil pH is below or equal to 5.0.

Beans can fix modest to good amounts of N if conditions permit (Hardarson et al., 1993), and climbing beans can actually contribute substantial amounts of N to the system. However, low P availability, high temperatures, or root diseases usually do not permit bean to maximize its N fixing potential. Rising temperatures will represent an even greater limitation on N fixation.

Apart from nutrient availability, various soil physical constraints also limit yields. Soil degradation is severe in Central America and Haiti, and is advancing in Africa (Ayarza et al., 2007; Sanginga and Woolmer, 2009). Erosion and loss of soil organic matter (SOM) is associated with lower availability of plant nutrients, declining soil structure, and reduced water-holding capacity. The vast Mexican plateau boasts a million hectares of beans and is characterized by soils that are frequently thin and with low SOM. The bean root system does not penetrate compacted soil well and can be severely limited by soil physical structure.

Drought and excess water

Drought affects up to 60% of bean production regions (Beebe et al., 2011b) and is endemic in Mexico, Central America, parts of the Caribbean, Ethiopia, northern Uganda, eastern Kenya, Tanzania, and Southern Africa. Some regions are expected to become progressively drier under climate change, especially Mexico, Central America, and parts of northeast Brazil and Southern Africa (Yadav et al., 2011). However, it will be the extreme climatic events that will be most limiting and the most threatening to food security, especially those associated with El Niño events.

Temperature

As a consequence of their mid- to high-altitude origin, beans are generally sensitive to high temperatures (Porch and Jahn, 2001). Night temperatures in excess of 20 °C can seriously reduce pollen fertility and pollination. However, current analyses suggest that nocturnal temperatures still seldom reach critical levels and that day temperatures may actually be more limiting (Yadav et al., 2011). Regions where bean is currently cultivated at the margins of its temperature adaptation range and that could soon suffer significant losses due to higher temperatures include lowland Central America and central Brazil (Figures 8-1A and 8-1B), West Africa in general, northern Uganda, and Southern Democratic Republic of the Congo (Figures 8-2A and 8-2B).

Key Eco-Efficiency Interventions throughout the Value Chain

Eco-efficiency interventions should be considered throughout the value chain, from farm to consumer. However our analysis suggests that the most successful interventions to favor eco-efficient agriculture will occur in the production arena.

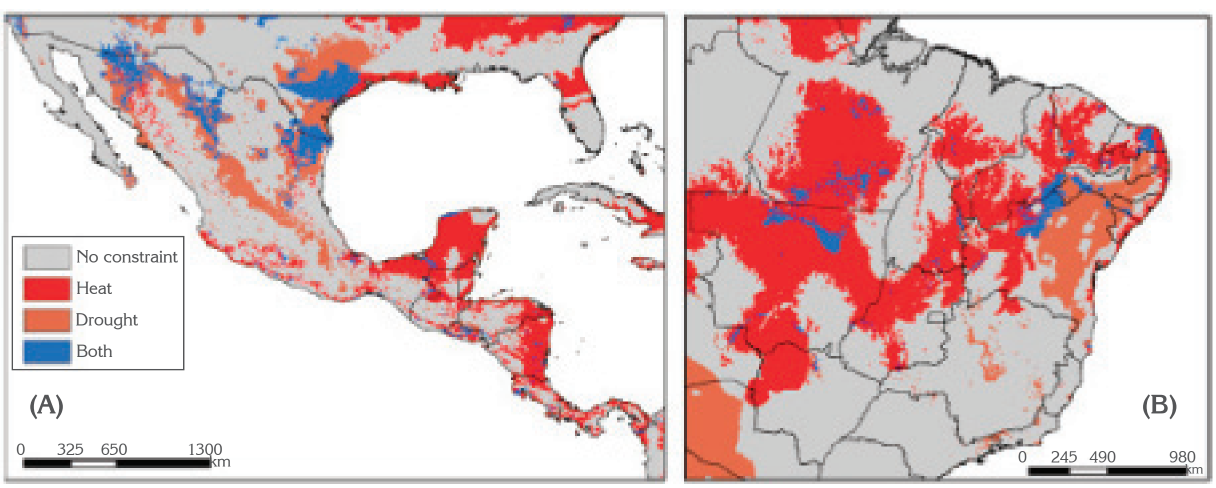

Figure 8-1. Regions in **(A)** Central America and **(B)** Brazil that suffer heat stress, drought stress, or both.
SOURCE: CIAT.

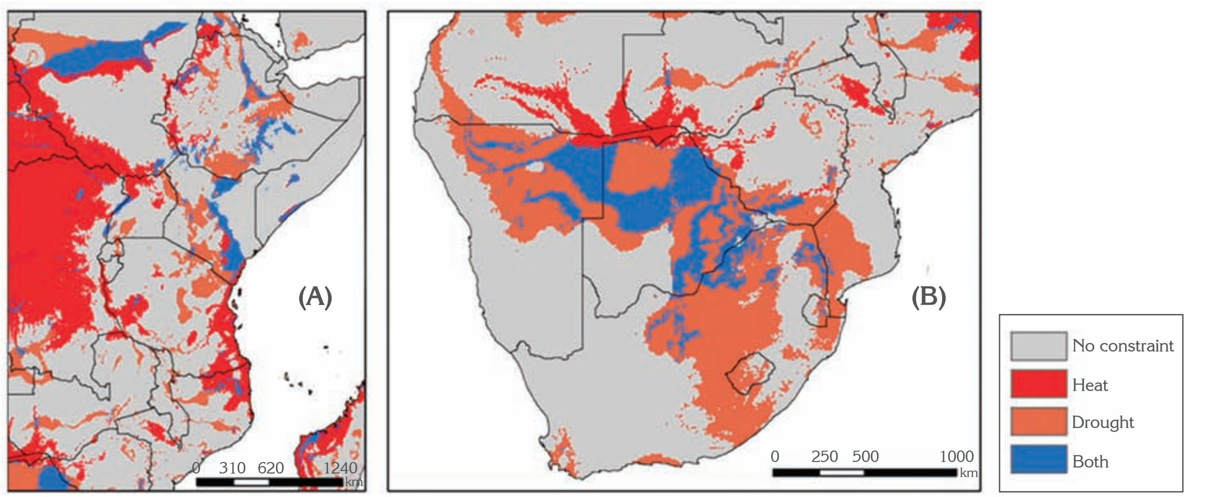

Figure 8-2. Regions in **(A)** East Africa and **(B)** Southern Africa that suffer heat stress, drought stress, or both.
SOURCE: CIAT.

Improving host plant resistance to biotic stress factors

Host plant resistance (HPR) as a first line of defense against diseases and insects is a primary goal of plant breeders working at CGIAR centers. In the case of beans, HPR combines several eco-efficiency attributes, especially reduction of pesticide abuse. Breeding for disease resistance is well advanced in the case of dry beans. Nonetheless the use of interspecific crosses with *P. coccineus* and *P. dumosus* should be broadened, especially in breeding for resistance to soil-borne pathogens for which resistance is incomplete and that may become more severe under population pressure and more intense cultivation. In Latin America, pesticides are readily available to farmers and pesticide abuse is common, especially on high-value crops such as snap beans (Cardona et al., 2001). High demands for very specific quality traits have slowed progress toward genetic resistance to diseases of snap beans. More intense rainfall will necessitate renewed effort to develop cultivars that are resistant to diseases, especially anthracnose, angular leaf spot, and *Ascochyta* blight.

DNA markers have enormous potential to improve the efficiency and precision of conventional plant breeding via marker-assisted selection (Collard and Mackill, 2008). They are increasingly being used in breeding for resistance to a number of important diseases of the common bean. Several markers have been identified that are linked to genes conferring resistance to angular leaf spot, anthracnose, common bacterial blight, BCMV and its necrotic strain, bean common mosaic necrosis virus, pythium, and *Fusarium* root rots (Miklas et al., 2006). SCAR (sequence characterized amplified regions) markers have been developed for some of these genes, principally for resistance to anthracnose, BCMV, common bacterial blight, angular leaf spot, and *Pythium* root rot (Miklas et al., 2006).

Extensive work has been done on charcoal rot and one major source of resistance, BAT477, has been studied (Mayek-Pérez et al., 2001; Hernández-Delgado et al., 2009). Quantitative resistance conditioned by four quantitative trait loci (QTLs) with relatively minor effects (13–19%) was reported in the Dorado/XAN 176 mapping population (Miklas et al., 1998). Two of the QTLs with larger effects that expressed across environments were located within resistance-gene clusters on linkage groups B4 and B7 (Miklas et al., 2000).

Improving nutrient acquisition and use efficiency

Fertilizer use efficiency per se has not received much attention in breeding programs, although attention has been directed toward adaptation to infertile soils. Such adaptation could be based on either efficiency of nutrient uptake (acquisition efficiency) or on efficiency of use per unit of nutrient uptake (use efficiency). Mechanisms include greater root hair density (Yan et al., 2004), exudation of organic acids to solubilize soil nutrients (Ramaekers et al., 2010), or greater root length density in superficial soil strata where nutrients are concentrated (Liao et al., 2004; Beebe et al., 2006; St. Clair and Lynch, 2010). Substantial mechanistic work has been carried out in common bean in this regard, although trait-based selection has seldom been implemented in breeding programs.

Alternatively, adaptation to infertile soils can be manifested as efficiency in production of grain per unit of nutrient taken up from the soil (nutrient use efficiency). Genotypic variability in this trait has been observed in common bean when grown in low-P soils or aluminum-toxic acid soils (Rao, 2001; Beebe et al., 2009; Table 8-2).

Although studied to date in the context of low native fertility of soils, increases in either nutrient acquisition efficiency or nutrient use efficiency would contribute to the increasing efficiency with which added fertilizer inputs are used as well. This would be one of the most important contributions to increasing yield in common bean in an eco-efficient way. In cropping systems where beans benefit from residual fertility following application of fertilizer to a cereal crop, either strategy would make better use of existing inputs and prevent mining the soil in the long run. In tropical soils with high P-fixing capacity, it is important to recover applied P before it is irretrievably fixed by iron and aluminum oxides (Rao et al., 1999). This implies an efficient root system that aggressively accesses soil nutrients. Combined with conservation agriculture, this could have great practical impacts.

Symbiotic nitrogen fixation (SNF) received ample attention in CIAT's research program in its early years, in genotype selection and especially in the search for efficient rhizobial strains (Graham, 1981; Kipe-Nolt et al., 1993). While *Rhizobium etli* typically gives better fixation in optimal conditions, *R. tropici* is more tolerant of heat and acid soil, and *R. tropici* strain CIAT 866 has been widely employed in inoculation studies (Hardarson et al., 1993; Graham and Vance, 2000). The quantity of N fixed is normally in direct proportion to the length of the crop cycle. Climbing beans have a longer growth cycle than bush beans, and are a good option for improving soil quality and contributing to the associated or subsequent maize crop yields (Pineda et al., 1994; Sanginga and Woolmer, 2009). In contrast, bush beans often present a negative N balance, removing more N from the system than they contribute. However, in optimal conditions of moderate temperature, adequate P supply in the soil, and modest starter N, even bush beans can fix up to 50 kg N/ha (Hardarson et al., 1993). However, such optimal conditions seldom exist, and bush beans therefore seldom contribute significant N to the system. Nitrogen fixation is one of the most sensitive plant processes to environmental stress and is reduced dramatically by P deficiency (Vadez et al., 1999) or drought (Serraj and Sinclair, 1998).

That said, significant progress has been made in recent years in improving tolerance to several of the physiological stresses that limit fixation, including drought (Beebe et al., 2008); aluminum (Beebe et al., 2009; Table 8-2); low P (Singh et al., 2003; CIAT, unpublished data), and combined stress factors of drought and low P (Table 8-2). It is therefore timely to revisit the issue of N-fixation capacity of common bean, to determine if alleviating other stresses through genetic improvement has had a beneficial effect on N fixation in suboptimal conditions.

This could also be an opportunity for studies on gene expression. The very high sensitivity of SNF to environmental factors suggests that the plant is actively shutting down its N fixation in the face of other limiting factors. Understanding this plant reaction could lead to selection criteria to recognize genes that are less prone to react negatively to external factors and to maintain fixation activity.

Improving agronomic management

Agronomic management is clearly necessary to improve bean yields, and conservation agriculture offers important opportunities for increasing production of common beans. Beans respond well to improvement in soil structure with

Table 8-2. Differences in grain yield, shoot phosphorus uptake, and phosphorus use efficiency of common bean genotypes grown under combined stress from drought and low P in Darién, Colombia, and under aluminum toxicity on an acid soil in Quilichao, Colombia.

Genotype	Combined drought and low-P stress			Aluminum toxicity		
	Grain yield (kg/ha)	Shoot P uptake (kg/ha)	P use efficiency (g/g)[a]	Grain yield (kg/ha)	Shoot P uptake (kg/ha)	P use efficiency (g/g)
A 774	913	2.34	390	427	3.11	137
BAT 477	805	2.17	371	637	1.81	352
Carioca[b]	614	1.05	585	693	3.23	215
DOR 390	958	1.81	529	358	2.03	176
EAP 9653-16B-1	549	1.64	335	762	3.71	205
G 40001[c]	212	0.67	316	431	1.89	228
NCB 226	1047	1.40	748	522	2.03	257
Perola[b]	992	1.69	587	493	1.63	302
San Cristóbal 83[b]	721	1.61	448	427	2.14	200
SEN 56	471	1.56	302	721	4.78	151
SER 16	584	1.64	356	381	1.35	282
SER 78	542	1.89	287	568	2.35	242
SER 128	590	1.80	328	501	3.08	163
SXB 412	1127	3.27	345	594	2.49	239
SXB 415	922	2.57	359	698	2.48	281
Tio Canela 75[b]	641	1.50	427	514	2.64	195
Mean	702	1.86	420	594	2.70	227
$LSD_{0.05}$	243	0.64	ND	250	1.80	ND

a. Grams of grain produced per gram of shoot P uptake.

b. Check cultivars.

c. *P. acutifolius* (tepary bean) germplasm accession.

ND = Not determined because P use efficiency was calculated based on mean values of grain yield and shoot P uptake.

SOURCE: J. Ricaurte, C. Cajiao, M. Grajales, S. Beebe, and I. Rao (unpublished results).

enhanced SOM. The root system of beans is less aggressive than that of cowpea, for instance, and heavy soils or soil compaction can be serious impediments of its root system. Conservation agriculture improves soil structure, water penetration, root development, and plant nutrition and therefore deserves more attention in a systems context, such as in the maize–bean system in Central America (Castro et al., 2009) or the mixed maize system in East Africa where bean is a common component (Hyman et al., 2008). For example, crop water productivity (kilograms of grain produced per cubic meter of water used) of common bean was higher in a slash-and-mulch agroforestry system than in the traditional slash-and-burn agricultural system (Castro et al., 2009).

Reducing carbon footprints through reduced transport and cooking time

The most energy-demanding process in the whole market chain is probably cooking. Even in the USA, where agriculture is almost entirely mechanized and production consumes large amounts of energy, 48% of energy in the food chain is spent in industrial processing and home cooking, compared with 21% used in production and 13% in transportation (CSS/UoM, 2011). Cooking common bean has a particularly high energy requirement because of its relatively long cooking time. Short cooking time regularly emerges as a consumer-preferred trait in studies in the developing world. There is ample variability in cooking time among bean lines, and exploiting this variability systematically would be both a contribution to energy efficiency and a welcome improvement among bean consumers.

In recent years, there has been a move toward consumption of locally produced foods. While this movement is based on multiple motivations, an important one is to reduce the carbon footprint along the food chain. For common bean, this could imply increasing production close to important urban centers that absorb large quantities of beans moved over long distances, including Mexico City, Sao Paulo, Kinshasa, Nairobi, and Johannesburg. The southern region of Mexico, although a traditional bean-producing area, is not self-sufficient in beans and imports beans from other parts of Mexico and from abroad. Local production would seem to be an attractive option, but further studies are needed to determine the competitiveness of different production regions and the yield levels needed on a local level to compete with beans carried over long distances.

Risk and Resilience Issues

We have referred to the likely effects of climate change, including changes to the distribution and intensity of biotic constraints; exacerbating effects of drought; and reducing yields due to higher temperatures in low-lying areas of Central America, Brazil, and Africa.

While soil conditions are similar year after year and temperatures vary within certain limits for a given site and time of year, drought, pests, and diseases are sporadic problems that make predictions of expected yields difficult. Investments that could raise yields, e.g., fertilizer, labor, or capital improvements, are unattractive in the face of such sporadic risks. Thus, while reducing risk may not affect average yields dramatically, it is a primary step toward other improvements in a system.

Resilience of a system is reflected in its ability to adapt to and recover from adverse conditions. Soil quality is an important determinant of the resilience of a farming system. Soil quality, and especially enhanced SOM, permits better root development, increasing accessibility of moisture, soil water-holding capacity, and availability of nutrients. Greater access to moisture will in turn permit the crop to transpire more, which cools the canopy and allows the key processes of leaf expansion and grain development to continue in the face of high air temperatures. While these effects would benefit all crops, beans would benefit in particular given their sensitivity to shortages of water and nutrients. Such system-based interventions are typically adopted more slowly than simpler interventions such as improved seeds or fertilizer, given their complexity and the fact that they often require capital investment. System interventions that benefit multiple crops will likely have a better chance of adoption by farmers than those that benefit only a single crop.

Adaptation to and Mitigation of the Effects of Climate Change

While common beans are relatively more sensitive to abiotic stress than other legumes such as cowpea, considerable progress has been made in breeding for tolerance to various abiotic stresses. For example, drought tolerance has been improved through intraspecific crosses, employing the naturally occurring variability within *P. vulgaris* (Beebe et al., 2008). However, interspecific crosses with sister species of the genus *Phaseolus* offer prospects of further progress. The genus *Phaseolus* originates in a remarkably wide range of ecologies, from tropical rainforest to arid desert (Freytag and Debouck, 2002), and species that are cross compatible with common bean cover most of this range. The secondary gene pool, including cultigens *P. coccineus* (runner bean) and *P. dumosus* (year-long bean) and wild species *P. costaricensis* and *P. albescens*, is readily crossed with common bean. The secondary gene pool is adapted to cool, moist environments and is a source of traits for environments that will likely receive excess moisture. At the other extreme, *P. acutifolius* (tepary bean) and its wild relative *P. parvifolius* evolved in semi-arid or arid environments and are a source of traits for hot, dry climates.

Improving drought tolerance

Drought tolerance has been the object of bean genetic improvement for at least 3 decades in CIAT and other institutions. Early work suggested that deep rooting was a critical tolerance mechanism (Sponchiado et al., 1989). Singh (1995) found superior drought tolerance in crosses that combined the genetic diversity found in the Mesoamerica and Durango bean races. This formula has continued to produce materials that perform well under drought stress.

Enhanced remobilization of photosynthate to grain under drought stress is another important mechanism of drought tolerance (Beebe et al., 2011b). The wild bean appears to suppress reproductive development in the face of stress (Beebe et al., 2011b). In the wild, this strategy is effective under a bimodal rainfall pattern, where late rains permit resumption of reproductive development. However, in a short-season cultivar, this strategy results in poor yields. Improved yield under stress is associated with maintaining reproductive development and photosynthate transport to seed. This trait also appears to be beneficial under favorable conditions and to a certain extent in conditions of low soil-P availability (Beebe et al., 2008).

Continued progress in breeding for drought tolerance will likely require accessing genetic variability in sister species of common bean. For example, tepary bean is reported to possess multiple drought-resistance traits, including dehydration avoidance (Mohammed et al., 2002). It has fine roots with high specific root length (Butare et al., 2011) and it expresses rapid root penetration to access moisture at deeper soil levels. Although crosses with common bean normally require embryo culture to obtain viable plants, intensive intercrossing has led to enhanced genetic exchange (Mejía-Jiménez et al., 1994), and a stock of introgression lines exists in CIAT (Muñoz et al., 2004) that can be mined for useful traits.

Although runner bean would seemingly not be a promising source of traits for drought tolerance, given its origins in moist environments, in fact it displays a unique root system with traits that could be valuable in some circumstances. For example, it is highly tolerant of toxic levels of soil aluminum and has a coarse root system that might be able to penetrate compacted soil more readily than that of common bean (Butare et al., 2011).

Our experience suggests that poor soil fertility is a serious constraint on the expression of drought tolerance. A crop that is poorly nourished will have a limited root system and will not have the vigor to resist additional stress from drought. Addressing soil fertility is a critical component of any strategy to combat drought.

Improving tolerance to excess rainfall

Climate change will result in some bean-growing regions receiving more precipitation than at present. Waterlogging and associated root rots may increase in East-Central Africa and the northern Andes. Restricting the amount of oxygen roots receive inhibits both symbiotic N_2 fixation and N uptake, reducing root growth and nodulation. Tolerant genotypes may have various adaptive responses (Colmer and Voesenek, 2009). More adventitious roots and/or larger aerenchyma in roots, nodules, and the base of the stem may enhance tolerance of waterlogging. Rapid, reliable screening methods are needed to evaluate waterlogging tolerance.

Improving heat tolerance

Beans are grown over a wide range of latitudes with mean ambient temperatures ranging from 14 to 35 °C. Temperatures of more than 30 °C during the day or more than 20 °C at night result in yield reduction. High night temperatures at flowering (and to a lesser degree, high day temperatures) cause flower and pod abortion, reduced pollen viability, impaired pollen-tube formation in the styles, and reduced seed size. Acclimation to occasional high night temperatures may be a genotypic resistance mechanism. A pollen-based method developed to evaluate heat tolerance in soybeans might be used to screen common-bean genotypes for tolerance to nocturnal heat stress (Salem et al., 2007).

To date there has been limited activity to identify tolerance to heat stress in common bean. Work has been carried out in controlled conditions at Cornell University (Rainey and Griffiths, 2003) but this has not been extended systematically to dry beans in the tropics. There is active interest in improving heat tolerance in Central America (Porch et al., 2007). Evaluation under high temperatures of advanced breeding lines developed for bean golden yellow mosaic virus resistance has been carried out in Central America, and the variety CENTA Pipil developed by the Pan-American Agricultural School of Zamorano, Honduras, has proven to be relatively tolerant in El Salvador. While incremental quantitative progress may be made with further efforts, tepary bean may be a promising source of heat tolerance in the long run. Some interspecific lines of tepary and common bean have been evaluated in Central America and in Puerto Rico, and while some appear to be promising, it remains to be seen if they represent an advantage over available genetic diversity within common bean germplasm. Nonetheless, mining the diversity of tepary bean would seem to be high priority for the future.

Improving disease resistance and grain yield

Bean diseases will be exacerbated in some regions as a result of climate change. Efforts to breed for resistance may need to resort to sister species for broader genetic variability. Runner bean has long been employed as a source of resistance for such difficult diseases as white mold caused by *Sclerotinia* spp. (Abawi et al., 1978) and *Fusarium* root rot caused by *Fusarium solani* (Wallace and Wilkinson, 1965). More recently progeny of crosses between runner bean and common bean have proven to be resistant to both *Fusarium* spp. and *Pythium* spp. (CIAT, unpublished data). While using runner bean or year-long bean as a source of resistance is not novel, the utility of interspecific progenies has always been limited by their poor agronomic quality and low harvest index. A recent study suggests that the quality of crosses with the secondary gene pool can be improved by using common bean with enhanced remobilization of photosynthate to grain (Klaedtke et al., 2012). Such parents can “tame” the excessive vegetative growth of these sister species and result in superior progenies.

Integrating beans into cropping systems to cope with high temperature

While specific agronomic interventions can be made to address the impacts of climate change, broader-based solutions may involve transformation of the whole cropping system. For example, high daytime temperatures might be addressed by adopting a cropping system that provides partial shade to the bean crop. Some such cropping systems already exist; for example, the bean–banana system of Uganda and northwest Tanzania (Wortmann et al., 1998). Beans could be intercropped with coffee to provide shade after pruning of the coffee and while the coffee plantation returns to production. Alley cropping, especially with profitable tree crops such as mangos or other fruits, offers some promise. Such a system could be better exploited if shading tolerance were enhanced in the bean crop.

One option that has emerged in past years and that is likely to expand in response to higher temperatures is the use of alternative planting dates. In Central America bean production has expanded dramatically on the Atlantic coast of the isthmus, in the cool, dry, winter season when the crop survives on residual moisture. In Brazil, the cool dry season has seen the expansion of high-input production under center-pivot irrigation. Given that such changes have been largely the result of pressure on land resources or to produce when beans are normally scarce and prices are high, the attraction of producing in a season with more-favorable temperatures will only enhance this tendency.

Expected impacts of improved adaptation to climate change

A modeling exercise was carried out to estimate the distribution and relative importance of climatic constraints to bean yields, and the potential value of genetic improvement (Beebe et al., 2011a; Figures 8-1 and 8-2). Breeding drought tolerance into bean could improve suitability of some 3.9 million hectares of land where bean is currently grown (the equivalent of 31% more land classified as highly suitable) and would allow the crop to be grown on another 6.7 million hectares currently not suitable. Heat tolerance could increase the suitability of 7.2 million hectares of land where bean is currently grown. Drought tolerance would also improve productivity on some of this land and could increase the area designated as highly suitable by some 54%. Thus, both drought tolerance and heat tolerance are important objectives for genetic improvement. Although heat tolerance may offer wider impact, drought causes great year-to-year yield variability and must also be given priority.

Quantifying Eco-Efficiency and Developing Indicators

In rainfed agriculture, water use efficiency will be a useful parameter to identify eco-efficient bean genotypes (Table 8-3). In trials at the CIAT-Palmira (Colombia) testing site, several breeding lines were identified to be superior to the checks.

Phosphorus use efficiency will be a useful parameter to identify bean genotypes for use on P-deficient soils or those suffering from aluminum toxicity (Table 8-2). Some breeding lines performed better than the check lines under combined stress conditions of drought and low P and under aluminum toxicity (Table 8-2).

On small-scale farms with minimal use of fossil fuel, energy input is in the form of work done by humans and animals—calculation of which would be irrelevant for the world's energy balance but highly meaningful to the farmer. Similarly, reduced cooking time would make a miniscule contribution to reducing CO_2 emissions but would be highly significant for the people who must search for firewood, usually women and children.

Table 8-3. Differences in grain yield and agronomic water efficiency[a] of common bean genotypes grown at CIAT-Palmira, Colombia.

Genotype	Grain yield (kg/ha)		Agronomic water efficiency (kg/mm)[a]	
	Irrigated	Rainfed	Irrigated	Rainfed
A 774	2731	839	9.59	6.52
BAT 477	2213	722	7.77	5.61
Carioca	2563	797	9.00	6.19
DOR 390	2345	674	8.23	5.24
EAP 9653-16B-1	2685	1054	9.42	8.19
G 40001[b]	2190	1144	7.69	8.89
NCB 226	2571	1269	9.02	9.86
Perola	1926	654	6.76	5.08
San Cristóbal 83[c]	2136	495	7.50	3.85
SEN 56	2888	1102	10.14	8.56
SER 128	2453	1263	8.61	9.81
SER 16	2696	1025	9.46	7.96
SER 78	2352	1361	8.25	10.57
SXB 412	2838	850	9.96	6.61
SXB 415	2806	999	9.85	7.76
Tio Canela 75[c]	2398	771	8.42	5.99
Mean	2307	898	8.10	6.98
$LSD_{0.05}$	426	319	1.49	2.47

a. Kilograms of grain produced per millimeter of water applied through either irrigation or rainfall.

b. *P. acutifolius* (tepary bean) germplasm accession.

c. Check cultivars.

SOURCE: J. Polanía, M. Rivera, M. Grajales, S. Beebe, and I. Rao (unpublished results).

Reducing the amount of energy expended in transport by promoting local production could be measured by cost differentials between local and imported products. Such a differential would in fact reflect multiple factors but transport cost per ton can readily be obtained. Translating this cost into carbon emissions would require an added level of assumptions.

Opportunities to Enhance Impact and Scale out from Initial Studies and Interventions

Impact from seed-based solutions would follow from the models of seed dissemination that have been used for standard agronomically improved materials. Recent years have seen a diversity of models emerging, from formal revolving seed models, to decentralized seed production, to small packets of seed and fertilizer and seed loans. Nonetheless, no novel system will alter the fact that long-term adoption will depend on the farmer appreciating added value in the new materials. In the case of germplasm that is resistant to the effects of climate change, farmers will likely be able to see the value of drought tolerance or disease resistance within 2 or 3 years where these stresses are endemic. Tolerance to high temperatures may be more difficult to appreciate, as its effects will be felt more gradually.

Agronomic solutions are typically more difficult to deploy. Participatory research should be practiced from the outset, given the complexity of incorporating what are often system-level interventions.

Soil-management practices cut across the entire farming system and go far beyond individual crops (Sanginga and Woolmer, 2009). The contribution of a particular crop could be in generating synergistic benefits that make the system more attractive for adoption. For example, climbing beans are far more productive than bush beans, and anecdotal reports suggest that agroforestry was more readily adopted where it served as a source of staking material for climbing beans. Similarly, planting beans among trees during the establishment phase of plantations was reported to have made planting of trees more attractive to farmers by creating a source of income in the short term, and to have aided tree establishment by encouraging weed control. These cases have not been documented, but such potential interactions should be sought.

Perspectives: Key Lessons and Opportunities for Research, Development, and Policy

Experience in breeding for drought tolerance suggests that stress tolerance does not necessarily imply a yield penalty (Beebe et al., 2008, 2009). However, the greater the degree of stress that we encounter, the greater will be the demands on obtaining adequate levels of tolerance. Once again, dealing with average conditions will not be nearly so challenging as dealing with extreme events of drought, excess rainfall, and high temperature. Breeders would benefit from more-precise estimations of the frequency and intensity of these extreme events.

The genus *Phaseolus* spans a wide range of stressful environments, offering the prospect of finding the necessary genes for stress tolerance. Tolerance to heat and drought can be found in the tertiary gene pool, for example, and tolerance to excess rainfall can be found in the secondary gene pool. Interspecific crosses, by their very nature, require long-term effort, with the need to overcome negative genetic linkages and/or poor chromosome pairing and slow introgression. These are obstacles that are best overcome with time and patience rather than a frenetic investment of research funds on a 3-year project time scale. Thus, such crossing should receive more systematic attention as of now, albeit at a modest level.

If at some time gene expression can be manipulated, then studies of other *Phaseolus* species might reveal which genes will confer tolerance, and these can become targets for enhanced expression or for gene cloning and eventual transgenesis. Efficient transformation remains a challenge in common bean, and the development of an efficient and effective system is yet another area of research.

Little is yet understood about what might be the effects of higher CO_2 concentrations in the atmosphere. Crop experiments conducted in different parts of the world suggested that a doubling of CO_2 from current levels will lead to approximately a one-third increase in grain yield of C_3 crops such as common bean. However, more recent field studies on CO_2 enrichment indicated that this may be an overestimate (Long et al., 2006; Ainsworth and Ort, 2010) and a more realistic estimate is about half of that, i.e., a one-sixth increase. One study on common bean suggests that different genotypes will react differently to higher CO_2, with seed yield at high CO_2 levels ranging from 0.89 to 1.39 times that at ambient CO_2 (Bunce, 2008). There may be opportunities to exploit this dimension of climate change to the benefit of the crop and possibly the system. However, research is lacking in the tropics to determine the impact of higher CO_2 in cropping systems that are limited by other factors. For example, does CO_2 have a positive effect when the crop is simultaneously limited by low soil P availability and/or drought and high temperature? In this respect and others, agricultural research in the tropics must be more integrative (Thung and Rao, 1999; Keating et al., 2010; Chen et al., 2011) and less reductionist so that farmers as end users can benefit from research to improve their livelihoods.

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CHAPTER

9

Eco-Efficient Interventions to Support Cassava's Multiple Roles in Improving the Lives of Smallholders

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Abstract

Because of its long growing season and sensitivity to low temperatures, cassava (*Manihot esculenta* Crantz) is exclusively a crop of the tropics and subtropics. This effective exclusion from production in most of the developed world has had a strong and largely negative influence on the research investment in the crop. In spite of being one of the world's major calorie producers for human sustenance (second most important source of calories in sub-Saharan Africa after maize), cassava is little known in the developed world. Research investment into the crop was sparse until two centers of the CGIAR Consortium – the International Center for Tropical Agriculture (CIAT) and the International Institute of Tropical Agriculture (IITA) – began research on the crop in the mid-1970s.

Cassava produces better than many crops on acid and low-fertility soils, and under periodic or even extended droughts. Because it has no specific maturity period, there is no period of growth during which it is especially vulnerable to environmental stresses. On the other hand, because of its long growing cycle, typically 10–16 months, it may be exposed to many stresses during this period. Especially, it may endure a number of pest and disease attacks or periods of drought in some environments.

Cassava is more resilient than most crops in the face of multiple biotic and abiotic constraints, but it is vulnerable if inappropriately managed. On the one hand, this allows farmers to be moderately

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productive with low inputs, or even with crop and soil mismanagement. It is for this reason that cassava is sometimes cultivated on sloped lands without due protection against erosion, or on soils with declining fertility status and organic matter. The solutions lie in a combination of new eco-efficient technologies, education, policy, and improved market conditions so that farmers have fact-based advice and can afford to apply the appropriate inputs. Breeders, agronomists, and plant protection specialists should focus on technologies that support farmer income and food security through efficient use of inputs, natural resource management, and optimizing the genetic variability in genebanks to develop eco-efficient varieties.

Background

In early 2012, a press release picked up by several major media outlets announced that cassava is the "Rambo of the crop world" for its ability to stand up against the projected heat and drought stresses that will affect large areas of the tropics in the coming decades. The story was based on a special issue on cassava in the journal *Tropical Plant Biology* [vol. 5(1)]. This is hardly news to anyone who grows cassava or has been involved in its research for any period of time, but it was an important wake-up call for policy makers, research and development (R&D) agencies and donors – looking for opportunities to make agriculture more "climate change ready." Most people in the developed world have never heard of cassava, in spite of its status as the fourth crop in importance in the tropics, just behind rice, maize, and wheat. In sub-Saharan Africa, it is second behind maize as a food security crop.

The impending effects of climate change on crops are steadily gaining urgency for scientists and policy-makers. But climate change is only one of many forces that play out in the daily challenges that cassava farmers face. Eco-efficient cassava-based systems can contribute to multiple development goals aimed at some of the world's most vulnerable people living in hotspot environments.

The people who rely on cassava to provide a significant part of their income or nutritional needs are typically among the world's poorest (Table 9-1). They are often farmers who earn their living cultivating degraded and marginal lands, or urban poor who subsist on the lowest-cost sources of calories. At the same time, rapidly

Table 9-1. Global production (% of total) of cassava and comparison to other major starchy staples.

	Developing Countries				Least Developed Countries			
	Africa	Asia	LAC	**Total**	Africa	Asia	LAC	**Total**
Bananas	2.7	1.1	3.8	**1.7**	3.5	0.6	5.8	**2.3**
Cassava	12.4	1.1	4.7	**3.6**	17.9	0.4	7.5	**10.7**
Potatoes	1.5	2.7	2.9	**2.5**	1.3	2.4	0.2	**1.8**
Sweet potato	1.8	1.9	0.5	**1.7**	3	0.3	3.5	**1.9**
Yam	3.3	0	0.3	**0.7**	1	0	4.2	**0.6**
RT&B*	**21.6**	**6.7**	**12.1**	**10.1**	**26.7**	**3.8**	**21.1**	**17.3**
Maize	22.3	4.9	30.8	**10.6**	22.9	5.3	14.6	**15.7**
Millet	6.7	1.7	0	**2.5**	8.3	1	0	**5.3**
Rice	10.6	46.5	17.6	**37**	11.7	76.1	33.4	**38.0**
Sorghum	9.4	1.2	0.2	**2.7**	12.4	0.9	3.4	**7.7**
Wheat	23.5	35.2	31.1	**32.6**	11	11.5	20.4	**11.3**
Other crops	5.9	3.8	8.1	**4.4**	6.9	1.5	7.1	**4.7**
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

* RT&B: Roots, tubers, and bananas.

SOURCE: www.rtb.cgiar.org/resources/proposal-documents/final-proposal-annexes/

expanding new markets for cassava products – especially in Asia, but increasingly in Africa and the Americas – are providing unprecedented opportunities for farmers to improve their income and well-being, and to better supply the needs of multiple markets. These changes are creating both opportunities and challenges across an array of system components. This chapter explores the key roles that research on eco-efficient production, processing, and marketing can play in improving farmers' and consumers' lives – through income generation, improved food security, better nutrition, and a healthier environment.

By far the most important product of the cassava plant is the starchy roots. They may be peeled, boiled, and eaten directly, or may be processed into a wide array of products for food, feed, and industry. The roots are typically about 85% starch, on a dry-matter basis (Sánchez et al., 2009). Their principal nutritional value is calories. Leaves are consumed in some countries, especially in Africa, and they are very nutrient dense, especially in protein.

A range of evolutionary, agronomic, and commercial factors define where cassava is grown, how it is grown, how it is used, and the challenges growers face. The crop originated in the Americas, and was widely distributed throughout the tropics and subtropics of the western hemisphere before the arrival of Europeans in the 15th century (Allem, 1990; 2002; Allem et al., 2001; Olsen and Schaal, 2001; Nassar and Ortiz, 2008). Traders carried it to Africa relatively quickly after Columbus. While the introduction to Asia is not well documented, it appears that Spanish traders introduced the species from Mexico to the Philippines in the 19th century, and independently from Africa to India.

While about 100 countries grow cassava (FAOSTAT, 2012), production is skewed toward a relatively few major ones (Figure 9-1). Four countries harvest almost half of global output of fresh roots: Brazil, Indonesia, Nigeria, and Thailand; and three-quarters of production come from just ten countries. Over half the production area is in Africa, but only one of the top four producers is located there. The remainder of production consists of about 30% from Asia and 16% from the Americas.

The species is uniquely tropical. Its long growing cycle of about eight months to a few years (average is about a year) and high susceptibility to frost limit its production to warm climates. In the subtropics, especially in southern

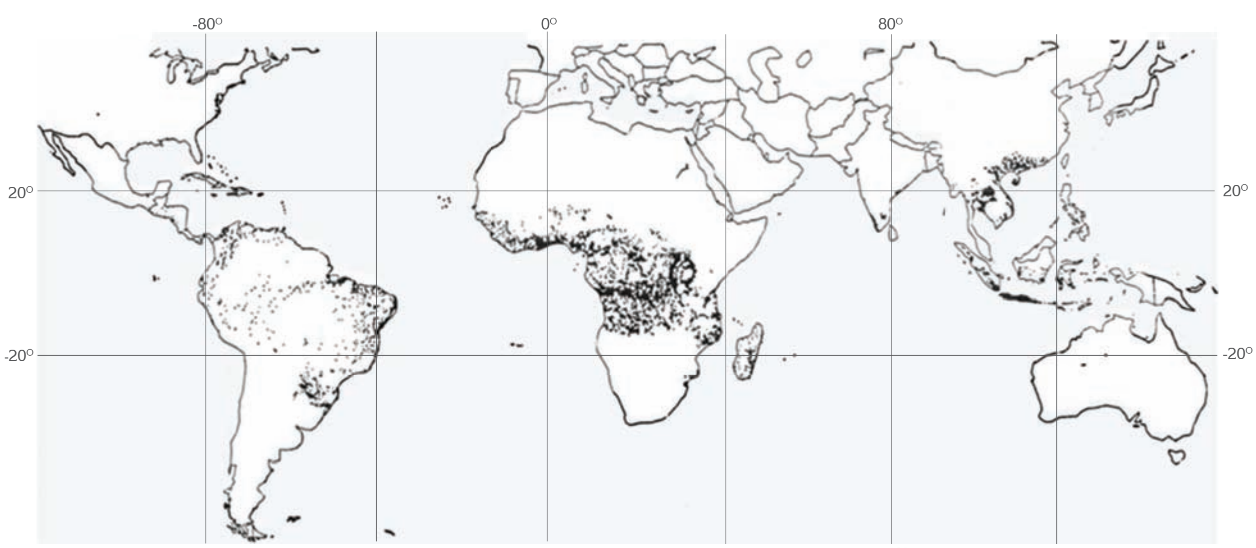


Figure 9-1. Distribution of cassava in the world. Each dot represents 1,000 ha.
SOURCE: Henry and Gottret, 1996.

Brazil, farmers often cut back the stems at the onset of winter, and the crop continues growth again in the spring, allowing harvest at about 18 months.

Cassava roots can be "stored" in the ground for many months as part of an intact growing plant; there is no well-defined maturity period, although root quality may vary over time due to plant age and environmental factors. However, after harvest, roots begin to deteriorate quickly, often from a day to a few days (Beeching et al., 1993; Reilly et al., 2007). Over millennia, this rapid post-harvest deterioration stimulated the invention of many types of treatments and processing techniques to convert the roots into less perishable products. The main primary processes involve one or more of the following: Grating or grinding and drying to produce flour; slicing or chipping and drying; and starch extraction. Variations include fermentation before or after grinding; forms of compressing to remove water; sun or artificial drying; and toasting or baking. Secondary processes include the production of a wide array of pellet-, flour-, and starch-based products for food, feed, and industry (Cock, 1985).

The primary processes not only convert a perishable product into one that can be easily stored, but also they greatly reduce the poisonous component contained at lower or higher levels in all cassava varieties – cyanogenic glucosides that enzymatically break down to release HCN when cell structure is compromised (Du et al., 1995; McMahon et al., 1995; Wheatley and Chuzel, 1993; Andersen et al., 2000; Mkumbira et al., 2003). Roots that are boiled and eaten without additional processing need to be from types with low cyanogenic potential.

While every cassava-producing continent encompasses a wide array of production systems and uses for this crop, some broad generalizations apply. These system characteristics impact the design of eco-efficient research strategies. In Africa, cassava is mostly grown on small farms (often less than one hectare) and intended for human food. Areas where fresh consumption is common include Ghana and Uganda. The leaves are an important source of protein, vitamins, and several minor nutrients, most notably in the Democratic Republic of the Congo (DR Congo). Production in Asia is also mainly by smallholders, with a few exceptions such as some large plantations for starch production in Cambodia, Indonesia, Lao People's Democratic Republic (Lao PDR), and others. Uses are highly diversified within and across countries. India, Indonesia, and the Philippines produce mainly food products. China, Thailand, and Vietnam produce mainly animal feed and industrial starch; and China is also moving aggressively into biofuels from cassava. In the Americas, Brazil is by far the largest producer. Production systems range from the large plantations (up to a few thousand hectares) in the south to the small landholdings for local markets in most of the rest of the country. In most other countries of the Americas, production is on small farms. In all continents, the vibrant market situation of recent years is attracting new, large investors. Often there is inadequate planning for the management implications of scaling up quickly in large plantations, and many of them have experienced early difficulties in production (Table 9-2).

There are several reasons why cassava tends to be a crop of the poor, and these have strong implications for the kinds of eco-efficient research interventions that can lead to positive changes, from both socio-economic and environmental perspectives.

- The crop is better adapted than many others to the harsh agro-environments where the rural poor tend to be concentrated, e.g., where rainfall is uncertain and drought stress is common; on soils with multiple production constraints, such as high acidity/high Al content and low native fertility; and on sloped lands where soils are prone to erosion and mechanization is difficult.

Table 9-2. Consumption of cassava as percentage of total for each region.

Region	Food	Feed	Export	Other
Africa	91	8	0	1
Asia	50	8	32	10
South America	43	51	1	5

SOURCE: Lynam, 2008.

- It is a crop that will in many cases produce reasonable yields with few or no purchased inputs, such as fertilizers, pesticides, or irrigation. Its vegetative multiplication means that farmers do not need to purchase seeds. The planting material is usually produced on-farm or shared among farmers. There are few commercial initiatives to produce planting material.
- Production practices are difficult to mechanize, although there has been considerable recent progress. Therefore, its cultivation can be a comparative advantage for farmers whose principal input resource is family labor.
- In many environments, cassava can produce nearly year-round (no specific maturity period, plus ability to store roots in the ground as part of the growing plant). Thus it has appeal to the poor, who may lack resources to pay for and manage storage facilities, such as might be required for a grain crop. It can be harvested when farmers need it. In Africa, even where cereals are the main crop, cassava plays a key role as a back-up crop when cereal production fails.

Although cassava is mostly cultivated under low-input and suboptimal soil and environmental conditions, in fact the crop has a very high production potential when provided optimum conditions. Both hypothetical models and field data show that cassava has a yield potential on the order of 80–90 t/ha per year (El-Sharkawy, 2012; El-Sharkawy et al., 1990). With a global average yield of about 12 t/ha, it is easy to see that there is a large yield gap that needs to be addressed to bring cassava's potential benefits to producers and consumers.

Production Constraints

It is common to find references in the early literature to cassava's "rustic nature," or its ability to produce a crop under difficult conditions. Historically many scientists considered it a crop with few pest or disease problems, and easy to grow with minimum inputs and little care. At the same time, it has developed a reputation as a crop that, more than most, causes environmental degradation, especially soil nutrient depletion and erosion. While there are elements of truth that underlie all of these assertions, none accurately reflects reality on a broad scale. Growers face a range of biotic and abiotic constraints, which vary by region, cropping system, and season. Research organizations need to pay considerable attention to developing eco-efficient approaches to managing production constraints.

Biotic constraints

More than 200 arthropod pests and pathogens affect cassava (Bellotti, 2002; Bellotti et al., 1999). Most do not reach economic threshold levels of damage; however, they are living organisms with the capacity to move across regions and national boundaries, and to evolve and adapt to new conditions and new hosts. Climate change especially opens new possibilities for distribution and adaptation in new areas where these organisms may not have existed, or they may increase due to more-favorable conditions for their etiology (Ceballos et al., 2011; Herrera-Campo et al., 2011).

One of the main features of the cassava crop that distinguishes it from the majority of annual crops is its long growing season. Pests and pathogens may complete many generations during the growing cycle. Furthermore, if host material is available in the field throughout the year, these pests and pathogens have no natural break in their cycle to limit their epidemiology. In this sense, cassava is an annual crop that has many of the features of a perennial crop, from the perspective of pest and pathogen dynamics.

The historical belief that cassava was not vulnerable to pests and diseases came from a period when most of the crop was cultivated on small and isolated plantations, often in intercropping systems, and before there was extensive international travel that readily carried pests and pathogens among regions.

Yield losses from pests and diseases are now understood to be common and widespread (Bellotti, 2002; Bellotti et al., 1999; Calvert and Thresh, 2002; Hillocks and Wydra, 2002). Nonetheless, the estimates of yield losses are generally on an experimental or localized level, and it is difficult to quantify losses on a broad scale. CIAT's Cassava Program attempted to develop realistic yield loss estimates for a broad range of constraints, including pests and diseases (Henry, 1995).

In the Americas, where the crop evolved, the pests and pathogens co-evolved and attained their greatest genetic diversity. Additionally, the natural enemies of pests also co-evolved and became a fundamental part of the means for pest suppression. This combination of crop genetic diversity, pest/pathogen diversity, and natural enemy diversity has, for the most part, resulted in a reasonable suppression of the biological constraints in the Americas under traditional cultivation systems. The exploitation of these biological control agents can be one of the most eco-efficient approaches to pest control.

In Africa, now with a history of some 500 years of cassava cultivation, there have been both the time and the means to introduce many cassava pests from the Americas. The cassava green mite (*Mononychellus tanajoa*), cassava mealybug (*Phenacoccus manihoti*), and cassava bacterial blight (*Xanthomonas axonopodis* pv. *manihotis*) are major constraints in Africa, originally introduced inadvertently from the Americas. Others have arisen indigenously either as newly evolved species or through some form of adaptation from other crops to cassava. Cassava mosaic disease (CMD) and cassava brown streak disease (CBSD) are both caused by viruses that appear to have arisen indigenously in Africa. To date they have not been reported in the Americas, but a variant of CMD is present in India and Sri Lanka.

In Africa, green mites and mealybugs were quickly able to colonize cassava and spread across national borders. Without the genetic diversity of germplasm having some degree of host plant resistance, and without the presence of the natural enemies that helped suppress the same pests in the Americas, these pests spread virtually uninhibited throughout large areas of the African cassava belt in the 1970s and 1980s. CBSD is now raising similar concerns as it spreads widely within East Africa.

In Asia, cassava was able to escape some of the most destructive pests until very recently. Growers in most areas did not have many concerns about pest and disease attacks, except in India (as mentioned above) where a variant of CMD from Africa has been a serious yield constraint since the first half of the 1900s. This is changing. In 2009, Thailand reported the presence of the cassava mealybug, and within a few years it was causing yield losses up to 80% in some fields. In 2010, on a national basis, yield losses were reported at 30%. Cassava is Thailand's second most economically important crop after rice, and the impact on the country was a wake-up call, both internally and for neighboring countries, facing the possibility of movement throughout the region.

There are several broad lessons from our experience with biotic constraints in cassava, which inform eco-efficient approaches to their management. We will expand on these strategies in subsequent sections.

- Cassava is host to a wide range of mites, insects, bacteria, fungi, phytoplasms, and viruses. While a limited number are currently highly destructive, and usually on a limited regional basis, many others can evolve into economic pests if conditions are right. There is no room for complacency in any cassava growing area.
- Pests and pathogens can move globally in spite of existing quarantine regulations and the precautions of the scientific community. Most of the destructive pests and pathogens in Africa and Asia were introduced from the Americas via unauthorized movement of planting material.
- Pests and pathogens can move from other crops and evolve into major problems to cassava. They may also evolve to overcome existing resistance mechanisms. Fortunately, there have been few instances of the latter, probably in part as a result of breeding for multi-genic, multi-mechanism resistance.
- Experiences with intensified production give clear warning that changes in management can set the stage for pest and disease problems to change – often to become more severe unless integrated pest management

strategies are incorporated in the production package.
- There is emerging evidence that climate change will broadly affect pest and pathogen dynamics (Ceballos et al., 2011; Herrera-Campo et al., 2011; Jarvis et al., 2012). Rising temperatures and changing rainfall patterns will affect insect/pathogen distribution and development.

Abiotic constraints

In many areas, cassava tends to be a *second choice* for farmers. If growers have better land, or have access to inputs that will improve growing conditions, they will often plant higher-value crops. It is part of the phenomenon that makes cassava a crop of the poor and one that faces a host of abiotic constraints. However, this is changing in some areas of strong market growth for cassava products, especially in Southeast Asia, where cassava prices have risen sharply in the past few years.

Soil conditions. Cassava production predominates on acid and less-fertile soils (Howeler, 2011a). It has the well-known ability to tolerate high soil Al concentrations and soil acidity without lime amendments. In fact, where there is economic response to lime, it is often as a result of response to Ca rather than response to soil pH (Howeler, 2011a). This adaptation to soil acidity favors cassava production across large areas of the cassava belt of Africa, in the southern cone of South America, the savannas of Colombia and Venezuela, in Mesoamerica and the Caribbean, and in southern China.

Cassava is especially adapted to soils with low P availability. The association with root mycorrhizae allows the plant to very effectively extract P from soils with very low levels. In fact, without the mycorrhizal associations, cassava grows poorly even where P levels are moderately high (Howeler, 2002).

Cassava production is also common in sandy soils with low water-holding capacity. In these soils, many crops suffer quickly from short dry periods. Crop failure can result from longer dry periods. Risks in these soils are often not so much related to total annual rainfall as to the likelihood of dry periods during critical phases of crop ontology such as flowering time in cereal or grain-legume crops. Cassava has no critical growth phase after establishment. Also, these soils tend to be leached and have low nutrient status because of the low organic-matter status.

Rainfall. Rainfall and soil conditions are highly interrelated in their effects on crop growth and development, as noted above. Cassava is adapted in the tropics and subtropics from some of the driest (e.g., 400 mm annual rainfall) in the Sertao of Northeast Brazil, to some of the wettest agricultural environments (e.g., 4000 mm annual rainfall) in the Pacific coast region of Colombia. Cassava uses several complementary mechanisms to tolerate long dry periods, including deep rooting to access subsoil moisture reserves; stomata that respond quickly to low ambient humidity, thereby reducing transpiration when water is limiting; and the ability to draw on carbohydrate and water reserves in the starchy roots (El-Sharkawy, 2012). Some of these mechanisms come at the expense of optimum yields, but they do allow the plant to survive and produce something where other crops may fail completely.

Cassava is intolerant of flooding. Relatively short periods of submersion, of only a few days or less, can destroy a plantation. In heavy soils and in poorly drained soils, cassava often suffers from root rots and generally performs poorly.

Market Constraints

Certainly not all cassava growers are linked to markets; some are subsistence farmers, who grow only for family use. For these farmers, food security is often the first concern. However, increasingly, cassava farmers grow at least part of their crop for sale. Entry into the marketplace generates income to improve the family's ability to obtain a diversified and healthy diet, as well as broadly improve livelihoods. Access to markets is a critical part of food security for cassava growers. There is now a widespread interest, even for those countries where cassava's role is mainly for food security, to gradually transform it into a cash crop.

Value addition of cassava, to bring benefits to growers, is currently a key objective in many countries in Africa, most notably in Nigeria. This transformation should result in poverty alleviation, rural development, and strengthened links between producers and their markets (Nweke et al., 2002).

Nonetheless, in much of the cassava-growing world, and especially in Africa, most production is traded locally and is less influenced by global markets. Farmers who are connected to markets may face both the advantages and the disadvantages of a crop whose market prices are not closely linked to global grain markets.

Lack of synchronization between production and market demand, especially in emerging markets, often creates wide fluctuations in farm-gate prices. But even in countries with a long-established market tradition in cassava products, such as Thailand, the rapid market diversification is driving changes in the way the crop is grown, processed, and marketed. Where there is greater market diversity, there is greater chance of stable demand and more-stable prices. The mature markets of Asia include animal feed, starch for food and industry, biofuels and processed products for human food. While any one of these markets may experience considerable fluctuation in demand and prices, together they stabilize the prices that farmers receive. Stable markets encourage farmers to adopt new technologies (varieties, use of fertilizers, and soil conservation measures), which result in enhanced productivity and ultimately in more competitive prices, which in turn consolidate the competitiveness of these markets.

Typically large farms have advantages over small farms in marketing their products. This is especially a challenge for cassava, since small farms remain the norm around the world even as industrialization of the crop progresses. The move to more intensive, industry-oriented production has not necessarily meant a move toward large farms in the case of cassava. Southern Brazil and Northeast Thailand present two contrasting cases in this regard. Southern Brazil produces cassava mainly for the starch market, based on large farms, often over a thousand hectares. It is an environment where large farms have been the norm for many years, and cassava production and processing have been adapted to this land tenure system. In Thailand and Paraguay, on the other hand, cassava farms remain small, usually a few hectares or less. Large centralized processing plants need to coordinate and aggregate the production from many farmers. Also typical in cassava processing plants is their location near the production areas because of the bulkiness and perishability of the roots. This is an important way for their operations to contribute to rural development. Nonetheless, there are increasingly examples of interest by companies buying or contracting large land areas for industrial use of cassava, e.g., in Cambodia, Colombia, Guyana, Indonesia, and Nigeria. Organizations focused on development-oriented support to cassava research will need to closely monitor the impact of such trends and the implications for target beneficiaries.

Increasingly, food security and improved livelihoods will be associated with the ability of farmers to sell their products in the marketplace. The association between capacity to improve income and expansive markets is clear worldwide. Farmers adjust their choice of crops, the way they are grown, and how they are marketed based on access to markets. Few farmers, when given the choice, will remain poor subsistence growers, enduring long hours of backbreaking fieldwork, if there are available markets to sell their products at a profit and make their lives more comfortable and prosperous.

Market development for cassava has certainly evolved in most parts of the world, to one degree or another. But in Africa and in much of the Americas, these remain limited local markets, subject to easy saturation and price fluctuations. More robust, broader-scale markets typically need some initial support from public–private partnerships.

Market expansion and market development often depend as well on new products, and these new products may need new varietal traits and new processes. The intricate linkage between production, processing, and marketing is not automatic at the outset, especially in most of the situations where new cassava markets are needed, i.e., where farmers are small scale and poor, infrastructure is limited, and credit for development is poor or non-existent. Research for development (R4D) organizations need to bring these initiatives into the context of an integrated and comprehensive project, in partnership with government agencies and the private sector. From the outset, such projects need to have a plan for reduced dependence on public subsidies and greater reliance on the marketplace for sustainable success.

An analysis of the potential markets for cassava and its products in each cassava-producing country is well beyond the scope of this paper. Both Latin America and Africa can learn considerably from the experiences of Asia, but clearly local conditions will dictate different products and different pathways. The free market tends to be a rather effective regulator of supply and demand in mature industries, but until that situation is reached, there normally needs to be some intervention to balance the *push* and *pull* factors along the value chain development. Bringing the poorest farmers and small landholders into the equation for successful market development can be especially difficult, but that is precisely what is needed if cassava is to contribute its potential to raising the standard of living of the poor who rely on it.

An important lesson can be drawn from Vietnam. Cassava productivity in Vietnam in 1990 was almost the same as the average for Africa. However, as markets expanded there was a sharp surge of productivity that in few years almost doubled the levels of 1990. This is a clear indication of the beneficial effects of strong markets for cassava products. Where there is a market, farmers will seize the opportunity, invest in the crop, and increase their income. Another interesting example is cassava productivity in Thailand during the transition period when exports to the European Union (EU) were gradually phased out and before domestic markets in Asia developed. The upward trend in productivity reversed for few years. Only after the 1990s, yields started to increase and at a very healthy rate.

The case of Vietnam offers another lesson. An important bottleneck in the development of markets is that they require cassava to reach a competitive price, which in turn depends on farmers investing and using proper technologies and inputs. There is always a subtle and difficult step to break a vicious cycle: There is no market because there is no cassava at a competitive price, and cassava does not reach the markets at competitive prices because the lack of markets does not encourage farmers to invest in inputs and technologies. Although it is difficult to demonstrate that this was the case, it is tempting to hypothesize that in the case of Vietnam the vicious circle was broken because initially there was on-farm processing. Farmers did not sell their cassava but used it to feed pigs, which was their final product. This on-farm processing (not capital intensive) generated enough motivation for farmers to adopt new technologies that eventually allowed the conditions for the emergence of local processing plants (mostly for starch production or drying yards).

Key Eco-Efficiency Interventions for Productivity

Already in the early years of cassava research by international centers CIAT and IITA, it was understood that the *Green Revolution* approach to improving cassava was not broadly applicable. The high inputs of fertilizer and irrigation, and dwarf architecture that had brought high yields to wheat and rice were not appropriate for cassava in most of the areas where it is grown (Kawano and Cock, 2005). Production and marketing systems, policy, and the nature of the crop were all very different from the cereal grains, and different approaches were required. This was not universally understood or accepted, however, and there was a number of programs that attempted to apply high-input practices to cassava, most of which were unsuccessful. The reasons for lack of success were a combination of socio-economic, agronomic, and genetic factors.

Up to recent times, few cassava farmers anywhere in the world had access to purchased inputs to improve production, e.g., fertilizer, irrigation, chemical pest and weed management; or mechanization for land preparation, planting, or harvesting. There were, however, some important exceptions, such as in India, where farmers achieved high yields with moderate fertilizer inputs and irrigation. Because of its long crop cycle, cassava may be exposed to a wide range of pests and diseases over many months, such that successful chemical control of pests often needs to be repeated many times, and thereby is often costly. Because of the crop's drought tolerance, it is often not cost effective to invest in irrigation systems. Even though cassava typically responds to soil fertility improvement, access to fertilizer and credit are typically out of the reach for cassava growers.

Current buoyant demand for cassava and its by-products is motivating farmers, industry, and policy-makers to seek solutions to the problems that limit yield and income improvement from cassava production. The following sections review some of the eco-efficient alternatives that farmers and national, international, and private sector programs have developed and implemented.

Soil fertility maintenance and nutrient use efficiency

Soil fertility maintenance is a fundamental component of successful crop agriculture. Crops extract nutrients from the soil, and without their replenishment, yields in most soils will decline over time. Low soil fertility may be the single most pervasive constraint to high and sustainable cassava production worldwide. But it is highly amenable to improvements through eco-efficient intervention. Results from many cassava soil fertility trials have demostrated that (1) yields steadily decline without soil amendments, and (2) yields can be stable when appropriate amendments are made. Substantial improvements to crop productivity usually include the application of exogenous nutrients in organic or inorganic form (Howeler, 2011a).

There are compelling reasons to work toward soil fertility solutions based on crop nutrient demand and optimized economic response. Fertilizer costs continue to rise worldwide, and their inappropriate application is frequently associated with nutrient runoff into water systems or seepage into groundwater. This creates imbalances in aquatic ecosystems and raises human health hazards from drinking water contamination, and wastes money for producers.

In addition to practices that may be more broadly applicable to many crops, there are several innate characteristics of cassava that allow us to design eco-efficient agronomic management approaches. As already mentioned, the root association with mycorrhizae allows a very efficient extraction and uptake of soil phosphorus. The fungus exists naturally in virtually all cassava-growing areas, and usually no special management is required to achieve good root infection for efficient P absorption. In some situations, where cassava is newly introduced into an area where it has not previously been planted, there may be an economic advantage to inoculation (Howeler et al., 1987).

There has been limited research on the selection of more efficient biotypes of the fungus, but there are indications that this could be a productive line of research (Howeler et al., 1987). The main constraint to testing and selection of efficient biotypes is the difficulty of managing the inoculant, e.g., artificial production, controlling native populations, and cost-effective inoculation procedures. Because of these difficulties, there has been little commercial use of mycorrhizal inoculations in cassava.

Development and application of crop management practices should avoid interference with the effectiveness of native populations. While the effect of agronomic practices on native systems is poorly understood, cassava researchers should be aware of, and test for, any deleterious effects that new inputs could cause. For example, systemic fungicides or herbicides should be especially monitored for their effect on mycorrhizal associations.

CIAT has carried out multi-year germplasm screening for efficiency of nutrient use, especially emphasizing potash (K_2Cl), which is used in relatively large quantities by cassava (reviewed by El-Sharkawy, 2012). There were large differences among genotypes, and probably these could be exploited through breeding. However, establishing selection systems that take into account nutrient use efficiency is an expensive and complicated addition to the many other selection criteria that breeders need to include in their program. As an alternative to a complex system that evaluates nutrient use efficiency by comparing response to low and high nutrient levels, CIAT has routinely selected under low nutrient levels, to allow the more-efficient types to express their favorable traits. This is a research area with potential to benefit from development of molecular markers and the use of marker-assisted selection or genome-wide selection.

Drought tolerance

Cassava is in the field for long periods, and it has no post-establishment critical period of drought vulnerability. This means that drought tolerance becomes very difficult to define. Drought can be comprised of a wide range of variables, e.g., total rainfall during the growing season; length of period(s) with low or zero rainfall; and the growing phase during which drought stress occurs (e.g., early, mid-, late season). While there would be clear advantages to better understanding of the mechanisms involved and the genetic control of tolerance to water deficits, this understanding will require much more research than is possible under natural and variable conditions.

CIAT physiologists have extensively studied genetic variation and mechanisms for drought tolerance and water use efficiency in cassava. One of the key approaches has been to compare varietal responses under irrigated and non-irrigated conditions in dry environments. There appears to be wide genetic diversity (reviewed by El-Sharkawy, 2012). Several mechanisms come into play that confer a high degree of drought tolerance to cassava compared to many other species. Water use efficiency is largely the combination of stomatal sensitivity to low atmospheric humidity (stomata close and conserve water when humidity falls), deep-rooting systems, and high photosynthetic activity. Some varieties also appear to tolerate drought by an excessive leaf area index under favorable conditions, which is reduced to ideal levels (about four) under drought stress, thereby maximizing yield.

Breeders have capitalized on this genetic variation through various strategies, but mainly by planting breeding nurseries under drought stress conditions. This strategy has some advantages and disadvantages. The advantages include simplicity of management, and the possibility to simultaneously select different mechanisms through exposure to conditions that are representative of where new varieties will actually be grown. Disadvantages include the fact that the specific conditions of drought tend to be highly variable from year to year. This means that in any given year, it may not be possible to target the specific desired varietal traits. CIAT, for example, has had a few experiences of "drought" trials in environments with historical severe drought stress, where the trials have been destroyed by flooding (LA Becerra 2011, pers. comm.).

Weed management

Because of cassava's relatively slow early growth, canopy closure can take up to three months or more, leaving the crop vulnerable to weed infestation. Weeds can be a serious constraint to crop growth and yield, and their economic control a major challenge. Typically, manual weed control requires about 40% of labor inputs to produce a cassava crop. Weeding is often done by women, especially in Africa and Asia.

Research on eco-efficient weed management has received relatively little emphasis to date. In part this is because most weed management in cassava is still by hand hoeing, especially in Africa. However, this is changing as farmers look for more ways to reduce the high labor inputs and cost of growing cassava. Chemical weed control is possible, and herbicide use is rising, but mainly in Asia and in larger plantation systems elsewhere. Mechanized weeding is somewhat difficult in cassava except during the earliest stages of growth. Researchers face multiple challenges to integrate effective and economical weed control, with eco-efficiency principles, and gender-sensitive approaches. It is a research area that will become increasingly important and will require greater research emphasis.

Herbicide-resistant cassava could be a popular option for farmers, as it has been for crops like maize, soybeans, and canola. Technically it will probably not be very difficult to incorporate resistance (e.g., to glyphosate) through transformation protocols. But the licensing, regulatory, and socio-economic issues (e.g., gender implications; consumer acceptance) will likely mean that any such technology is many years from widespread use.

Weed control is often the costliest input to cassava production, and it is imperative that science aggressively contribute to eco-efficient solutions as a means to reduce costs of production and increase farmer profits while protecting the environment.

Erosion control

Because cassava is among the most tolerant of crops in marginal conditions, it often occupies lands that are prone to erosion. This is true worldwide, but is particularly an issue in the Andean zone of South America and in Southeast Asia. Slow early growth and relatively wide spacing among plants mean that canopy closure can take 2–3 months – a period when the soil remains exposed to the heavy rains which typically occur near planting time. This situation can lead to severe soil erosion with devastating environmental and social consequences. Soil erosion in cassava systems is one of the most urgent problems for the long-term sustainability of cassava-based farming systems to support smallholder farmers.

Erosion control can be accomplished through soil preparation practices (e.g., ridge planting; conservation tillage, which leaves soil-protecting residues on the surface and soil-holding roots below the surface); strip cropping; intercropping; terracing; live barriers; practices that allow good ground cover (mulching; use of herbicides instead of hoeing); and practices that promote rapid canopy closure to protect exposed soil from direct rainfall impact (e.g., high early-vigor varieties; fertilization to promote rapid early growth). One of the most successful technologies is planting of vetiver grass barriers (Howeler, 2011b). However, farmers often are reluctant to invest in practices that do not provide short-term payback, especially if land is rented or, otherwise, not securely available for the long term.

Very little research has been done on conservation tillage systems for cassava. Clearly there are challenges, namely, the need to plant a large stem piece instead of a small seed, the inevitable soil disturbance that takes place at harvest, and the scarcity of good weed management systems without soil disturbance. Nonetheless, the potential payoff in lowering costs of production, in soil conservation, and in energy conservation makes this a research area worth pursuing.

Advances in small-plot mechanization may make no-till planting technologically feasible. Selection for herbicide-resistant varieties would also facilitate no-till technology, but is not a prerequisite for its success. Demonstration plots using farmer-participatory approaches have been widely used in Asia to highlight the risks of soil erosion and the benefits of implementing preventive measures.

The bottom line is that in spite of all these practices being well known at the research level, their adoption worldwide has been limited. The solution is a combination of opportunities provided by the marketplace, education, policy, and research into new avenues for erosion control.

When market prices rise, farmers will be more easily convinced to invest in inputs that increase their productivity and profitability. In general, the market for cassava products has been buoyant over the past several years, giving hope that farmers will have greater motivation to invest in long-term sustainability of their systems through eco-efficient technologies.

The impact of erosion control is often not immediately evident to farmers, nor easily quantified. Their concept of long-term income loss may not be based on real, field-level data over time. This is also a management area that will depend almost wholly on the public sector initiatives; there are, in a broad sense, few options that can be offered that will be brought about through a profit motive of the private sector. This gives the public sector a heavy responsibility to thoroughly research eco-efficient erosion control methods, to educate growers, and to educate policy-makers on the need for policy support.

Pest and disease management

Eco-efficient pest management systems focus on three main solutions: Host plant resistance, crop management, and biological control. The combination of these approaches can be effective for most pests and pathogens of economic importance in cassava. Use of chemical control has a low priority for research, with the exception of highly targeted applications such as for planting material (stakes) treatment or infestation focal points.

Selection for resistance. Cassava evolved under pressure from many pests and diseases, and as a consequence genetic resistance co-evolved and was further brought into play by the conscious or unconscious selection by farmers. In many of the major crops, plant breeders protect nurseries with pesticides generation after generation, such that many resistance genes were probably lost due to genetic drift. In the case of cassava, this has rarely happened. First, cassava breeding has been practiced on a limited scale and for a limited time worldwide. Secondly, most cassava breeders allow natural infestations of pests and pathogens as a way of selecting for resistance. These strategies have allowed a remarkable opportunity for capitalizing on host plant resistance in cassava, without breeders having to use exotic material or wild species in lengthy pre-breeding programs. Host plant resistance is a clear and successful example of the development of eco-efficient practices. Nonetheless, as new pest challenges arise, especially as a result of climate change, there is greater likelihood of the need to delve further into germplasm collections and engage in pre-breeding to extract new resistance genes.

Breeders have made excellent gains in developing resistance to several key pests and pathogens, including cassava bacterial blight, CMD, superelongation disease (*Sphaceloma manihoticola*), *Phoma* leaf spot, thrips, cassava green mite, and whiteflies (Jennings and Iglesias, 2002). In recent years, molecular tools have begun to aid in selection, specifically with CMD in Africa. A molecular marker for a single-gene resistance not only allows speeding up the breeding process, but it has allowed the selection for resistance in Colombia, where the disease does not exist. Breeders now have a greater ability to combine desired traits from the Americas with the virus resistance needed for adaptation in Africa (Okogbenin et al., 2011). While molecular-assisted selection is so far very limited for cassava, this is likely to change quickly in the next few years as the costs of sequencing and of various *–omics* technologies decline rapidly.

Crop management. The long growth cycle of cassava is conducive to the build-up of many types of pests and pathogens. This creates challenges, but also opens up many opportunities during the crop's long period in the field, to introduce variable management packages for suppressing pest and pathogen damage. Some of the common practices that can contribute to pest suppression include adjusting planting date, plant spacing, and intercropping. Early trials in the Eastern Plains of Colombia showed that planting near the end of the rainy season was a viable strategy for reducing losses from bacterial blight and superelongation disease (CIAT, unpublished). One of the challenges of using management practices to control pests and pathogens is to assure that any changes in management do not reduce yields even more than the pest under standard crop management.

Biological control. Biological control is one of the most eco-efficient practices possible for pest management. The development time can be relatively rapid (in contrast to the long lead time for developing resistant varieties, for example); there is virtually no trade-off in yield or quality with the application of biocontrol methods; and in many cases, the control can be long lasting without the continued need to reintroduce the organisms.

In the Americas, biocontrol agents (parasites and predators) evolved along with the crop during many millennia. However, when traders introduced cassava to Africa and Asia, most of these beneficial organisms were left behind. When new pests were introduced, they were often able to spread uninhibited by the natural enemies they faced in their evolutionary homeland. There have been several examples of the introduction of natural enemies to successfully control mites and insects. In Africa, the cassava mealybug caused devastating losses until *Anagyrus lopezi* (a parasitic wasp) – an effective natural enemy – was introduced in the 1980s, saving billions of dollars in potential crop losses (Zeddies et al., 2001).

The same predator was introduced to Thailand in 2010 after the cassava mealybug appeared there. By 2012, monitoring studies showed that *A. Lopezi* had become established throughout nearly the entire cassava-growing area where the mealybug was found, and is effective in control (Chariensak 2012, pers. comm.). It is hoped that the parasite will establish widely in other countries as well, following the mealybug spread in the region, to reduce population densities to economically insignificant levels.

The cassava green mite also became a serious introduced pest of cassava in Africa by the late 1980s. Many different phytoseiid predators (also mites) act as biological control agents against the green mite. They probably account for the absence of major outbreaks of the green mite in the Americas (Bellotti et al., 1987). CIAT and IITA introduced many of these phytoseiid predators into Africa but *Typhlodromalus aripo* was most successful, reducing populations of the green mite by 35–60% with a parallel increase in fresh-root yield by 30–37% (Bellotti, 2002). Implementation of the biological control by *T. aripo* depends on the morphology of the apex and on the volatiles emitted by the plant host. Both characteristics are determined by the cassava genotype. This is a promising case of genotype-by-biological control interaction, hypothetically representing an opportunity to breed for a cassava plant that will favor the establishment and survival of the predator for a more efficient control of the green mite.

Biological control never results in complete control, which leaves open the potential for fluctuations in levels of pest populations (similar to most types of host plant resistance as well). In some years and in some locations, economic damage levels may be significant. Like other types of pest management, biological control must be accompanied by constant monitoring, preparation for additional releases, and preparation for supplemental management within an integrated pest management system.

An integrated strategy for eco-efficient production

Despite cassava's global importance, the research investment has historically been far below that for other crops of similar importance. One of the reasons is its cultivation almost exclusively in developing countries. While there has been more public and private sector interest in recent years, there is not by any means a level of research funding that allows research institutions to carry out the kind of comprehensive research agenda possible for rice, wheat, maize, or potatoes, for example. This means that we need to be especially creative to find solutions with the most output per unit of input.

Research needs to begin by understanding the combinations of biotic and abiotic stresses and pressures that farmers face now and may face in the future. Only then can we offer an effective means to find the right balance of traits and practices to optimize economic yield for the grower, while protecting the environment. One of the most effective strategies over some 40 years of research at CIAT has been the identification of research sites that are representative of broad target regions, in terms of soils, climate, pests, and pathogens. This has allowed effective development of integrated variety development and management systems that balance the needs for adaptation in the agro-ecological zone, along with yield potential and root quality. As techniques are developed or new genes identified, they can then be incorporated into the system to fine-tune the adaptation and resistance features.

Cassava is exposed to a wide array of stresses during its growth in most parts of the world. Breeders and agronomists do not have the luxury of a long history of research to adequately understand mechanisms and the genetic basis for eco-efficient responses. Therefore, until now we have mainly relied on the plant response in selection environments and with management practices that place the crop under conditions that farmers will typically encounter, or can reasonably and economically create through use of inputs. In this way, without the deep understanding of physiology or genetics of each trait, we have developed varieties and management practices that contribute to eco-efficient production. Additional investment, an ever more precise set of measurement tools for plant response, and genetic tools for crop manipulation should provide greater progress.

The key role of genebanks

In the arena of cassava technology development, some of the world's greatest assets are the germplasm collections around the world. CIAT holds the largest of these as an *in vitro* collection at headquarters in Cali, Colombia. The CIAT genebank holds about 5500 landrace accessions, along with another approximately 600 advanced varieties and breeding lines. The collection is available to all interested parties, under the conditions of exchange and use of the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA).

The genebank probably represents most of the genetic diversity that exists in cassava, although the actual tests of this hypothesis have yet to be carried out. With the decreasing costs of sequencing and molecular marker development, the time is right to begin the genome-wide characterization of cassava genetic diversity and to fill gaps in the collection (see also next section). Nonetheless, based on the coverage of collected areas, we can probably make a reasonably safe assumption that the existing diversity is adequate to continue to make progress in genetic improvement for many years to come. On the other hand, there are known gaps in the collection that need to be filled before valuable diversity is lost. CIAT's collection has limited representation from Central America or Bolivia, and no accessions from Suriname or French Guyana, for example.

In addition to cultivated cassava, there are some 100 wild relatives that are poorly collected and poorly evaluated. Many populations are at risk in their native habitats due to urbanization and expansion of agriculture. It is imperative to extend the collection of these species for their future potential contributions to eco-efficient production solutions.

Africa has had limited exchange of germplasm with the Americas or with Asia due to the presence of some viruses in Africa that do not exist elsewhere, and several viruses in the Americas that also do not exist in Africa or Asia. Modern molecular methods now allow a very high level of security for the detection and cleaning of viruses, but it is still very difficult to exchange vegetative material between Africa and the Americas. Exchange between Asia and the Americas has been relatively straightforward.

The CIAT genebank is an engine for eco-efficient technologies – a resource that has already been extensively tapped to produce income-generating technologies for farmers worldwide. But it has much more to offer in the future as the need for new traits expands, and as our ability to find those traits improves. The coordinated phenotyping and genotyping of the cassava genetic resources held in genebanks will be a core strategy toward development of eco-efficient technologies to improve people's livelihoods from cassava while protecting the environment.

The role of molecular technologies

The development of molecular marker techniques for genetic analysis has increased our knowledge of cassava genetics and our understanding of the structure and behavior of the cassava genome. While microsatellites have been the basis for most work in cassava genetics, other valuable markers have also been used – including random amplified polymorphic DNA (RAPD) and amplified fragment length polymorphism (AFLP) markers – to produce cassava genetic maps.

The availability of a cassava genome sequence since 2006 has allowed the identification of thousands of candidate simple sequence repeat (SSR) markers which may be used for genetic mapping and marker-assisted selection. However, the sequencing of multiple genotypes (including wild species) would provide the cassava community with a much greater density of markers in the form of single nucleotide polymorphisms (SNPs). These SNPs can be used to construct improved genetic maps and look for trait associations; the high density of SNPs will increase the likelihood of identifying markers tightly linked to loci encoding traits of interest such as drought tolerance or whitefly resistance.

The combination of sequences from both wild species as well as cassava itself will give researchers the opportunity to discover genomic regions and individual genes which have played a role in the domestication of cassava. Having whole genome sequences allows the exploration of copy-number variations (CNVs) and genomic rearrangements which may be related to different characteristics of interest. While use of SNP markers can focus the search for causative trait loci, having a large number of genomic sequences from a variety of genotypes for a given region provides the wider genomic context and will enhance genomics-assisted breeding in cassava, boosting our breeding activities to develop desirable breeding lines in a shorter term.

Molecular technologies have evolved at astonishing speed. The cost and efficiency of genotyping have advanced so much that the phenotyping that is often required along the molecular work is now the real bottleneck. Deficient field data and unreliable phenotypic information constrains the applied uses of molecular markers in cassava genetic enhancement. Plans are underway to sequence a large sample representing nearly the full range of cassava genetic diversity, set to begin in late 2012 and 2013.

Eco-Efficiency in Processing

Cassava conversion to marketable products can involve a wide range of processing techniques and some of them produce large amounts of waste that can contribute significantly to environmental pollution and depletion of water resources (FAO, 2001). Into the early 1990s, much of Thailand's cassava was chipped and dried on large patios, a process that was essentially pollution free and relied primarily on sun energy for drying (plus use of tractor power for turning and collecting the chips). With the rise of the starch industry throughout Southeast Asia, and the ethanol industry in China, waste management is a growing concern, and many creative new technologies and systems are being developed to minimize environmental impact and increase profitability.

The main issues are:

- Use of large quantities of water for starch extraction
- Environmental risks of wastewater disposal, especially when discharged into streams or bodies of water
- Potential pollution from residues of processing
- High energy use for artificial drying of chips for animal feed, starch, flour, or other end products (cost and CO_2 generation)
- High energy use for ethanol distillation (cost and CO_2 generation).

The treatment of effluent waters is a major issue in the process of starch extraction. It results in major economic costs (if the effluents are not properly recycled or otherwise managed) or environmental costs (if effluents are dumped into the surrounding environment). CLAYUCA Corporation has developed technology to efficiently produce high-quality flour that can substitute for starch for many uses, but whose processing has far less impact on the environment. Water is used only in the whole-root washing, while the flour is extracted simply by grinding dried root.

Arising technologies

Cassava markets will continue to change quickly. Eco-efficient production and processing technologies are closely linked and need to be developed in parallel. This can be quite challenging, given the lead time required for many types of technology, and especially for the breeding of new varieties.

Two examples of production technologies that impact eco-efficiency of processing involve variations in starch functional properties:

- The identification of a natural mutation of amylose-free starch in cassava (Ceballos et al., 2007) has generated a keen interest and investment by the starch sector. This mutation will allow industry to develop certain starch-based products without the chemical modification that is currently required, with potential benefits to both the environment and human health.
- A different starch mutation (Ceballos et al., 2008) was generated through mutagenesis, resulting in the production of small starch granules (about 1/3 the normal size) with rough surfaces. This mutation would be ideal for the bioethanol industry as the starch is more easily degraded into simple sugars, a necessary step before fermentation can be initiated. This should result in lower energy use in the conversion process.

A FAO study (FAO, 2001) concluded that cassava processing can have negative – mainly site-specific – effects on the environment, by producing unpleasant odors and an unsightly display of waste. However, the long-term and broad-based impact on the environment is generally minimal and can be corrected by proper waste treatment with technologies that are presently available or under development.

Moreover, there is ever greater economic incentive to make use of the by-products from the development process of marketable value-added products. The residue from starch factories can be used in animal feed rations, to reapply to fields as a crop nutrient, or as a substrate for the culture of mushrooms, for example. While policy will be an important element for limiting environmental impact from cassava processing, the more-effective strategies will be based on methods that generate greater income for processors.

Addressing Climate Change

As mentioned at the outset of this chapter, there is an emerging consensus that cassava is among the most promising options of tropical crops in the context of rising temperatures and increasingly uncertain rainfall patterns. Achieving an eco-efficient response to climate change represents one of the great challenges of agricultural research, and cassava presents unique opportunities.

Climate change may have direct effects on crop growth and development (temperature, rainfall, CO_2 levels) or indirect effects (soil organic matter, soil erosion, pest and disease patterns), and therefore the needed response through eco-efficient solutions can be complex and far-ranging.

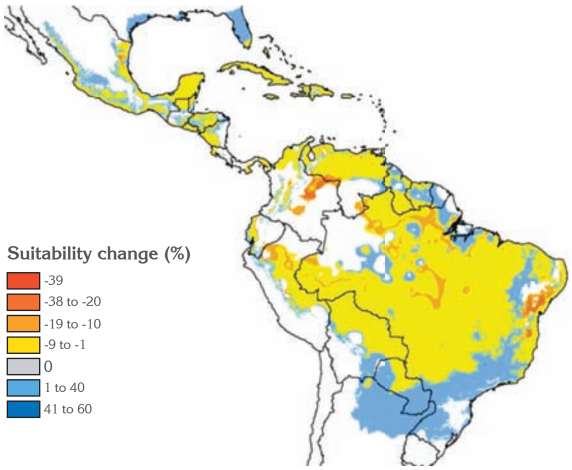
Temperature and rainfall patterns

Climate maps combining temperature and rainfall parameters specific to cassava's growth responses (Figure 9-2) indicate that cassava will probably continue to be grown in nearly all areas where it is currently adapted. This is largely because of its combined high temperature and drought tolerance, even in some areas where these changes will create severe stress for other crops. In fact, cassava is likely to expand into new areas of the subtropics that become more suitable as temperatures rise, and into areas where more-sensitive crops decline or disappear.

On the whole, cassava is tolerant of very high temperatures compared to many crops. This is in part because there is no critical stage, such as flowering, when brief periods of high temperatures will cause drastic yield losses. Increasing temperatures may not have a large direct effect on cassava production. On the other hand, areas that become too hot for other crops could create new growing areas for cassava to fill the gap. Some climate models show that India could be especially affected by rising temperatures, with broad shifts away from grains and pulses in some areas (Ceballos et al., 2011).

Possibly the most significant effect of temperature rise on cassava's adaptation will be to allow it to move into higher-altitude and higher/lower- latitude regions. Currently, cassava's limit at the Equator is at about 2000 masl, and this just for a narrow range of germplasm accessions from the Andean zone of the Americas, especially Colombia. These extended new highland areas for cassava are likely to be most important in East Africa, and in the Andes of Colombia and Ecuador. Currently cassava can be grown in latitudes near the Tropics

Global cassava suitability will increase 5.1% on average by 2050, while many areas of Latin America will suffer negative impacts



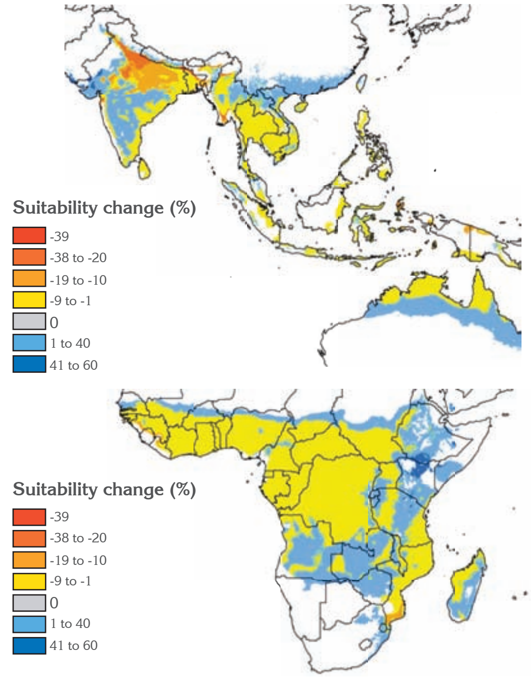


Figure 9-2. Impact of climate change on cassava suitable environments.
SOURCE: Decision and Policy Analysis (DAPA) Research Area, CIAT.

of Cancer and Capricorn. Global warming may extend this range, as winters become milder. This is of particular interest in China, which is looking for options to expand planted area but has a relatively limited region within the subtropics that is suitable for cassava. This is not to say that global warming will have overall positive effects on agriculture, but there will be opportunities for farmers to adapt with new crops and new practices if science can provide the appropriate technological support.

Drought promises to be one of the most widespread negative impacts of climate change on crop production in general. Lower overall rainfall and greater uncertainty both come into play in climate change scenarios. Therefore, it is logical that breeding programs in many crops have begun to take into account major efforts to select for drought tolerance. Cassava models appear to indicate a different strategy.

First, cassava will likely move into areas where other crops are constrained, especially grain crops, with their susceptibility to drought during certain development stages, such as flowering and early grain filling. But cassava is broadly drought tolerant already, so it will do quite well in areas where other crops cannot succeed. But the question remains about the advisability of stressing selection for drought tolerance in traditional cassava-growing areas that are already dry, and will become drier with climate change. Although breeding for drought tolerance has been limited, there are clear indications from physiological studies that selection for even better tolerance could succeed. So it is a matter of comparing returns on investment from alternative breeding goals. Climate change models and crop models suggest that other constraints brought about by climate change, and especially the effects of pests and diseases, are likely to be more severe, and often more amenable to management through breeding for resistance/tolerance than is drought.

The other side of the rainfall issue is excess water. Cassava typically does not tolerate waterlogging. Root rots can become common if soils are waterlogged even for relatively short periods of time. Breeding has shown little promise, and in most cases management practices are probably more appropriate as an adaptation strategy.

Increase of atmospheric CO_2

Atmospheric CO_2 is one of the major causes of climate change and has increased by 40% from a pre-industrial revolution baseline. Confined-environment studies indicate that increases in atmospheric CO_2 concentration could result in a reduction in root production. Concentration of cyanogenic glucosides in the roots was not affected by increases in CO_2. On the other hand, there was a large increase of glucosides in the leaves of plants grown in higher CO_2 concentrations (Gleadow and Woodrow, 2002; Gleadow et al., 2009). These results contradict earlier ones reported by Imai et al. (1984). Free-Air CO_2 Enrichment (FACE) methods allow field evaluation of crops under elevated CO_2 concentrations which simulate the predicted levels for the decades to come (El-Sharkawy, 2009). These studies suggest that photosynthetic efficiency would increase more in C_3 (like potatoes and cassava) than in C_4 crops (like maize and rice) (Long et al., 2004; 2006). Modeling and FACE results could guide the molecular optimization of the photosynthetic apparatus to maximize carbon gains without increasing crop inputs (Rosenthal and Ort, 2012).

Pest and pathogen response to climate change

There are several reasons why risks are increasing for introduction and spread of pests and pathogens into new areas. These include:

- More international travel
- Greater interest in introducing new materials by uninformed travelers, e.g., businessmen or women managing cassava plantations or processing plants
- Greater potential for introduced pests or pathogens to encounter host plants (increasing area planted to cassava globally, e.g., larger contiguous cassava plantings that allow pests to spread quickly)
- Climate change that transforms less suitable environments into more suitable ones for introduced pests or pathogens
- The interest in new crops, such as *Jatropha* (also a member of the Euphorbiaceae family) which can be a reservoir of pests and diseases that can also affect cassava. The recent interest in this crop has resulted in vast and unregulated exchange of germplasm.

The first defense against pest and pathogen spread to new areas is the double-pronged approach of education and regulation. The principle audience needs to be the general public – about the risks of moving uncontrolled plant materials and agricultural products across national borders. This is not to downplay the importance of official channels. Most countries have strict quarantine regulations on the books, but lack personnel and budget for enforcement. Understanding the risks is the primary motivation for investing in better enforcement.

Climate change modeling, layered with pest adaptation maps, illustrates the potential spread to new areas in the context of climate change. This allows the application of resources in hotspot areas for monitoring, diagnosis, and management. It is expected that pests affecting cassava will evolve into more dynamic patterns, particularly as a result of increased temperatures that reduce the relevance of diapause and/or shorten their life cycle (Ceballos et al., 2011).

Figures 9-3 and 9-4 illustrate areas where cassava green mite and whitefly, respectively, are likely to increase or decrease in severity due to climate change by 2020. For both species, there will be widespread effects in the Americas and Africa, but less so in Asia.

Effective pest and pathogen monitoring and diagnosis systems are essential to early detection and effective management. Fortunately, such systems may be implemented across a number of crops, and do not need to be re-invented for each individual crop. The *PlantWise* system of CABI, for example, may be a good model to incorporate cassava data and take advantage of a system that is applicable for a broad range of crops. A pilot system is being established for Southeast Asia, which should develop into globally applied systems for information exchange about pests and diseases.

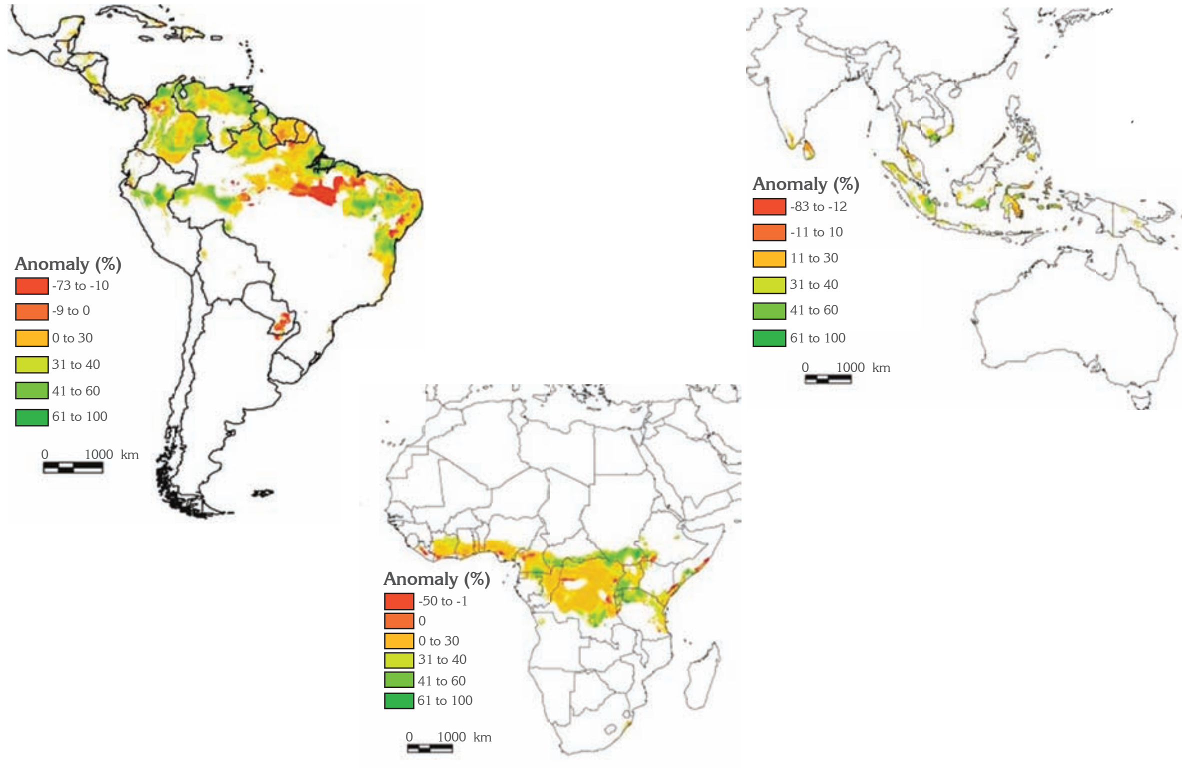


Figure 9-3. Climate change impacts on cassava green mite (*Mononychellus tanajoa*) by 2020.
SOURCE: Decision and Policy Analysis (DAPA) Research Area, CIAT.

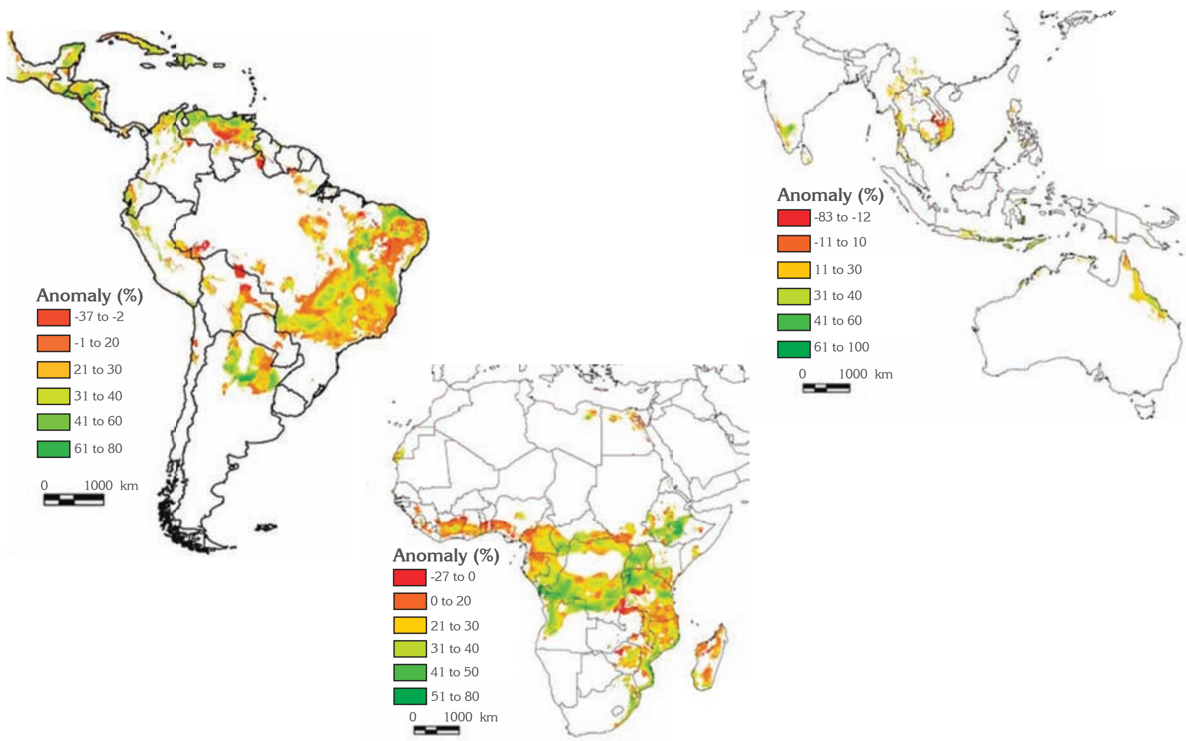


Figure 9-4. Climate change impacts on cassava whitefly by 2020.
SOURCE: Decision and Policy Analysis (DAPA) Research Area, CIAT.

Soil degradation

Some of the new soil-related challenges likely to be exacerbated by climate change are: More rapid loss of organic matter due to higher soil temperatures; planting in areas more vulnerable to erosion (e.g., further up hillsides as temperatures rise); and greater nutrient leaching in areas where rainfall has increased.

For cassava in an era of climate change, one of the great challenges for sustainable soil management is in areas where the crop expands to replace species that are less adapted to drier conditions. Unless this expansion into new areas is accompanied by appropriate management and technologies, there is a risk that growers without the experience of growing the crop will use practices that exacerbate erosion. Certainly there should also be attempts to introduce diversification programs, such as the planting of perennial crops/pastures/trees in the most vulnerable areas.

Conservation tillage or no-tillage systems have had relatively little application in cassava. Alternatives to conventional tillage will be important both in areas of reduced and increased rainfall. In reduced rainfall, conservation tillage conserves soil water. Under heavy rainfall, it reduces erosion and improves soil structure for better drainage. These advantages need to be weighed against the possibility of sacrificing yield or income as a result of adoption of these practices. The development of herbicide-tolerant genotypes would greatly facilitate the adoption of reduced-tillage practices. Technically, this should be relatively easy through transgenic methods, but the licensing, regulatory, and consumer acceptance issues would be huge hurdles to ultimate success. There need to be intensified efforts at the discovery of herbicide tolerance that is not transgenic. The most likely approaches are through screening of a broad genetic base of progeny from selfed genebank accessions, and through mutation and selection at the cellular level.

The Key Role of Partnerships

Little is accomplished in isolation. Science and its successful application require partnerships among a range of public and private organizations. There is a need for concerted capacity building and interchange to assess and develop eco-efficiency goals and methods for cassava technologies (see Chapter 14, this volume). The new CGIAR structure takes a step in that direction through capitalizing on the potential synergies among centers working on several vegetatively propagated crops, and by bringing together the wide range of partners that can collaborate toward common goals. This new CGIAR Research Program on Roots, Tubers and Bananas (CRP-RTB) continues many of the same goals and activities as previously carried out by CIAT and IITA for cassava. However, there is now greater emphasis on linking research to development outcomes and on realizing the synergies among the various root, tuber, and banana crops and the centers that work on them (see www.rtb.cgiar.org/). The long history of collaboration between CGIAR centers and other entities working on cassava will be further enhanced under the new system.

Gender and Eco-Efficient Cassava Systems

There is a wide contrast on the use of cassava ranging from a key element in subsistence farming in Africa to mostly a cash crop to be used by different processing industries in Southeast Asia. CIAT is aware that in many cases well-intentioned interventions result in undesirable unforeseen impacts. A major thrust in our research is toward the gradual transformation of cassava from subsistence farming into income-generating crop. However, it has to be acknowledged that whenever this occurs, some gender-related issues may arise. In many resource-limited farming households, it is women who stay in the farm attending to the different chores, while men go to the villages in search of income-generating activities. If cassava becomes a cash crop, it is likely that the role women and men play will change. Many social scientists have expressed their concern that some of these changes may be negative, but also could result in positive trends, such as "the return of men to the farm for a reunited family." The impact of turning cassava into a cash crop from the gender perspective is difficult to predict, not to mention to modulate, from a research position. It is important, however, to monitor them and make whatever intervention may be required to maximize the positive impacts while minimizing the negative ones.

Researchers need to monitor potential gender-related impact. Moreover, we actively search for potential areas where gender plays an important role. For instance, it has been recognized for many years that it is typically women who are in charge of weeding cassava fields in many regions of Africa. This implies that very often, women will invest the first two months of the crop in weed-control activities. Development of herbicide tolerance is therefore one such issue. It is envisioned that, in principle, this trait should benefit women as they could redirect their effort to other more-productive endeavors. Whenever the trait is identified or induced, however, careful analysis of its expected advantages will be tested through participatory approaches to make sure that the technology is well appreciated by the women we are targeting to benefit.

Another activity typically linked to women and children is the peeling of cassava, for example, in the production of *farinha* in Northeast Brazil or *gari* and *fufu* in Western Africa. It is known that peel thickness is another trait that may offer a gender bias. Awareness of such a situation is relevant for orienting research in the right direction. A thin peel is desirable for those industries where the entire root is processed, since it maximizes the proportion of valuable tissue. On the other hand, a thick peel facilitates the operation of manual peeling reducing the overall cost of such operations, thus maintaining its competitiveness.

Most importantly, gender bias studies need to be part of research design from the outset, rather than an afterthought after a technology is already developed and disseminated.

Key Lessons and Opportunities for Policy Interventions

Policies aimed specifically at eco-efficiency of crop research are nearly non-existent in developing countries. The scientific community has a major challenge to educate, inform, and advocate for such policies. We present a few examples here, although this is not by any means a comprehensive list.

Policy on food security and equity

Developing countries that support technological and economic progress as a means of addressing food security and equity will find that cassava, where it is adapted, can often play significant food security and equity roles.

Policy on market development

Policies that favor new industries can open opportunities for cassava markets. The broad range of products that can derive from cassava provides an ideal vehicle for new industry development. Multiple industries can evolve from the many cassava end-uses, to the advantage of cassava growers. Multiple market opportunities for farmers mean that there are likely to be better prices and lower swings in the market prices. A key example of this kind of intervention is the policy to mix 10% cassava flour with wheat flour for the baking industry. However, as discussed during the West Africa Root and Tuber Crops Conference (Accra, Ghana, 12–16 Sept 2011) (Dixon, 2011), policies need to be turned into laws for an effective impact.

Trade policy

Open versus protectionist trade policies will impact the kinds of markets where cassava can be competitive. Certainly the global tendency is toward more open markets, but there are many exceptions. Strong policies that protect local agricultural and industrial development are often a necessary short- to medium-term strategy in order to develop a competitive global position. On the other hand, protectionist policies tend to promote inefficiencies and, ultimately, higher prices for consumers. In any case, trade policies will rarely be developed specifically with the cassava market in mind, but rather with a broad agricultural or industrial vision.

Policy on biofuels

China is leading the way in biofuels from cassava, as a result of a dual policy that aims, on the one hand, to reduce reliance on fossil fuels and, on the other hand, to keep staple foods from competing in the biofuels market. Thus, cassava, as an efficient energy producer and with a very minor role as a food in China, is an ideal option. In Africa the situation is more complex, where cassava for biofuels is likely to compete with food markets, and where most of those who rely on cassava for food are not able to absorb cost increases even of small levels without suffering serious consequences.

Policy on agriculture in fragile ecosystems

Thailand attempted for many years to support crop diversification in the northeast of the country, to prevent the continued spread of cassava into fragile soils. The policy had limited success because cassava is so much better adapted than most other crops that can provide a profit to farmers. These types of policies are, however, rather rare on a global basis. In order to succeed, they need to either strictly prevent the growing of cassava in inappropriate environments, or provide equal or better alternatives through technology support and/or subsidies that give farmers attractive options. In fact, effective policies that address the use of fragile landscapes are sorely needed in many countries. Along with policy, education of growers and the offering of eco-efficient technologies are needed for positive impact.

Policy on research and extension support

Until recent times, there was nearly no private sector support to cassava research. This is changing, but slowly. In Thailand, for example, the private sector provides modest support for development of specialty starch varieties, provides extension services in the form of advice on management practices, and provides growers with biological control organisms for the cassava mealybug, a newly emerging pest problem. There are examples elsewhere as well of important but quite limited industry support to technology development. This means that public support for research is the main determinant of the success of cassava research in any given country. CIAT and IITA have strong multidisciplinary research programs, but they also rely on the capacity of national partners to jointly develop that technology and deliver it to farmers or to industry. Policy that supports a sustainable research and extension system is essential to the ability of cassava to play its full role as a vehicle for eco-efficient development.

The public sector for cassava research is seriously underfunded in most countries. In Africa, donor support in the last few decades has made a dent, but the long-term consequences of donor-dependent funding of research are uncertain. On the one hand, it seems to be a necessary intermediate step, while local public and private support and capacity are developed. All too often, however, this support is not prioritized, leading to programs falling by the wayside when donor funding diminishes or dries up. There needs to be much more support from studies illustrating the impact of investment in research by national and local governments.

Policy on credit and crop insurance

The long cycle of cassava from planting to harvest often implies a heavy burden for the farmers because of the long time required to recover their investments. It is becoming a common practice for governments through different banking systems to provide soft credits to farmers, particularly in cases where they have some sort of agreement with the processing sector and after it has been demonstrated that proper inputs and management practices will be used in growing the crop. This practice offers several advantages as it promotes linkages between the production and processing sector and encourages the adoption of technologies for the sustainable and competitive production of cassava. Within the same policies, farmers can also have access to crop insurance. For insurance to have more widespread impact, however, more data on production risks are necessary.

Summary: Approaches to Eco-Efficient Research for Cassava

CIAT works with partners to develop technologies that are more productive, profitable and competitive, sustainable, resilient as well as more sustainable. The following summarizes how this relates to CIAT's cassava research for development.

- **More productive**: *Providing inexpensive and nutritious food for poor consumers.* This is largely the CIAT legacy of its first 45 years, by producing clones with high and stable productivity, and giving special consideration to dry-matter content (Kawano, 2003; Kawano and Cock, 2005).
- **More profitable and competitive**: *Creating new opportunities for growers to increase their incomes.* New or expanded markets are needed for cassava farmers to pull themselves out of poverty. Without markets to absorb increased productivity, moving beyond subsistence is only a dream for many. High-value traits such as the *waxy* and small-granule starches (Ceballos et al., 2007; 2008; Sánchez et al., 2009) and enhanced carotenoids contents are examples of traits that can move into new specialty markets.
- **More sustainable**: *Environmentally, economically, and socially.* Pest and disease management strategies fit mainly in this area (but also in others). Genetic resistance and biological control are the central elements of integrated pest management. Managing soil erosion and maintaining/improving soil fertility are probably the most critical needs to achieve sustainability in many cassava-growing regions.
- **More resilient:** *Reversing land degradation and adapting to the new conditions caused by climate change.* Cassava is already one of the world's most resilient crops, and it has the potential to be even more resilient through a combination of genetic and management approaches. Its inherent drought tolerance, adaptation to high temperatures, efficient use of soil nutrients, and tolerance to highly acid soil conditions make it a popular crop where these conditions already exist. And with climate change, it will replace other crops as these conditions are newly created in some regions.
- **More equitable:** *Providing new opportunities for the rural poor.* Equity issues that cassava can help address include income generation for the poor, and technologies that are pro-women. The very nature of traditional cassava production by smallholders and processing at the local level has contributed to equity issues. The challenge is to continue to address equity issues as scale of production increases and more-sophisticated markets are developed.

Specialty cassavas, such as waxy-starch varieties, should lead not only to increased value and higher incomes to farmers, but also should promote a closer association between farmers and processors (e.g., contract farming) which can favor both layers of the value chain.

While biofuels are often seen as working against equity issues, examples in cassava illustrate other options. CLAYUCA Corporation is developing a model for cassava based on decentralized small plants at the village level that produce 50% ethanol, which is then shipped to a more sophisticated central plant for dehydration to 99%.

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CHAPTER

10

Improving Rice Production Systems in Latin America and the Caribbean

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Contents

Abstract

The Latin American Fund for Irrigated Rice (FLAR, its Spanish acronym) is a public-private partnership between rice institutions in 17 countries and the International Center for Tropical Agriculture (CIAT, its Spanish acronym), which was formed in 1995 with the aim of improving people's lives through improved rice production. FLAR has a holistic approach to improving rice production, taking into account farmers' economic, social, and environmental situations. New high-yielding, high-quality varieties, improved crop management practices, and the use of water harvesting to expand irrigated production have been the main FLAR interventions among its 17 associated countries. Forty new varieties have been released in 13 countries to the end of 2011 and many more are in the pipeline. Farmer-to-farmer transfer and extension programs to improve crop management have been developed in 14 countries, and a pilot project on water harvesting to expand irrigation on small-scale, resource-poor farms is under way in Central America. FLAR has successfully developed eco-efficient technologies, which have helped the Latin American rice sector produce more rice, with fewer inputs, at lower costs per unit of output, contributing to enhancing the well-being of the rural and urban poor in the region.

Introduction

Rice is a relatively new crop in Latin America and the Caribbean (LAC). Although it was introduced into the region in the sixteenth century by Spanish colonists, it was not widely grown until the twentieth century. It is now grown throughout the region, in a wide range of agroecosystems,

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ranging from upland systems in the Brazilian Cerrados and some hilly areas of Bolivia, Colombia, and Central America to high-tech irrigated systems in the Southern Cone region. About one million farmers in the region, 80% of them poor smallholders, depend on rice as their main source of energy, employment, and income (Maclean et al., 2002).

Rice is now the most important food grain in most of the tropical areas of LAC, where it supplies more calories in people's diets than wheat, maize, cassava, or potatoes, and is also the leading source of protein for the poorest 20% of the population in tropical areas (Maclean et al., 2002). The crop provides an average of 27% of daily calorie intake in LAC as a whole, ranging from 8% in Central America to 47% in the Caribbean region (FAOSTAT).

Total production of paddy rice increased from around 8 million tons in 1961 to more than 28 million tons in 2009, an increase of over 250% (Table 10-1). Over this period the area under rice increased by only 35%, hence the majority of the increase in production came from yield gains. However, there is still a negative balance between production and consumption in the region as a whole.

There is thus clearly a need to increase rice production in the region. It is vital, however, that this is done through eco-efficient production systems. Eco-efficiency implies producing more while using fewer resources and creating less waste and pollution. Eco-efficient rice production should be profitable, competitive with other agricultural or commercial activities, and ecologically sustainable. It should also be resilient in the face of climate change and socially equitable, giving small-, medium-, and large-scale producers access to new practices and technologies. In summary, eco-efficient rice production allows farmers to derive more benefits from rice cultivation using fewer resources.

FLAR is a public-private partnership between local rice institutions and the International Center for Tropical Agriculture (CIAT). It was established in 1995 to improve people's lives through the

Table 10-1. Paddy rice area and production for selected countries in Latin America and the Caribbean, 1961 and 2009.

	Area ('000 ha)			Production ('000 t)		
	1961	2009	Change (%)	1961	2009	Change (%)
South America						
Argentina	46	194	322	149	1,334	795
Bolivia	24	180	650	34	396	1,065
Brazil	3,174	2,872	-10	5,392	12,651	135
Chile	38	24	-37	105	127	21
Colombia	237	543	129	474	2,985	530
Ecuador	95	395	316	203	1,579	678
Guyana	106	215	103	215	554	158
Paraguay	8	50	525	19	215	1,032
Peru	81	405	400	333	2,991	798
Uruguay	17	161	847	61	1,287	2,010
Venezuela	58	250	331	81	1,330	1,542
Subtotal	**3,884**	**5,289**	**36**	**7,066**	**25,449**	260

(Continued)

Table 10-1. (Continued).

	Area ('000 ha)			Production ('000 t)		
	1961	2009	Change (%)	1961	2009	Change (%)
Central America and Mexico						
Belize	1	5	400	1	21	2,000
Costa Rica	48	63	31	60	260	333
El Salvador	9	6	-33	18	40	122
Guatemala	9	8	-11	13	23	77
Honduras	9	9	0	12	45	275
Mexico	146	54	-63	333	263	-21
Nicaragua	24	74	208	39	335	759
Panama	100	107	7	109	242	122
Subtotal	**346**	**326**	**-6**	**585**	**1,229**	**110**
Caribbean						
Cuba	150	216	44	207	564	172
Dominican Republic	58	182	214	113	848	650
Jamaica	3	0	-100	5	0	-100
Trinidad and Tobago	5	1	-80	10	2	-80
Subtotal	**216**	**399**	**85**	**335**	**1,414**	**322**
Total	**4,446**	**6,014**	**35**	**7,986**	**28,092**	**252**

SOURCE: FAOSTAT.

development of improved rice technology (Zorrilla-de San Martín, 2010). By 2012, more than 30 institutions, including farmers' associations, national research institutes, and private companies, in 17 countries were participating in FLAR.[3] Since its establishment, FLAR has implemented programs to promote use of improved varieties and management practices, and better use of natural resources.

This chapter summarizes some results from the main interventions FLAR and its members are promoting, with special emphasis on their impact on eco-efficiency.

[3] FLAR Members: **Argentina** – National Institute of Agricultural Technology (INTA), Copra S.A. (private company), Adeco Agropecuaria S.A. (private company); **Bolivia** – National Rice Council (CONARROZ); **Brazil** – Rio Grande Rice Institute (IRGA); **Chile** – Federation of Rice Producers; **Colombia** – National Federation of Rice Growers (FEDEARROZ); **Costa Rica** – Seeds of the New Millennium (SENUMISA); **Dominican Republic** – Genetics of Rice (GENARROZ); **Ecuador** – National Autonomous Institute for Agricultural Research (INIAP); **Guatemala** – Guatemalan Rice Association (ARROZGUA); **Guyana** – Guyana Rice Development Board (GRDB); **Honduras** – Directorate of Agricultural and Livestock Science and Technology (DICTA), Honduran Association of Rice Producers AHPRA; **Mexico** – Mexican Rice Council (CMA); **Nicaragua** – Nicaraguan Association of Rice Farmers (ANAR); **Panama** – Panamanian Rice and Grain Federation (FEDAGPA), Panama Institute of Agricultural Research (IDIAP), CONAGRO S.A. (private company), Seeds of Coclé (SECOSA; private company); **Peru** – El Potrero Hacienda; **Uruguay** – National Institute of Agricultural Research (INIA), Association of Rice Growers (ACA); **Venezuela** – National Rice Foundation (FUNDARROZ); and the International Center for Tropical Agriculture (CIAT).

Rice Breeding: New Varieties that Produce More Rice with Fewer Inputs

The so-called "green revolution" in rice started with the release of the semi-dwarf variety IR8 in 1966 by the International Rice Research Institute (IRRI) in the Philippines (Hargrove and Cabanilla, 1979; Khush, 1999). Less than two years later IR8 was introduced in Colombia by Peter Jennings and a pioneering breeding program was initiated by CIAT, the Colombian Institute of Agriculture (ICA, its Spanish acronym), and the National Federation of Rice Growers (FEDEARROZ, its Spanish acronym). This program soon developed new semi-dwarf varieties that increased rice production in Colombia and in the whole region. Average yields in Colombia rose from 1.5 t/ha in 1965 to 4.4 t/ha in 1975 (Scobie and Posada, 1977). Between 1968 and 1990 rice yields in Latin America increased by 20% due to new semi-dwarf varieties (Muchnik de Rubinstein, 1985).

Between 1975 and 1995, some 250 improved rice varieties were released in LAC. The adoption of these improved varieties enhanced food security and reduced the real price of rice (Maclean et al., 2002).

FLAR's goal is to develop a cooperative and efficient breeding program aimed at producing and releasing high-yielding varieties with desirable agronomic and grain quality traits. The program is based at CIAT headquarters in Cali, Colombia, but is administratively independent of the Center's rice-breeding program. This arrangement gives FLAR immediate access to improved material developed by the Center and provides a direct link with other international research institutions, such as IRRI.

FLAR's breeding program focuses on developing varieties for tropical and temperate zones. FLAR breeders introduce new materials, make around 800 hundred triple crosses a year, advance and select 5000 to 6000 breeding lines in different environments, and produce and select elite breeding lines (FL lines). Breeding and initial evaluation are done at CIAT headquarters and the Santa Rosa Research Station near Villavicencio in Colombia's Llanos Orientales or Eastern Plains. Elite lines are selected annually in nurseries called "VIOFLAR Trópico" and "VIOFLAR Templado" and distributed to FLAR members. Members evaluate and further select these FL lines in their local environments, register lines that perform well, and release them as new varieties. The first variety of FLAR origin was released in 2003, and a total of 40 new cultivars have since been registered in 13 countries up to the end of 2011.

FLAR members invest their own resources in the program and contribute to the breeding strategy. This encourages greater engagement between the members and the network. One common problem faced in open germplasm networks is the very poor feedback of information on the performance of lines at the different testing sites. In contrast, FLAR members provide performance information on about 80% of the material received, providing FLAR breeders with the feedback needed to fine-tune their breeding strategies.

The program is subdivided into tropical and temperate regions. The main common breeding objectives in both subprograms are: high yield potential; resistance to rice blast [*Magnaporthe grisea* (Herbert) Barr (anamorph *Pyricularia grisea*)] and other fungal diseases; resistance to lodging; high milling and cooking quality; and tolerance of delayed harvest (i.e., grain retention). For the tropics, the program is also breeding for resistance to rice hoja blanca virus and its insect vector [*Tagosodes orizicolus* (Muir)]. For the temperate region, tolerance to low temperatures is an important trait. Planting early in the season is critical in the Southern Cone to allow flowering to coincide with peak solar radiation and ensure good grain filling. Thus, cold tolerance at seedling stage is needed, as is some cold tolerance at the reproductive stage, because low temperatures may occur any time during the season.

The following are some examples of the characteristics and uptake of the varieties developed through FLAR.

Venezuela 21 was the first variety from FL material to be released by a FLAR member

(FUNDARROZ, 2003). It has excellent yield potential (8 t/ha) and yield stability across seasons, much better disease tolerance than checks, and good grain quality. By 2009, it accounted for 31.6% of the total rice seed market in Venezuela.

The Panama Institute of Agricultural Research (IDIAP, its Spanish acronym) released two FL-based varieties in 2005: IDIAP 54-05 and IDIAP 145-05 (Camargo, 2006). Both have good resistance to the main diseases occurring in Panama (rice blast, and panicle blight caused by *Burkholderia glumae*), give high yields under both rainfed and irrigated conditions, and have excellent grain milling quality. In the 2010/11 cropping season, each of them was planted on more than 20% of the country's rice area.

In Costa Rica, Seeds of the New Millennium S.A. (SENUMISA, its Spanish acronym) released Palmar 18 in 2006. The variety has high yield potential under both irrigated and rainfed conditions, good tolerance to main diseases (rice blast, panicle blight, and grain discoloration caused by a fungus complex), a short growing cycle, and excellent grain quality. By 2009, it accounted for 46.7% of the certified rice seed produced in Costa Rica (Oviedo, 2010).

The Guyana Rice Development Board (GRDB) released GRDB FL 10 in 2009. In trials between 2008 and 2010, GRDB LF 10 outyielded the check variety by an average of 28.3% across spring and autumn cropping seasons (Persaud, 2010). By the beginning of 2011, the variety covered 15% of the area planted to rice in Guyana.

Genetics of Rice S.A. (GENARROZ, its Spanish acronym) released Jaragua FL in the Dominican Republic in 2010 (Moquete, 2010). This variety was selected from FL material introduced in 2007. Jaragua FL has high yield potential (more than 8 t/ha) under a range of planting systems and environments, excellent milling performance (62–64% of whole rice), very low percentage of "white belly" (opaque endosperm), and excellent cooking quality. It also has very good tolerance to major fungal diseases and some tolerance to saline and acidic soils.

Agronomy: Improving Eco-Efficiency by Crop Management

Eco-efficient agriculture depends not only on good varieties, but also on several other factors, such as sustainable use of natural resources, farmers' skills, and crop management techniques. The yields for farmers in LAC remain well below the yield potential of the varieties grown, largely as a result of suboptimal crop management (Pulver, 2001). Bridging this yield gap could increase rice production in LAC by 27% (Sanint, 2004).

In 2003, FLAR, with financial support from the Common Fund for Commodities (CFC), initiated a technology transfer program in the state of Rio Grande do Sul, Brazil, and Portuguesa and Guarico states, Venezuela, aimed at reducing this yield gap. The program later expanded to include Argentina and Uruguay in the Southern Cone and Costa Rica and Nicaragua in the tropical zone.

The program focused on six basic strategic management practices:

1. Appropriate planting time
2. Low seeding rate
3. Use of high-quality seed and seed treatment against insect pests
4. Early weed control
5. Fertilizer management
6. Irrigation management

These practices were usually complemented by site-specific practices developed by local research and/or through farmer-participatory research at the trial sites.

FLAR employed a farmer-to-farmer extension approach, using a farmer leader to transfer the technology to other growers. At each location, an initial survey of the rice sector was conducted to identify the main technological weaknesses. Innovative farmers who had the capacity and willingness to communicate their experiences were then selected. These farmer leaders received farmer leaders received extensive training in the recommended practices, and demonstration plots were established on each farmer leader's land. Groups of growers in the vicinity of each pilot farm visited the demonstration plots regularly and discussed their observations with the farmer leader, often leading to modification of the recommended practices. These growers were then assisted in adopting the recommended practices.

Following the success of the initial project, activities were extended to Bolivia, Chile, Dominican Republic, Ecuador, Guyana, Honduras, Mexico, and Panama.

In total, the program worked with nearly 8000 farmers growing nearly 600,000 ha of rice, and achieved yield increases between 0.6 and 1.7 t/ha (Table 10-2).

The State of Rio Grande do Sul in Brazil and neighboring areas of Argentina and Uruguay provide good examples of the impact of improved crop management on rice production. Since early 2000, this region has shown a revolution in rice production driven by improved crop management. FLAR has had different grades of involvement in this process working with the Rio Grande Rice Institute (IRGA, its Portuguese acronym) in Brazil, the National Institute of Agricultural Technology (INTA, its Spanish acronym) in Argentina, the National Institute of Agricultural Research (INIA, its Spanish acronym) in Uruguay and the Rice Farmers Association (ACA, its Spanish acronym) also in Uruguay to boost rice production. As a result of these programs, total annual rice production increased from an average of 7.0 million tons in 2000–2002 to 9.4 million tons in 2006–2008, an increase of 35% (Figure 10-1). Over the same period, yield increased from 5.4 t/ha to 7.2 t/ha, an increase of 33%, while the area planted has been almost stable. Thus, the increase in production was largely the result of increased yields. Over this period, there was little change in the varieties planted, hence the production gains are the result of improved agronomic practices.

Table 10-2. Summary of activities and estimated impacts from FLAR Agronomy and Technology Transfer Program. (Carmona and Pulver, 2010).

Country	Period[1]	Demonstration Plots	Field Days	Trained Farmers	Area of Impact[2]	Yield Increase[3]
Argentina	2005-08	27	34	150	40,000	1.5
Bolivia	2006-10	20	15	920	10,000	1.5
Brazil	2003-06	121	346	4,895	414,240	1.7
Chile	2010	8	4	120	650	0.6
Costa Rica	2005-10	45	20	150	9,000	1.6
Dominican Republic	2008-10	20	2	20	2,000	1.0
Ecuador	2006-07	20	4	100	1,000	1.3
Guyana	2006-08	44	88	200	10,000	1.0
Honduras	2006-07	22	3	55	3,000	0.8
Mexico	2007-10	55	15	330	10,000	1.8
Nicaragua	2005-10	20	20	120	10,000	1.5
Panama	2006-10	20	10	80	5,000	1.2
Uruguay	2005	13	18	45	16,000	1.5
Venezuela	2003-10	250	148	570	40,000	1.3
Total		**685**	**787**	**7,755**	**570,890**	

1. Period of direct intervention in the country.
2. Estimated annual area attained by the program at the end of its intervention.
3. Yield increases estimated over the area associated with the program (t ha^{-1}).

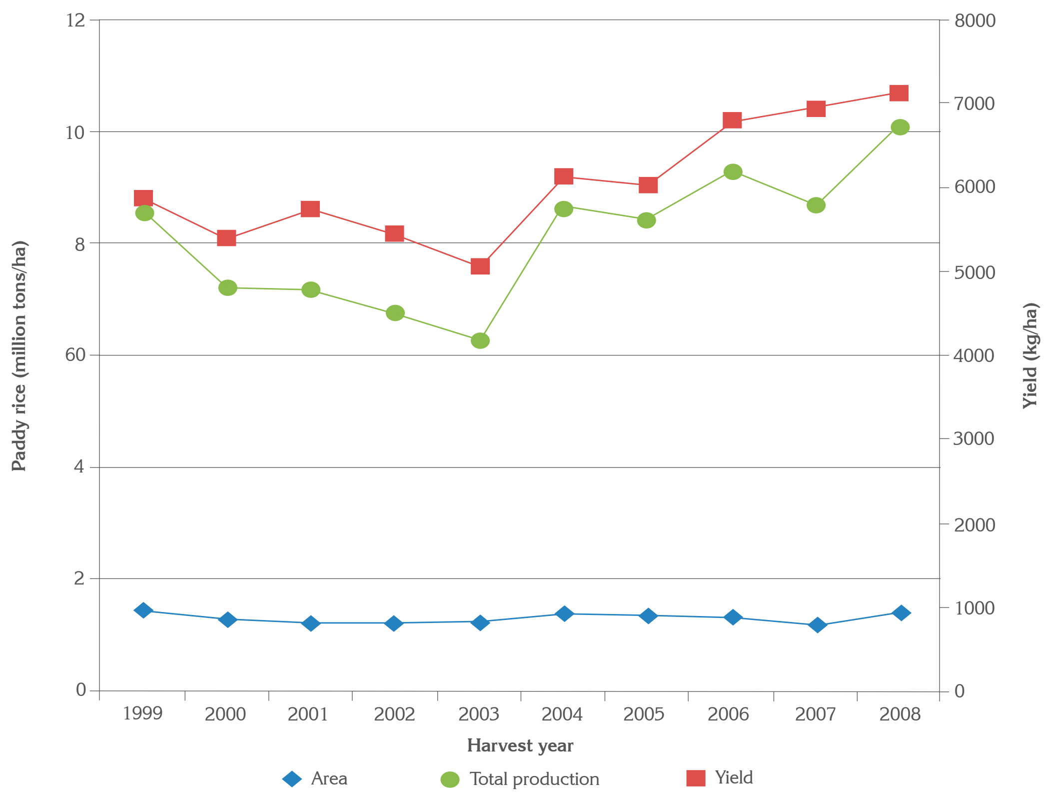

Figure 10-1. Combined production, area and yields in the irrigated rice region of the Southern Cone associated with FLAR: Rio Grande do Sul State in Brazil, Argentina, and Uruguay.

SOURCE: Annual statistics Rio Grande Rice Institute (IRGA), Brazil; Rice Farmers Association (ACA), Uruguay; Corrientes Rice Planters Association (ACPA), Argentina.

Water Harvesting: Taking Advantage of an Underexploited and Abundant Natural Resource

Less than a quarter of the rice area in LAC is irrigated, ranging from 79% in Brazil to only 1% in Mexico. However, overall the region is well endowed with water resources (Table 10-3). Even Mexico, nearly one-third of which is arid, has extensive water resources in its central and southern areas. Additionally, most of the renewable water resources in Latin America are surface water, which is essentially from rain water. Consequently, the problem in Latin America is not scarcity of water, but ineffective use of water resources to produce food and reduce poverty in the rural areas.

FLAR has been investigating the potential of water harvesting to increase the use of irrigation in upland rice production. In 2008, FLAR and CIAT initiated a project on "Transformation of upland to irrigated rice through use of water harvesting in Costa Rica, Mexico, and Nicaragua". The project is sponsored by CFC and co-sponsored by SENUMISA in Costa Rica, the Mexican Rice Council, and the Nicaraguan Association of Rice Farmers.

This pilot project is introducing proven water harvesting techniques, training local staff to identify suitable sites for catchment facilities, and demonstrating the economic benefits of a diversified rice-based production system under irrigation. The target audience is small-scale farmers currently involved solely in rainfed

Table 10-3. Renewable water resources in several Latin American countries compared to major rice-producing countries of Asia.

Country	Water resources: Total renewable (actual) (km^3/year)	Surface water: Produced internally (km^3/year)	Water resources: Total renewable (actual) (m^3/capita per year) (2000)
Central America and Mexico			
Costa Rica	112	75	27,932
Honduras	95	86	14,949
Mexico	409	361	4,634
Nicaragua	196	185	38,787
Panama	148	144	51,814
South America			
Argentina	814	276	21,981
Brazil	8,233	5,418	48,314
Colombia	2,132	2,112	50,635
Ecuador	432	432	34,161
Paraguay	336	41	61,135
Peru	1,913	1,616	74,546
Uruguay	139	59	41,654
Major Rice Countries in Asia			
Bangladesh	1,210	83	8,809
China	2,829	2,711	2,258
India	1,896	1,222	1,880
Indonesia	2,838	2,793	13,381
Philippines	479	444	6,332

SOURCE: FAO-AQUASTAT 2000: Renewable water resources in the world by country.

agriculture. The project is focusing on simple, low-tech, low-cost water harvesting techniques, essentially small- and medium-sized earth dams constructed in farmers' fields to take advantage of topography and an adequate water catchment basin. These dams allow farmers to harvest and store rain water that can then be used for full or supplemental irrigation by gravity. The ponds can also be used for fish production, bringing another high-value product to farmers.

Harvesting water during the rainy season allows for high-yielding irrigated agriculture during the high-solar-radiation dry season and doubles job opportunities in regions like northern Nicaragua, where there are 6 months with minimum activity on the farms.

In trials in Mexico, despite being established too late in the season (April/May 2010) for optimum yield, irrigated rice still yielded 65% more than neighboring non-irrigated rice crops (Table 10-4). If the crops had been established in February as planned, yields of 10 t/ha would have been achievable.

In Jalapa Department in north-central Nicaragua, one farmer planting irrigated rice during the dry season reported a yield of 10.5 t/ha, and a net profit of US$2,000/ha. This compares with net profits of less than US$100/ha for rainfed maize and less than US$50/ha for rainfed beans grown during the rainy season.

These initial results demonstrate the potential of water harvesting and storage to diversify smallholder farmers' production options and to boost income and food security.

Table 10-4. Yield of rainfed and irrigated rice at two sites in Mexico, 2010.

Location	Yield, kg/ha	
	Rainfed	Irrigated
Escuela Texistepec, Veracruz	4,362	6,800
Carlos Contreras, Cosamaloapan	3,623	6,343
Mean	3,993	6,572
Mean increase in yield with irrigation (%)		65

Concluding Remarks

FLAR has developed a holistic approach to improving the rice industry in LAC, addressing genetics, crop management, and natural resources utilization. Being a public-private alliance in which most rice farmers' organizations are represented along with national research institutes and private companies, it helps not only small-scale, resource-poor rice growers, but also the whole rice sector.

There are enormous challenges ahead, including rising food demand, competition for land, the need for reducing environmental footprint, and dealing with climate change. New products from agricultural research addressing yield potential, resistance or tolerance to changing pests and diseases, resistance to abiotic stresses and new quality requirements will be essential to cope with those challenges. FAO, with its many members from almost all Latin American countries, provides a platform through which the products of research can be rapidly extended to farmers, increasing food production, reducing rural poverty, and enhancing food security.

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CHAPTER 11

Tropical Forage-based Systems to Mitigate Greenhouse Gas Emissions

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Contents

Abstract

Agriculture and livestock production are major contributors to greenhouse gas emissions. Forage-based systems dominate much of agriculture in the tropics, providing livelihoods to farmers but also affecting local and global environments. In this chapter, we attempt to answer the question: How can farmers and livestock keepers improve their livelihoods while reducing negative impacts on the environment? We focus on forage-based systems in the tropics, emphasizing smallholders and the role of forages. In particular, we address the potential of tropical forage-based systems not only to contribute to reducing greenhouse gas emissions but also to sequester carbon in soil in substantial amounts to mitigate climate change. We also discuss the associated benefits of forage-based systems to enhancing the eco-efficiency of farming in the tropics and to improving rural livelihoods. We identify opportunities in forage-based systems that are economically sustainable and socially equitable with the lowest possible ecological footprint. With the global community increasingly aware of the environmental implications of agriculture, forage-based systems should figure prominently as "LivestockPlus" (meat, milk, and more) options in future innovative agricultural systems. We hope that this chapter will stimulate discussion that leads to further investment from donors in research on improving the eco-efficiency of forage-based systems in the tropics.

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Background

Climate change is one of the greatest challenges to human development in general and food security in particular in recent history. Even if we act decisively now, temperatures by 2050 will be at least 2 °C, and perhaps as much as 5 °C, above those of pre-industrial times (IPCC, 2007; The World Bank, 2010), threatening sustainable food production worldwide. Developing countries are more exposed to the hazards of climate change and less resilient to them (Morton, 2007). Moreover, they will have to bear an estimated 75–80% of the costs associated with the impacts of climate change (Hope, 2009; Smith et al., 2009; The World Bank, 2010). Undernourished people, estimated at 925 million worldwide in 2010 (FAO, 2010a), most of whom live in the tropics, are especially vulnerable.

Contribution of agriculture and livestock to climate change: Greenhouse gas emissions

Agriculture, including meat and milk production, produces three main greenhouse gases (GHGs): carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). In terms of climate forcing, one unit of CH_4 is equivalent to around 21 units of CO_2 and one unit of N_2O is equivalent to 310 units of CO_2 (Forster et al., 2007). Agriculture is a major contributor to climate change, producing 14% of GHG emissions at the global level, with a further 17% attributed to land use change and deforestation. In low-income countries, the contribution of agriculture to emissions is even higher, with 20% and 50% attributed to agriculture and land use change, respectively (The World Bank, 2010). Although debate continues about the actual numbers, there is little doubt about the relative importance of agriculture, and livestock production in particular, as emitters of GHG (Anderson and Gundel, 2011; Herrero et al., 2011).

Livestock systems are estimated to contribute about 50% of all agricultural sector GHG emissions (Steinfeld et al., 2006; Scherr and Sthapit, 2009), contributing up to 9% of all anthropogenic CO_2 emissions, 37–52% of CH_4, and 65–84% of N_2O (Smith et al., 2008; FAO, 2009). Large ruminants (cattle and buffalo) emit more GHG per kilogram of meat than monogastrics (pigs and poultry).[5] In addition to GHG from enteric fermentation and manure, large ruminants are also associated with land use changes such as deforestation (Steinfeld et al., 2006; FAO, 2009), particularly in Central and South America (Szott et al., 2000; Wassenaar et al., 2007; Barona et al., 2010; Pacheco et al., 2011). However, the direct and indirect causes of deforestation are complex and can be difficult to attribute (Geist and Lambin, 2002), and the impact of improving livestock technologies is debated (e.g., Angelsen and Kaimowitz, 2004; Kaimowitz and Angelsen 2008). For particular locations, these data require further analysis, since land use change is strongly influenced by policy interventions and the level of enforcement (Steinfeld and Gerber, 2010).

LivestockPlus

Comparative analysis of GHG emissions between diverse production systems should include the environmental costs of feed production, including its transport. For example, in the case of soybean produced in the Amazon that supplies European feedlots (Herrero et al., 2009; Anderson and Gundel, 2011), transport accounts for 11–12% of GHG emissions (Garnett, 2011) and contributes more to GHGs than feed produced near feedlots in midwestern USA (Pelletier et al., 2010). Feedlot cattle produce fewer GHG emissions than forage-fed cattle, mainly due to better feed conversion (Casey and Holden, 2006; Gerber et al., 2010; Pelletier et al., 2010). However, the potential to mitigate climate change and other co-benefits of forage-based systems[6] (Figure 11-1) are often not considered. It is these benefits of forage-based systems in the tropics that need to be recognized

[5] Because of their relative unimportance as emitters of GHGs, we consider monogastrics further only in passing.

[6] In addition to perennial pastures for grazing, forages include herbaceous and woody plants, and perennial and short-lived forage crops for cut-and-carry. We use the term "forage-based systems" to include all systems that include forage plants as a component, including ley systems that include several years' cropping before returning to pasture, agropastoral systems, and rangelands (native grasslands and savannas). They all contain a substantial component of animal production.

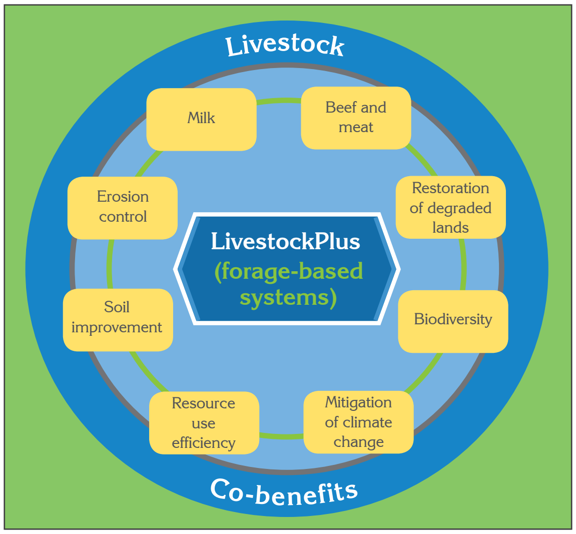


Figure 11-1. LivestockPlus: Forage-based systems for agriculture and the environment.

by the global community. We call this concept "LivestockPlus".

The importance of tropical forage-based systems and the role of sown forages

In this chapter, we discuss the role of tropical forages in mitigating climate change. We focus on forage-based production systems in which forages have a multifunctional role, in contrast to feedlot-based systems. Sown tropical forages are mostly selections from undomesticated grass and legume species but can include genetically improved varieties. In Latin America and the Caribbean (LAC), cattle are raised largely on sown pastures; in West Africa, cattle typically graze native pastures; in tropical Asia, cut-and-carry systems are predominant; and in Eastern, Central, and Southern Africa, both grazing native pastures and cut-and-carry systems are common. Monogastrics are fed with a diverse range of materials, particularly by smallholders where locally produced feed is important.

Sown forages also have a role in many systems to enhance production efficiency and contribute to other functions such as erosion control, soil improvement, restoration of degraded lands, and improving biodiversity.

Livestock are a crucial component of livelihoods and food security of nearly 1 billion people in the developing world, contributing 40% of the global value of agricultural output. Livestock contribute 15% of total food energy, 25% of dietary protein, and some micronutrients that are not available from plants. Globally, four of the five agricultural commodities with the highest economic value are livestock-related; in order of value, these are milk, rice, and meat from cattle, pigs, and poultry. East and Southeast Asia and LAC show the largest increases in consumption of livestock products between 1961 and 2005 (FAO, 2009). Consumption is expected to continue to increase (Delgado et al., 1999; Herrero et al., 2009).

The livestock sector is the largest user of land resources, employing 3.4 billion hectares for grazing and 0.5 billion hectares for feed crops (Steinfeld et al., 2006), 30% of the ice-free terrestrial surface, and nearly 80% of all agricultural land. The share of grazing land in the overall land area is higher in developing countries than in developed countries (FAO, 2009).

There are regional differences in the types of mixed crop-livestock systems (FAO, 2009). The temperate regions of Europe, Central Asia and the Americas, and the subhumid regions of tropical Africa, LAC, the Middle East, and parts of Southeast Asia have rainfed mixed-farming systems. Globally, they produce 48% of beef, 53% of milk, and 33% of mutton. Livestock are mostly fed grass, crop residues, and crop by-products (Herrero et al., 2010). Irrigated mixed systems in areas of high population density in East and South Asia provide about one third of the world's pork, mutton, and milk, and one fifth of its beef.

Of the world's total, developing countries produce about 50% of beef, 41% of milk, 72% of mutton, 59% of pork, and 53% of poultry. Crop-livestock systems produce 50% of global cereals; on current trends, feed grain may amount to more than 40% of global cereal use by 2050, mainly utilized in industrial pig and poultry production (Herrero et al., 2009, 2010).

The demand for livestock products must be reconciled with the environmental impacts of livestock. The aim should be greater eco-efficiency, i.e., highly productive forage-based systems with a small ecological footprint that are economically sustainable and socially equitable (CIAT, 2009; Keating et al., 2010). Although tropical agriculture contributes to GHG emissions, it can also mitigate climate change by reducing emissions (abatements) and absorbing GHGs (Rosegrant et al., 2008). In the remainder of this chapter, we focus on the role of sown forages in mitigating the contribution of tropical agriculture to climate change.

Productivity, profitability, and environmental impacts of land used for forages are interrelated. The extent of land degradation influences the potential of forages to mitigate climate change, because degradation reduces the potential to sequester carbon and is difficult to reverse (Lal, 2010). Heerink et al. (2001) estimate that 35% of all land in Asia, 45% in South America, 75% in Central America, and 65% in sub-Saharan Africa is in various stages of degradation,[7] largely due to overuse and overgrazing. Globally, 20% of the world's pasture and grasslands are degraded (FAO, 2009), reaching 50% in tropical Brazil (Boddey et al., 2004; Cederberg et al., 2009), up to 60% in Central America (Szott et al., 2000), and as high as 73% in dry areas (UNEP, 2004). Many tropical forages are well adapted to marginal environments (Peters et al., 2001) and have the capacity to reverse degradation and enhance soil fertility (Fisher et al., 1997; Guimarães et al., 2004; Rao et al,. 2004; Amézquita et al., 2007; Ayarza et al., 2007).

Opportunities to Utilize Improved Tropical Forage Options to Reduce Greenhouse Gas Emissions and Mitigate Climate Change

There are five strategies to reduce terrestrial GHG emissions (Scherr and Sthapit, 2009): (1) carbon-rich farming; (2) farming with perennials; (3) climate-friendly livestock systems; (4) conserving and restoring habitats; and (5) restoring watersheds and degraded pastures. Sown tropical forages can contribute directly to all five strategies. In particular, forages mitigate GHG emissions in three ways: (1) by sequestering atmospheric CO_2;[8] (2) by reducing ruminant CH_4 emissions per unit livestock product as compared to a lower quality rangeland/degraded pasture and/or offsetting emissions via carbon sequestration; and (3) by reducing N_2O emissions. We discuss the role of sown forages in influencing the atmospheric concentrations of each of these three important GHGs. Additionally, through their role in intensification of production systems, improved tropical forages can reduce pressure on forests by producing more output from the same unit of land and thus contribute to abating emissions. This, however, requires policies to prevent expansion beyond existing agricultural land and thus protect forests and other natural reserves.

Improving carbon sequestration

Agriculture could offset up to 20% of total global CO_2 emissions (Smith et al., 2008). Eighty-nine percent of the potential climate change mitigation of agriculture comes from terrestrial carbon sequestration, 9% from CH_4 reduction, and 2% from reduction of N_2O emissions, although this potential has largely been ignored in climate change discussions (Smith et al., 2007a, 2008; Scherr and Sthapit, 2009). Guo and Gifford (2002) analyzed the results from 74 papers on the effects of land use changes on soil carbon stocks. While soil carbon stocks declined in conversion from pastures to plantations and from forests or pastures to crops, they increased when converting annual crops to plantations, crops to pastures, crops to secondary forest, and, interestingly, forest to pastures (Table 11-1). Powers et al. (2011) reported increases in soil carbon stock when forest or savanna was converted to pastures (5–12% and 10–22%, respectively).

[7] We define land degradation as a temporary or permanent lowering of the land's productive capacity.

[8] The term "sequestered" is widely used in the literature. Strictly, unless it is known that the accumulated carbon is held in some recalcitrant form (and usually it is not known), it should not be termed "sequestered". We forego this distinction in this chapter and use "sequestered".

Table 11-1. Effects of land use change on soil carbon stocks (%), from 74 papers analyzed by Guo and Gifford (2002).

From\To	Pasture	Forest	Plantation	Crops
Pasture		no data	-10	-59
Forest	8		no data	-42
Crop	19	53	18	

Most of the above-ground carbon in vegetation is lost when forests are cleared for pastures, but soil carbon stocks are often the same over the long term or can increase substantially (Amézquita et al., 2010). Studies from the tropical rainforest of the Colombian Amazon region indicate that total carbon stocks are highest in native forests, followed by well-managed sown pastures and silvopastoral systems, with degraded pastures and degraded soils lowest (Gobbi et al., 2008; Amézquita et al., 2010). In contrast to annual crops, well-managed pastures maintain a cover of vegetation on the soil, which reduces fluctuations in soil temperature and adds organic matter (Brown and Lugo, 1990). Pastures in areas receiving 2000–3000 mm annual rainfall have a higher potential to sequester carbon than forests under similar climatic conditions (Guo and Gifford, 2002).

Improved management of crops and grassland and restoration of degraded land and organic soils offer the greatest opportunities for mitigation of GHG emissions (Smith et al., 2008). Agriculture in 2030 could potentially offset 5500–6000 million metric tons (t) of CO_2 equivalents[9] per year, although lower levels could be economically viable depending on the market prices for carbon. The mitigation potential of improved grassland and cropland management is about 1350–1450 million t CO_2 equivalents/year each, which, together with 1350 million t CO_2 equivalents/year for restoring cultivated organic soils, and 650 million t CO_2 equivalents/year for restoring degraded land, is about 75% of the global biophysical mitigation potential (Smith et al., 2008). Sown forages, through their effects on livestock systems and cropping systems, can contribute to this potential in all of them.

Regionally, Southeast Asia, South America, and East Asia have the highest total mitigation potentials, while South America and Africa have the potential for carbon sequestration from recuperating degraded grasslands (Conant et al., 2001; Conant and Paustian, 2002). Sown pastures of *Brachiaria* grasses have large potential for carbon sequestration in LAC (Thornton and Herrero, 2010), with Central America having particular potential for carbon sequestration because of higher levels of land degradation (Heerinck et al., 2001). Of the overall carbon mitigation potential, 29% will be from pasture land (Lal, 2010).

Forages are also key components of minimum- and no-till cropping systems in Brazil (Landers, 2007) and Colombia (Sanz et al., 2004). Conversion of native grassland to agropastoral systems in the Cerrado of Brazil and the Eastern Plains of Colombia, with adequate soil and crop management, generates benefits to both agriculture and the environment (Guimarães et al., 2004; Rondón et al., 2006; Fisher, 2009; Subbarao et al., 2009). For example, in contrast to annual crop species, most tropical forages are perennials and provide a permanent soil cover and thus prevent soil surface erosion. The latter is of particular importance as erosion also results in loss of soil organic matter, which is largely oxidized, releasing CO_2 to the atmosphere (Lal, 2010).

Within a given grassland ecosystem, climatic and management-related factors interact to

[9] Invariably practitioners measure the carbon in soil and vegetation. It is converted to CO_2 equivalents, which is relevant to the atmospheric concentration, by multiplying by 3.67.

influence GHG balance over a specified period of time (Liebig et al., 2010). Management practices that reduce carbon loss and increase carbon sequestration in European grasslands include: (1) avoiding soil tillage and the conversion of grasslands to arable use; (2) moderately intensifying nutrient-poor permanent grasslands; (3) using light grazing instead of heavy grazing; (4) increasing the duration of grass leys; and (5) converting grass leys to grass–legume mixtures or to permanent grasslands (Soussana et al., 2010). The mitigation potential of tropical forage plants is favored by prostrate growth habits (e.g., *Brachiaria humidicola, Arachis pintoi*) but a precondition is proper pasture management. Optimal grazing management can enhance accrual of soil carbon (Guo and Gifford, 2002), highlighting the importance of grassland productivity in carbon sequestration. Sown tropical forages can sequester large amounts of carbon in soil, particularly in the deeper layers (Fisher et al., 1994, 1997, 2007; Rao, 1998). The potential of sown forages under adequate pasture and animal management to sequester carbon is second only to forest (Fisher et al., 2007; Fisher, 2009). Soil organic carbon (SOC) levels under the Colombian Eastern Plains are as high as 268 t carbon/ha in the top 80 cm of soil under a *B. humidicola–Arachis pintoi* pasture, with 75% of the carbon found below 20 cm (Fisher et al., 1994).

Compared with the native savanna, a sown grass pasture sequestered an additional 26 t carbon/ha in 5 years, increasing 2.7-fold with an associated legume (Fisher et al., 1994). Unlike the carbon accumulated in most other systems, which is rarely deeper than 20 cm, carbon accumulated in the deeper soil layers is likely to have long residence times, even if it is not truly sequestered (i.e., it is not physically protected or chemically inert). It is also likely to be unaffected in any cropping phase that there might be in mixed crop–pasture systems (Fisher et al., 1994). Pasture in Bahia, Brazil, sequestered half as much carbon as the Colombian Eastern Plains, probably due to seasonally lower temperatures that limit net primary productivity (Fisher et al., 2007). It should be noted, however, that there is discussion in the literature on the potential of carbon sequestration of pastures and the interactions with a particular environment and intensity of degradation (e.g., Conant et al., 2001; da Silva et al., 2004).

Globally, agroforestry systems show lower potential for carbon sequestration than do croplands under improved management, grazing land and livestock, and restoration of degraded lands (Smith et al., 2008). Above-ground carbon stock is usually higher in land use systems that include trees, however, and planting trees may also increase soil carbon sequestration (Smith et al., 2007b). We suggest that the inclusion of trees in agroforestry and agrosilvopastoral systems could further enhance the overall efficiency of crop–livestock systems (Fujisaka et al., 1998; see also Chapter 4 of this volume).

It is expensive to measure carbon sequestration in soil with the current methods of soil sampling, hence simple indicators (proxies) are needed to allow for transparent consolidation over larger areas (Fisher, 2009). FAO has developed an ex-ante carbon calculator (Bernoux et al., 2010; FAO, 2010b), which shows promise. The carbon calculator assumes that renovated pastures would increase soil carbon stock by 17% in natural pastures, 21% in moderately degraded pastures, and 67% in severely degraded pastures. Based on this, and assuming that there are 78 million hectares of moderately degraded sown pastures in Brazil, renovating them with improved and highly productive sown forages would sequester on average 146 million t CO_2 equivalents/year over a period of 14 years (S. Graefe and G. Hyman, unpublished data). This is equivalents to 18.6 years of current emissions of diesel vehicles in Brazil.

Reducing methane emissions

Emissions of CH_4 from enteric fermentation in ruminants account for 25% of GHG emissions from livestock (Thornton and Herrero, 2010) (Table 11-2), and is the largest single-source agricultural emission. Although there are differences among regions and production systems (Herrero et al., 2008), increasing animal productivity per unit of CH_4 emitted can be a viable strategy for reducing GHG emissions from

Table 11-2. Methane production according to pasture type and product in grassland-based humid–subhumid systems in tropical Central and South America.

Option	kg CH_4/t milk	kg CH_4/t meat
Native grassland (Cerrado)	78	1,552
100% adoption† of *Brachiaria* pasture	31	713
30% adoption† of *Brachiaria* pasture	64	1,300

† "Adoption" refers to the proportion of total milk and meat production in 2030 from implementing the option analyzed.

SOURCE: Adapted from Thornton and Herrero (2010).

livestock production. Diets with high digestibility and high energy and high protein concentrations produce less CH_4 per unit of livestock product. Improving these characteristics in forages could reduce CH_4 emissions from beef production by 15–30% (Gurian-Sherman, 2011). Legumes contain less structural carbohydrates and more condensed tannins than does grass, and adding legumes to the diet can further reduce CH_4 emissions per unit of meat or milk produced (Woodward et al., 2004; Waghorn and Clark 2004). In addition to reducing GHG emissions, intensification of animal production using high-yielding sown forages requires fewer animals for the same output, and reduces pressure on land and water resources if managed appropriately (LivestockPlus). Feeding crop residues and by-products is also an option to reduce GHG. The use of this highly digestible crop "waste" has a greater impact on both CH_4 and CO_2 emissions than grain supplements (Thornton and Herrero, 2010). Integrating tropical forages with crops can enhance soil fertility as well as the quality and quantity of crop residues, giving higher system efficiency (Ayarza et al., 2007). There are trade-offs between crop and livestock production, however, such as using forages either as animal feed or as green manure (Douxchamps et al., 2012).

Emissions of CH_4 can be reduced by dietary additives (Smith et al., 2008), including oils (Henry and Eckard, 2009), feeding silage instead of hay (Benchaar et al., 2001), and by manipulating the rumen flora (Henry and Eckard, 2009). While legumes can help to reduce GHG production, there are trade-offs. Condensed tannins from legumes can reduce CH_4 production in ruminants (Woodward et al., 2001), but they often also reduce animal performance mostly by reducing feed digestibility (Woodward et al., 2001; Waghorn et al., 2002; Tavendale et al., 2005; Tiemann et al., 2008). Condensed tannins in tropical legumes are highly reactive and are variable in quantity and quality, which remains a challenge to their use to reduce CH_4 production by ruminants. If a tropical species with the typically good agronomic performance on poor soils of tanniniferous shrub legumes, combined with a reduction of ruminal CH_4 production without inhibiting forage digestibility and protein availability (as found for some temperate Lotus species), were to be identified, it could have large beneficial impact on climate-friendly livestock production.

While tropospheric OH (hydroxyl radical) is the largest sink, aerobic soils are the second largest global sink for tropospheric CH_4, removing methane equal to 10–15% of global emissions (Reeburgh et al., 1993; IPCC, 1995). In a comparison of arable land with woodland and grassland, the methane oxidation rate of grassland was about 10 times that of arable land and equal to that of woodland in temperate conditions (Willison et al., 1997). Especially during the dry season, abandoned tropical pastures are strong sinks of CH_4, consuming even more than secondary and some primary forests. This general ability depends largely on grazing management and is inhibited, for example, if gas diffusion is restricted by soil compaction through trampling (Mosier et al., 2004), so that the potential of pastures as CH_4 sinks must take account of the livestock production system under consideration.

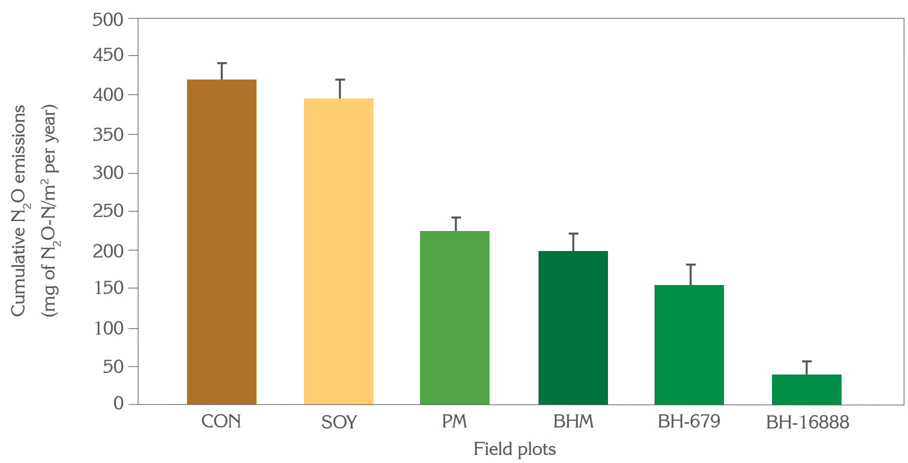
Reducing nitrous oxide emissions

Nitrification is a key process in the global nitrogen cycle. It generates nitrate through microbial activity and is primarily responsible for the loss of soil and applied nitrogen via leaching and denitrification (Subbarao et al., 2006). In agricultural systems,

N_2O is generated largely from nitrification and denitrification processes (Bremner and Blackmer, 1978). Nearly 17 million t of nitrogen is currently emitted to the atmosphere as N_2O each year (Galloway et al., 2008; Schlesinger, 2009). By 2100, global N_2O emissions are projected to be four times the current level, due largely to increasing use of nitrogen fertilizers (Galloway et al., 2008; Burney et al., 2010; Kahrl et al., 2010). Up to 70% of the nitrogen applied as fertilizer in intensive cereal-production systems is lost following rapid nitrification (Raun and Johnson, 1999). Controlling nitrification in agricultural systems is thus critical to reduce both N_2O emissions and nitrate contamination of water bodies (Subbarao et al., 2012).

Tropical forages, in particular *Brachiaria* spp., suppress activity of nitrifying bacteria by releasing inhibitors from roots and therefore reduce soil nitrification (Sylvester-Bradley et al., 1988; Subbarao et al., 2009) in a process called biological nitrification inhibition (BNI) (Subbarao et al., 2007, 2009). There is a wide range in the BNI ability of the root systems of tropical forage grasses and cereal and legume crops (Subbarao et al., 2007). *Brachiaria humidicola* and *B. decumbens*, both of which are well adapted to the low-nitrogen soils of South American savannas (Miles et al., 2004), showed the greatest BNI-capacity among the tropical grasses tested (Subbarao et al., 2007). In contrast, the major cereals (rice, wheat, and maize) have little BNI capacity (Subbarao et al., 2007). The major nitrification inhibitor in *Brachiaria* forage grasses is brachialactone, a cyclic diterpene (Subbarao et al., 2009).

Brachiaria humidicola also has substantial genotypic variation for BNI. The ongoing *Brachiaria* breeding program at the International Center for Tropical Agriculture (CIAT), conducted in collaboration with the Japan International Research Center for Agricultural Sciences (JIRCAS), plans to identify genetic markers associated with BNI ability in crosses between apomictic and sexual accessions of *B. humidicola*. Field studies in CIAT headquarters (Cali, Colombia), on a Mollisol, indicated a 90% decrease in the oxidation rates of soil NH_4^+ in *B. humidicola* plots, largely due to low nitrifier populations. N_2O emissions were also suppressed by more than 90% in field plots with *B. humidicola* compared with the emissions from plots planted to soybean, which lacks BNI ability (Figure 11-2). Grasses with greater BNI ability in their roots emitted proportionally less N_2O in a field experiment over 3 years (Subbarao et al., 2009).



CON: control (plant-free) plots; SOY: soybean; PM: *Panicum maximum;* BHM: *Brachiaria* hybrid cv. Mulato; BH-679: *B. humidicola* CIAT 679 (standard cultivar); BH-16888: *B. humidicola* CIAT 16888 (a germplasm accession). Values are means ± SE from three replications.

Figure 11-2. Cumulative N_2O emissions (mg of N_2O-nitrogen/m^2 per year) from field plots of tropical pasture grasses monitored monthly over a 3-year period, from September 2004 to November 2007.

SOURCE: Adapted from Subbarao et al. (2009).

Tropical forage grasses with high BNI ability and perennial growth habit favor the accumulation of sufficient inhibitors to suppress soil bacterial nitrifier activity. The pasture component in an agropastoral rotational system could provide the required BNI-activity to improve the nitrogen-economy of annual crops that follow the pasture phase. For example, *Brachiaria* pastures that have high BNI ability could be rotated with annual crops such as maize or upland rice, which have low or very low BNI ability but receive substantial nitrogen fertilizer. The inhibitors accumulated in the soil in the pasture phase would increase the recovery of applied fertilizer nitrogen, which could lead to improvement in the overall nitrogen economy of the system (Subbarao et al., 2012).

Potential differences in N_2O emissions exist among plant species in general and among pasture plants in particular (Subbarao et al., 2009). These differences are not considered by the Intergovernmental Panel on Climate Change (IPCC) in their estimates of projected N_2O emissions from agricultural systems (Stehfest and Bouwman, 2006). For example, there are more than 250 million hectares of South American savannas occupied by native grasses or by sown grasses such as *Brachiaria* spp. (Fisher et al., 1994) that have moderate to high BNI ability; these areas emit markedly lower amounts of N_2O than if they were planted to field crops. If a substantial area of these savannas were to be converted to soybean and maize, which lack BNI ability, there would be profound implications for N_2O emissions (Subbarao et al., 2009). The impact of such a conversion could be reduced if an adequate BNI ability were to be incorporated into the system, such as by integrating a high-BNI pasture phase into the system (Ayarza et al., 2007). These systems, however, must remain highly productive to meet the ever increasing demands for food from a growing world population, a challenging task for researchers, policy makers, and farmers alike.

Animal urine and manure are also major sources of N_2O. One way in which N_2O emissions from urine may be reduced is by increasing the content of hippuric acid in the urine, as demonstrated in laboratory trials (Bertram et al., 2009). The effect could not, however, be replicated in the field (Clough et al., 2009). Phenolic compounds of tropical forages can cause a shift in the nitrogen excretion in urine towards hippuric acid (Lowry et al., 1993). Grazing management may also affect N_2O emissions from pasture; for example, in Inner-Mongolia, increasing stocking rates of sheep reduced N_2O emissions compared with those from ungrazed pasture (Wolf et al., 2010). However, there are no comparable data from the tropics, an obvious research gap.

Reciprocity of CH_4 and NO, N_2O, and NO_x release and decomposition

Microbes such as methanogenic archeae, methanotrophs, nitrifiers, and denitrifiers are important in both the formation and the oxidation of GHGs in natural and agricultural systems. These microbes interact closely, especially in the soil, and possibly also in the rumen (Mitsumori et al., 2002; Kajikawa et al., 2003). It is therefore possible that nitrification inhibition might also inhibit the desirable oxidation of methane in soils (Bronson and Mosier, 1994); as demonstrated by Yue et al. (2005). A possible explanation is that some methanotrophs produce nitrous oxide (Lee et al., 2009) through various biochemical pathways (Powlson et al., 1997). Because of the radiative forcing difference between CH_4 and N_2O (Forster et al., 2007), reciprocal effects should always be considered and studied in a holistic mitigation concept.

Land use Change and Leakage

Land use change and leakage (i.e., the effects of reducing an activity in one location but increasing it in another) affect the contribution of agriculture to GHG emissions and strategies are needed to mitigate these. Wassenaar et al. (2007), using a novel approach to project the spatial trends of deforestation for the neotropics from 2000 to 2010, concluded that livestock production causes deforestation, since it is the main land use after clearing the forest. They also concluded that livestock production is to some extent responsible for the expansion of cropland into forest. Using the Amazon region as an example, however, the intensification of pastures using sown forages could just as well reduce deforestation by reducing pressure on land through increased efficiency of livestock production (higher livestock output per unit of land). But higher efficiency also increases the productivity of livestock operations, which could prompt further deforestation (White et al., 1999; Kaimowitz and Angelsen, 2008). Pasture establishment is also often used in conjunction with expansion of soybean production (i.e., a pasture phase employed after deforestation, which then is succeeded by soybean cultivation) further increasing pressure on forests (Hecht, 2005). In summary, it is not clear what effect the intensification of livestock production based on improved forages would have on deforestation, and any effects would also depend on policy interventions (e.g., White et al., 1999; Steinfeld and Gerber, 2010).

Life-cycle analysis

Life-cycle analysis (LCA) has been used recently to analyze the implications of system intensification for GHG emissions. To assess the net abatement potential of each strategy, it must be subjected to whole-farm systems modeling and a full LCA, to ensure that a reduction in emissions at one point does not stimulate higher emissions elsewhere in the production system (Eckard et al., 2010). Peters et al. (2010) and Pelletier et al. (2010) have discussed the case for reducing emissions through systems with higher feed-conversion efficiency such as feedlots. Most studies assess emissions only (Cederberg et al., 2009; Gerber et al., 2010; Peters et al., 2010), however, and do not consider the positive effects of mechanisms such as carbon sequestration and BNI from pastures. Similarly, the majority of GHG balances assume equilibrium conditions in SOC in established systems (Pelletier et al., 2010).

Increasing the digestibility of cattle rations by feeding grains and whole-plant silage from maize does mitigate CH_4 emissions, but the loss of SOC and the loss of carbon sequestration potential caused by plowing grassland to grow maize are much larger than the mitigation obtained by feeding more maize (Vellinga and Hoving, 2011). A sensitivity analysis in the USA that compared the total GHG balance in intensified grazing systems, including SOC sequestration, with that of feedlot-finished beef found that pasture-fed beef produced 15% less net GHG (Pelletier et al., 2010). This supports our analysis of the mitigation potential of forages through carbon sequestration outlined above.

Technology options and decision-support tools

Where the positive and negative impacts of technology on land use are closely related, and in view of the global implications (Foley et al., 2005), it is useful that technology options be combined with decision-support tools. The aim is to foster policies with a minimum ecological footprint, such as the conservation of forests (Szott et al., 2000; Neidhardt and Campos-Monteros, 2009), to reduce land degradation and to maintain vital ecosystem services. Avoiding land clearance in the Amazon, Central America, and the Caribbean regions could save GHG emissions of 1.8 billion t CO_2 equivalents/year (Vosti et al., 2011). Increasing the eco-efficiency[10] of agriculture in these regions, in which land is often degraded, may have the largest effect on mitigation of GHGs, through the combined effects of avoiding deforestation and realizing the land's mitigation potential.

Financing Schemes Involving Integration of Improved Tropical Forage Options

Options to mitigate agricultural GHGs are cost competitive with options to mitigate GHGs from other sources such as energy, transportation, and forestry (Smith et al., 2007a). However, these options have not received adequate attention in the climate change negotiations. Benefit schemes are difficult to implement in terms of accurate

[10] Eco-efficiency, as explained elsewhere in this volume, includes the economic, social, and environmental components of a particular technology that is within the reach of the less wealthy, together with policies that enable its users to generate both cash profits and environmental benefits.

measurements of emissions and uptakes, and the definition of appropriate and equitable funding schemes. Curbing deforestation, reforestation, and payments for improved carbon management are among the most promising strategies (Stern, 2006). Important elements in agriculture include management of rice paddy, reduced tillage, perennial land covers, restoration of degraded lands, and improved livestock and manure management (Scherr and Sthapit, 2009; The World Bank, 2010). Selecting or breeding a new generation of crops and forages that will reduce GHG emissions is a paradigm shift in agriculture that offers the possibility of securing crop and livestock productivity while at the same time moderating the effect of agriculture on climate change (Kell, 2011; Philippot and Hallin, 2011). The barriers to realizing the mitigation potential of agriculture include: (1) lack of permanence of sequestered carbon; (2) the requirement for additionality, i.e., the net reduction of GHG emissions should be supplemental to ongoing activities; (3) uncertainty, in terms of the complex biological and ecological processes and seasonal/annual variability; and (4) leakage, discussed above (Smith et al., 2007b).

Further biophysical research is needed to assess the mitigation potential of tropical forages in crop–livestock systems (including other interventions such as including trees in the production system, and crop management). This needs to be combined with assessment of economic feasibility of mitigation options and socio-economic modeling to target policy support. Another level of complexity is the assessment of co-benefits, especially win–win situations. For example: (1) Increased SOC enhances soil quality and pasture productivity, which frees other areas for alternative production and conservation, although explicit policy regulation may be needed to avoid negative outcomes such as deforestation; (2) Reduced soil nitrification of sown pastures with high BNI capacity can improve the recovery of applied nitrogen by subsequent cereal crops in agropastoral systems; and (3) Increased below- and above-ground biodiversity has both landscape and sociocultural implications (Smith et al., 2007b; Herrero et al., 2009; Anderson and Gundel, 2011). Linking complementary farming systems in space and time, particularly specialist crop and livestock farms, for nutrient and, to a lesser extent, feed exchanges, also increases eco-efficiency in land management (Wilkins, 2008).

It is expensive to measure soil carbon sequestration and CH_4 and N_2O balances over broad areas. We need tools that allow us to estimate GHG fluxes accurately, supported by cost-effective measurements and modeling techniques (The World Bank, 2010). Promising approaches include satellite imaging, combined with airborne light detection and ranging and field plots for carbon assessment (Asner et al., 2010), together with methods such as the FAO *Ex Ante* Appraisal Carbon-balance Tool (EX-ACT) (Bernoux et al., 2010; Branca and Medeiros, 2010), but they need further development before they can be applied widely. We also need methodologies to assess the opportunity costs of land use change for smallholders to evaluate the impacts of management options on both livelihoods and the environment (White and Minang, 2010). The global climate change community has not yet broadly addressed N_2O emissions, but they need to be included in the future in schemes to mitigate GHG emissions (Smith et al., 2007b).

Because of their national, regional, and global mitigation potential, all forage-based systems (grasslands and pastures as well as forage production on croplands) should be included as potential components in negotiations of GHG emissions. If the mitigation potential of agriculture is to be realized, it should be included in schemes such as reducing emissions from deforestation and degradation (REDD), the clean development mechanism (CDM), and expanded REDD schemes such as carbon in agriculture, forestry, and other land uses. If the cost of establishing forage-based systems and agroforestry systems, for instance, could be met through payment for environmental services (PES) via REDD program financing, we could anticipate a triple-win situation combining social, economic, and environmental benefits. Direct-cost recovery with minimum time lags in the payment scheme is a critical requirement for smallholders with limited resources and in risky production environments (The World Bank, 2010).

Market differentiation and price premiums would be feasible by combining direct payment with certification for climate-smart forage-based systems such as livestock and crop production based on improved forages and better utilization of crop residues. If so, higher returns to smallholder farmers would be possible, providing both improved equity and mitigation of GHG emissions. It is essential, however, that national agricultural policies are aligned with global environmental objectives (Steinfeld and Gerber, 2010).

Conclusions and the Way Forward

Livestock production is a large source of GHG emissions, and reducing meat consumption or changing from ruminant to non-ruminant meat could have a number of environmental benefits (Stehfest et al., 2009; Wirsenius et al., 2010). However, in many publications, analysis is restricted to the emissions from livestock production without mentioning compensating factors such as potential for carbon sequestration and reducing N_2O emissions. For example, Wirsenius et al. (2010) suggest substituting beef with pork and poultry, due to their higher feed conversion efficiency. We argue, however, that comparing GHG emissions from livestock production in the tropics with other systems must be based on LCA analysis and that the potential contribution of forages to mitigation must be taken into account. Assessments of grain-based feedlots must account for the whole GHG cost of the feed supplied and take into account that forages are often produced on land less suitable for crop production (Schultze-Kraft and Peters, 1997; Peters et al., 2001). As we describe here, improved grassland management and intensification of forage-based systems (through improved resource use efficiency, improved carbon sequestration, and reduced emissions due to BNI) are key to mitigating GHG emissions from livestock production, and will deliver other co-benefits such as resource conservation, reduced costs, and social and cultural benefits.

Due to the importance of forage-based systems, including feed production on cropland, we argue that the international community should give much greater attention to systems based on sown forages. At least 70% of agricultural land is covered by these systems and they impact GHG emissions, resource use efficiency, and resource degradation. Sown forages have substantial potential for carbon sequestration and for reducing CH_4 and N_2O emissions per unit livestock produced. Because of their multipurpose role (feed, green manure, soil improvement, erosion control, and biodiversity), sown-forage-based systems may be among the most promising means of mitigating the impacts of agriculture on GHG emissions (Smith et al., 2008). We estimate that sown forages alone could contribute 60–80% of the total potential carbon sequestration on agricultural lands through their contribution to the management of crop and grazing land and to the restoration of degraded lands and cultivated organic soils. IPCC (2007) reports that improving management of grazing land has the greatest mitigation potential of all agricultural interventions, over 1.5 billion t CO_2 equivalents/year, sufficient to offset all the emissions from livestock production. In view of the extent of pasture areas and the dominance of crop–livestock systems in land use, we suggest that no strategy for mitigating global climate change can be comprehensive or successful if it fails to recognize the importance of forage-based systems. Sown forages can also be integrated into agroforestry systems to enhance their eco-efficiency, not only to mitigate GHG emissions but to optimize resource use equitably and profitably.

Reduced consumption of animal products may be desirable in rich countries, but from a nutritional and sociocultural standpoint is probably not an option for countries where consumption is currently low (Herrero et al., 2009; Steinfeld and Gerber, 2010; Anderson and Gundel, 2011). Failing to take advantage of the mitigation potential of sown forages may leave 50–80% of the mitigation potential of agriculture untapped. It is therefore essential to: (1) further increase knowledge about the quantitative contribution of different processes such as carbon sequestration, BNI, reduced GHG emissions per unit of livestock produced, and co-benefits in terms of resource use efficiency (e.g., land, water, and nutrients); (2) refine comprehensive assessment of complex systems by using approaches such as LCA;

(3) integrate these results into more manageable monitoring systems using proxies (parameters representative of the actual situation that can be collected at relatively low financial and time cost to allow for regular revisions); (4) develop policy and financial incentives for livestock and crop producers via direct PES, e.g., to enhance efficiency of crop–livestock systems through prefinancing planting of improved forages and establishing agroforestry systems; and (5) provide additional market incentives for producers/farming communities through certification of climate- and resource-friendly livestock production.

The majority of GHG emissions originate in the 151 non-Annex 1 countries (less industrialized countries without binding Kyoto Protocol obligations to reduce emissions) where growth of livestock production is expected to be particularly high (Gerber et al., 2010). It is essential to develop a climate policy framework that provides incentives for these countries to participate (Gerber et al., 2010; Anderson and Gundel, 2011). To address issues of leakage, incentives need to be accompanied by policy regulations to avoid deforestation and conversion of fragile lands into croplands.

Further research to enhance eco-efficiency of agricultural systems should focus on the following actions to realize the potential of sown tropical forages to mitigate GHG emissions:

- Conduct long-term field experiments and rigorous data collection combined with simulation modeling for rainfed smallholder agricultural systems with a particular emphasis on crop–livestock systems to assess the potential of tropical forage options for reducing GHG emissions.
- Continue research to quantify further the carbon sequestration effects of agropastoral systems such as crop–pasture rotations, as there is very limited information on synergies between the crop and livestock components.
- Conduct full LCAs that include CO_2, CH_4, and N_2O emissions in various target regions to define better the role of sown tropical forage plants (grasses and legumes) in improving eco-efficiency of crop–livestock systems and mitigation of GHG emissions.
- Develop new approaches to integrating sown forages to achieve eco-efficiency in smallholder agriculture in the tropics, e.g., through enhancing capacity building and their inclusion in payment-for-environmental-services schemes, possibly linked to access to credit and certification of climate-friendly livestock production.
- Breed tropical grasses for increased BNI to reduce N_2O emissions, while at the same time exploring the best ways to exploit BNI.
- Assess the importance of microbial interactions on reciprocity of GHG emissions.
- Assess the impacts on GHG emissions of pasture management and changes in ruminant nitrogen excretions resulting from changes in forage sources.
- Investigate the potential of tropical forage legumes to (1) supply nitrogen to grass and to improve carbon accumulation in deep soil layers, and (2) contribute, via legume-specific chemical compounds such as tannins, to reduced CH_4 production by ruminants.

In summary, we consider that well-managed tropical forage-based systems can contribute not only to improved livelihoods of the rural poor in the tropics, but also to the overall quality of the environment. With a global community increasingly cognizant of the environmental implications of agriculture, forage-based systems should figure prominently in future innovative agricultural systems. We hope that this paper stimulates intensive discussion that leads to further investment from donors for research on improving eco-efficiency of forage-based livestock production in the tropics.

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CHAPTER
12

Eco-Efficient Research to Provide Safe, Profitable, and Environmentally Sustainable Production of Fruits and Vegetables

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Contents

Abstract

Fruits and vegetables have a major role in ensuring that the world is not only fed but also nourished. They supply many of the micronutrients that combat malnutrition and contribute to balanced diets required for good human health. However, because of the large number of pests and diseases that challenge these crops, current crop management practices may often be deleterious to the health of farmers, consumers, and the environment. There is an urgent need to develop technologies that will enhance production of common fruit and vegetable crops in a more ecologically sustainable manner. If such opportunities are to be exploited effectively, they need to build on the foundations of strong local knowledge and a comprehensive understanding of the real needs of poor farmers and their communities. For the less-known crops, for which the potential for development opportunities are high among smallholder farmers, it is appropriate to consider new strategies to increase production, open markets, and increase incomes in ways that minimize negative environmental impacts, thus helping to maximize the longer-term sustainability of production systems. To properly formulate such strategies requires a wide range of partners, from both the public and the private sector, to be brought together to address whole value chains, and sufficient financial resources to accomplish the research and development required.

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This chapter highlights the importance of fruits and vegetables in combating world malnutrition. We examine the major constraints to production and consumption in the developing world, and various eco-efficient approaches to enhancing production efficiency and produce quality and safety. We stress the value of improved, resilient germplasm, safer pest and disease management practices, more appropriate water and soil fertility management, and ways in which technology dissemination might be made more effective. The chapter includes examples of eco-efficient interventions in production of fruits and vegetables, the risks of such interventions and opportunities to enhance their impact, and key lessons for research, development, and policy.

Fruits and Vegetables to Alleviate Global Malnutrition and Improve Livelihoods of the Rural Poor

Fruits and vegetables are highly nutrient dense. They contain vitamins, fiber, minerals, antioxidants, and other micronutrients essential for human health, and thus are excellent food sources to combat malnutrition. Micronutrient malnutrition, resulting from an imbalanced diet, is prevalent globally regardless of age, location, or income category, and is often the main cause of various debilitating chronic and fatal diseases. While 925 million people currently suffer from hunger, approximately 1.6 billion are malnourished (FAO, 2010; WHO, 2011). This high prevalence of micronutrient malnutrition is mainly the result of an insufficient intake of vitamins and minerals (WHO and FAO, 2006). Among the poor, the cause of malnutrition can be linked directly to their limited access to adequate amounts of appropriate food to satisfy their nutritional requirements for good health. Examples of the effects of malnutrition that are common in developing countries include maternal mortality and premature birth caused by iron deficiency; and night blindness and an impaired immune system caused by insufficient vitamin A. Being malnourished does not necessarily mean hungry, as a result of consuming excess carbohydrates and fats, thus bringing the accompanying medical effects of high body mass index. In the developed world, malnutrition can be attributed to an unwise diet choice and a pronounced tendency to consume an excessive amount of fats, carbohydrates, and protein. Obesity (which often leads to diabetes) and consequent cardiovascular and other chronic diseases are the prime silent manifestations of malnutrition caused by inappropriate consumption, in both developing and developed countries. The resulting cost to national health services is very large and growing steadily.

More investment is needed to increase availability and consumption of fruits and vegetables worldwide if we are to both feed the world and also nourish its population to the level needed to assure good health, and thus deliver improved livelihoods. Under-consumption of fruits and vegetables is among the top 10 risk factors leading to micronutrient malnutrition and is associated with the prevalence of chronic noncommunicable diseases (Ezzati et al., 2002). Noncommunicable diseases such as hypertension, cardiovascular diseases, cancer, diabetes, and obesity may be the causes of a high proportion of untimely deaths, for example, in some African countries (Ganry, 2011). In these countries, the availability of fruits and vegetables is often far below the intake of 400 g/day per capita recommended by the World Health Organization (WHO). Currently the agricultural research community's main goal is to increase production of grains and other staple crops to feed a growing world population. However, for a development strategy to be effective and sustainable, it is necessary to ensure that both food and nutritional security are delivered simultaneously and at the same time the environment and enterprises in which production occurs are not chronically degraded.

Fruits and vegetables can also fight hunger, malnutrition, and environmental degradation indirectly. Their high market value contributes to generating income through direct sales and added value, thus alleviating rural poverty and providing additional opportunities to purchase nutritious foods. Profitable fruit and vegetable production systems can take place even in smallholdings (due to limited economies of scale). Some of these crops can be grown with relatively low capital investment (Shackleton et al., 2009). Even with restricted but judicious inputs there can be quick returns to investment for the poor in both rural and urban areas. Moreover, investing in suitable inputs to prevent mining of soil nutrients and adoption of better land management practices have the potential to be extremely environmentally beneficial within a resource-poor farmer context. Fruit and vegetable production tends to be labor intensive and therefore provides employment and generates income across the community; it also empowers women, who often have a major role in fruit and vegetable value chains. Indigenous fruits and vegetables are regularly sold in local markets and, in some cases, can achieve a sufficient level of quality and consumer acceptance to permit commercial cultivation by smallholder farmers.

Constraints to Fruit and Vegetable Production and Consumption in the Developing World

Enhanced per-capita consumption of fruits and vegetables among all sectors of society would help fight malnutrition and poverty along the value chain from the field to the table. Fruit and vegetable enterprises need to ensure availability and affordability for consumers to maximize the benefits for both consumers and producers. Producers in developing countries have to overcome various constraints in sustaining sufficient product availability. These constraints include: lack of access to improved, superior-quality seeds; limited knowledge of effective production practices, particularly with regards to using available water resources efficiently; and ensuring that soil health is not compromised by either nutrient mining or excessive use of fertilizer. In addition, ineffective and harmful pest and disease management practices may threaten not just the profitability of the farm enterprises but the very health of farmers, families, consumers, and the surrounding environment.

Climate uncertainty, manifested by unpredictable, harsh weather events, has exacerbated the constraints that smallholder farmers face. This includes increased pest and disease pressure, and the resulting challenge of producing residue- and contaminant-free products. In the case of fruit growers, for instance, increases in relative humidity that occur as a result of unpredictable rain near harvest carry the risk of fungal infections that become evident only after the fruit is sold to the markets. Temperature fluctuations are increasingly accompanied by changes of population dynamics in both pollinators and insect pests. For example, increases in temperatures have meant that insects such as the fruit fly (*Anastrepha fraterculus*) are now found where they were normally absent, such as areas where Andean blackberry (*Rubus glaucus*) is cultivated. Events like these have caught growers off guard and have resulted in loads of fruit being rejected at processing facilities (A. González 2010, pers. comm.). Unexpected rains may cause temporary flooding, which can have disastrous effects on tomato (*Solanum lycopersicum*) and many other crops.

Most vegetables and some annual fruit species are particularly susceptible to drought, even when experienced for very short periods of time. Drought is especially challenging in highland landscapes, where irrigation is usually not available. Even with the use of irrigation, however, unexpected lack of water will cause severe losses.

There are many opportunities for growing underutilized or indigenous fruit and vegetable species, which are often less susceptible to climatic events than introduced species. Unfortunately, historically there has been very little investment in research on the physiology and other attributes of these species despite the fact that they provide very tangible alternatives to the more widely grown crops in improving nutrition and income for the rural poor.

An Eco-Efficient Approach to Enhancing Production Efficiency and Produce Quality and Safety

As described in Chapter 2, eco-efficient agriculture aims to increase productivity while reducing associated negative environmental impacts. It must be profitable, competitive, sustainable, and resilient while meeting the economic, social, and environmental needs of the rural and urban poor. Producing enough food to assure both food and nutritional security for the global population while preserving or enhancing the environment and minimizing health risks requires more efficient and ecologically friendly production systems.

An eco-efficient approach can be pursued and applied at each step, from seed production to postharvest value addition. These approaches could include ecologically appropriate practices in seed production and in the seedling nursery, utilization of cover crops that enhance mulching and fertilizer effectiveness, more efficient irrigation systems, pest and disease management techniques of low ecological risk, diversification of production systems, and efficient preharvest and postharvest management methods. The following sections describe some examples of eco-efficient production practices. Their practical application and research results are described in the case studies section.

Improved, resilient germplasm

Improved, superior lines of fruits and vegetables are one affordable tool that smallholder horticultural producers can use to address the ever-increasing challenges of biotic and abiotic stresses linked to climatic changes (de la Peña and Hughes, 2007). Many wild relatives of cultivated varieties possess genes that make them more adaptable and tolerant to harsher environments in which they can thrive. For example, *S. chilense*, a wild relative of the cultivated tomato, is indigenous to the desert areas of northern Chile and is adapted to extreme aridity, soil salinity, and to low temperatures (Chetelat et al., 2009). Two wild nightshade species from the same region (*S. sitiens* and *S. lycopersicoides*) share such traits. Gene transfer from these wild species could facilitate the development of drought- and salt-tolerant traits in standard tomato varieties. The genetic factors that are responsible for these traits have been identified and efforts are being made to transfer them into cultivated tomato by hybridization and introgression.

Unfortunately, the search for tolerance to biotic and abiotic stress is occurring mainly in highly commercial vegetables and temperate fruit species. The underutilized species, which are consumed and marketed by many families in developing countries, remain very much understudied and are at risk of being lost to deforestation and land use changes (Keatinge et al., 2010). Many indigenous vegetable species, such as amaranth (*Amaranthus* spp.), kangkong (*Ipomoea aquatica*), and Malabar spinach (*Basella alba*), are infested by very few pests and infected by only a few diseases. Thus they can thrive with very limited external production inputs. However, in the case of some of the underutilized fruit species, such as the Andean fruit species naranjilla or lulo (*S. quitoense*), resistance to biotic stresses (e.g., nematodes and root rot) has not been found. Naranjilla is economically important to smallholders in several Latin American countries, but is highly susceptible to many pests and diseases. A closely related species, *S. hirtum*, has fruits that are not appealing to consumers but has shown resistance to the main root nematode pest, *Meloidogyne incognita*. *Solanum hirtum* was used in hybridization programs in Colombia and a tri-hybrid variety has been released out of this cross (Bernal et al., 1998).

Given the large potential diversity of fruits and vegetables, cultivation of traditional species adapted to different agroecological environments offers an opportunity to improve production and increase incomes for smallholders. Increased production and utilization of these traditional species need to be promoted. Expansion of the current cultivated crop range with indigenous species would not only enhance the resilience of these crop production systems but increase the diversity of fruits and vegetables available to consumers.

The search for genes controlling those characteristics that can facilitate adaptation to changing ecological and climatic conditions is becoming urgent. Consequently, efforts to collect, conserve, and utilize genetic diversity are assuming critical importance. Collections of fruit and vegetable germplasm are important reserves of genes to confer pest and disease resistance, tolerance to flooding, improved nutritional content, longer shelf life, better yield and market quality, and other desirable traits. For example, screening of accessions from the genebank of the AVDRC - The World Vegetable Center has resulted in the identification of pepper (*Capsicum annuum*) lines tolerant to anthracnose (*Colletotricum acutatum*), cucumber lines resistant to powdery mildew (*Podophaera xanthii*), and pepper lines with resistance to aphids (*Myzus persicae*) and broad mites (*Polyphagotarsonemus latus*), among others.

Unfortunately, no such intensive and targeted institutional efforts have taken place to search for genes of interest in tropical fruit collections. Efforts to conserve genetic resources of tropical fruits, if they exist within a country, tend to be diffused between the national research organizations, local universities, and local farmers. Screening of germplasm of Andean blackberry from the national collection held at the Colombian Corporation of Agricultural Research (Corpoica), resulted in identification of accessions tolerant to anthracnose (Kafuri, 2011). Many other examples of evaluation of national collections have shown that efforts should be devoted to characterizing existing collections rather than further collecting. There is a risk that valuable genes could be lost if the collections are not well maintained, and the collections may not represent the full genetic variability of the species.

Safer pest and disease management practices

Horticultural production systems in the tropics and subtropics are often strongly affected by pests and diseases. As a result, sustainable production is not easily attainable without proper management strategies. Unfortunately, the majority of smallholder producers in developing countries have only limited access to technologies, information, financial resources, and professional services to deal with pest and disease problems. The pressure to maintain high levels of production pushes them towards misuse and/or overuse of pesticides. Some work among fruit and vegetable producers has shown that farmers often rely on calendar-based pesticide applications, often using mixtures of products and without a clear underlying rationale for their use. A study conducted by a non-governmental organization (NGO) in India showed that out of five internationally banned pesticides, four were found to be commonly in use or being tested on vegetables and fruits in New Delhi (Garg, 2011). In a participatory survey among passion fruit growers in Colombia, 47% of growers interviewed applied a mixture of pesticides up to four times a month rather than basing their applications on a damage threshold (Romero and González, 2010).

Although larger enterprises often have some access to technologies and professional services that permit them to be more judicious in the chemicals and application rates used, this is not always the case. While large-scale producers may have better capacity to maintain the yields of their production systems, the pressure to satisfy the preferences of higher-end consumers for unblemished produce may still encourage them to overuse crop protection agrochemicals to assure market acceptability. When combined with inappropriate pesticide applications prior to harvest, this excessive use of inputs can result in considerable levels of harmful residues in the harvested produce. These residues have the potential to offset the nutritional benefits of vegetables and fruits. Not only does pesticide misuse affect consumers' health, it can also be hazardous to the health of farm workers if protective measures are not taken during application, which is often the case in developing countries. Overuse of agrochemicals can also dramatically increase production costs, eroding smallholder farmers' profits and thus their ability to create sustainable enterprises. The health of consumers and producers must not be jeopardized by harmful agricultural practices used to produce nutrient-laden fruits and vegetables.

Studies show variable concentrations of chemical residues on and in fruits and vegetables. For example, 21 pesticide residues were detected in the cabbage samples at the farm-gate in Cape Coast, Ghana (Armah, 2011). Out of those, two were at exceedingly high levels (allenthrin at 9.57 mg/kg and phorate at 2.08 mg/kg) and three were potentially carcinogenic compounds although at toxicologically acceptable levels (cypermethrin at 0.31 mg/kg, permethrin at 0.15 mg/kg and parathion at 0.019 mg/kg). In Germany, the Federal Office of Consumer Protection and Food Safety (BVL)—management authority for health-related consumer protection— reported that out of 65% passion fruit samples containing pesticides residues, 35% were above the acceptable levels (BVL, 2008). When pesticides are used appropriately, their residues in harvested crops are below maximum residue levels (MRLs)—the maximum concentrations legally permitted in or on food commodities entering a country—and the crops are considered to be toxicologically acceptable. Bayoumi et al. (2006) compared chemical residues in cucumbers sprayed only once, as recommended by the product label, with those on cucumbers that received numerous applications, following the growers' practices. The results indicated that the numerous applications resulted in pesticide residues above the MRLs. Measurement of pesticide residues is mandatory only for fruits and vegetables exported from their country of origin, in order to comply with importing country regulations. However, having little or no pesticides in fruits and vegetables is equally important for domestic consumers.

The ability of fruit and vegetable cropping systems in developing countries to tolerate, and adapt to, climate uncertainty will undoubtedly determine their viability in the future (FAO, 2001). Researchers are developing technologies to help smallholder farms and farmers be more resilient to the increasing frequency and intensity of biotic and abiotic stresses associated with climate change. As smallholder farmers are usually resource limited, these technologies must be affordable, simple to use, and accessible.

Integrated pest and disease management (IPM) is one environmentally sound approach to manage biotic stresses in fruit and vegetable production systems. IPM practices enhance the role of natural enemies, of plant defense systems, and of environmental factors to reduce pest and disease incidence in a sustainable way. Should chemical inputs be deemed necessary, the selection of appropriate chemicals and the dosage and frequency at which they are applied must be done with careful consideration for the safety of the environment and human health, and to minimize negative impacts on the various interacting pest and disease management components. IPM not only provides a safer method to manage pests and diseases but also often reduces input costs due to the more judicious use of pesticides.

Water and soil fertility management

Informed soil and water management is an essential feature of eco-efficient systems. Failure to address such issues in a timely fashion will surely compromise system sustainability. Micro-irrigation systems, such as drip irrigation, can increase crop productivity per unit of water used compared with less-efficient irrigation systems, and are now affordable for poor farmers. In many arid or semi-arid locations, such systems are the only solution, simply because there is too little water available to use less-efficient systems. Nevertheless, many smallholder farmers are still unfamiliar with the concept and practicality of micro-irrigation techniques. Access to these technologies in some areas is still fairly limited, making it even harder to adopt and, where necessary, to adjust the technology to meet local, specific requirements.

Because drip irrigation avoids prolonged direct contact between the water and the upper part of the plants, it may also minimize the spread of soil-borne microbial contamination to fruits and leafy vegetables. Using the same logic, use of grey water for irrigation may be safer when applied using micro-irrigation methods. However, recent occurrences of contaminated vegetables in Europe are putting these practices under the spotlight. Authorities and farmers should be aware of the danger of biological contamination in irrigation systems. Irrigation water runoff, which may contaminate groundwater and other water resources with fertilizer and pesticide residues, is also minimized in production systems using micro-irrigation.

Smallholder fruit producers currently use multi-strata and multi-species production systems to boost water productivity. However, while the farmers have built on traditional knowledge, their production systems have been devised with very little technical information or access to new technologies. Research is needed to provide more-sound alternative production practices, such as the growing and incorporation of cover crops that can help boost water-holding capacity in fruit orchards as well as contribute to soil fertility and structure, which helps the main crop withstand climate extremes. These alternative production practices need research and validation and could prove very useful to reduce herbicide application, ensure soil water retention, mitigate the effects of short-term droughts, and control erosion in high rainfall areas. However, when selecting cover crops, farmers need to consider carefully the cover crops' effect on insect diversity, as this could increase the number of crop pests. Conversely, the cover crop selected could be beneficial to the biological control agents of the insect pests (Wood et al., 2011).

In some vegetable species, the issues of flooding and the presence of soil-borne diseases may be addressed by using grafting. This practice has been used for centuries in temperate fruit production, and is becoming more prevalent in some tropical and subtropical fruits, e.g., avocado, citrus (*Citrus* spp.), mango, and soursop (*Annona muricata*). The scion (upper part) of superior cultivated crop plants can be grafted to rootstocks of plants with important characteristics such as resistance to flooding and/or certain soil-borne plant diseases. Grafting tomato or pepper varieties to bacterial-wilt-tolerant eggplant rootstocks can drastically reduce the incidence of the wilt caused by *Ralstonia solanacearum*. Flood-tolerant eggplant rootstocks also enable farmers to produce tomatoes during rainy seasons in the tropics, ensuring production and availability of the crop all year round. *Ralstonia solanacearum* is also the causal agent of moko disease, which is responsible for severe losses in plantain in Latin America and the Caribbean. Unfortunately, no grafting is possible in monocotyledonous species like banana or plantain (*Musa* spp.) and thus alternative solutions are needed.

Because fruits and vegetables are among the most input-responsive of crops, they are often cultivated in intensive production systems with high fertilizer input. This can lead to an over-reliance on inorganic fertilizers to increase yields, but failure to apply enough nutrients will lead to mining of soil nutrients. An appropriate balance of input and offtake of nutrients is required for good soil health. Injudicious use of fertilizer may, however, contribute to the deterioration of soil quality. Accumulation of salts and nitrates from fertilizers in vegetable cropping systems in the North China Plain, for example, has resulted in reduced soil pH, higher electrical conductivity, and raised cadmium concentrations, contributing to rapid soil deterioration (Ju et al., 2007). Leaching of inorganic fertilizer into groundwater may also contaminate water sources used for human and animal consumption, possibly compromising human and animal health. There have been few attempts to investigate nutrient budgets of fruit and vegetable production, but such studies are required to optimize nutrient use and reduce the energy cost of fruit and vegetable production.

Research is under way on the use of "biochar"—charcoal created by pyrolysis of plant biomass—as one alternative or adjuvant to fertilizer. Biochar may enhance soil physical, chemical, and biological properties. In contrast to the burning and natural decomposition of trees and agricultural matter, which releases a large amount of carbon dioxide to the atmosphere, biochar sequesters carbon. Tropical soils are commonly low in organic matter and available nutrients due to high soil temperatures and severe leaching caused by high rainfall. Application of biochar to the soil may improve soil water retention, fertility, and overall quality, thus improving agricultural productivity.

Effective technology dissemination

For agricultural research and development to achieve societal impact, it is imperative that the results are delivered to, disseminated among, and adopted by the target beneficiaries. Smallholder farmers need to be better advised on the availability of potentially affordable eco-efficient production systems, on what other alternatives may be available and appropriate, and what technologies are available for adoption or adaptation. Therefore, the participation of farmers, as ultimate users of new or adapted agricultural technologies, is crucial when designing research and development activities. An understanding of the constraints and opportunities that farmers encounter and of their assessment of the type of intervention they are willing to adopt and level of risk they are prepared to take is essential to ensure that any innovations are properly targeted to generate effective uptake. Because a sense of ownership is created through the active involvement of the intended users, the outputs of participatory research and development are more likely to be adopted by the target beneficiaries. Information, technical advice, and market price data can be effectively disseminated using popular information technology tools such as mobile phones and the internet. Videos posted on the internet can potentially reach thousands of growers and are cheap to make. Agricultural extension services also play an important role in technology dissemination. NGOs, when provided with appropriate technologies and information, can also deliver important support to smallholder farmers.

Case Studies

Controlling the eggplant fruit and shoot borer in South Asia

This case study is based on Alam et al. (2006).

Eggplant is very common in the South Asian diet. It is an economically important vegetable, and one of the very few that are available throughout the year at prices generally affordable to everyone. Its intensive cultivation provides a valuable source of income for farmers with small land holdings. Nutritionally, eggplant is a rich source of vitamins B6, C, and K. It also contains dietary minerals such as magnesium, phosphorus, potassium, manganese, and copper, as well as dietary fiber and folic acid. The eggplant fruit and shoot borer (*Leucinodes orbonalis*) causes damage to the plant by boring into and feeding on both the plant shoots and fruits. It can substantially reduce yields and marketable eggplant fruit harvest and can decrease farmer income significantly. Yield losses of up to 75% are reported in India.

Eggplant farmers in Gujarat state, India, have attempted to control the borer by relying exclusively on pesticide sprays. As the borer gradually developed resistance to the commonly applied pesticides, farmers were forced to spray more and more frequently. They started spraying pesticides one month after transplanting and sprayed more than 40 times over the 5- to 6-month growing season. A study in Bangladesh has suggested that farmers may have sprayed up to 90 times during the winter cropping season and 110 times during the summer cropping season. This increased the cost of production significantly, reducing farmer net income.

Most farmers adopted some personal protective measures while spraying, thus demonstrating their awareness that pesticides can be harmful to human health. Protective measures ranged from covering their faces with cloth to wearing full protective clothing and washing their hands with soap after spraying. The majority stated that they harvested their eggplants within 2 days of spraying, thus considerably increasing the exposure of both the farmer and the consumer to hazardous pesticide residues both by contact and in the diet. At these spray application intensity levels, pesticide residue can potentially contaminate local drinking water through runoff and seepage.

Based on knowledge of the eggplant fruit and shoot borer's biological characteristics, the type of damage to the plants, the agronomy and production requirements of the eggplant, and the local environment; research trials were conducted to develop an intervention strategy to control the borer. This resulted in a simple and affordable IPM strategy that consisted of four parts:

1. Sanitation of the planting area by judiciously disposing of eggplant crop residue from the previous season.
2. Prompt cutting and disposal of all damaged shoots and fruits throughout the growing season.

3. Installation of traps baited with the borer sex pheromone at the first flush of flowering.
4. Withholding use of pesticides for as long as possible to allow survival and proliferation of native predators and parasitoids attacking the borer.

This approach was simple to apply and very affordable since it withholds use of pesticides for as long as possible and only one component (the borer pheromone) needs to be purchased by the farmers.

This IPM intervention technology was first disseminated in Jessore district of Bangladesh, in Gujarat and Uttar Pradesh states of India, and in the Central Province of Sri Lanka. After the pilot project demonstrated the success of the intervention in reducing pest damage to an economically tolerable level, the technology was widely implemented in other intensive eggplant cultivation areas in South Asia. Distribution of extension brochures in local languages, publicity through print and electronic media coverage, local documentary screenings, and dramas encouraged widespread uptake and adoption by farmers.

Subsequent yield losses caused by the eggplant fruit and shoot borer were reduced to 10–15% from an average 34–40%. A preliminary impact study conducted in Bangladesh at the end of the fourth year of the dissemination effort showed a drastic reduction of pesticide use—down from 90 applications to only 21 pesticide applications in the winter season and from 110 applications to 33 applications during the summer season. In India, interviews indicated that 146 farmers sprayed their eggplant crop more than 50 times in the growing season prior to the project. After the project had been implemented, only 27 farmers still continued this intensive spraying regime. The increased yield and decreased expenditure on pesticides resulted in a substantial increase in the farmer incomes. Farmers who adopted the technology achieved a mean net rate of return for eggplant cultivation estimated at 150–240% greater than that of those who continued with their old pesticide application regime.

Another significant benefit from this intervention was the growth of small- and medium-sized enterprises selling the sex pheromone lure. At the beginning of the project, the sex pheromone was not commercially available. Within 3 years, three entrepreneurs had started selling the product, and at the end of the project there were nine such businesses in India alone. The combined sales of the two pioneering companies had tripled in two years. In turn, this also benefited the farmers as it further reduced the cost of eggplant production using the IPM technology. Other benefits from the success of the intervention, which were inferred rather than measured, were less pesticide residue on eggplants in the market, reduced health hazards faced by farmers as a result of spraying pesticides less frequently, and better environmental quality in the eggplant production areas.

Breeding for resistance to tomato yellow leaf curl disease

This case study is based on Muniyappa et al. (2002) and NRI (2008; 2009).

Tomato yellow leaf curl disease (TYLCD) first became a problem on tomato in the eastern Mediterranean region in the mid-1960s. The disease is caused by a begomovirus, Tomato yellow leaf curl virus (TYLCV), transmitted by the whitefly (*Bemisia tabaci*). The disease can cause total crop loss and is a serious constraint to tomato production globally. Because few varieties can withstand the disease, tomato farmers had no other choice than to control the whitefly with intensive pesticide use, thus encouraging pesticide misuse. The farmers' overreliance on pesticides has spurred the emergence of new, aggressive biotypes of whitefly that are highly mobile and resistant to pesticides. The spread of these more efficient whitefly biotypes with a wide host range has resulted in TYLCD gradually becoming a worldwide problem.

Host plant resistance is the ideal cornerstone of control against TYLCD in tomato. It is cost effective and very simple to use as it is incorporated in the seeds that the farmer plants. Thus, research was conducted to develop tomato varieties resistant to the disease. The first resistance gene, *Ty*-1, conferred resistance to the then prevalent species of the virus and was identified in the wild tomato species, *S. chilense*. This was bred into commercial varieties, but it soon became apparent that this resistance was ineffective against some emerging species or variants of the virus in some regions. The search then began for other resistance genes. The *Ty*-2 resistance gene was identified in another wild tomato species, *S. habrochaites*, and since then a further three resistance genes (*Ty*-3, *Ty*-4, and *Ty*-5) have been identified in other wild species and used in various areas of the world. A 10-year breeding program involving international and advanced agricultural research institutions, the University of Agricultural Sciences, Bangalore, India, and national agricultural research and development systems incorporated these resistance genes into domesticated lines. Three tomato varieties resistant to TYLCV were released in Karnataka state, India: 'Sankranthi', 'Nandhi', and 'Vybhav'. These varieties are high yielding, tolerate high ambient temperatures, and are also resistant to bacterial wilt caused by *R. solanacearum*.

Farmers who grew the resistant varieties were able to harvest a much higher yield of tomatoes than non-adopters, even during the peak seasons of disease incidence. Their income levels were seven times as much as those of farmers who grew susceptible varieties; the extra income was used by the households to improve their diet, education, and health care.

The resistant germplasm has now been distributed to more than 26 public and private institutions in 13 countries. Private seed companies have started to utilize the germplasm in their breeding programs to produce hybrids, encouraging the scaling out of the benefits of using TYLCV-resistance genes.

In addition to planting resistant varieties, farmers were also trained in IPM and encouraged to use it in their production systems to protect the tomato crop from whitefly infestation without overuse of pesticides. Nets were erected over the tomato seedlings to protect them from the disease vectors. The reduced use of pesticides has enabled the development of value-added products such as tomato juice and sauces that are almost free of pesticide residues.

Grafted naranjilla benefits smallholders in Ecuador

This case study is based on CIAT (2010).

Naranjilla (*S. quitoense*) is found in several countries in Latin America, but is economically important mainly in Colombia and Ecuador where more than 30,000 rural families rely on it for their income. It is grown between 700 and 2200 masl on small hillside plots. Naranjilla produces marketable fruits after just 8 months, and continues to produce fruits for 2 to 3 years depending on the health of the plants. The market price of fruits remains fairly stable throughout the year as there is little seasonality of production. Local and international demand is growing, but the crop can be difficult to grow without the use of pesticides, which can result in fruits contaminated with pesticide residues.

Naranjilla is highly susceptible to fungal diseases and to pests, including nematodes and fruit borers. Farmers have managed the nematode problem by planting the crop in new plots cut from primary forest to provide land that is free of nematodes and soil-borne diseases that could infect the crop. The alternative is to apply large amounts of chemicals. Both Colombia and Ecuador have developed hybrid varieties of naranjilla with pest and disease resistance. In Ecuador, the interspecific hybrids 'INIAP Puyo' and 'INIAP Palora', developed by the country's National Autonomous Institute for Agricultural Research (INIAP), have been widely grown by smallholder farmers. However, their fruit quality, with respect to fruit size and aroma, is inferior to the almost-extinct local varieties.

To address this problem, INIAP scientists searched for and identified disease resistance in closely related species and selected some resistant populations for use as rootstocks. Between 2006 and 2009, field experiments were used to test the performance of the preferred naranjilla variety grafted onto two related, highly compatible species. The resulting cultivar/ rootstock combination was named 'INIAP Quitoense 2009', and was distributed to farmers under an agreement with a commercial nursery. The field data showed a large significant increase in productivity when compared with the interspecific hybrids. In addition, the grafted plants require less chemical input because of their resistance to nematodes and diseases. More than 115 ha were planted with the grafted plants within a year, and farmers are receiving a greater economic return (290%) as a result of the greater consumer appeal of better flavor. As the fruits are less likely to be contaminated with toxic pesticides, there are also now possibilities to address potential export markets.

Tackling passion fruit pest problems in Colombia

This case study is based on Wyckhuys et al. (2010) and Rengifo et al. (2011).

Throughout the developing world, minor tropical fruits generate income and employment opportunities, sustain local livelihoods, and constitute the basis for an emerging agro-industry. In stark contrast with major crops such as mango, pineapple, papaya (*Carica papaya*), avocado, banana, and citrus, minor fruits still receive comparatively little research attention. However, they are being consumed and traded to an increasing extent. In Colombia, 95% of minor fruit production is in the hands of smallholder farmers, who have few financial resources and are commonly bypassed by government extension programs where they exist. Despite bright market prospects for these fruit crops, stagnant yields, poor management systems, and phytosanitary impediments prevent smallholder producers from fully benefiting from current market opportunities. Phytosanitary issues affect minor fruit production in several ways: directly impacting yield, triggering costly pesticide applications, or subjecting the crops to strict quarantine restrictions on foreign markets.

In Colombia, several passion fruit species (*Passiflora* spp.) are commercially exploited. Most are grown by small-scale, resource poor farmers in some of the country's most deprived and socially volatile rural areas. Lance flies (Diptera: Lonchaeidae) are key pests of these crops, but little information exists regarding their biology, ecology, and management. Incomplete information on the crop's susceptibility to Tephritid fruit flies has resulted in restrictions on exports of fresh fruits to the lucrative US market. Local farmers experience considerable yield losses due to pest attack. They lack the necessary knowledge to properly manage pests and suffer financial losses as a result of pest damage and infestation.

A research consortium involving international organizations, local universities, and farmers' associations was formed to devise cost-effective, sustainable, and environmentally sound pest management options for local passion fruit producers. Field surveys from 2008 to 2010 in the major passion fruit production regions shed light on the pest complex, its population dynamics, and geographical infestation patterns. A broad complex of lance fly species was associated with the passion fruit crop, affecting flower buds, flowers, or fruits, and attaining regional infestation levels up to 40%. Repeated field surveys involving more than 200 farmers were unable to find evidence of attack by quarantinable pests such as Tephritid fruit flies. Field studies complemented with laboratory assays were used to investigate the host status of passion fruit crops with respect to one of the most notorious quarantine pests, the Mediterranean fruit fly (*Ceratitis capitata*). Until now, there is no evidence that purple passion fruit is a host for *C. capitata* and thus quarantine restrictions for this pest–fruit complex for the US market may have to be revised.

Next, a national farmer survey was conducted to gain insights into the agroecological knowledge and pest management behavior of local farmers. Aside from the almost universal use of calendar-based insecticide sprays, farmers experimented to a considerable extent with bait traps and low-cost bait types. A few farmers also invented toxic bait sprays and sanitary practices. Using participatory research approaches in five farming communities, some of these local innovations were compared with scientifically defined management tools. Through this approach, farmers discovered for themselves that some of their management tactics were futile while others were much more effective and less costly than their current pesticide use patterns. Farmer experiences were documented using film, and these are currently being shown in multiple communities. Farmers are often eager to try out the practices that are promoted by their peers.

Given continuing incidences of injudicious use of insecticides by farmers to manage pests in their crops and the unrelenting importance of pest problems to farm enterprises, research was conducted in collaboration with the National University of Colombia to quantify the susceptibility of passion fruit to attack by lance flies. Lance fly attack was mimicked by removing a different number of flower buds per plant, and the resultant crop yield was recorded. Results showed that passion fruit plants effectively compensated for flower bud loss and only showed sharp drops in yield at relatively high injury levels (K. Wyckhuys 2011, pers. comm.). These findings are currently being used to formulate threshold levels at which insecticide use is justified. This may help farmers move away from current pest management schemes that are costly and harmful to the environment and to the health of farmers and consumers alike.

Through this research project, the partnering institutions elucidated the key pest complexes associated with passion fruit, clarified the crop's susceptibility to quarantinable pests, and laid the basis for IPM in the crop. The joint social and ecological project focus proved highly effective in identifying pest management alternatives and further promoting those with local smallholder farmers. In the meantime, the absence of Tephritid fruit flies in these crops could generate tangible market opportunities for smallholder passion fruit producers in Colombia and beyond.

Case studies: Conclusions

In summary, it appears that the examples of eco-efficient management interventions for poor farmers given in this paper can be profitable and sustainable. Nevertheless, such systems tend to be quite knowledge intensive and need to be well understood by farmers if their rate of adoption is to be sufficient to create wide-spread impact. Failure to address such knowledge needs may result in a second generation of problems; it is thus necessary to be sensitive to the additional risks that may be caused by such changes in management systems.

Risks Associated with Eco-Efficient Interventions

One major challenge when using resistance traits to manage pests and diseases is how to ensure the durability of the resistance. The composition and structure of pest and disease populations can evolve rapidly. For example, viruses are notorious for having the ability to recombine and mutate into a wide range of highly diverse variants, which can overcome plant resistance genes and defense mechanisms. In many cases, the change is spurred by selection pressures created by the resistant germplasm. In the case of TYLCV, for example, it is becoming apparent that if only one or two *Ty* resistance genes are present in a tomato variety, there is a strong selection pressure for the virus to overcome the resistance. Thus the challenge to the breeders is to incorporate several disease-resistance genes in one variety to provide higher levels of resistance to a broad range of variants of the pathogen. Stacking or pyramiding resistance genes in various combinations reduces the possibility of encountering a pathogen species or strain that can overcome the combined resistances, thus improving the chances of durable resistance. The performance of resistant lines in different geographical locations demonstrates that different combinations of resistance genes need to be evaluated locally for durable resistance.

An integrated approach, combining various methods to overcome constraints to fruit and vegetable production systems, can raise the resilience of eco-efficient interventions. The sustainability of TYLCD management could, for example, be enhanced by combining host plant resistance to begomoviruses with resistance to the virus vector and IPM practices to control the whitefly vector. Research is underway to attempt to pyramid genes for whitefly resistance into existing tomato lines with multiple *Begomovirus*-resistance genes. Combinations of host plant resistance against these viruses and IPM against the whitefly vectors have been implemented successfully in various cropping systems and regions of the world: on tomato-based mixed cropping in Southeast Asia, on common bean (*Phaseolus vulgaris*) production in Central America and the Caribbean, and on cassava (*Manihot esculenta*) and sweet potato (*Ipomoea batatas*) production in sub-Saharan Africa (CIAT, 2008; Nweke, 2009).

The IPM intervention to control eggplant fruit and shoot borer is relatively resilient because several methods are being used to disrupt the insect's lifecycle at various points. A potential risk to the impact of the intervention arises if the pests move from field to field or encroach from surrounding areas. An active network of community-based organizations and policy makers can provide substantial support by encouraging farmers across wider areas to implement agreed intervention practices. Pest and disease management over wide areas is important to ensure impact, as it has been demonstrated by using male sterility to control fruit flies in several countries.

Although plant breeding can be used to confer pest and disease resistance in many species, efforts to breed for disease resistance in underutilized vegetables and tropical fruits are almost nonexistent. The focus on tropical fruit production and export in developing countries is relatively new (except in a few specific cases, such as banana and pineapple), and the appearance of these crops in international markets dates back only perhaps a generation or so. The visibility of these crops was based on the selection of particular germplasm that suddenly becomes the prevalent variety in a given region, as was the case for the Gros Michel banana. Multiple examples in avocado, mango, and citrus also exist. Development of pest and disease resistance by breeding programs is likely to have more immediate impact in species with short production cycles than in perennial tropical fruit species. Fruit consumers prefer particular varieties that combine particular color, shape, aroma, and flavor, combinations that are not easy to achieve quickly through breeding. Given the low current investment and research efforts in tropical fruits, it is wise to consider the expertise and knowledge of fruit growers as experimenters, rather than necessarily applying formulaic research-station-based technologies.

Opportunities to Enhance Impact

Participatory research should be promoted and supported to ensure that the science-based technologies are combined with farmers' and fruit growers' experiences and needs and hence deliver technologies that are adapted and adopted. It is also critical to stakeholders along the value chain, from seed or seedling production through to consumption and the health sector, as well as policy makers, national agricultural research and extension services, the private sector, NGOs, and community-based organizations, all of which influence the eventual uptake and potential success of new technologies.

One of the key drivers of success of the TYLCV project in India was the active participation of the target beneficiaries from the start of the project (NRI, 2009). The disease had already been documented as a severe constraint to growers through the national media and farmers' fora. Farmers were consulted to identify their perceived constraints and their target markets and to describe the production and value chains in which they were involved. Farmers and other project participants developed a sense of ownership and pride in the new technology, resulting in increased levels of adoption and multiplying the positive impacts of the intervention. The private sector often has an extended sales and farmer network, and thereby has an advantage in the efficient dissemination of information and improved agricultural technologies. Private seed companies, for example, are important partners in increasing the availability and rate of dissemination of improved, high-quality vegetable seeds. Local communication networks and traditional methods of mass communication (especially rural radio) can also be utilized to promote dissemination of information about new technologies. Film and drama performances, mobile telephones, and other social communication media need to be harnessed to enhance the spread, uptake, and impact of eco-efficient technologies.

A further major issue for fruit and vegetable products is that generally they are highly perishable. A recent study in Africa, India, and other developing countries indicated that postharvest losses in fruits and vegetables are probably in the range of 30–40%. The persistently high postharvest losses in the tropics are due to incorrect harvesting times, mishandling, poor packaging, lack of temperature management, difficulties in transportation to markets, and the tendency for horticultural crops to have a definite peak period of production. This production peak, which can saturate markets and decrease the market value of the crop, may force growers to abandon their produce before sale (Kitinoja, 2010). If postharvest losses are not reduced, they may wipe out the gains from eco-efficient production systems. Postharvest management and processing of fruits and vegetables are opportunities to reduce losses, add value, and thus increase net returns. Simple technologies, such as using ice to cool harvested leafy greens prior to transportation to the market and better packaging to reduce losses (e.g., modified-atmosphere packaging), can add value and reduce risk along value chains. Careful targeting of products (e.g., juice, dried fruit, pickled products) helps ensure a consistent market for produce.

Key Lessons for Research, Development, and Policy

There are numerous opportunities to enhance the productivity of fruits and vegetables using eco-efficient methods that will promote consumer safety, reduce risks to farmers, and ensure sustainable and profitable production systems. Building farmers' ability to navigate the future uncertainty of climate change is one of the main strategies in the development of climate-smart production systems. It is therefore imperative to actively involve the farmers themselves in the process. Farmers have a wealth of knowledge and many coping strategies. Their assessment of interventions needed, opportunities, and the level of risk they are willing to bear must be taken seriously in any research and development activity intended to benefit those farmers and their communities. Strong collaboration between the stakeholders along the whole value chain is essential to ensure the development of production systems that are competitive, resilient, and sustainable in the face of future uncertain conditions, be they environmental or economic.

Engaging the private sector and development agencies effectively can have benefits for development-oriented research. Although many small- and medium-sized enterprises do not have the capacity to conduct their own research and development activities, they may be willing to provide some financial resources for research that will benefit themselves as well as the public domain. Likewise commercial seed companies can multiply and market fruit and vegetable varieties bred by the public sector, helping ensure that they reach as many farmers as possible. Large NGOs that seek adapted and effective technologies to accomplish their goals also can provide substantial funding for research and development activities on issues identified by themselves and their target communities. Such research and development activities are likely to address neglected and underutilized species that receive little research attention through more formal channels.

Development of eco-efficient interventions in fruit and vegetable production will only be possible if dependable, long-term funding is available. Currently, however, research on vegetables and fruits is severely underfunded. Fruits and vegetables have a vital role in ensuring human health; policy makers worldwide should recognize this and provide resources for research and development efforts on behalf of poor farmers. They should be made aware of other benefits likely to be associated with a greater consumption of fruits and vegetables, such as reduced medical expenditures and improved environmental health. Climate-smart and ecologically sound fruit and vegetable production systems will be a key tool in helping smallholder, poor farmers to grow themselves permanently out of poverty, allowing them not only to feed themselves and their communities but also to better nourish the world. If the Millennium Development Goals are to be achieved, such products will need to be available and affordable worldwide. Much good knowledge is already available as a foundation on which to build but political commitment is essential if the world is to benefit from more eco-efficient fruit and vegetable production technologies and systems.

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CHAPTER 13

A Policy Framework to Promote Eco-Efficient Agriculture

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Contents

Abstract

Agricultural production systems have to meet the food needs of a growing world population without reducing the environmental carrying capacity of the planet. As standards of living improve in developing countries, people demand more and better food, often increasing consumption of foods of animal origin. Aging populations, especially in developed countries, will create new, specialized food demands. Meeting these growing and changing demands will require changes in the way we produce food if we are to support socio-economic growth for present generations without compromising the welfare of future generations. This is the essence of sustainability. These changes require shifts in the agricultural policy framework and institutional arrangements to focus on long-term food security and eco-efficiency. Life-cycle analysis, development of eco-efficient technologies and green production chains, measurement of water use and carbon footprints, and plans to adapt to and mitigate climate change must take precedence in the setting of future strategies. This chapter summarizes examples of good eco-efficiency practices and identifies policy and institutional frameworks needed to move agriculture towards global eco-efficiency.

Sustainability and Eco-efficiency on the International Political Agenda

After the Great Depression of the 1930s and the Second World War, there was a general shift in developed countries towards state intervention in the economy, including the agricultural sector. Common instruments included government-financed programs in research, extension, and irrigation; subsidized loans to farmers; and government-managed price stabilization schemes. For example, the USA encouraged land reforms in countries under its influence, while agriculture was collectivized in many socialist countries. Newly independent countries in Latin America, Asia, and Africa also adopted state-led agricultural development processes. Thus, from the 1930s through the early 1970s there was a common belief that state intervention was necessary to ensure equitable agricultural and rural development. Necessary elements for agriculture

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(such as land, water, transport, seeds, fertilizers, pesticides, and animal feeds, among others), as well as financial instruments (such as affordable credit, crop insurance, stability of prices), could only be provided by the state. Also, the state should provide or subsidize services like buffer stocks, trade protection, insurance, and support for processing and marketing (Chang, 2009).

However, this model led to many examples of waste, inefficiencies, and corruption, and by the 1970s there was a growing movement that promoted market-based economic development. This culminated in the implementation of structural adjustment programs by the International Monetary Fund (IMF) and the World Bank (Kay, 2006). This new approach later became known as the "Washington Consensus," a phrase coined in 1989 by economist John Williamson, then of the Institute for International Economics.

The 1960s and 1970s also saw the emergence of environmental issues in public arenas, culminating in the United Nations Educational, Scientific and Cultural Organization (UNESCO) conference on "Man and his Environment: A View towards Survival" in 1969 and the first United Nations Conference on the Human Environment in Stockholm, Sweden, in 1972 (Dunlap, 1991; Jones and Dunlap, 1992; Kraft and Vig, 2006).

Early environmental policy frameworks focused on the conservation and rational use of natural resources. This approach aimed to rationally exploit resources as a means to ensure continuous production in an optimal way. Renewable natural resources were considered as unconnected fragments: forests as a source of wood; soil as a support to monoculture production or a deposit for wastes; and freshwater resources as input for various human, industrial, and agricultural uses, or as a place to dispose of contaminated water (Rodríguez and Martínez, 2009).

By the mid-1970s, there was a growing recognition of the complex interrelations among organisms, and between organisms and non-living components in their environment. The right to a healthy environment for current and future generations (sustainable development), and the concept of environmental sustainability of productive activities and balance, including agriculture, gained more attention (Miller and Rothman, 1997). As Daly (1974) said, "It is simply a strategy for good stewardship, for maintaining our spaceship and permitting it to die of old age rather than from the cancer of growthmania."

The report of the World Commission on Environment and Development (commonly known as the "Bruntland Commission") *Our Common Future* (WCED, 1987) was a major milestone in promoting the broader concept of sustainable development at the global level, defining sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." The Commission laid the groundwork for the United Nations Conference on Environment and Development (UNCED), held in Rio de Janeiro, Brazil, in June 1992; the Rio Declaration on Environment and Development; and Agenda 21, a comprehensive action plan for the UN system, governments, and others in every area in which human activities impact on the environment (www.un.org/esa/dsd/agenda21/). UNCED not only exposed 110 heads of state to the vision of sustainability, but an influential group of actors in the private sector also began to appreciate that sustainability issues extended beyond the obligation of public policy to become a fundamental part of business strategy.

After UNCED, several countries revised their institutional arrangements and policies to promote sustainability. In the agricultural sector, the emphasis has been mainly on increasing production of food while assuring the capacity of the environment to recover and provide ecosystem services. Biodiversity loss, water supply deterioration, and soil and water pollution have been increasingly recognized as severe symptoms of a crisis represented by the loss of the capacity of natural resources to sustain agricultural systems.

Eco-efficiency: A concept that arises from the private sector

For many sectors, especially private entrepreneurs, the necessary symbiosis between economic, social, and environmental sustainability meant approaching the issue from a more positive perspective. Thus, in the 1990s, new concepts such as cleaner production and eco-efficiency were introduced with a focus on combining both economic and environmental efficiency.

In 1992, a group of businessmen led by Stephan Schmidheiny created the World Business Council for Sustainable Development (WBCSD) and promoted the concept of eco-efficiency in a book entitled *Changing Course* (Schmidheiny, 1992). According to the WBCSD, eco-efficiency is achieved through the delivery of "competitively priced goods and services that satisfy human needs and bring quality of life while progressively reducing environmental impacts of goods and resource intensity throughout the entire life cycle to a level at least in line with the Earth's estimated carrying capacity" (WBCSD, 2000). In the agricultural sector, eco-efficiency was promoted as the aspiration to maintain or improve the economic sustainability of crops (yields), while contributing to the environmental sustainability (less use of natural resources). Chapters 1 and 2 of this volume devote considerable space to the history and definitions of the eco-efficiency concept in agriculture.

Eco-efficiency: A paradigm shift

The ability to increase agricultural productivity will be facilitated by advances in life sciences, including a better understanding of the dynamics of ecosystems and their environmental services. One of the conclusions of the special rapporteur of the United Nations (UN) (De Schutter, 2010) is that it is not enough to designate large amounts of money for agriculture. There need to be measures that facilitate the transition to a type of agriculture that is low in carbon emissions and that conserves natural resources in a way that benefits the poor.

According to De Schutter (2010), agricultural production will have to increase by 70% by 2050 to meet anticipated demand. Achieving this will require technologies that are both more efficient and environmentally friendly, reducing the negative impacts of agriculture on the environment and society. Such production technologies will offset the harmful effects of economic development on environmental quality.

Institutions and Policies for an Eco-efficient Future

Agricultural institutions in developing countries have immense food security and eco-efficiency challenges. While most agriculture ministries tend to be based on centralized governmental models, reforms in many countries have moved toward privatization of state-owned enterprises and elimination of marketing boards and other regulatory agencies. However, the historical value of such institutions and the public goods they provided has not always been fully appreciated. Public sector investments in the development of input and output markets, in agricultural extension, and in applied agricultural research have been vital to agricultural development in every economy in the world. Institutional reform without investment in these public goods does not produce economic growth in the agricultural sector. Conducive institutional and policy environments remain cornerstones of agricultural development (Koroma, 2007).

The changing relationship between the public sector, civil society, and the private sector will require a unified, comprehensive, and adaptive vision toward the increasing scarcity of natural resources and external factors such as climate change to achieve greater environmental and economic efficiency in the medium and long term in developing countries. There is no unique policy prescription that fits the diversity of the agricultural sector in the developing countries. While enhancing productivity is a common essential requirement, the nature of the increase in productivity envisaged, including eco-efficiency parameters, will determine the appropriate policy mix.

Change is not easy; encouraging new, sustainable, and eco-efficient agricultural practices is a slow process. It entails transaction costs: the new practices require that farmers understand and are trained in new techniques, development of innovative financial alternatives, creation of market value and markets for new products that help alleviate poverty, and development of policies that promote long-term food security.

There are several policy dimensions that governments should address to push forward the eco-efficiency agenda into modern laws, policies, and renewed agricultural institutions. The following sections explore how states can reorient their agricultural systems towards modes that are more productive and efficient and that assure long-term sustainability and equity for present and future generations.

Investing in eco-efficiency practices

Strengthening eco-efficiency in agriculture requires changes to approaches for maintaining soil fertility and improving yields, and increasing the efficiency of use of external inputs by farmers. Common practices such as subsidies on fertilizer and pesticides, for example, while conducive to short-term increases in production, are likely to result in farmers adopting practices that are neither eco-efficient nor sustainable. A case in point is Malawi (see box). Policies that encouraged use of hybrid seed and fertilizer resulted in record maize harvests in 2005/06 and 2006/07 (although this was in part due to favorable rainfall patterns in those years) (Dorward et al., 2008). However, they also encouraged reliance on purchased inputs rather than more-sustainable production practices such as crop rotations. To address this, the government has subsequently implemented programs to encourage farmers to adopt sustainable land management practices and build soil fertility, prevent soil erosion, and conserve rain water through practices such as manuring, composting, contour ridging, minimum tillage, and agroforestry, as well as diversifying production of food crops (Daudi, n.d.).

Rather than relying completely on chemical fertilizers, farmers can sometimes increase soil fertility by using improved agronomic practices, such as planting trees, legumes, and forages that fix atmospheric nitrogen. Agroforestry is widely practiced in Asia, Africa, and Latin America. In Tanzania, for example, more than 350,000 ha have been rehabilitated with agroforestry practices. Diversification of agricultural systems is also an important element of eco-efficiency, contributing to maintenance of soil fertility, prevention of soil erosion, enhancing overall system productivity and provision of ecosystem services, and increasing resilience to shocks such as climate change or sudden changes in markets. It also contributes to providing a more balanced diet and creates employment opportunities.

Governments should also promote local seed systems that are able to provide farmers with high-quality seed of appropriate crops and varieties, rather than relying on imported seed. Selection of varieties for local adaptation and consumer needs can typically bring productivity and sustainability advantages over those selected in non-targeted environments. Unless modern varieties are selected for local needs, local landraces may perform just as well, and be preferred by farmers (Van Mele et al., 2011). Strengthening local capacity for seed production will help farmers cope with changing or harsh conditions. Support might include financial instruments for seed production, empowerment of seed producers, and provision of appropriate irrigation infrastructure (Dalohoun et al., 2011).

Investment in human capital, research, and training

According to IFPRI's Agricultural Science and Technology Indicators (ASTI), average age of agricultural researchers, teachers, and technicians in developing countries is quite high. In some cases, this problem is a threat to the continuity of agricultural research and development (R&D) and training in developing countries. Country reports can be downloaded from ASTI's web page at www.asti.cgiar.org/publications, and examples are noted in Figure 13-1.

Investment in agricultural R&D and extension has stagnated in recent years except in a few countries such as Brazil, China, and India (Beintema and Stads, 2010; Stads and Beintema, 2012), despite evidence that such investment

Malawi: Policy reforms for enhancing agricultural productivity

Agriculture is a key sector of the Malawian economy. It employs over 80% of the workforce, provides an estimated 64% of total income of the rural people, contributes over 80% of foreign exchange, earnings, and accounts for 39% of GDP.

In early post-independence days, the government was heavily involved in the smallholder agricultural sector in areas of production, extension, technology development, and marketing of agricultural commodities. However, despite these efforts, poverty remained widespread and severe. In 1979, the government oriented its policies towards poverty reduction and introduced a structural adjustment program with support of the World Bank and the International Monetary Fund. There was a price decontrol to allow market forces and competition. Other reforms included the Special Crops Act, the Seed Act, and the Chemical and Pesticide Act. However, lack of concerted efforts by actors in the sector compromised the success of the policy reforms.

Since the beginning of the new millennium, policies have changed to address increased productivity. Free-input programs and input subsidy programs were developed to provide farmers with coupons to buy hybrid seeds and fertilizers at subsidized prices. At the same time, the Government developed a minimum floor price for the purchase of several crops such as maize, cotton, and tobacco.

The country realized maize surplus production since the start of the program. Malawi was able to attain food security and produce sufficient surplus maize to export to other countries.

Attaining food security implied having the resources to address sustainability and eco-efficiency issues. Several programs are currently in place to sustain land and water management in view of weather variability and climate change. There are programs to encourage farmers to adopt sustainable land management practices and build soil fertility, prevent soil erosion, and conserve rain water. Current practices include manuring, composting, contour ridging, minimum tillage, and agroforestry.

Ongoing efforts to strengthen research in agricultural production and utilization of available technologies in collaboration with farmer-led extension services are being introduced with an emphasis on market- and industry-oriented research.

The experience of Malawi shows that agricultural productivity in developing countries needs concerted government efforts to raise productivity, consolidate markets, promote technologies that match the farmer resources base and have the capacity then to ensure eco-efficiency practices to sustain natural resources.

But, while the Malawi experience of concerted policy action by a national government is an encouraging sign of policy leadership, important questions remain around the sustainability of the higher-input production practices, the eco-efficiency of inputs used, and the efficiency of the whole value chain for the Malawian food systems.

SOURCE: www.un.org/esa/dsd/dsd_aofw_wat/wat_pdfs/meetings/ws0109/1_Malawi_Daudi.pdf

reduces rural poverty as well as increases agricultural productivity (Fan, 2010).

Developing and promulgating eco-efficient agricultural systems will require increased investment in training scientists and educators who can deliver new practices through renewed agricultural extension services. These services require training at all levels. Agro-ecology will need to be incorporated in high-school curricula. Agricultural technicians also should receive a strong grounding in agro-ecology. University agriculture curricula should encompass innovative research, science, and technology. Integrating traditional production systems with more modern and scientific methods will promote adaptation of technologies and knowledge assimilation and application at the local level. This will require new information platforms and technology transfer.

For agricultural R&D to accomplish their objectives, it is imperative that the target beneficiaries understand and adopt the approaches

Figure 13-1. Age profiles of agricultural researchers, teachers, and technicians in selected countries of Africa, 2007. SOURCE: www.asti.cgiar.org/publications

developed. Most research projects that have delivered impact have included the active participation of the target beneficiaries from the start of the project. Therefore, governmental policies should encourage extension services to actively involve farmers and other stakeholders along the value chain in developing and testing novel approaches.

Achieving greater agricultural eco-efficiency will require a push by both governments and the private sector. Both will have to seek to combine the best of traditional agricultural practices with modern technologies and inputs to deliver sustainable, eco-efficient agricultural systems (Uphoff, 2001).

Investing in public goods to promote equitable development

More people in developing countries are opting to move to the cities in order to improve their economic and social conditions, and to have better access to basic services, such as health and education, and other public goods provided by the government (Stern, 2007). The rural areas require urgent investments to maintain the rural communities in place. Agricultural growth and poverty reduction depend critically on investments in rural infrastructure (irrigation, roads, transport, power, and telecommunications), markets, rural finance, research, education, and extension. Such investments have rates of return of more than 35% in sub-Saharan Africa and around 50% in Asia (The World Bank, 2008).

The World Bank (2008) concludes that investing in public goods could have a greater impact on per-capita income than investing in private goods such as pesticides or fertilizers, while assuring more-sustainable practices. In Latin America, the share of rural subsidies provided by governments is greater where income inequality is highest. Better policies are needed to ensure that the poorer, especially smallholder producers, have access to basic services and infrastructure. Reassigning spending toward public goods without increasing the overall level of spending on agriculture might be sufficient to transition into eco-efficient agriculture (The World Bank, 2008). According to Allcott et al. (2006), "even without changing overall expenditures, governments can improve the economic performance of their agricultural sectors by devoting a greater share of those expenditures to social services and public goods instead of non-social subsidies."

Political and economic pressures that determine budget allocations must be addressed to ensure transparency, equity, and accountability of resource allocation.

Promoting green supply chains

Major businesses are increasingly aware of the benefits of eco-efficiency – at the producer level – of their production chains. For example, Unilever's target for 2020 is to source 100% of their agricultural raw materials from sustainable production systems. Other businesses are thinking not only about eco-efficiency, but also about the nutritional quality of each product. Some large companies are involving communities and small-scale growers as co-owners and participants in their production chain – sharing benefits.

To generate efficient green supply chains, producers must be linked to modern supply chains that are increasingly dominated by supermarket chains and multinational companies. For example, by the early 2000s, supermarkets accounted for more than half of all retail food sales in many countries in Latin America (Reardon and Berdegué, 2002; The World Bank, 2008). Supermarket buying agents prefer to buy from medium- and large-scale farms, as it is easier for them to deliver standardized product, and dealing with a small number of large suppliers reduces transaction costs for the buyer. However, consumers are increasingly demanding environmentally safe and socially responsible products. Retailers such as Whole Foods in the USA who meet this demand are growing rapidly (Marquis et al., 2009).

In this context, the role of public policies can be to help smallholders expand and upgrade to meet the necessary requirements of modern supply. Such policies should support market-oriented extension services, establish grades and standards, assist farmers in contract design and management (including understanding their rights and obligations), create an enabling environment for insurance and credit markets, and be based on an understanding of social and environmental requirements to be able to provide for green supply chains.

Governments could also create public procurement programs, with incentives for organic food or fair-trade chains. For example, the strategy of the United Kingdom (UK) for sustainable farming and food (DEFRA, 2002) and the country's organic action plan (DEFRA, 2003) both highlight the public sector as a key area in which to market UK-produced organic food (OAPSG, 2008). The message that procuring eco-efficient goods can have a positive impact on the economy is important. There is also a potential to broaden policy goals, e.g., to improve health and education, increase opportunities for small- and medium-sized enterprises working in the food sector, and create jobs, as well as to support environmental objectives and local producers.

Generating and promoting sustainable markets

Urbanization can help reduce poverty in developing countries by increasing proximity between resources and markets and through economies of scale that enable cost-effective, efficient delivery of basic infrastructure and services (Stern, 2006). For example, Mogues (2011) found that public investment in transportation networks gave the highest return-on-investment ratios of any state interventions in Ethiopia, but variability of returns between regions within the country suggested that regional planning was necessary. However, not everyone in urban areas benefits equally, and special attention will need to be paid to the urban poor, who are particularly vulnerable to food insecurity (Mason et al., 2011). In 2002, the urban poor accounted for 59% of the total population in Latin America, 30% in sub-Saharan Africa, and 25% in India (Chen and Ravalliona, 2007).

However, changes in consumer preferences due to increased income or access to more-sophisticated markets boost demand for food that requires more resources to produce, e.g., meat and animal products. Consequently, livestock numbers are expected to double by 2020 (IPCC, 2001), increasing significantly the amount of methane released into the atmosphere and contributing to climate change. Also, intensity of fertilizer use and energy is expected to increase in all developing regions.

Globalization has meant that food supply chains are increasingly long and complex, but there is also a trend toward consolidation of these chains in the hands of large, multinational companies. These companies influence what is grown, where, how, and at what price. Increasingly, however, large companies are beginning to understand that their long-term competitiveness depends on protecting the environment and the services it provides (Bishop et al., 2010). New environmental and social concerns are influencing the way food is produced and the rules under which it is traded. Consumers are beginning to demand that producers engage in fair trade, management of the ecosystem and environmental services, minimization of climate impacts, food safety measures, and improving working conditions. This calls for transparency of production standards and traceability, which can be promoted through green certification schemes and eco-labeling. While many certification and labeling schemes have rigorous standards and third-party auditing, many more do not. Making these schemes effective will require government support for certification and verification.

In addition, elements of eco-efficiency are beginning to play a prominent role. Sustainability standards are becoming more important every day. Prices of the food products we consume must now cover not only the direct cost of production but also the costs of making the production chain sustainable and reducing the environmental and social footprint in the countries of origin.

Ministries of trade, environment, and agriculture, in concert with investment and export agencies, should consider creating efficient platforms to address green production chains and develop specific policies on fair trade and sustainability standards in general.

Organic agriculture in China and India

China and India, the two most populous nations on the planet, have chosen to support organic agriculture, especially for poor farmers, as a means of alleviating poverty in rural areas.

In both countries, organic products take up only a small fraction of the food market. According to the Foundation Ecology and Agriculture (SÖL), there were just over 300,000 ha of certified organic crops in China (Giovannucci, 2005), out of the 130 million ha of arable land. The domestic market in China was valued at nearly US$250 million. In India, according to SÖL, in 2004 the organic production was done in 76,000 ha out of the 180 million ha of arable land. Even though these values are relatively small, the organic production has been rocketing in recent years and constitutes a good example of effective strategies that promote eco-efficient practices.

In the case of China, officially supported organic farming started in the 1980s, and by the year 1990, the Nanjing Institute of Environmental Sciences (NIES) began implementing protocols of international organic certification. The objective of this strategy in China is to: (1) help decongest the farmland near big cities, which has been intensively cultivated over the centuries, and (2) assist smallholder farmers in remote areas to produce with less reliance on expensive external inputs (Giovannucci, 2005). While organic farms originally belonged to local governments, the central government has adopted a policy of developing market mechanisms. Thus, local governments have been gradually handing over property rights to private companies and individuals, giving financial and technical support for a more efficient resource management and market access of products to farmers.

Given the variety and importance of its agricultural products, India has had a tradition of organic farming that goes back centuries. Organic production has traditionally been practiced by civil society and particularly NGOs and farmer groups. They have also developed various practical schemes in different regions to suit weather conditions and rainfall, as well as existing varieties. Because 60% of all crops in India are rainfed, the government has placed emphasis on organic agriculture as a strategy to ensure food security and poverty reduction. To implement a plan of norms and standards, the Ministry of Agriculture has set up a special Working Committee for organics and the Ministry of Commerce set up a National Steering Committee (Giovannucci, 2005).

Both cases show how government could implement organic policies that could influence productivity chains at the global scale, given the large populations of both countries.

Changing consumption patterns

Every day consumers play a more fundamental role in promoting eco-efficiency options through their selections of food and other products. Food-borne diseases and poor nutrition continue to be widespread, and more consumers are interested in knowing the quality of their food. In this regard, green certification and eco-labeling are tools that play a more critical role so that consumers have references of what they buy. Under these terms, transparency and traceability are two key issues that need attention. Producers must be transparent about the eco-efficiency and sustainability parameters of their production chain. They must try to make their products, origins, and production systems traceable, as well as create a transparent system of social and environmental accountability that can be understood by the consumer and the producers. There are many eco-labels in the market, related to fair-trade schemes, eco-efficient agricultural practices, footprint reduction, tracing sources or ensuring food quality and safety. While many eco-labels have rigorous standards and third-party auditing, the labels themselves are only emblems of the certification scheme, providing consumers little information and requiring that everyone conduct their own research. With so many labels in the marketplace, even the environmentally conscious shopper can become easily confused.

Eco-labels, however, are feasible if governments support the certification and verification schemes to help market dynamics to align with equitable and sustainable development and eco-efficient principles. Governments should facilitate sustainable production systems including incentive schemes to achieve initial momentum. In addition, they should also monitor the results and foster public–private schemes that promote food sustainability.

Public subsidies and incentives

Public procurement systems, tax and credit incentives, and land policies should be designed to facilitate transition toward eco-efficient agriculture. Such policies include, for example, temporary tax exemptions for farms adopting eco-efficient practices and preferential interest rates for investments in eco-efficient systems.

Regularization of land tenure and the creation of a solid property rights framework also encourage farmers and landowners to invest in the long-term fertility of land. These should include forms of land tenure that are more accessible to women and formal recognition of traditional forms of land ownership and tenure (The World Bank, 2008). In addition, cross subsidies and incentive schemes can also promote eco-efficient agriculture. For example, in 2009 the Government of Brazil issued a law requiring at least 30% of school meals to consist of food from local family farms.

At the same time, governments could organize or steward markets to protect smallholder farmers from price volatility, and create or eliminate production subsidies to help small-scale producers, without affecting competitiveness at the regional level. Governments often implement open-trade policies that lead to the import of products that are cheaper than those produced locally. One way of enhancing local competitiveness would be to generate models of association where small-scale producers can join value chains that add value to local activities. Another related strategy would be to discourage the use of imported pesticides and fertilizers, encouraging use of local alternatives and production practices to reduce costs and enhance sustainability.

Governments will have to increase their investment in the agriculture sector to promote eco-efficiency (Horlings and Marsden, 2011). Similarly, the financial sector can contribute with new financial instruments, e.g., equity funds that invest in green production chains. Agricultural banks need to produce collateral-free financial schemes, create consistent lines of credit and guarantees, and facilitate access to credit for small-scale farmers.

There is an ongoing debate about the wisdom of state intervention, which can distort markets and create inefficiencies (Chang, 2009). It is clear, nevertheless, that some interventions are necessary to correct situations that would create larger distortions if not addressed. Such is the case of subsidies and incentives to create or

Change of perspective in Thailand

From the 1960s, Thailand immersed itself in agricultural development based on increased productivity and use of agricultural surplus to boost other sectors, with strong orientation towards exports (Buch-Hansen, 2001). This scheme was successful during the decades of the 1970s and 1980s, making the Southeast Asian "tiger" a world-class agricultural producer. The 1997 Asian economic crisis, with the overheating of the economy and the financial meltdown, led the government to change their perspective about agricultural development in Thailand. The Eighth National Development Plan (1997–2001) and the Ninth (2002–2006) and Tenth (2007–2011) changed the emphasis of development strategy to give greater weight to citizen participation and criteria of self-sufficiency, poverty alleviation, and environmental protection. One of the biggest changes occurred in agricultural policy, which promotes sustainable agriculture, to reverse the damage to the environment (Amekawa, 2010). At present, the Thai government is putting considerable effort on research and technology developments of agricultural production that are friendly to the environment and at the same time increase productivity.

provide public goods, such as agricultural research, that otherwise would not be sustainable. Incentives or subsidies are also welcome when vulnerable groups are losing ground (The World Bank, 2008).

Finally, governmental policies in agriculture, environment, energy, transportation, and other sectors should be more coherent and interlinked. Agricultural governance[3] and resources that regulate, guide, and direct the process of agricultural and rural development must have a renewed vision. This vision is one that recognizes the benefits of eco-efficient farming methods that are more productive, sustainable, and less harmful to the environment.

Community empowerment

The empowerment and mobilization of rural communities is a very powerful tool to ensure sustainable development and eco-efficient practices. Numerous studies have shown that involvement of stakeholders, communities, and other potential beneficiaries in planning and management increases the probability of success of development efforts (Rondinelli, 1982; Uphoff, 1996; Bakker, 2011). Such community-driven development mobilizes community groups and involves them directly in decisions on public spending, harnessing their creativity, capabilities, and social capital (The World Bank, 2008). Community-driven projects have shown the potential to scale up, be more cost effective, make fiscal transfers more efficient, and increase income from agriculture. Achieving this requires a policy environment that supports capacity strengthening in rural communities, learning and adoption of new technologies, participatory research and R&D extension networks, knowledge management, and sharing of best practices (Horlings and Marsden, 2011). Governance has to be reinforced by making all decision processes more transparent and participatory.

Social accountability mechanisms that guarantee transparency on government investments will increase community participation in the new production structure (Reuben, 2005). Information policies and tools will enable rural populations to assimilate and claim ownership of the new eco-efficient concepts (Keating et al., 2010).

Institutional arrangements for eco-efficiency

The structural reforms of the 1980s often dismantled the public agencies that provided services to farmers, such as access to credit, insurance, inputs, and information in the developing world (The World Bank, 2008), with the expectation that the private sector would take over these functions in a more effective way. The private sector, however, has developed only slowly, leaving farmers, especially small-scale farmers, with little or no access to these services in many countries. Restoring these services requires an analysis of what worked and what did not, and clarification of roles between the private and public sectors.

[3] Understood as the sum of organizations, policy instruments, financing mechanisms, rules, procedures, and norms.

Policy makers need to be informed about important concepts such as sustainability, agro-ecological farming, and environmental services, and should understand the implications of sustainable agricultural production, to effectively create the necessary new legislation and supervise its enforcement.

The private sector needs to be more involved in agricultural production, particularly through public–private partnerships (Swanson and Samy, 2002). Engaging the private sector will require the correct incentives, an appropriate business environment, and solid property rights (Fan, 2010).

Poor infrastructure and limited access to markets hinder production and diminish profits for smallholder farmers in remote or poorly serviced regions. Transport and communications infrastructure has to be built or improved to allow products to reach markets as fast and inexpensively as possible. This might entail the construction and improvement of roads, railways, storage and distribution centers, and market places. Improving education and health infrastructure in rural areas will help reduce rural–urban migration and promote economic growth in rural areas.

The challenges facing the agricultural sector are complex, not the least of which are population growth, environmental degradation, and climate change. Efforts to address these challenges will require concerted action of various sectors – environment, education, health, trade, among others – and planning tools that are capable of integrating these areas. Agriculture ministries will need to devise new visions and means of cooperation with the ministries responsible for these other sectors.

International Policies

Policy and climate change

The Commission on Sustainable Agriculture and Climate Change, established by the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), has identified seven key actions to achieve food security in the face of climate change (Beddington et al., 2011). These are:

1. Integrate food security and sustainable agriculture into global and national policies.
2. Significantly raise the level of global investment in sustainable agriculture and food systems in the next decade.
3. Sustainably intensify agricultural production while reducing greenhouse gas (GHG) emissions and other negative environmental impacts of agriculture.
4. Develop specific programs and policies to assist populations and sectors that are most vulnerable to climate changes and food insecurity.
5. Reshape food access and consumption patterns to ensure basic nutritional needs are met and to foster healthy and sustainable eating patterns worldwide.
6. Reduce loss and waste in food systems, targeting infrastructure, farming practices, processing, distribution, and household habits.
7. Create comprehensive, shared, integrated information systems that encompass human and ecological dimensions.

Action on climate-smart agriculture will require large investments. The share of agriculture in official development assistance, which declined from 19% in 1980 to 3% in 2006, is now around 6% (The World Bank, 2008). The World Bank recently estimated the annual adaptation costs in the agriculture sector in developing countries to be US$2.5–2.6 billion per year between 2010 and 2050 (The World Bank, 2010). Mechanisms for increasing investment in climate-smart agriculture include, for example, public–private partnerships, carbon-offset markets, and long-term international official development assistance combined with carbon finance.

In the forest sector, approaches such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation in Developing Countries) are emerging that involve market instruments based on real emission quantification results. Mechanisms to protect forests while increasing agricultural production will require incentives to employ eco-efficient agriculture practices in conjunction with measures to prevent deforestation from agricultural expansion. This will depend on raising awareness of the role of forests in providing ecosystem services and their contribution to livelihoods. Ra et al. (2011), for example, indicate that households living near forests in Cambodia generate 21–34% of their income from the forests.

However, for REDD+ to be effective, new institutions capable of implementing payment mechanisms based on reporting, monitoring, and verification are required (Angelsen et al., 2009). In this context, it will be essential to implement policies that ensure that indigenous communities, peasants, and women are involved in the national-level decision-making processes of REDD+ schemes.

Many governments around the world are now promoting low-carbon economies. Member countries of the Organisation for Economic Co-operation and Development (OECD) have committed themselves to promoting green investments and sustainable management of natural resources, with incentives to build low-carbon infrastructure economies as well as research in science and technology to achieve sustainable societies "low in carbon" (OECD, 2011a). Asian countries signed a unified vision toward green growth in 2005 at the Ministerial Meeting on Environment and Development in Asia and the Pacific. Several countries have

Korea: Policy measures for green growth in the agricultural sector[4]

Korea has seen a continual expansion of environmentally friendly agriculture, with an annual growth of about 70% since 2000 and with a strong government support through a five-year plan. In April 2010, the president enacted the Framework Act on Low-Carbon, Green Growth.

Strategies for green growth in agriculture, forestry, fisheries, and food sectors included six implementation projects:

- Green life: comprehensive plan for fostering urban agriculture
- Green energy: activating energy of livestock manure and expanding use of biomass to generate renewable energy. Innovations in energy efficiency for agriculture include geothermal heat pumps, light, bio-energy, and plant factories
- Low-carbon policy: carbon labeling system; target management of GHGs
- Infrastructure of green industry: green R&D investment, environmentally friendly agriculture infrastructure
- Sustainable resource management: ecosystem conservation
- Strengthening international cooperation: global partnership.

The agro-green strategy required a paradigm shift to low-carbon and resource circulation agriculture with a vision to reduce, recycle, and reuse. It also required a shift from a productivity-oriented quantitative approach to a qualitative approach based on ecological efficiency (maximized production to optimized agricultural production) with green technologies as well as a policy mix through integrating agricultural and environmental policy programs.

The programs implemented the expansion of environmentally friendly farming practices in districts and the establishment of a Regional Circulation Agricultural Support Center. The government promoted environmentally friendly agri-business (biopesticides, organic fertilizers, natural enemies), established a special district of organic agriculture, and promoted the consumption and marketing of organic products.

The development and dissemination of green technologies involves all kinds of innovations – from reduction of methane from irrigated rice fields to the production of bioethanol energy crops as well as plant factories, vertical farms, and biorefineries.

The green agriculture strategy involves financial mechanisms as well as substantial investment and support for education and training programs.

[4] SOURCE: Presentation of Chang-Gil Kim from the Korea Rural Economic Institute (KREI) at the UN Regional Symposium of Low-Carbon Economy in Bali, Indonesia, 2010.

Brazil: Agriculture and the low-carbon economy

The Brazilian parliament adopted a voluntary goal of reducing emissions in 2020 by about 37% against current projections. Brazil's GHG emissions per person each year are less than half the global average. However, the biggest source of GHG emissions comes from deforestation, mainly from the expansion of livestock farming, maize cultivation, and ethanol biofuel production from sugarcane. Agriculture accounts for a quarter of Brazil's emissions.

In 2010, the Brazilian Ministry of Agriculture announced a new credit line of R$2 billion (approximately US$1.1 billion) over the next 10 years to finance rural agriculture activities that use technologies to reduce GHG emissions. The Low-Carbon Agriculture (ABC) Program aims to reduce carbon-equivalent emissions from Brazilian agriculture by up to 176 million tons by the year 2020 (Table 13-1).

The investment is intended to encourage the increased use of sustainable practices in the Brazilian agricultural sector, considered the fastest-growing in the world (OECD/FAO, 2010). One of the sustainable practices to be funded by the ABC program is the no-tillage system, which dispenses with the traditional, intensive use of soil grids and plows by instead sowing directly over the crop residues left from the previous harvest. The procedure preserves nutrients in the soil, thus increasing crop yields. Through the ABC program, the Ministry of Agriculture plans to expand the use of this technique to cover a land area of 33 million ha, up from the current 25 million ha. This increase would reduce emissions by 16–20 million t CO_2 equivalents over the ten-year period.

A crop–livestock–forestry system also ensures carbon retention in the soil, allowing farmers to alternate from pastures to agriculture to forestry on the same piece of land, thus restoring the soil and increasing income. The program aims to increase use of the system in Brazil by 4 million ha over the next decade, while reducing CO_2-equivalent emissions by 18–22 million tons over the same period.

Brazilian farmers often plant commercial forests to supplement their income, and the Ministry of Agriculture has set a target to increase Brazil's planted forest area from 6 to 9 million ha by 2020. This will result in a reduction of approximately 8–10 million t CO_2 equivalents over ten years.

"Brazil is a leader in using efficient, productive systems that respect the environment. This is evidenced by the expansion of grain production in Brazil by almost 24 million tons since 2003, while the planted area grew by only 3.6 million ha," said Brazil's former Minister of Agriculture, Wagner Rossi.

The ABC program is consistent with Brazil's National Plan on Climate Change, a set of integrated programs to curb emissions generated by the Brazilian economy and to reduce Amazon deforestation by 80% by 2020, compared to 1996–2005 average deforestation levels. In December 2009, Brazil approved its National Policy on Climate Change, which established goals to cut projected emissions between 36.1 and 38.9% by 2020.

Table 13-1. Low-carbon agriculture targets in Brazil, 2010–2020.

	Current Land Area: 2010 (in million ha)	Target Land Area: 2020 (in million ha)	Reduction of GHG Emissions by 2020 (in million t CO_2 equivalents)
Planted forests	6	9	8 – 10
Crop–livestock–forestry integration	2	6	18 – 22
No-tillage system	25	33	16 – 20
Recovery of degraded areas	40	55	83 – 104
Biological nitrogen fixation	11	16.5	16 – 20

SOURCE: The Secretariat of Social Communication of the Presidency of Brazil (SECOM).

developed concrete green growth and low-carbon policies, including Brazil (Zanella, 2011), China, Korea, Malaysia, and Thailand; and countries in the Near East and North Africa, Latin America, and Africa are ready to follow suit. Korea's green-growth strategy integrally promotes sustainable agriculture with innovation, policies, and financing (Kim, 2010).

Water availability, use, and pricing instruments

The agricultural sector consumes nearly 70% of available fresh water, compared with 22% used for manufacturing and energy, and 8% used for drinking, sanitation, and recreation (WWAP, 2009). Increasing demand from all sectors and likely changes in supply resulting from climate change will increase strains on existing supplies.

Large irrigation systems were the models in the 1970s, with investments that were later challenged for being inefficient, generating corruption schemes and degrading the environment without achieving reasonable long-term use of water. At the same time, individual water schemes from aquifers increased the ease of having pumps and extraction mechanisms, depleting and contaminating much of the world's aquifers. In the face of increasing food consumption, production systems need to ensure a water supply to meet global production needs.

Water sources such as rivers, lakes, and aquifers rarely lie within the boundaries of single nations, and hence managing water resources will require international cooperation and international and regional policy measures. Hermans et al. (2005) note several regional schemes that provide funds for improving the management of water catchments and therefore the long-term water supply.

Furthermore, techniques for the efficient use of water for agriculture exist in various forms. A prime example exists in Israel, where drip irrigation developed on the kibbutz in the 1960s was exploited as an export opportunity. In Italy, the open irrigation systems were converted into irrigation pipes, reducing the evaporation and loss from the inefficient system. There are also individual control systems of irrigation with computer models that allow to reduce the volume, while making more equitable use of water by various users (OECD/FAO, 2010).

Measuring water footprint will be critical. Agricultural industries will have to take into account estimates of their water usage and implement measures to minimize it (Segal and MacMillan, 2009). For example, following a series of water-footprint studies, Coca-Cola is seeking to reduce its water footprint by developing and encouraging more-sustainable agricultural practices that benefit suppliers, customers, consumers, and local watersheds (The Coca-Cola Company and The Nature Conservancy, 2010).

Eco-agri-"culture"

Solutions to poverty, hunger, and the climate crisis require agriculture that promotes producers' livelihoods, knowledge, resiliency, health, and equitable gender relations, while enriching the natural environment and helping to balance the carbon cycle (IAASTD, 2009). In line with this, some governments currently rethinking agriculture have placed those who produce, distribute, and consume food at the heart of food systems and policies, rather than the demands of markets and corporations. Connecting producers and consumers through fair-trade and green production chains is emerging as a win–win policy to address poverty issues, feed the world, and have a healthier planet.

Consumers are increasingly demanding transparency about origins of food products, trading conditions, and carbon footprints, leading to a rise in eco-labeling and certification schemes in global agricultural markets. Supermarket chains supporting these processes, such as Sequoia in Belgium and Whole Foods and Trader Joe's in the USA, have gained favor with consumers and grown comparatively faster than competitors who have been slower to embrace these schemes (Marquis et al., 2009).

Reducing postharvest losses and food waste would go a long way towards reducing the ecological impact of food production. It is estimated that more than 30% of the food produced is wasted, especially by the final consumer in developed countries (Gooch et al., 2010). Much of the loss in developing countries is due to poor storage, packaging, and transport. Improvements in storage and transport infrastructure, packaging, and marketing would reduce losses and the environmental impact of food production.

The Common Challenge: Science and Technology towards Eco-Efficiency

Developing policies that encourage adoption of new agricultural technologies that can increase productivity, while preserving environmental resources, is a key strategy for governments that seek to reduce the negative environmental externalities caused by agricultural activities (Fuglie and Kascak, 2001).

The recent International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) conducted by the World Bank in collaboration with a group of agencies of the United Nations called for technological development through networks and associations, and development of capabilities across borders and regions. Our future food security will depend on sharing research and development results and on increasing budgets for research, science, and technology.

The European Union (EU) is taking an unprecedented leap in establishing a green growth policy for the agricultural sector. Several EU countries have been pioneers in this field. For example, the Netherlands has a long tradition in policies promoting sustainable agriculture, including restricting the use of pesticides, management of soil and water acidification, landscape management, and biodiversity. Their strategy to remain one of the world's largest agricultural producers as a small country is to differentiate themselves in environmental management and general innovation.

Green growth has become one of the highest priorities of the Organisation for Economic Co-operation and Development (OECD) governments. A press release from the agriculture ministers meeting at OECD in 2010 notes that "Ministers recognized that green growth offers opportunities to contribute to sustainable economic, social, and environmental development; that agriculture has an important role to play in the process, as do open markets that facilitate the sharing of technologies and innovations supportive of green growth, and that, in this context, care needs to be taken to avoid all forms of protectionism. Climate change presents challenges and opportunities for the agricultural sector in reducing GHG emissions, in carbon sequestration, and the need for adaptation" (OECD, 2011b).

There is increasing international coordination of research addressing climate change issues facing agriculture, such as:

- The CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) – a strategic partnership between CGIAR and the Earth System Science Partnership (ESSP) – brings together researchers in agricultural, climate, environmental, and social sciences to identify and address the most important interactions, synergies, and trade-offs between climate change and agriculture. (http://ccafs.cgiar.org/)
- The Global Research Alliance on Agricultural Greenhouse Gases was launched in December 2009, and now has more than 30 member countries from around the world (www.globalresearchalliance.org).

Similar partnerships are needed on shared ecosystem services management, biodiversity use and conservation, second- and third-generation bioenergy, green production chains, and health and food security management.

Finally, all this will be possible only if there is a fundamental shift in food consumption, from foods with high input demands to less resource-intensive foods, and if waste and postharvest losses are reduced.

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CHAPTER 14

Strengthening Capacity to Achieve Eco-Efficiency through Agricultural Research for Development

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Contents

Abstract

Global climate change and food security are complex and closely intertwined challenges. A key requirement for dealing with them successfully is that agriculture becomes more eco-efficient. As researchers work toward this goal, they must always ask, "Efficiency for whom?" Finding answers to this question requires that research be conducted from a systems perspective in a broadly participatory manner involving complex collaborative arrangements.

In recent decades, training and other efforts to strengthen the capacity of national partners in such collaboration have declined because of funding scarcity. As a result, key links in the chain that connects research with development have been weakened, thus diminishing the ability of research to reach end users effectively. Many approaches, backed by practical experience, have been developed in an effort to reduce the gaps between research and development. Among these approaches are new partnership styles, participatory research methods, novel strategies for strengthening agricultural value chains, qualitative monitoring and evaluation, and knowledge management and sharing. All of them contribute broadly to capacity strengthening by empowering stakeholders and by fostering joint learning rather than reinforcing unidirectional technology transfer. These approaches can contribute importantly to mainstreaming eco-efficiency in agricultural research for development, particularly if currently separate and isolated interventions are combined under a comprehensive strategy.

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Introduction

This chapter describes five key interventions that are important for mainstreaming eco-efficiency in research for development:

1. Partnership strategies
2. Participatory research
3. Learning alliances
4. Monitoring and evaluation
5. Knowledge management and sharing

Each aims to foster innovation and social learning, which are essential for adapting agricultural systems to changes in the climate and in local and global economies. These practices can be particularly effective if used in an integrated manner.

Evolving approaches

Capacity strengthening has evolved considerably over the years, as agricultural research has come to focus more sharply on development. Table 14-1 summarizes this shift from a relatively narrow focus on training for improved food production, mainly through plant breeding, to a more systemic approach for rural innovation.

As research for development has evolved, it has searched for better ways to reach large numbers of end users. Reflecting on obstacles to research impact in the 1990s, social scientists began to question the so-called "pipeline" approach for addressing farmers' problems through scientifically proven technologies. Starting about 30 years ago, various participatory approaches were developed and tested, with emphasis on the learning cycle, in which users of agricultural research products and services learn together through partnerships and stakeholder engagement, thus increasing the chances of research results being put to use.

Social learning and innovation

Current approaches have their roots in two closely related theoretical fields: social learning and innovation systems. According to Leeuwis and Pyburn (2002), academics introduced the concept of social learning with an interest in studying and promoting sustainable development (Dunn, 1971; Friedmann, 1984; Milbrath, 1989; Woodhill, 2002). Social learning, as described by Röling (1992), assigns a central role to multi-stakeholder platforms that facilitate interaction and promote learning for change. The facilitator's role is to help establish these platforms and catalyze dynamics that foster synergy.

The concept of innovation systems emerged from inquiries into research and technology transfer, leading to an examination of the wider innovation process (Hall et al., 2004). Innovation is a complex process, described by Smits (2002) as the successful combination of "hardware" (new technical devices), "software" (new knowledge and modes of thinking), and

Table 14-1. Evolving approaches to capacity strengthening.

Decade	Research focus	Key partners	Principal mode of knowledge exchange	Entry points for capacity strengthening
1960s and 1970s	Improving food production through plant breeding	National agricultural research institutes	Technology transfer through extension	Training
1980s and 1990s	Natural resource management and sustainability	Advanced-research institutes	Networks	Participatory research
2000s	Development challenges and innovation systems	Multi-stakeholder partnerships	Multi-stakeholder platforms	Learning alliances

SOURCE: Based on Ekboir and Sette (2010).

"orgware" (new institutions and forms of organization). It depends on effective collaboration, networking of interdependent social actors, and other new forms of coordinated action. Innovation is thus a collective achievement rather than the result of individual adoption (Leeuwis, 2004).

A key message of this chapter is that making agriculture more eco-efficient requires a major commitment to developing capacity for innovation through continuous learning, particularly for stakeholders who have previously been excluded in research. One recent study (Mehta-Bhatt and Beniest, 2011) suggests that CGIAR centers have responded in various ways to new trends in capacity development. The sections that follow explore some of the results.

Partnerships: From Knowledge to Action

The authors of a recent working paper (Horton et al., 2009) define partnership as "a sustained multi-organizational relationship with mutually agreed objectives and an exchange or sharing of resources or knowledge for the purpose of generating research outputs (new knowledge or technology) or fostering innovation (use of new ideas or technology) for practical ends." As this definition suggests, partnerships may involve diverse actors, working under informal or formal arrangements while sharing responsibilities and decision making. They may also have a wide range of objectives—from the delivery of specific research products to the creation of a shared context for innovation and joint learning.

Partnerships are essential for achieving impact through today's complex and ambitious agenda of agricultural research for development. Key actors in this work include civil society organizations, national research and educational institutions, the private sector, national policy makers, regional multi-stakeholder networks, donors, and the media. Such partners bring diverse perspectives to bear on shared goals, providing the basis for an equitable learning culture. This can increase the potential for solving problems successfully, generating useful knowledge, and empowering local actors. Further benefits include stronger resource mobilization, greater legitimacy, reduced risks, and increased flexibility.

More systemic approaches to partnership

Partnerships have evolved in step with the broader trends in agricultural research that are described in the introduction to this chapter (see Table 14-1). The purely research alliances

Fruit and vegetable research: Moving in the right direction

As described in Chapter 12, researchers are using participatory methods to develop technologies aimed at ecologically sustainable improvement in the production of fruits and vegetables. This work provides a clear example of how research can help build the capacity of smallholder farmers to deal more effectively with shifting production constraints and market conditions through more eco-efficient practices.

Such initiatives require that scientists take a more systemic view, emphasizing the importance of crop diversity and of maximizing the producivitty of varied ecological niches. It is also important for donors and other stakeholders to create a policy environment that encourages collaboration between research and development agencies. Financial and human resources must be dedicated to the promotion of greater crop diversity and to the development of more resilient and profitable agricultural systems. A different type of education is needed to avoid overspecialization in agriculture and to promote better understanding of integrated crop management options, of the need to balance crops and livestock, and of the importance of balanced human diets.

of the 1960s have given way to new contractual relationships, which in the best cases transform knowledge into action, leading to sustainable development outcomes.

This shift involves more systemic approaches to partnership, in which research is just one part of a complex puzzle (Kristjansen et al., 2009) or "complex adaptive system," which also involves development methods and evolving knowledge, attitudes, and skills. Current partnerships often use tools such as outcome mapping, participatory impact pathway analysis (Álvarez et al., 2010), and other types of stakeholder analysis, such as social network analysis, for joint planning. Such approaches are useful for determining each partner's degree of influence on users of research products and therefore their potential multiplier effect and contribution to impact.

Partnerships figure importantly in the new research strategy resulting from recent CGIAR reforms (CGIAR, 2011). They are central to more-innovative arrangements in research for sustainable development that involve advanced research institutes, reduce costs, and deploy new technologies, among other ends (Spielmann et al., 2007).

Partnerships for eco-efficient agriculture

Since eco-efficient agriculture aims to reduce negative environmental impacts, its success depends on partnerships involving stakeholders engaged in environmental research and advocacy. Civil society organizations have an especially important role to play in these partnerships because of their ability to achieve positive multiplier effects (CGIAR, 2006), including the development of site-specific solutions that address the needs of the rural poor.

Partnerships for eco-efficient agriculture must pay particular attention to the needs of women. According to FAO (2011), women comprise, on average, 43% of the agricultural labor force in developing countries, ranging from about 20% in Latin America to almost 50% in Eastern and Southeastern Asia and sub-Saharan Africa.

Interestingly, the report observes that female farmers produce less than male farmers, not because they are less efficient but because of differences in their use of inputs. This underscores the need for further research on the relationship between gender, production, and eco-efficiency. It is also important for research partners to be selected on the basis of their gender vision and practices, with the aim of achieving gender balance in partnership governance.

Partnerships as learning opportunities

Institutional arrangements in research for sustainable agricultural development are increasingly based on equity and accountability among all stakeholders (GFAR, 2010). Establishing trust and respect are fundamental for building confidence and empowering stakeholders.

As development expert Robert Chambers noted in a recent interview:

> "So much in a partnership depends on what sorts of people are involved, how they relate to one another, how participatory they are, whether they dominate or whether they facilitate, how they make other people feel, whether they feel comfortable, whether they feel they can be open, or whether they feel they are vulnerable to criticism. Linked with this are power relations, which are inevitable, particularly when funding is involved. (ILAC, 2010)"

Partnerships offer three main opportunities to strengthen capacity for innovation and social learning:

1. **Complementary competencies:** Achieving sustainable development requires that diverse partners pool their assets—such as specialized knowledge and human capital—

Nontraditional partnerships for impact

Multi-stakeholder roundtables, such as the Better Sugar Initiative, the Roundtable for Sustainable Palm Oil, and the Roundtable for Responsible Soya, among others, demonstrate increasing concern about more-sustainable agricultural development. With growing frequency, even the major actors in food production are asking whether it makes sense to develop a market unless it can be done in a sustainable way.

The US-based Sustainable Food Lab and the European Sustainable Agriculture Initiative Platform promote collective action across sector boundaries in such initiatives as certification schemes and smallholder inclusion. Unilever has set the goal of making every supply chain it works with (cocoa, sugar, tea, soybean, and so forth) sustainable by 2020. For this purpose, the company has developed its own sustainable agriculture code, which identifies social inclusion as the best way to practice corporate responsibility.

Roundtables, codes, and guidelines provide important opportunities for the private sector to engage with agricultural science aimed at achieving eco-efficiency. While big NGOs and private-sector actors set the rules, agricultural science can contribute high-quality research and strong public-sector connections.

under new institutional arrangements. The idea is to form multidisciplinary teams that are able to learn together across organizational and geographical boundaries (Lundy et al., 2005).

2. **Increasing scale and reach:** Partners are potential multipliers of new information and knowledge. They can help fuse new knowledge with current knowledge and increase its flow into research and development networks and communities, often in multiple languages. Effective partnerships are useful for positioning such knowledge in the wider market, for example, among policy makers (CGIAR, 2008). Resulting growth in the scale and reach of knowledge compensates for the initial costs of creating and facilitating partnerships.
3. **Contribution to organizational development:** Working in broad, multidisciplinary and geographically dispersed partnerships is challenging, but this can contribute to greater institutional openness in terms of cultural and gender issues. Partnerships are especially useful for this purpose if participants share lessons and insights, thus contributing to the learning cycle in which mistakes and disappointments serve as a springboard for reflection and revision (Tennyson, 2003). What often happens instead is that partnerships remain at the periphery of institutional learning, and neither leadership nor individual partners share best practices (Smith and Chataway, 2009). Partnerships are often driven by personal relationships; researchers and stakeholders decide to work together because they know and trust one another and share a common vision and field of interest. More attention should be paid to ensuring that partnership behaviors, policies, strategies, and practices progress from the micro level of individuals to the meso level of the organization (Özgediz and Nambi, 1999).

Given the urgency of the multiple challenges that agriculture faces today, partnerships focusing on eco-efficiency must quickly provide strategies that translate knowledge into action and offer solutions that are effective and easy to implement. The increasing complexity of partnerships poses a major challenge. The following sections provide insights on how partnerships for eco-efficiency can be made to work.

Participatory Research

Participatory research methods arose in agriculture during the 1980s. They responded to the need for research to generate technologies that are more appropriate for small-scale farmers, resulting in wider adoption and greater benefits. The strategy for this work was to provide small-scale farmers with assistance in managing risky innovations collectively, obtain feedback for researchers from farmers, and delegate the implementation of adaptive technology testing to farmer associations or groups (Ashby, 1985). As participants in research, farmers can better communicate their perspectives on what, where, and when to research and their criteria for success. Farmers thus engage in the co-development of knowledge, taking responsibility for decisions about priority setting, implementation, and recommendations (Cárdenas-Grajales, 2009).

Farmers as researchers

Participation in research is not to be confused with the discovery learning process used to teach farmers about recommended technologies. The latter is an extension method, in which farmers conduct their own experiments to demonstrate known principles and practices. In contrast, participatory research involves collaborative investigation of options for innovation, about which researchers are just as uncertain of the outcomes as are producers.

Participatory research in agriculture evolved from participatory rapid appraisal in rural development projects to the application of similar techniques for the purposes of research. New methodologies soon followed, which national and international research centers used for participatory selection of experimental germplasm of grain legumes (Mazon et al., 2007), applied research in farmers' fields (CORPOICA, 2002), and research to develop and strengthen community organizations and their links with markets (CRS, 2007).

Participatory research and social analysis

To be effective, participatory research methods should be used in conjunction with social analysis. This is essential for determining who should participate, when, how, and where and also for ensuring that results are representative and can be generalized. In rice production, for example, achieving eco-efficiency implies very different outcomes for women who transplant rice, men who own rice paddy land, and ethnic minorities who want to preserve forests from encroachment by rice cultivation. The gender, ethnic identity, and social class of research participants must be investigated through social analysis to ensure that different groups in the intended beneficiary population are represented appropriately.

Participatory research approaches

Participatory methods have been applied in agriculture specifically for experimentation with farmers, participatory plant breeding, participatory technology development, participatory market appraisal, and communication for development.

Participatory methods have been widely used for farmer experimentation in Latin America (Braun and Hocdé, 2003). One such experience involved a method centering on local agricultural research committees (or CIAL, its Spanish acronym). These are groups of volunteer farmers from a community or farmer

The value of participatory technology evaluation

Experience in Malawi with the evaluation of legumes for soil fertility improvement demonstrates the value of participatory technology evaluation. At first, farmers were averse to adopting legumes for this purpose, despite having serious soil fertility problems. But they adopted the practice enthusiastically after participatory technology evaluation helped researchers understand farmers' priorities. Testing with more than 3000 men and women farmers showed that they preferred edible species, such as pigeon pea and groundnut, over mucuna, a green manure crop that researchers had recommended.

By 2001, 72% of the target farm population had adopted pigeon pea and groundnut, compared with only 15% the year before. Evaluations found that children were better nourished in households that had adopted the edible legumes.

SOURCE: Kerr et al. (2007).

association who apply a simple form of the scientific method to study different options for improving local agriculture (Ashby et al., 2001). Participatory plant breeding is used worldwide for the evaluation of crop varieties and selection of parental materials and their crosses (Goncalves and Saad, 2001; Almekinders et al., 2006). New information and communications technologies have created opportunities for applying participatory principles and methods in combination with technology-mediated learning approaches involving video, radio, and web 2.0 technologies (Van Mele et al., 2010), as well as knowledge-sharing tools and methods (Staiger-Rivas et al., 2009).

Institutionalizing participatory research

Participatory research capacity forms a crucial part of the overall capacity for innovation that is needed to achieve eco-efficient agriculture. It is particularly essential where public and private organizations are ill-equipped to address the multiplicity of small adaptive changes and trade-offs between desired environmental and production outcomes that farmers must constantly deal with as they fit new technologies to changing circumstances.

Strengthening capacity for participatory research must involve a wide array of professionals providing agricultural research and advisory services as well as others who contribute to innovation, including farmers, traders, and consumers. To institutionalize participatory research requires changes in policies and procedures aimed at making agricultural research and advisory services more accountable to farmers and other stakeholders. Thus, capacity strengthening must go beyond the use of participatory methods to include significant institutional changes, which are critical for achieving an eco-efficiency revolution.

Evidence of impact and future opportunities

The impact of participatory research has been widely evaluated. Impacts include increased yields in small-scale crop production (Catavassi et al., 2009) and higher yields and adoption rates as a result of participatory plant breeding (Ceccarelli et al., 2000).

Experience in Honduras shows how a participatory approach enabled farmers to obtain maize varieties that are well adapted to local growing conditions. As shown in Figure 14-1, 59% of the farmers who were CIAL members engaged in participatory selection of maize varieties reported yield increases, compared with only 28% of those who were not CIAL members (Classen et al., 2008).

In Latin America, plant breeders have used participatory technology evaluation widely to obtain information about farmers' preferences. Recently published work includes case studies organized according to the stage of the plant breeding cycle in which farmers participated. Overall, the results consistently show that when varieties are evaluated with farmers, the rates of acceptability and adoption are higher. Involving farmers at an early or mid-stage in the breeding cycle—that is, well in advance of prerelease testing—allows breeders to take into account farmers' preferences when setting priorities, thus enabling them to provide farmers with benefits in less time than with conventional breeding (Ashby et al., 2009).

Described below are two new opportunities for using participatory research methods:

- **Training in innovation:** Institutionalizing participatory research as a means to promote pro-poor innovation is important for achieving eco-efficient agriculture. Capacity

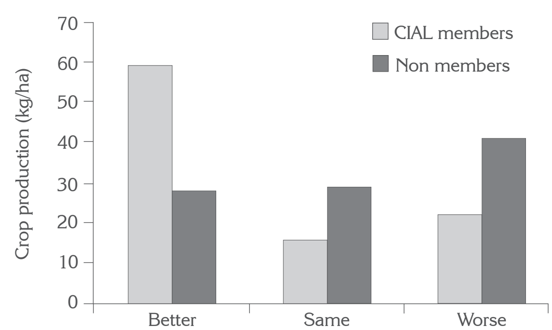

Figure 14-1. Changes in maize yields in Honduras, 2007.

strengthening in available tools through partnerships with universities and development agencies is an effective way to heighten awareness of this approach and strengthen capacity to use the tools available. Demand for this service is growing among national and international non–governmental organizations (NGOs), such as World Vision, and agencies such as Oxfam International and the World Food Programme. They are particularly interested in monitoring and evaluating the use of participatory methods to promote technological innovation as they shift emphasis from humanitarian relief to food production.
- **Climate change:** To assist farmers in coping with the impacts of climate change, research must incorporate local knowledge. Participatory plant breeding, for example, can be used to develop crop varieties that are not only better adapted to harsher conditions but closely match farmers' other needs, providing broad genetic diversity and more-flexible seed systems.

Making agriculture more eco-efficient involves choices based on value judgments about alternatives. Some options may have positive or negative implications or involve trade-offs between competing objectives and interests. For that reason, researchers must always ask, "Efficiency for whom?"

Participatory research is one of several approaches that can help address this question. It is particularly useful for taking into account different perspectives and priorities when deciding what the research problems are and what constitutes an eco-efficient innovation. Understanding farmers' demands and limitations is essential for finding solutions that are feasible for participating farmers.

Learning Alliances to Connect Research with Development

The gold standard of research consists of publishing one or more articles in peer-reviewed journals aimed at a scientific audience, which may number in the thousands. Traditional development practice, on the other hand, focuses on solving problems for as many people as possible as quickly as possible. Its gold standard constitutes a favorable impact assessment, showing that a project has delivered considerable livelihood gains for the poor both in quantitative and qualitative terms.

Somewhere along the continuum between these caricatures of research and development lies the current reality. The CGIAR has recently announced that it will focus more strongly on achieving research outcomes that are reflected in measurable improvement of rural livelihoods. Yet, the incentive structures still favor scientific outputs over development impact.

Meanwhile, development practitioners have adopted various approaches to monitoring, evaluation, and learning in an effort to enhance performance. Learning alliances provide an institutional framework for facilitating more effective and consistent connections between research and development, as both strive to improve the lives of the rural poor.

The learning-alliance approach

Learning alliances differ substantially from common training practices, especially those involving short, one-off courses. This approach involves rather an iterative learning process undertaken jointly by multiple stakeholders, with the aim of improving the learning and innovation capacity of agencies that support farmer associations. There are three types of learning alliances (Table 14-2; Best et al., 2009).

Partners in such collaboration need to agree on basic principles of collective work, including:

- **Clear objectives:** These must reflect the needs, capacities, and interests of the participating organizations and individuals. What does each organization bring to the alliance? What complementarities or gaps exist? What does each organization hope to achieve through the collaboration?
- **Shared responsibilities, costs, and credit:** A learning alliance seeks to benefit all parties, so

Table 14-2. Types of learning alliance.

Type	Need	Focus
1	Building capacity and skill	Training and learning using concrete, practical approaches and proven methods
2	Developing new methods, tools, and approaches	Action research that generates methodology guides based on good practice, which is then validated through capacity-development learning cycles
3	Generating information that can influence policy	Conventional socio–economic research to understand principles and lessons across experiences

SOURCE: Best et al. (2009).

costs, responsibilities, and proper credit for achievements should be shared among partners.

- **Outputs as inputs:** Rural communities are diverse, and there are no universal recipes for sustainable development. In learning alliances, the outputs of research and development are viewed as inputs for rural innovation at specific places and times. The particular methods and tools employed may change, as users adapt these to their needs and circumstances. Key challenges are to understand the reasons for adaptation and its positive or negative impacts on livelihoods as well as to document and share lessons learned.
- **Differentiated learning mechanisms:** Learning alliances involve diverse participants. Determining each group's willingness to participate in the learning process is critical to success. This requires flexible but connected learning methods, which range from participatory monitoring and evaluation through conventional impact assessment to the development of innovation histories.
- **Long-term relationships based on trust:** Rural development takes place over many years. To influence positive change and understand why change has occurred requires long-term, stable relationships capable of evolving to meet new challenges. Trust is the glue that binds these relationships.

Capacity strengthening for innovation and scaling up

Under learning alliances, the learning process typically spans 12 to 24 months (Best et al., 2009). It involves learning cycles, which include feedback loops and opportunities for reflection and documentation aimed at improving practice. This approach consists of four interrelated learning strategies:

1. **Capacity building:** This activity is not limited to training but focuses on practical application of methods in the field, follow-up, adaptation, and improvement. Partners receive ongoing support as they implement prototypes. This process is linked to specific learning cycles, which strengthen partners' ability to use specific tools and approaches, adapt them to their needs, and discern when particular methods might or might not be useful.
2. **Targeted action research:** Such research addresses specific knowledge gaps identified with partner agencies. Key research questions are identified and fieldwork designed and implemented collaboratively by research and development agencies. Outcomes and findings are shared with other partner agencies, selected decision makers, and the general public through workshops and in electronic formats.
3. **Connectivity and knowledge management:** These aim at strengthening the relationships that form the basis of the learning alliance through densification of networks and personal connections. To achieve this, the alliance can use face-to-face meetings, training-and-exchange visits, and virtual tools such as a web site and list server.
4. **Evidence-based decision making:** Aimed at influencing organizations in the public and private sectors, this strategy has been markedly less successful than the other three. Nonetheless, learning-alliance partners consider it to be critical for leveraging high-level change based on field results.

Alliance partners learn primarily through a learning cycle for each topic of interest, as shown in Figure 14-2.

The learning alliance model involves the following activities, themes, and challenges:

- **Identifying learning topics:** Identifying and clearly articulating the content of a given learning cycle requires extensive discussion, which is often time consuming and may become acrimonious. Nonetheless, once the partners reach consensus, the result is a more effective learning cycle.
- **Identifying good practices:** This step generally involves a thorough literature review. It is essential to avoid "reinventing the wheel," so an adequate budget is required. The review can be brief if acceptable methods and tools are already available.
- **Prototype development:** At this stage, the challenge is to strike a balance between tools of interest to development actors and testable hypotheses of interest to researchers. Without this balance, partners end up spending more time than anticipated to develop a prototype. A related challenge is that researchers, accustomed to working with academic publications, may not be capable of producing effective field materials.
- **Field testing:** A major challenge of this work is to develop an evaluation framework—one that is robust yet simple and cheap—for measuring field performance of the prototype. This requires a mix of development actors and researchers, with a budget for monitoring and evaluation.
- **Documenting results:** Documenting the learning process can be difficult with development actors who are not accustomed to writing technical reports. One way to address this problem is through "write-shops," whereby project participants document their results through structured reflection with the end goal being to produce written documentation. The task requires a

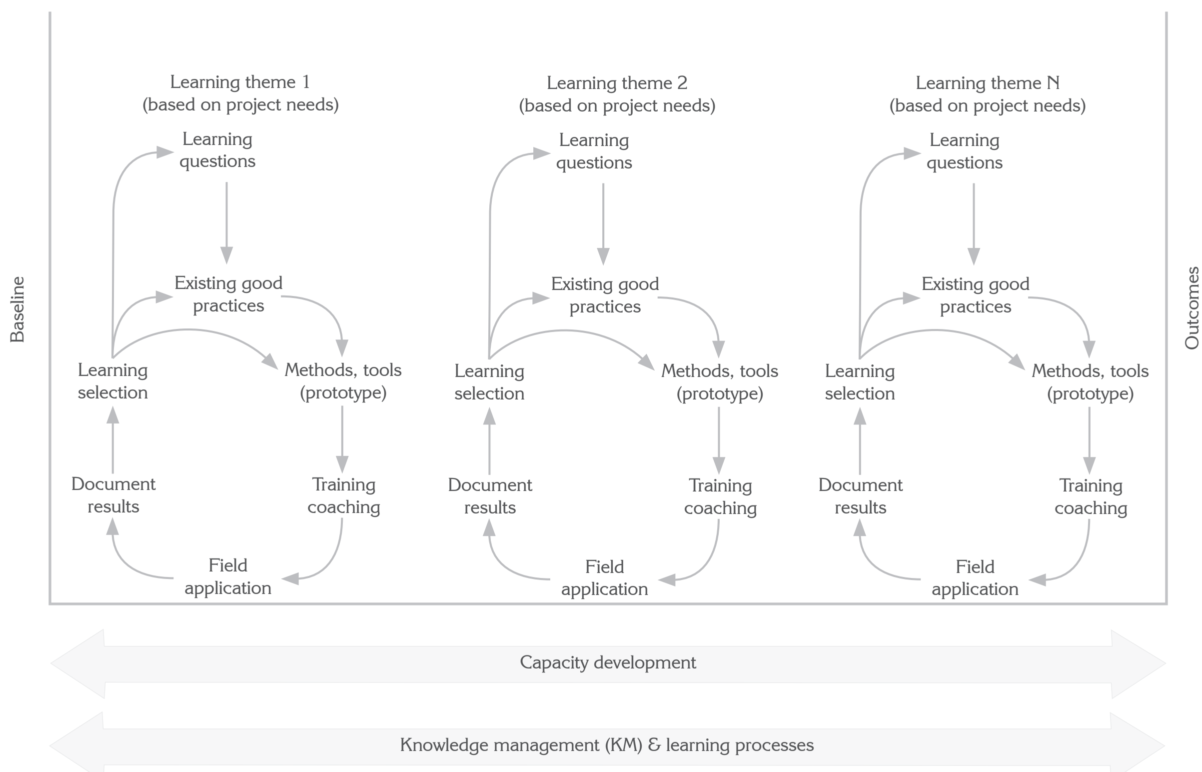

Figure 14-2. Learning-alliance model.

significant effort on the part of researchers to ensure that the results are adequately linked to the monitoring and evaluation framework.

Make learning alliances work at scale

What insights can be derived from the attempts described here to bridge the gap between research and development? Here's an initial list:

1. **Begin at the beginning:** Before researchers and development practitioners embark on a joint project, they should meet to discuss issues on which both can contribute insights. Once they have established a shared learning agenda, they can bring together research and development capacities more effectively and align resources throughout the project.
2. **Measure what matters consistently:** Development outcomes for the rural poor constitute the common ground between development and research organizations. In order for their collaboration to be effective, the organizations need to develop a common and consistent set of indicators and tools to track development outcomes and understand what works where, for which populations, and why. Having a common evaluation framework facilitates learning and communication between disparate actors.
3. **Invest in relationships:** Building trust is essential for effective collaboration. To have a shared learning agenda (point 1) and a common evaluation framework (point 2) helps but is not enough. Research and development organizations need to invest in opportunities for people from both sectors to share ideas through, for example, exchanges, field visits, and ongoing communication involving all concerned. These are critical parts of a learning process that motivates researchers and development practitioners to engage with one another around common issues that both need to resolve. Ultimately,

Learning-alliance outcomes and impacts

A learning alliance in Central America for rural-enterprise development contributed to significant changes in the knowledge, attitudes, and practices of 25 partner agencies, which influenced a network of 116 additional organizations. By 2007, the alliance had contributed to benefits for 33,000 rural families (about 175,000 people) in El Salvador, Guatemala, Honduras, and Nicaragua.

The alliance resulted in stronger networks with end users, involving both development actors and researchers. Partners changed from competitive to collaborative attitudes as they saw evidence that working together enhanced their capacity to meet the needs of rural communities and to obtain donor funds. These shifts, in turn, contributed to a more efficient innovation system for rural-enterprise development, as evidenced by shared use and generation of information, joint capacity building, and large-scale collaborative projects.

A community-level assessment conducted in 2007 identified 30 cases that highlight the positive impact of methods and tools used by the learning alliance on income generation, natural resource management, and the role of women. On the strength of such results, Catholic Relief Services (CRS) adopted the learning-alliance approach within its global Agriculture and Environment Program. From small beginnings in East Africa and Central America during 2002–04, CRS has extended its learning alliances for agro-enterprise development to five regions involving about 30 countries (Best et al., 2009). The approach has also been adopted in the water and sanitation sector (Smits et al, 2007) and in India's rice sector (Prasad et al., 2007).

In July 2009, the learning alliance in Central America entered a new phase. Five organizations that participated in its first phase—CRS, The Netherlands Development Organisation (SNV), the Swiss Foundation for Technical Cooperation (Swisscontact), OXFAM-GB, and the Tropical Agricultural Research and Higher Education Center (CATIE, its Spanish acronym)—signed a five-year agreement to support a coordination unit that is currently facilitated by CATIE.

For more information: www.alianzasdeaprendizaje.org

learning-alliance partners must be accountable to one another as well as to their own stakeholders, and the partnership as a whole must be accountable to its stakeholders (APP, 2011).
4. **Cultivate an organizational support network:** It takes time and effort to build a shared learning culture. This is beyond the scope of a single project and requires ongoing support from staff and management in research and development organizations. To consolidate the learning culture requires a support network in both organizations, as it may run counter to short-term organizational thinking.

Many challenges must be addressed to make learning alliances sustainable. Both research and development organizations need to make significant changes in attitudes and practices while also creating clear incentives for effective learning. These organizations should also assign higher value to emerging knowledge and insights, which do not easily fit in project logical frameworks or academic journals. And they must allow for more collaboration across research and development boundaries. In addition, better documentation and measurement of results in a consistent and statistically valid manner are needed to complement current efforts focused on qualitative changes in knowledge, attitudes, skills, and practices.

The first round of learning alliances has provided useful lessons for the future, but important knowledge gaps remain. The overarching question is how to create and share knowledge within complex adaptive systems so that it contributes to sustained poverty reduction. Learning alliances and similar approaches provide opportunities to develop and test different hypotheses on this issue, which will remain an important concern for the foreseeable future.

Reaching Users through Monitoring and Evaluation

Project monitoring and evaluation (M&E) is a systematic approach to learning and capacity strengthening that involves all stakeholders (IFAD, 2002). Monitoring is periodic oversight of project implementation that seeks to establish whether the production of outputs is proceeding according to plan. Evaluation attempts to determine as systematically and objectively as possible the relevance, effectiveness, efficiency, and impact of activities in light of specified objectives. M&E is an action-oriented management tool and an organizational process for generating knowledge to improve decisions about policies, programs, and organizations (Horton et al., 2003).

Learning for enhanced adaptive capacity

Achieving eco-efficient agriculture entails complex, long-term research. Its results must inform decision making and uptake in specific contexts while also informing further research (Watts et al., 2008). M&E encompasses all the channels and methods by which evidence is gathered, documented, and shared in research, including its conclusions and recommendations. M&E of research and the resulting international public goods provide crucial support for learning by doing and other types of learning that can enhance adaptive capacity (Douthwaite et al., 2003). Unfortunately, evaluation is often limited to the purpose of justifying past funding and obtaining future funding by demonstrating accountability and impacts, which may be disconnected from the intended users of research results.

M&E and capacity strengthening are closely linked, as both emphasize learning in research for development. It is of paramount importance for organizations to promote an “evaluative culture” through investment in evaluation for learning. They can accomplish this by encouraging people to share best practices and lessons learned, by showing appreciation for attempts at reflection, by learning from multiple sources and perspectives, and by assessing constructively past mistakes or lost opportunities.

Recommended evaluation approaches

To involve stakeholders in evaluation and through their participation to promote learning from and about evaluation should be standard practice in systemic research. Methods such as inclusive and use-focused evaluation produce better results and yield more-accurate recommendations for enhancing program development and change (Bledsoe and Graham, 2005).

The main evaluation approaches currently in use are described briefly below, including comments on how M&E can be best organized and managed.

Theory-driven evaluation

With this approach—which is also known as program-theory evaluation, among other names—evaluation is based on an explicit theory or model of how programs may cause intended or observed outcomes (Rogers et al., 2000). Drawing on a synthesis of stakeholder program logic and social science theory, the approach defines what a program does and how, and gauges the effects of outputs on outcomes. This enables the evaluator to ascertain the actual causal mechanisms of program strategies and link these to changes in program participants.

Horizontal evaluation

This approach combines self-assessment with external evaluation by peers (Thiele, 2007). The two are then discussed and compared for the purpose of improving learning, communication, and sharing.

Participatory monitoring and evaluation (PM&E)

This is an action-oriented process through which stakeholders engage in monitoring or evaluation at various levels. They share control over the content, process, and results of M&E and engage in reflection, aimed at identifying corrective actions. PM&E provides ways to simplify complex plans through measurement frameworks that are owned by implementing partners. This approach not only measures the effectiveness of a project but also builds ownership of the content and promotes accountability for the outcomes at various levels (Muthoni, 2007).

Participatory learning and action (PLA)

This is an umbrella term for a wide range of methodologies, such as participatory rural appraisal, rapid rural appraisal, participatory learning methods, participatory action research, farming systems research, active method of research and participatory planning (MARP, its French acronym), and many others. The common theme in all these approaches is the full participation of people in learning about their needs and opportunities, and about actions required to address them.

Towards outcome-based evaluation

Recent evaluation methods go beyond a focus on outputs (for the sake of accountability) to examine outcomes, particularly the extent to which they reach intended users. Such methods are concerned with the impacts triggered among target groups of users during and after an intervention.

A method referred to as utilization-focused evaluation, for example, begins with the premise that evaluations should be judged by their utility (Patton, 1996). This method centers completely on the group of intended users and on the use they make of the information collected through the evaluation. Another option is outcome mapping, which does not assess the products of a program but rather focuses on changes in the behavior, relationships, and actions of the people, groups, and organizations directly involved. Then there is participatory impact pathways analysis—a planning, monitoring, and evaluation approach developed for complex projects in the water and food sectors (Álvarez et al., 2010).

These M&E methods are not yet part of standard practice in international agricultural research. However, they could gain currency if continued use demonstrates their value convincingly and if scientists adopt more widely the “innovation systems” view of agricultural research for development, as opposed to the more common linear model.

Where do we go from here?

Measuring research impact in a credible manner is a time-consuming and resource-intensive activity that requires specialized skills as well as research on new methodologies (CGIAR Science Council, 2009).

When M&E is done in a participatory manner focused on outcomes and learning, it can provide research managers with much useful information on the efficiency, relevance, sustainability, impact, and effectiveness of work in progress (Guijt, 1999). It can also contribute to adaptive management and improvement of a program, making it more relevant to users. The information derived from M&E offers research a "bigger picture" that reflects the complexity of any agricultural intervention. Through a continuous, inclusive, and well-organized information exchange and learning, M&E can strengthen partners' ownership of an intervention, thus increasing the chances of adoption and sustainability.

The way ahead for M&E in agricultural research concerned with eco-efficiency must involve a shift from summative evaluation driven by accountability concerns to M&E cultures and practices that are formative, inclusive, and systemic. Given growing pressures on funding and the urgency of addressing food insecurity, agricultural research must combine traditional impact assessment with more-timely, affordable, and inclusive ways of learning for the future.

Strengthening Capacity through Knowledge Management and Sharing

This section underlines the contribution that knowledge management can make in strengthening capacity to make tropical agriculture more eco-efficient. It first summarizes some

Monitoring and Evaluation (M&E) in the Pan-African Bean Research Alliance (PABRA)

PABRA is a CIAT-supported research partnership that improves the productivity and nutritional quality of beans, with the aim of improving the incomes, nutrition, and food security of the rural and urban poor. PABRA employs an inclusive M&E system that reflects the complementarities and synergies that are inherent in a partnership involving national agricultural research institutes, other government organizations, NGOs, extension service providers, and the private sector.

Based on the principles of PM&E, the PABRA system actively engages different partner groups in defining what will be evaluated, who will take part, when evaluation will take place, what quantitative and qualitative methods will be used to collect and analyze information, and how findings will be consolidated.

A PM&E facilitator guides the group through the generation of a results framework and measurement plan and also manages the group dynamics and social and political issues that arise when stakeholders having different information needs, priorities, and expectations are all involved in M&E. Some of the immediate results are a mutually defined framework for results-based management (RBM) in the form of a program logic model; a performance measurement framework, which provides guidelines for monitoring results; and review processes organized as workshops and fora.

These results provide PABRA with a platform that enables other partners in the region and beyond to participate in the alliance. PABRA's RBM framework also accommodates projects funded by specific donors, such as the work of the Sub-Saharan Africa Challenge Program on developing market, gender, and institutional arrangements for integrated research for development.

PABRA's social environment facilitates the introduction of new technologies and other innovations; its stakeholders are more tolerant of new ideas that emerge from discussions of research results and lessons learned. PABRA's member countries find it easy to replicate successful implementation of technologies and methods in other countries, thus boosting the rate at which innovations are taken up across the region.

Approaches such as participatory variety selection and private–public partnerships aimed at widening access to improved seed are still relatively new to the national institutions that are PABRA members. But some countries have quickly come to value and adopt these approaches based on reviews of case studies and lessons learned.

general trends in knowledge management and then looks into various aspects and applications of knowledge management and sharing as well as their respective tools and methods. These include: (1) participatory research communication and documentation; (2) open access to research outputs as well as to broadband tele-communications channels; (3) research project collaboration; and (4) information and communications technologies for development (ICTs4D).

Recent trends

Organizations engaged in research for development are necessarily knowledge organizations. Their core business is to combine primary information—data—with experience, context, interpretation, and reflection to generate what has been referred to as "tacit" knowledge (Nonaka, 1994). This knowledge is intended to help users make better-informed decisions and take appropriate actions.

Recent trends in knowledge management suggest that this is no longer a top-down process but rather has become a participatory activity, in which the role of management is to "make it possible for staff to act as the managers of their knowledge" (Wenger, 2004). Knowledge management has thus shifted from a managerial and technology-heavy discipline to one that centers on learning by doing and collective reflection and innovation (Hall, 2006). This shift has profound implications for the relevance of knowledge management to issues such as sustainability and equity in research for development. It has also created new opportunities to reach the intended users of new knowledge.

New opportunities for learning

Technology changes people's behavior, and new behaviors, in turn, create new contexts for technological innovation. Much the same thing happens with knowledge management.

The International Telecommunication Union (ITU, 2010) states that continuous improvement in connectivity has turned the internet into a general-purpose technology like electricity. By 2010, two billion people had access to the internet, and five billion had mobile phone subscriptions. This has created new opportunities for providing broad access to scientific knowledge around the world. Even so, significant barriers remain, such as a lack of content in multiple languages and limited access to broadband infrastructure.

Improved connectivity has also given rise to significant progress in technology-enabled human interactivity, providing new possibilities for the online co-creation, discussion, and promotion of content across organizational and geographical boundaries. The emergence of web 2.0 technologies has created an unprecedented entry point for practicing horizontal and decentralized communication and collaborative learning, which are crucial for multi-stakeholder and network-based activities such as agricultural research for development.

But not all knowledge management happens virtually. On the contrary, much experience and many studies suggest that face-to-face communication is crucial for creating new types of collegial relationships and fostering more-creative scientific collaboration because it creates the trust and other conditions needed for effective flow of knowledge among teams and partners (Staiger et al., 2005).

Knowledge management in research for development

The scientific community has not been quick to pick up on the opportunities created by these trends. Rather, it continues to rely on a few, traditional vehicles for sharing and validating new knowledge that involve relatively poor interaction. The most important of these are experiment replication, publication of research results in peer-reviewed journals, literature searches, and formal communication at conferences and workshops.

Many scientists worry that more open and rapid sharing of research under way might not only undermine the quality of its outputs but also make it impossible to publish the results in peer-reviewed journals. These still constitute the ultimate proof of high-quality science and therefore strongly influence researchers' incentives. However, there are many promising paths for combining traditional and modern vehicles for knowledge sharing. A recent working paper from the World Bank (McKenzie and Özler, 2011), for example, shows that blogging about a scientific paper causes a massive increase in the number of times the abstract is viewed and downloaded during the month after publication.

The principles, methods, and tools of knowledge management are designed to support collective action and learning. Their application in research for development not only creates a more positive environment for eco-efficient agriculture but also enhances research impact in concrete ways by involving users. It is particularly important to mainstream and apply in all areas of agricultural research the four knowledge management applications described in the sections that follow.

Participatory research documentation and communication

Over the past five years or so, new knowledge management tools and methods have widened the horizons of research communications. Communicators and knowledge management practitioners are moving from unidirectional use of almost exclusively agricultural media towards bottom-up communications (Shaxson, 2011), using interactive media and multimedia to engage users and enhance the adoption of research results.

Social media are providing endless possibilities for stakeholder engagement. Among the most popular channels are Wikipedia (24 million articles in approximately 270 languages), YouTube for videos (60 hours of video uploaded per minute), Twitter for microblogging (one billion tweets posted per week), Facebook for social networking (1 billion active users), WordPress for blogging (over 1 million posts daily). These figures give a perspective on the potential for engaging users on almost any issue or activity.

To exploit the power of social media, one must continuously cultivate relationships and networks virtually. This involves "social media listening" (i.e., posting and replying to comments); using information technology (IT) to monitor and optimize the use of social media (e.g., search engine optimization); combining social media with traditional media (such as radio, the press, and conferences); and providing high-level content to position issues among user communities, with the aim of opening dialogue instead of trying to sell an organization or product.

The use of communications as a strategic pathway for engaging stakeholders has profound implications for an organization's web publishing strategy. Rather than just serve as a mechanism to diffuse information, the web can promote interaction and learning in relation to research processes and products. Such an approach should have these three features:

1. **A mix of media:** Content is displayed using the most convenient media (photos on Flickr, PowerPoint presentations on Slideshare, and so forth) and from there fed into corporate web sites and other media. This mix of media enhances access to the information and multiplies the possibilities for users to find it through search engines.
2. **Alternatives to "all-rights-reserved" licensing:** A key issue for online interactivity is Creative Commons licensing, which provides simple and standardized alternatives to traditional copyright. Allowing users to remix, adapt, and reuse information creates the basic conditions for knowledge to travel from one user to another, which is essential for learning and innovation.
3. **No divide between internal and external communications:** Communication must start with teams and partnerships if it is to support the whole process of multi-stakeholder research for development rather than just promote final products. Such communication implies a blurring of the boundaries between internal and external communications (Manning-Thomas and Porcari, 2010). Web sites should provide windows onto unfinished research processes that have high social engagement value (such as photos, testimonials, documentation of monitoring and evaluation processes, trip reports, and reporting on live events) and allow multiple users to post content. Password-protected information is restricted to confidential information, such as primary research databases or financial and management information.

Communication units and staff have to acquire new skills so as to incorporate social-media practices and tools into their day-to-day work and promote these among staff and partners, with explicit support from management.

Open access

Although the scientific outputs of public international research are considered global public goods, access to them may be limited for various reasons. The information may not be available in public repositories; access to it may be blocked by the copyright restrictions of peer-reviewed journals; or key information may not be available in the languages of intended users (Arivananthan et al., 2010).

Access to research outputs is the first condition for learning and capacity strengthening. The Coherence in Information for Agricultural Research for Development (CIARD) initiative indicates useful pathways and provides step-by-step guides for creating favorable institutional conditions (such as licensing) for collecting and preserving research outputs (e.g., through digitization of older outputs and use of digital repositories) and for making content widely accessible on the web (e.g., through "self-archiving," which allows for publishing of a preprint or postprint of scientific papers submitted for publication in peer-reviewed journals or conference and workshop proceedings).

Easy access to information further depends on Information Technology (IT) infrastructure and broadband internet access. Improvements in these areas can make the internet available to all staff of an organization, better enabling them to promote its products and achievements. To create entry points for open access requires corresponding institutional policies and incentives.

Research project collaboration

Working in multidisciplinary global partnerships requires a change in individual computer work habits. Online collaborative tools (such as Google applications and wikis) and practices can be used to share work in progress, encourage regular feedback, and improve the use and reuse of information as well as to create and facilitate online communities. Recent experience demonstrates that these practices support the emergence of an ongoing learning process (Staiger-Rivas et al., 2009). They enhance team integration, engagement, and involvement and ultimately research impact. The organizational benefits include staff empowerment, increased transparency, and stronger internal capacity, which should contribute to organizational development and change.

Whether collaborative tools thrive in an organization depends on several key factors. IT support services must be open to software solutions that are non-proprietary and must move to a technology stewardship role (Wenger et al., 2009). The adoption of collaborative online tools requires patience and careful facilitation of the change in work habits. Before collaborative web tools are introduced, their purpose must be clearly identified, and the key people involved must understand and agree with their use.

Information and communication technologies for development (ICTs4D)—site-specific eco-informatics

The emergence of the internet made possible widespread use of new ICTs4D, based on the principle of connectivity as a powerful means of inclusion (www.ictinagriculture.org). The spread of mobile phones is rapidly overcoming barriers to access. According to ITU (2010), 86% of the world's population is covered by a mobile phone network, and 75% of the world's rural population is covered by a mobile phone signal.

The tools and possible applications for agriculture are limitless, including market information and financial services, land administration and risk management, advisory services, decentralized data collection, and many more. ICTs4D should contribute importantly to eco-efficiency in agriculture by providing smallholder farmers with inexpensive access to information that can help make their production more productive and competitive.

However, as often occurs with the introduction of new technology, adoption of ICTs4D has been hindered by flaws in the approach used. Initial efforts have focused too much on IT infrastructure and on access to hardware and have taken a top-down approach to information diffusion.

In order for projects involving ICTs4D to be more effective, they must meet several conditions (Rogers, 2011). First, the application must be relevant to the local context and correspond to local needs. Second, the available IT infrastructure capacity must be well understood. Third, steps must be taken from the start to ensure sustainability. And finally, applications must be developed in a participatory manner, focusing on what farmers have to offer, avoiding condescending assumptions, and providing opportunities for social learning.

In research centering on eco-efficient agriculture, ICTs4D should be a key focus for the development of applications that facilitate the creation and use of new knowledge. Several organizational changes are required to promote a knowledge-sharing culture:

- A clear commitment to horizontal forms of management and related incentives. Hierarchical handling of communications and decision making, in contrast, keeps staff from discussing research for development openly and learning from peers.
- A sustained effort to promote changes in national and regional research organizations that enhance knowledge flow between stakeholders, based on shared values and knowledge management practices.
- A shift in the orientation of IT personnel away from technology control and towards technology stewardship, aimed at helping users choose the best technologies, including those needed to foster knowledge sharing.

These changes are critical for strengthening capacity to achieve eco-efficient agriculture through active knowledge management and sharing in research for development.

The Way Forward

This chapter has examined various approaches by which stakeholders can mainstream eco-efficiency in the agricultural development agenda. To achieve this transformation will require a multidisciplinary effort to build innovation capacity through joint learning and stakeholder empowerment.

One of the chapter's key assumptions is the need for a systemic approach to research for development that acknowledges the complexity of research and of the interactions between those involved. Creating the institutional arrangements needed for such an approach is a huge challenge. How can organizations incorporate the notion of eco-efficiency into their work? How can they learn and adapt continuously? How can they handle complex processes and interactions efficiently? How can they walk their talk? Horton (2012) spells out the institutional changes that are required:

Becoming a learning organization frequently requires:

- Shifting from closed innovation strategies to more open ones
- Shifting from simple, hierarchical organizational designs to more complex ones that feature multidisciplinary teamwork and multi-organizational collaboration
- Shifting from traditional planning and implementation systems to adaptive management
- Expanding evaluation functions to encompass both accountability and learning
- Incorporating societal concerns and priorities into performance incentives.

Eco-efficiency starts at home

As agricultural research organizations begin to mainstream eco-efficiency, they can start by examining their internal capacities, policies, administrative processes, incentive structures, and other organizational arrangements. Suggested steps are to:

- Develop a good understanding of eco-efficiency internally through training, workshops, field visits, and seminars.
- Adopt appropriate business practices and policies, such as carbon-footprint standards and eco-efficient practices in office-space design, renovation, construction, landscaping, and supply-chain management.

- Widen staff skills to include new capacities in areas such as facilitation, mentoring, networking, and social media. These are essential for working with diverse stakeholders to identify and develop new opportunities for technical and institutional innovation (Horton, 2012).
- Use monitoring and evaluation methods and tools for learning and adaption in conjunction with traditional approaches centering on accountability and return on investment.
- Design incentives (such as appraisal criteria, competitions, rewards, and small grants) to promote teamwork, open knowledge sharing, and a practical focus on development results.
- Allow for adaptive management (Horton, 2012) in terms of planning, budgeting, reporting, and career development.

Organizations that take these steps can strengthen their capacity for innovation through a combination of bottom-up and top-down approaches, involving dialogue between staff, partners, and other stakeholders. Such organizations can learn from past experience and make better decisions that focus their research more sharply on development outcomes, leading to eco-efficient agriculture.

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Appendix 1
Acronyms, Abbreviations, and Technical Terminology

Entities

ACA	Asociación Cultivadores de Arroz [*Rice Farmers Association, Uruguay*]
ACPA	Asociación Correntina de Plantadores de Arroz [*Corrientes Rice Planters Association, Argentina*]
AGRA	Alliance for a Green Revolution in Africa
ASTI	IFPRI's Agricultural Science and Technology Indicators
AVRDC	The World Vegetable Center
BMZ	Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung [*German Federal Ministry for Economic Cooperation and Development*]
BVL	Bundesamt für Verbraucherschutz und Lebensmittelsicherheit [*German Federal Office of Consumer Protection and Food Safety*]
CATALIST	IFDC's project Catalyze Accelerated Agricultural Intensification for Social and Environmental Stability
CATIE	Centro Agronómico Tropical de Investigación y Enseñanza [*Tropical Agricultural Research and Higher Education Center*]
CCAFS	CGIAR Research Program on Climate Change, Agriculture and Food Security
CFC	Common Fund for Commodities
CGIAR	CGIAR is a global research partnership for a food secure future
CIALCA	Consortium for Improving Agriculture-based Livelihoods in Central Africa
CIARD	Coherence in Information for Agricultural Research for Development
CIAT	Centro Internacional de Agricultura Tropical [*International Center for Tropical Agriculture*]
CIRAD	Centre de Coopération Internationale en Recherche Agronomique pour le Développement [*French Agricultural Research Centre for International Development*]
CORPOICA	Corporación Colombiana de Investigación Agropecuaria [*Colombian Corporation of Agricultural Research*]
CRP-RTB	CGIAR Research Program on Roots, Tubers and Bananas
CRRI	Central Rice Research Institute, India
CRS	Catholic Relief Services
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAPA	CIAT's Decision and Policy Analysis Research Area
DGD	Belgian Directorate-General for Development Cooperation
EMBRAPA	Empresa Brasileira de Pesquisa Agropecuária [*Brazilian Agricultural Research Corporation*]
ESSP	Earth System Science Partnership
EX-ACT	FAO Ex-Ante Appraisal Carbon-Balance Tool

FACE	Free-Air Carbon dioxide Enrichment
FAO	Food and Agriculture Organization of the United Nations
Fedearroz	Federación Nacional de Arroceros [*Colombia's National Federation of Rice Growers*]
FLAR	Fondo Latinoameriano para Arroz de Riego [*Latin American Fund for Irrigated Rice*]
GENARROZ	Genética del Arroz C. por A. [*Genetics of Rice joint-stock company*]
GHCN	Global Historical Climatology Network
GRDB	Guyana Rice Development Board
GRDC	Grains Research & Development Corporation
IAASTD	International Assessment of Agricultural Knowledge, Science and Technology for Development
ICA	Instituto Colombiano Agropecuario [*Colombian Institute of Agriculture*]
ICAS	Institute for Climate and Atmospheric Science
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IDIAP	Instituto de Investigación Agropecuaria de Panamá [*Panama Institute of Agricultural Research*]
IFDC	International Fertilizer Development Center
IFPRI	International Food Policy Research Institute
IITA	International Institute of Tropical Agriculture
ILAC	Institutional Learning and Change Initiative
ILRI	International Livestock Research Institute
IMF	International Monetary Fund
INIA	Instituto Nacional de Investigación Agropecuaria [*National Agricultural Research Institute, Uruguay*]
INIAP	Instituto Nacional Autónomo de Investigaciones Agropecuarias [*National Autonomous Institute for Agricultural Research, Ecuador*]
INTA	Instituto Nacional de Tecnología Agropecuaria [*National Institute of Agricultural Technology, Argentina*]
IPCC	Intergovernmental Panel on Climate Change
IRGA	Instituto Rio Grandense do Arroz [*Rio Grande Rice Institute, Brazil*]
IRRI	International Rice Research Institute
ITPGRFA	International Treaty on Plant Genetic Resources for Food and Agriculture
ITU	International Telecommunication Union
JIRCAS	Japan International Research Center for Agricultural Sciences
KREI	Korea Rural Economic Institute
N2Africa	Project on putting nitrogen fixation to work for smallholder farmers in Africa
NIES	Nanjing Institute of Environmental Sciences
NRI	Natural Resources Institute
OECD	Organisation for Economic Co-operation and Development
PABRA	Pan-African Bean Research Alliance
REDD+	United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries
SECOM	Secretariat of Social Communication of the Presidency of Brazil
SENUMISA	Semillas del Nuevo Milenio S.A. [*Seeds of the New Millennium S.A.*]
SLU	Sveriges lantbruksuniversitet [*Swedish University of Agricultural Sciences*]

SNV	Netherlands Development Organisation
SÖL	Stiftung Ökologie & Landbau [*Foundation Ecology and Agriculture*]
Swisscontact	Organization of the Swiss private sector for development cooperation
TSBF-CIAT	CIAT's Tropical Soil Biology and Fertility Research Area
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNESCO	United Nations Educational, Scientific and Cultural Organization
VLIR	Vlaamse Interuniversitaire Raad [*The Flemish Interuniversity Council*]
WBCSD	World Business Council for Sustainable Development
WCED	World Commission on Environment and Development
WHO	World Health Organization

Other abbreviations and acronyms

AE	Agronomic efficiency
AFLP	Amplified fragment length polymorphism
AR4	Fourth assessment report of the Intergovernmental Panel on Climate Change
AWD	Alternate wetting and drying
BNI	Biological nitrification inhibition
CA	Climatic aptitude [in chapter 3]
CA	Conservation agriculture [in chapter 7]
CBA	Cost–benefit analysis
CDM	Clean development mechanism
CEA	Cost–efficiency analysis
CIAL	Comité de investigación agrícola local [*Local agricultural research committee*]
CLFIS	Crop–Livestock–Forestry Integration System
CNV	Copy-number variation
CRU	Climate Research Unit
DNA	Deoxyribonucleic acid
DR Congo	Democratic Republic of the Congo
DSSAT	Decision Support System for Agrotechnology Transfer
EU	European Union
GCM	Global climate model
GDD	Growing degree days
GDP	Gross domestic product
GHG	Greenhouse gas
GMO	Genetically modified organism
GSOD	Global Surface Summary of Day
HPR	Host plant resistance
ICM	Integrated crop management
ICTs4D	Information and communications technologies for development
IFS	Integrated farming system
IGP	Indo-Gangetic Plain
INM	Integrated nutrient management
IPM	Integrated pest and disease management
IRR	Internal rate of return
ISC	Integrated Striga control
ISFM	Integrated soil fertility management
IT	Information technology
KM	Knowledge Management
LAC	Latin America and the Caribbean
Lao PDR	Lao People's Democratic Republic
LCA	Life-cycle analysis
LCC	Leaf-color chart
LUI	Land use intensity
M&E	Monitoring and evaluation
MAC	Marginal abatement curves
masl	Meters above sea level
MJ	Megajoule
MRL	Maximum residue level
NDVI	Normalized differential vegetation index
NGO	Non-governmental organization

NPV	Net present value
NUE	Nitrogen use efficiency
NUV	Equivalent uniform annual net value
OEC	Operational effective costs
PE	Physiological efficiency
pers. comm.	Personal communication
PES	Payment for environmental services
PFP	Partial factor productivity
PLA	Participatory learning and action
PM&E	Participatory monitoring and evaluation
QTL	Quantitative trait loci
R&D	Research and development
R2	Coefficient of determination
R4D	Research for development
RAPD	Random amplified polymorphic DNA
RBM	Results-based management
RCT	Resource-conserving technologies
RE	Recovery efficiency
RT&B	Roots, tubers, and bananas
SCAR	Sequence-characterized amplified region
SED	Standard error of difference
SNF	Symbiotic nitrogen fixation
SNP	Single nucleotide polymorphism
SOC	Soil organic carbon
SOM	Soil organic matter
SRES	Special report on emissions scenarios - A special report of the Intergovernmental Panel on Climate Change
SSA	Subsaharan Africa
SSP	Single super phosphate
SSR	Simple sequence repeat
TLU	Tropical livestock unit
UK	United Kingdom
USA	United States of America
wt.	Weight
ZT	Zero tillage

Chemical elements and compounds

Al	Aluminium
C	Carbon
Ca	Calcium
K	Potassium
Mn	Manganese
N	Nitrogen
O	Oxygen
P	Phosphorus
Zn	Zinc
CH_4	Methane
CO_2	Carbon dioxide
HCN	Hydrogen cyanide
N_2O	Nitrous oxide
NO	Nitric oxide
NO_2	Nitrogen gas
NO_3	Nitrate

Pests and diseases

BCMNV	Bean common mosaic necrotic virus
BCMV	Bean common mosaic virus
BGMV	Bean golden mosaic virus
BGYMV	Bean golden yellow mosaic virus
CBSD	Cassava brown streak disease
CMD	Cassava mosaic disease
DM	Downy mildew
ELS	Early leaf spot
GRD	Groundnut rosette disease
LLS	Late leaf spot
TYLCD	Tomato yellow leaf curl disease
TYLCV	Tomato yellow leaf curl virus

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