Inland Valley Characterization Report 3

Regional Characterization of Inland Valley Agroecosystems in Sikasso, Mali and Bobo-Dioulasso, Burkina Faso

through Integration of Remote Sensing Global Positioning System, and Ground-Truth Data in a Geographic Information Systems Framework

Prasad S. Thenkabail and Christian Nolte

Inland valley watershed system highlighting the valley bottoms

- *Uplands*
- *Intensely cultivated valley bottoms*
- *Moderately cultivated valley bottoms*
- *Uncultivated valley bottoms*

International Institute of Tropical Agriculture with Inland Valley Consortium

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Preface

The inland valley characterization report series of the Resource and Crop Management Division (RCMD) is intended for the wide dissemination of results of research about the inland valley agroecosystems of sub-Saharan Africa. These research reports will address issues relating to characterization and diagnosis concerning inland valley agroecosystems. The range of subject matter is expected to contribute to existing knowledge on improved agricultural principles, practices, and policies that affect the sustainable development of these potentially rich and productive agroecosystems of sub-Saharan Africa. These reports summarize results of studies by IITA researchers and their collaborators; they are generally more substantial in content than journal articles.

The research report series is aimed at scientists and researchers within the national agricultural research systems of Africa, the international research community, policy makers, donors, and international development agencies.

Individuals and institutions in Africa may receive single copies free of charge by writing to:

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I

Introduction and Background

The International Institute of Tropical Agriculture (IITA) is currently conducting a characterization of inland valley agroecosystems in West and Central Africa (Izac et al. 1991). A macro-(subcontinental) scale stratification (level I) of West and Central Africa led to a map of 18 agroecological and soil zones (figure 1). Each of these zones represents an area of more than 10 million ha (table 1). Overall, about 36 million ha spread across 11 countries of West and Central Africa are targeted for level II characterization. This will be mesoscaled (regional, semidetailed). For this purpose, 11 Landsat Thematic Mapper (TM), and 5 *Le système pour l'observation de la terre* (SPOT) high resolution visible (HRV) data bases were acquired in sample areas of level I. Each satellite scene over a particular area will be referred to as a study area. Each study area covers one or more of IITA's level I agroecological and soil zones (figure 1 and table 1).

The objectives of level II (regional) characterization include inventorying and mapping inland valley bottoms; determining land use and land cover of inland valleys and their uplands; determining the cultivation intensities relative to settlements and the road network; mapping the spatial distribution of inland valley systems; testing hypotheses, such as relationships between upland/inland valley cultivation patterns and cultivation patterns within and across agroecological zones; and determining the location of potential benchmark research sites for technology development activities.

The level II characteristics are reported with respect to the subcontinental (level I) agroecological and soil zones (figure 1) and also with respect to geological and geomorphological land regions of the Wetland Utilization Research Project (WURP) in West Africa (Windmeijer and Andriesse 1993). The location of satellite images on the WURP map is shown in figure 2.

Readers of this inland valley characterization report are referred to the resource and crop management research monograph of IITA by Thenkabail and Nolte (1995a) for the background, definitions (see illustration in figure 3), rationale, objectives, approach, and methodology of level II characterization which remain consistent across the study areas. A brief overview of this methodology is described below.

1. The valley bottoms were delineated using image enhancement, display, and digitizing techniques.
2. The valley fringes were mapped by delineating the areas immediately adjoining valley bot-toms, by using a search radius on either side of valley bottoms equivalent to the mean fringe width measured during the ground-truthing.
3. Land-use/land-cover studies were carried out separately for valley bottoms, valley fringes, and uplands using unsupervised classification of multiband data.
4. Several other characteristics such as the percentage area of inland valleys cultivated at varying distances from roads and settlements, have been extracted through spatial data manipulation (e.g., boolean logic interpolation and contiguity analysis) of Geographic Information Systems (GIS) datalayers.
5. A methodology for key site/key watershed selection was developed based on expert knowledge and GIS modeling of various spatial datalayers.
6. Ground-truth data, Global Positioning Systems (GPS) data, and other data sources were incorporated into digital image analysis.

Analyses were conducted using Earth Resources Digital Analysis System (ERDAS 1991).

Table 1 Parameters describing the level I agroecological and soil zones

Level I AEZ[a]	Agroecological zone according to IITA's definition	LGP[b] (days)	Major FAO soil grouping[c]	Area[d] (million ha)
1	northern Guinea savanna	151-180	Luvisols	25.2
2	southern Guinea savanna	181-210	Luvisols	18.4
3	southern Guinea savanna	181-210	Acrisols	12.4
4	southern Guinea savanna	181-210	Ferralsols	11.9
5	southern Guinea savanna	181-210	Lithosols	10.7
6	Derived savanna	211-270	Ferralsols	47.2
7	Derived savanna	211-270	Luvisols	24.9
8	Derived savanna	211-270	Nitosols	14.2
9	Derived savanna	211-270	Arenosols	14.0
10	Derived savanna	211-270	Acrisols	11.7
11	Derived savanna	211-270	Lithosols	10.8
12	Humid forest	> 270	Ferralsols	150.1
13	Humid forest	> 270	Nitosols	27.2
14	Humid forest	> 270	Gleysols	19.2
15	Humid forest	> 270	Arenosols	18.9
16	Humid forest	> 270	Acrisols	18.0
17	Midaltitude savanna		Ferralsols	45.4
18	Midaltitude savanna		Nitosols	12.3

Notes:

a. AEZ: level I agroecological and soil zones

b. LGP: length of growing period

c. Names refer to the soil classification scheme of FAO/UNESCO (1974)

d. The area figures are for West and Central Africa and were determined using the AREA procedure of IDRISI (1992)

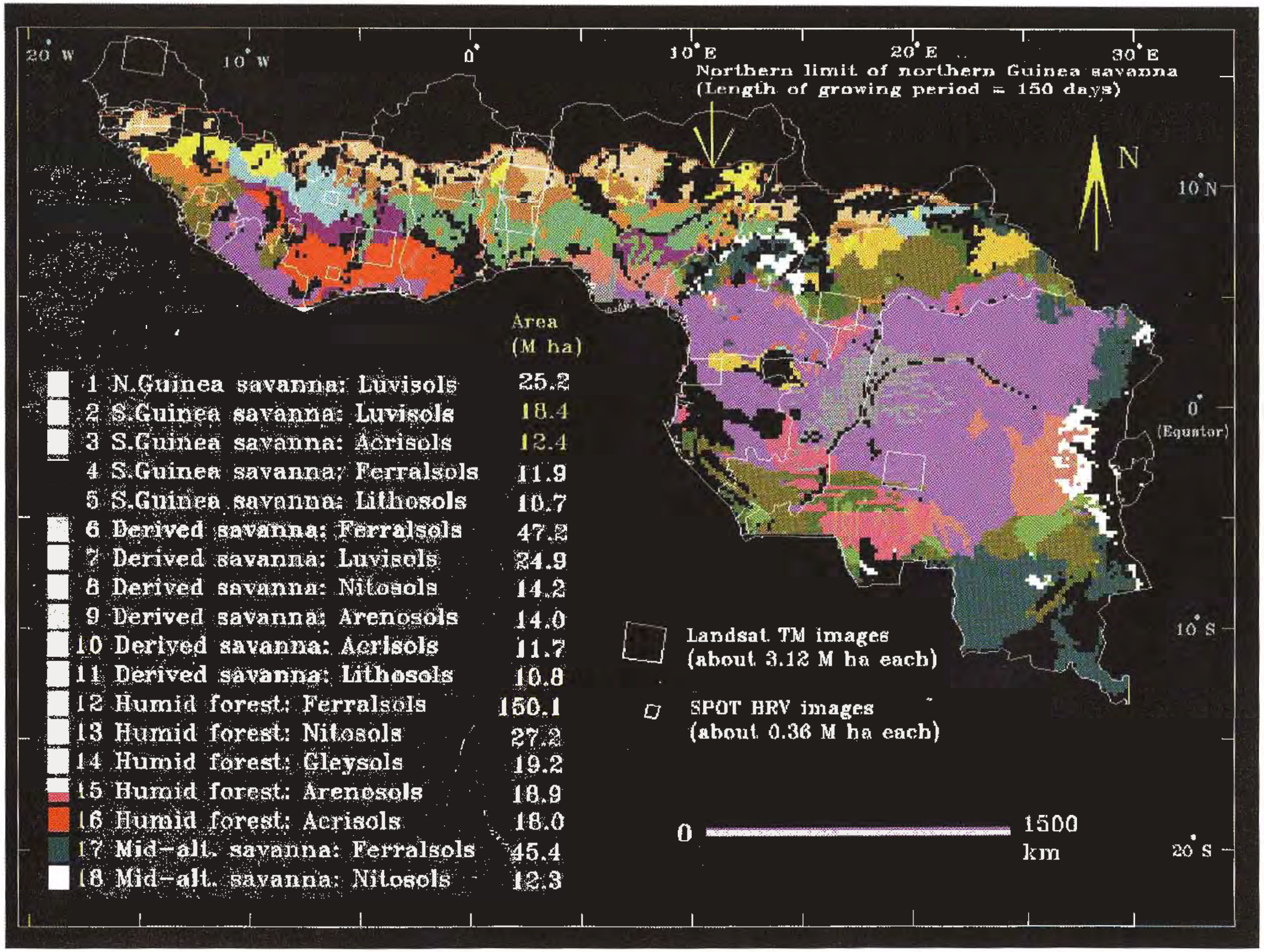

Figure 1. Landsat TM and SPOT HRV acquisitions for level II characterization of inland valley agroecosystems located in the level I map of agroecological and soil zones in West and Central Africa

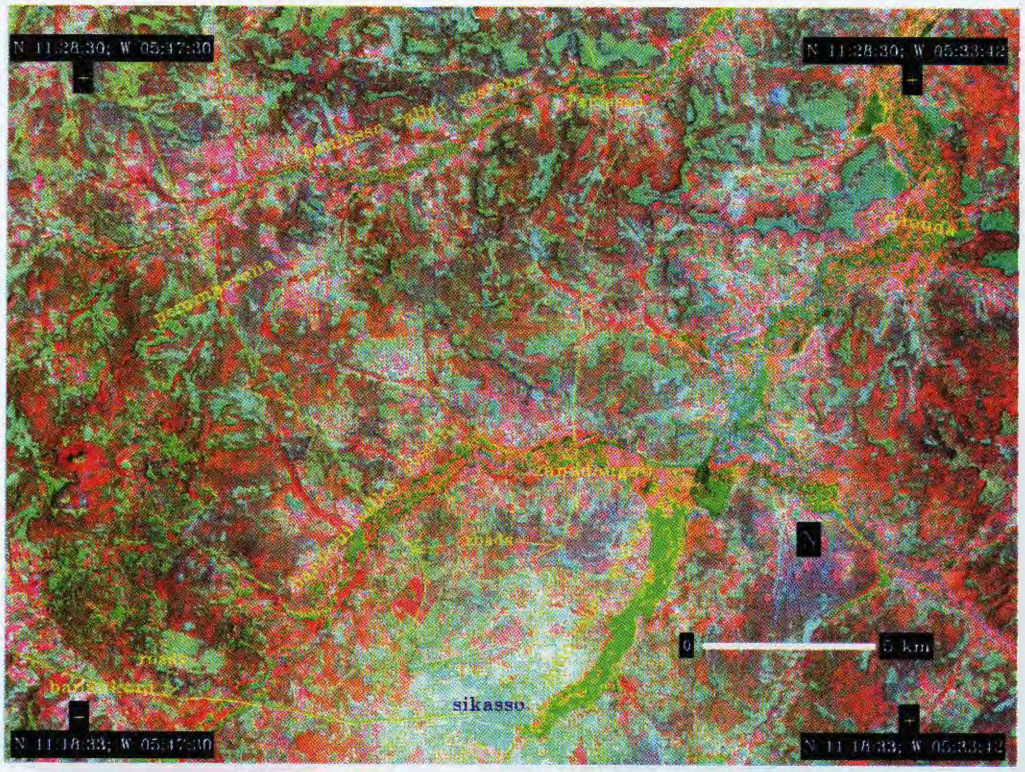

Plate 1 False color composite of TM4 (red), TM3 (green), TM5 (blue) highlighting the broad inland valley bottoms near Sikasso, Mali. For example, the bottom widths of valley bottoms were: 250-500 m in Peniassa, and 500-800 m in Banankoni and Lotio

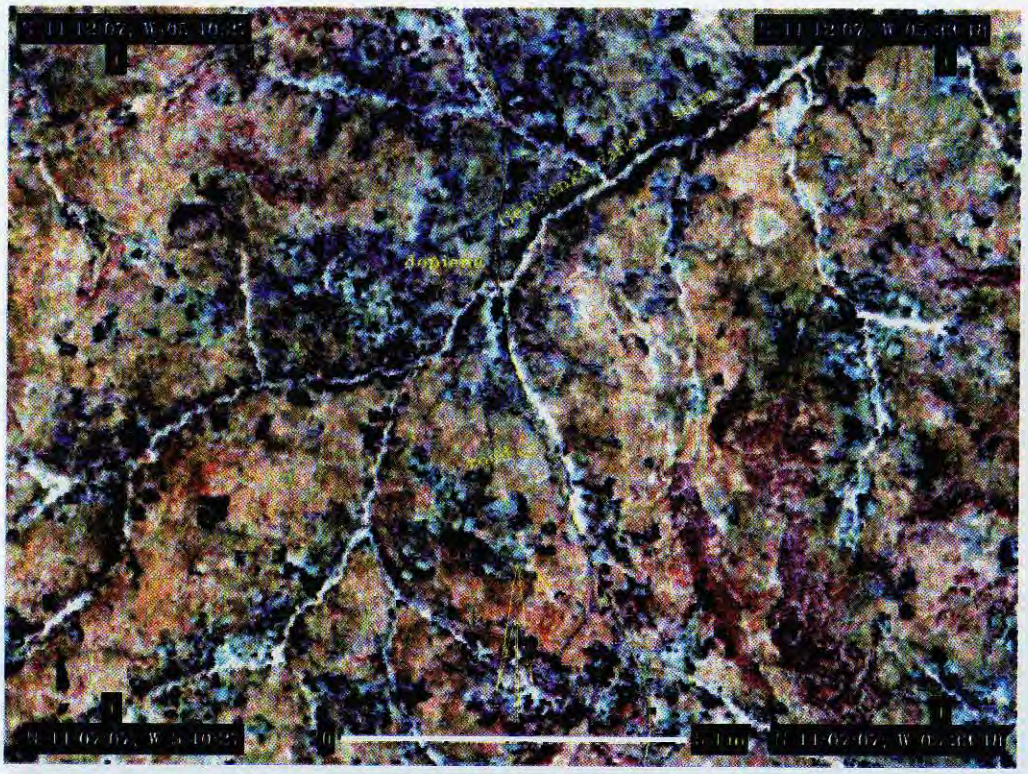

Plate 2 Distinguishing the inland valley bottoms from the valley fringes and uplands through ratio RGB image of TM4/TM7 (red), TM4/TM3 (green), and TM4/TM2 (blue)

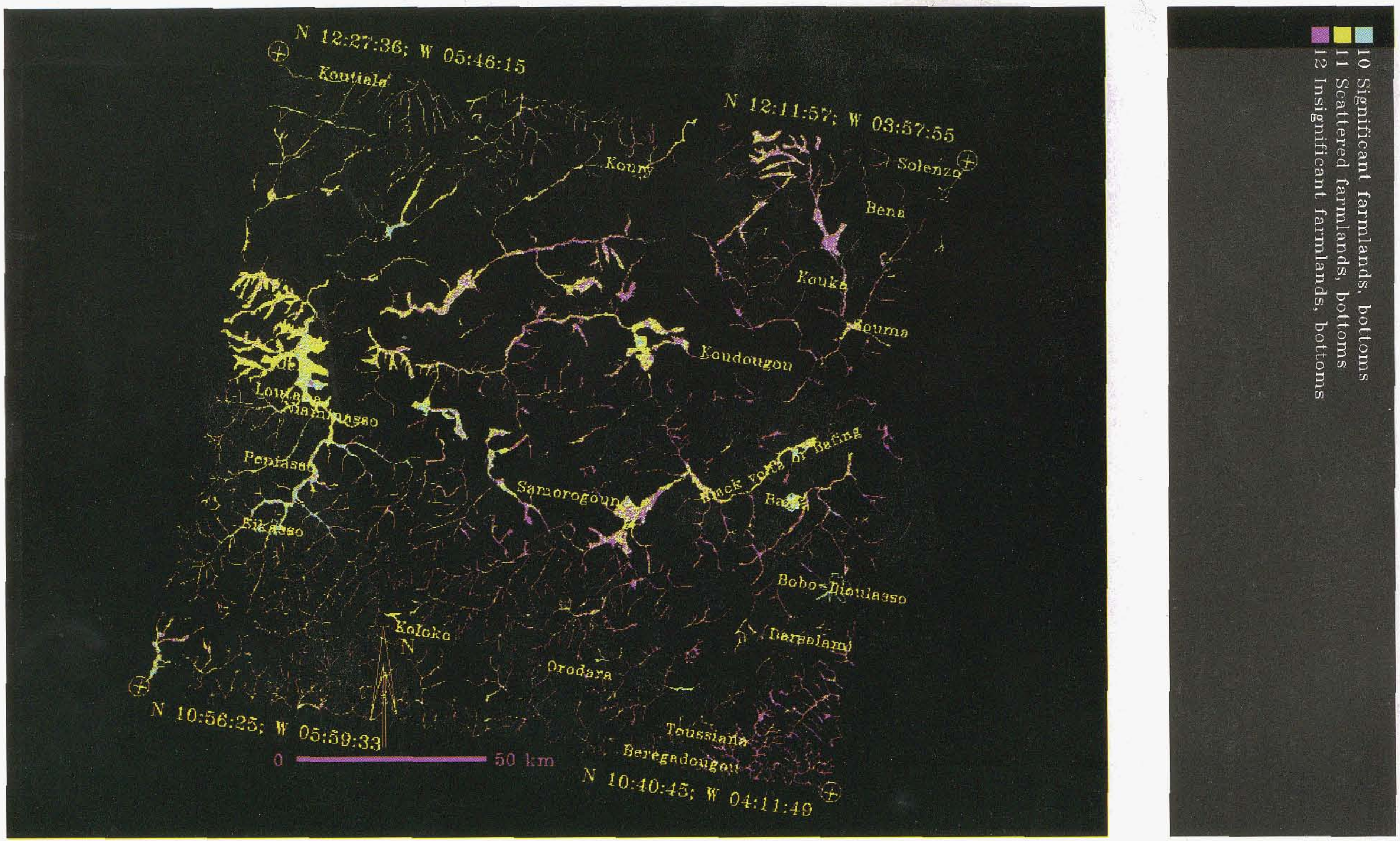

Plate 3 Inland valley bottoms delineated and mapped for the entire study area of Landsat Path: 197, Row: 52 (Sikasso, Mali; and Bobo-Dioulasso, Burkina Faso) along with land-use classes. Valley bottoms were 8.6 percent (0.27 million ha) of the total study area (3.13 million ha)

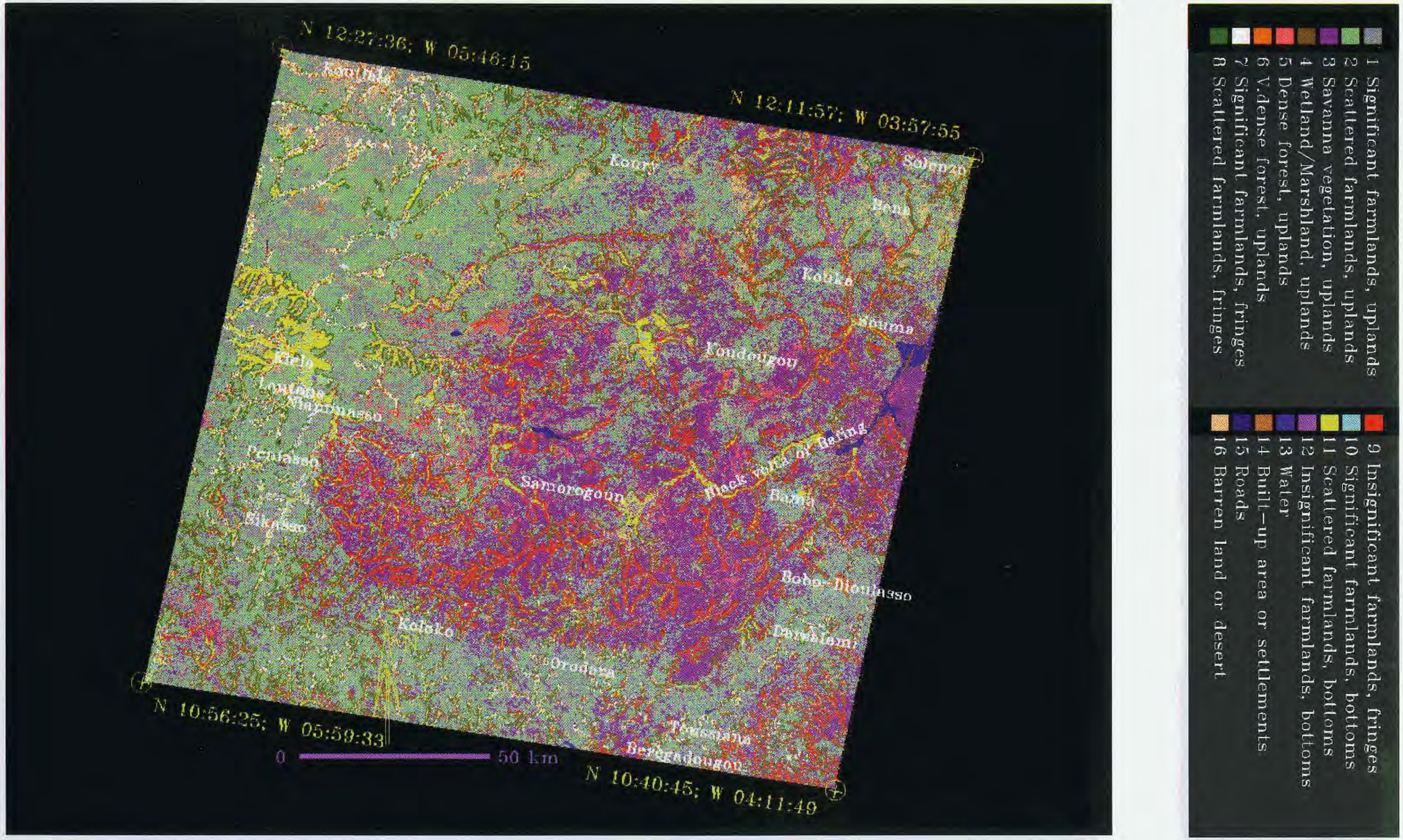

Plate 4 Land-use classes mapped for the different components of the toposequence (valley bottoms, valley fringes, and uplands) for the entire study area of 3.12 million ha covered by Landsat Path: 197, Row: 52 in Sikasso, Mali; and Bobo-Dioulasso, Burkina Faso (see the legend for color key)

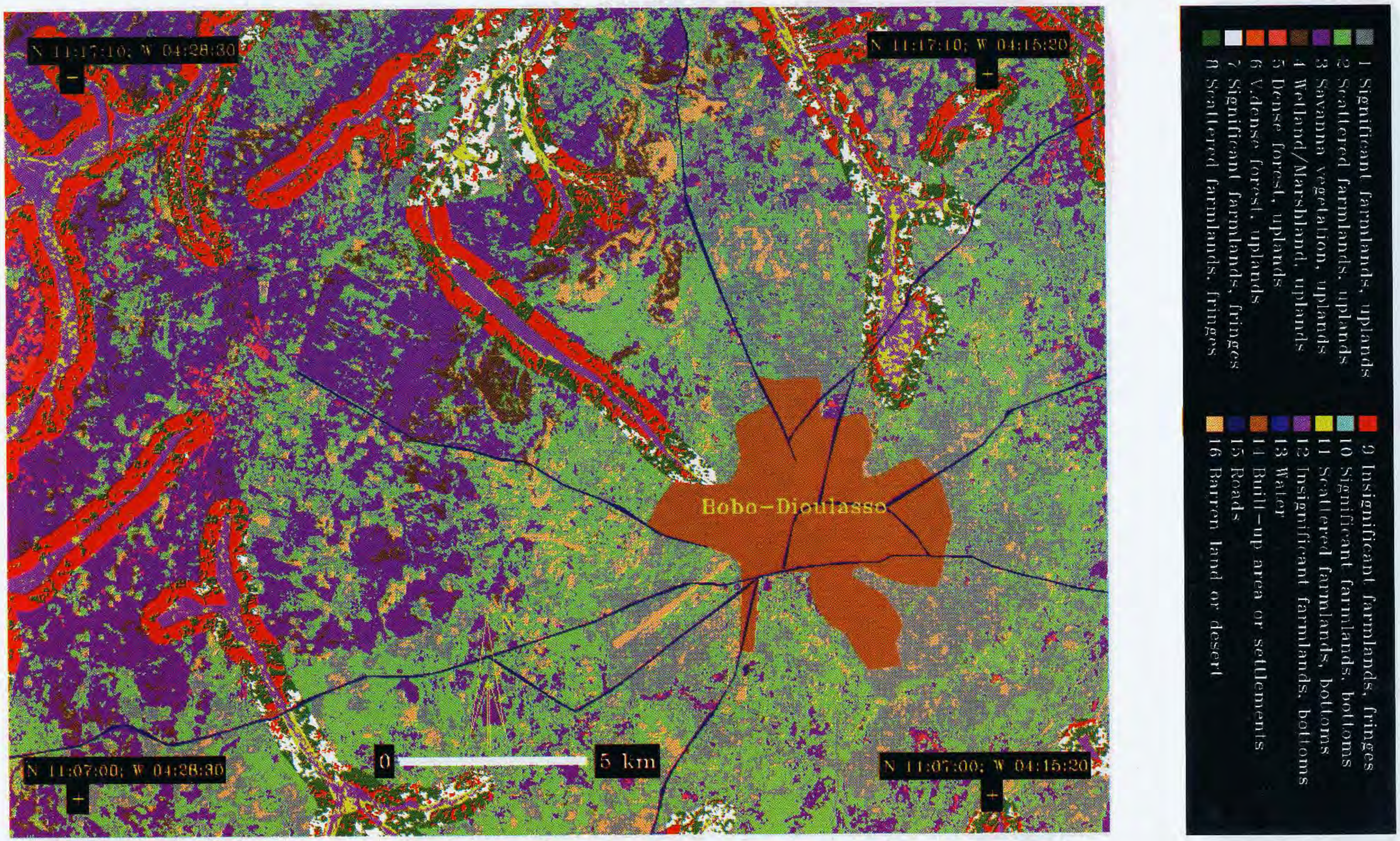

Plate 5 Land-use classes in a sub-area near Bobo-Dioulasso, Burkina Faso. Note the relatively high density of cultivation across the toposequence in areas adjoining roads and settlements (see legend for the color key)

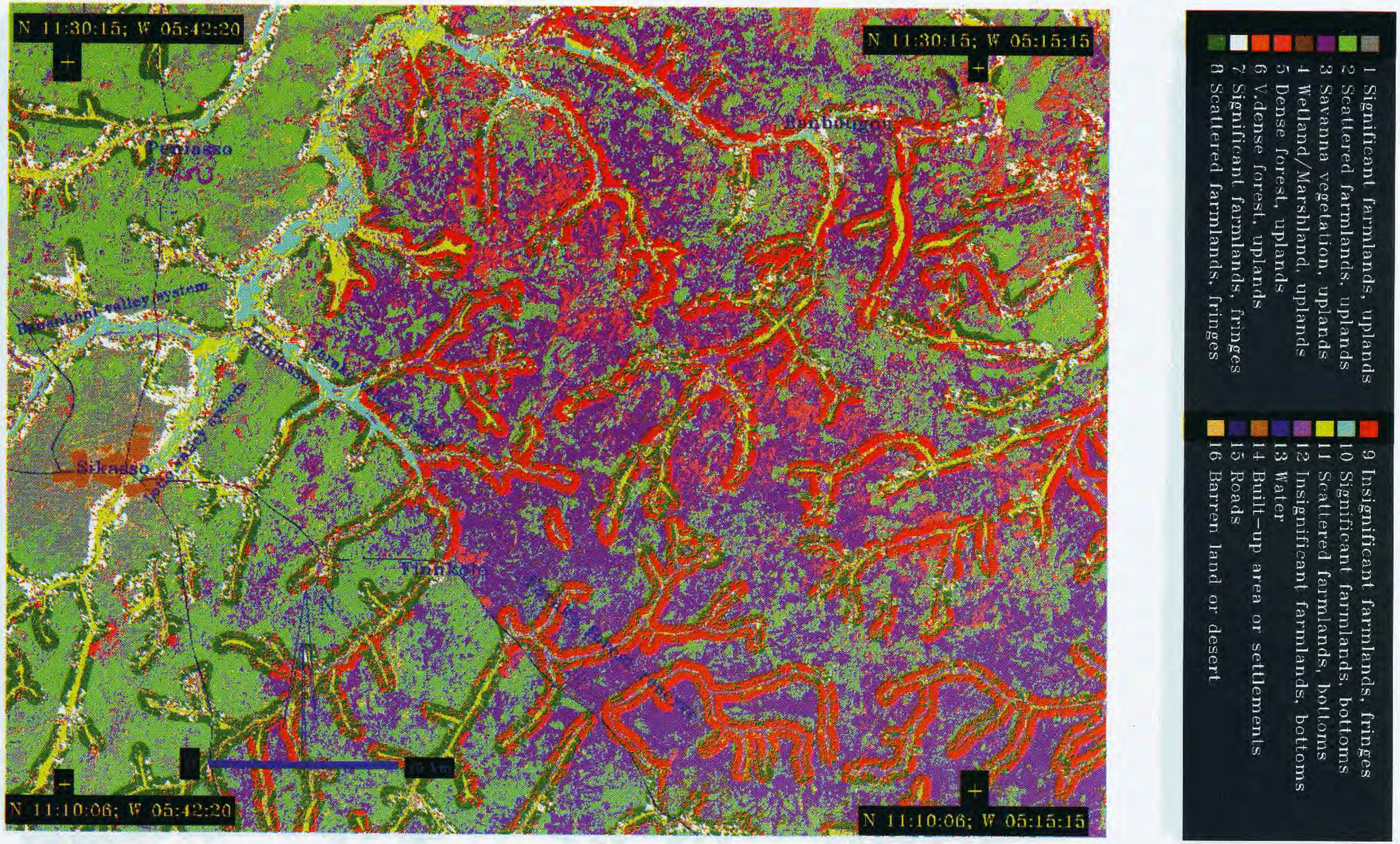

Plate 6 Land-use classes in a sub-area near Sikasso, Mali. Note the dramatic differences in land use in the Farako reserve forest and in the area in the immediate neighbourhood of Sikasso (see legend for color key)

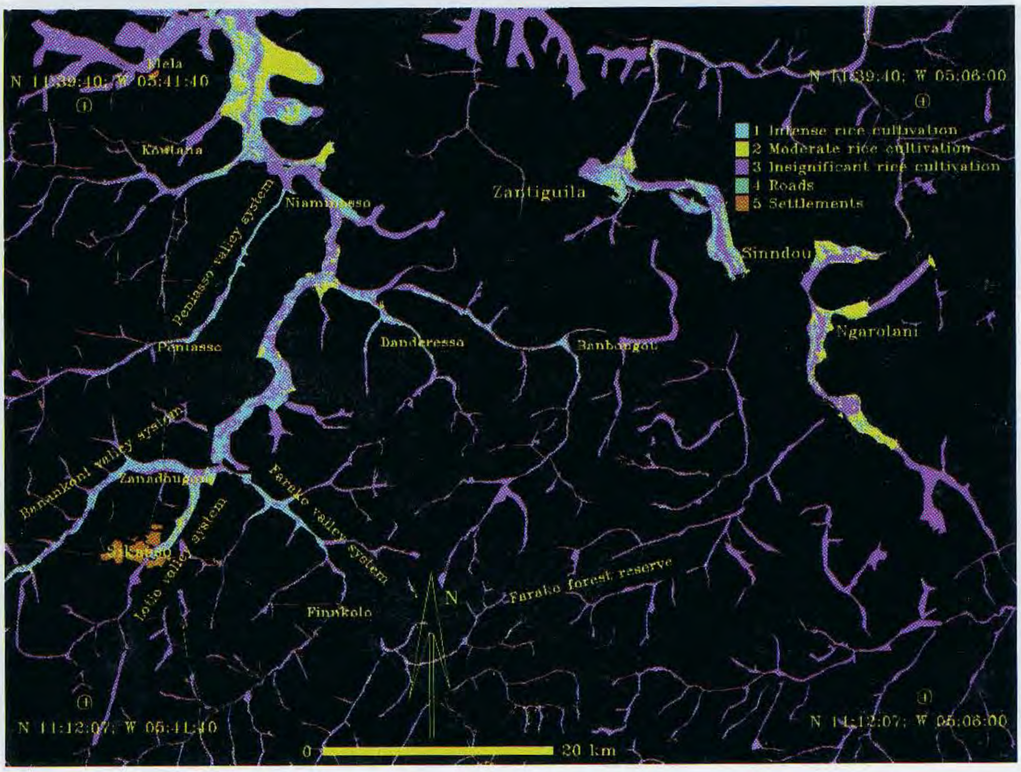

Plate 7 Rice cultivation in valley bottoms surrounding Sikasso, Mali. Observe the contrast between the valley bottoms of the Farako forest reserve and the valley bottoms near and north of Sikasso

Plate 8 Location of potential benchmark research sites for technology development research activities in the study area covered by Landsat TM Path: 197, Row: 52 (Sikasso, Mali, Bobo-Dioulasso, Burkina Faso)

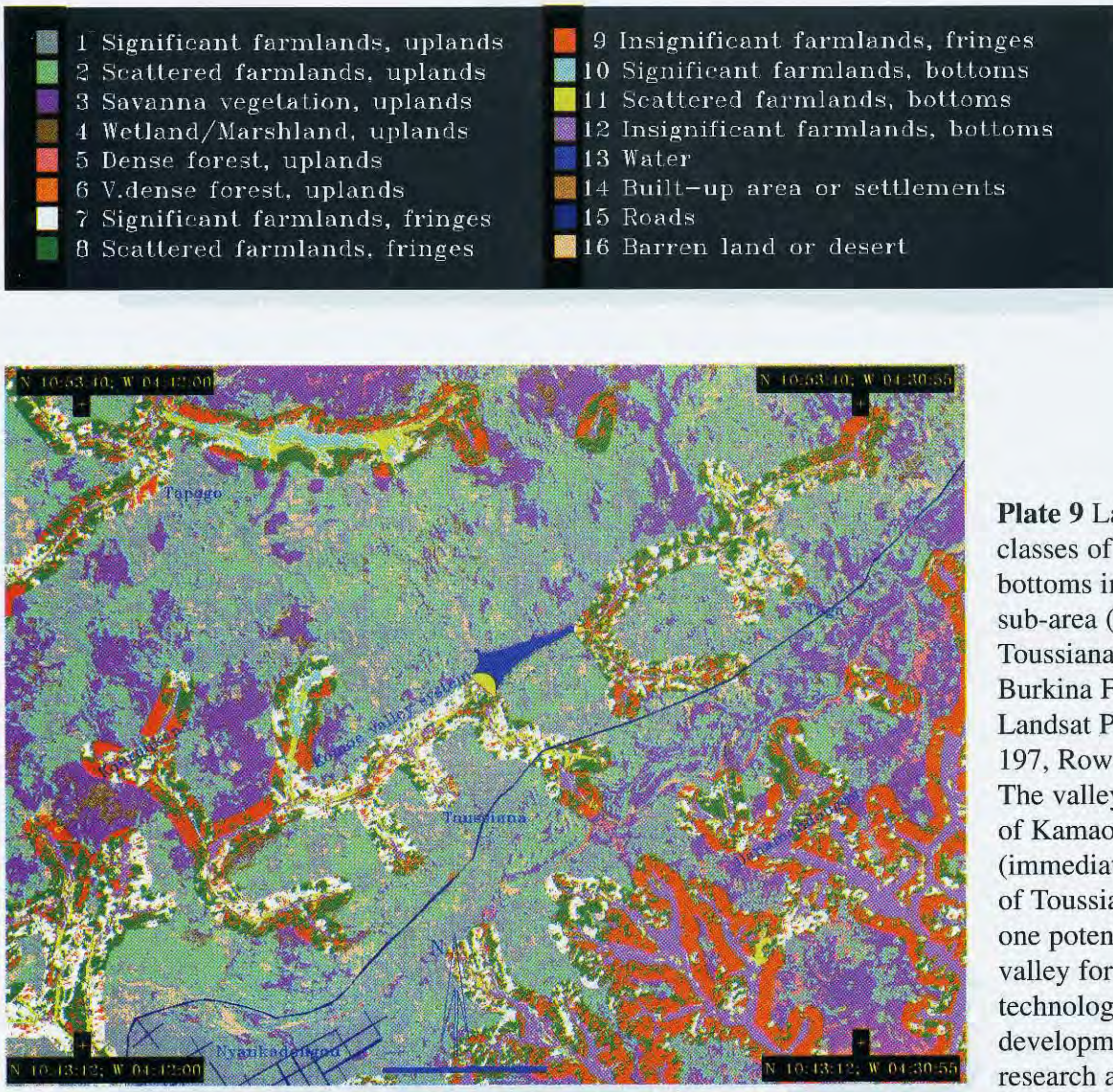

Plate 9 Land-use classes of valley bottoms in a sub-area (near Toussiana, Burkina Faso) of Landsat Path: 197, Row: 52. The valley system of Kamao (immediate west of Toussiana) is one potential valley for technology development research activity

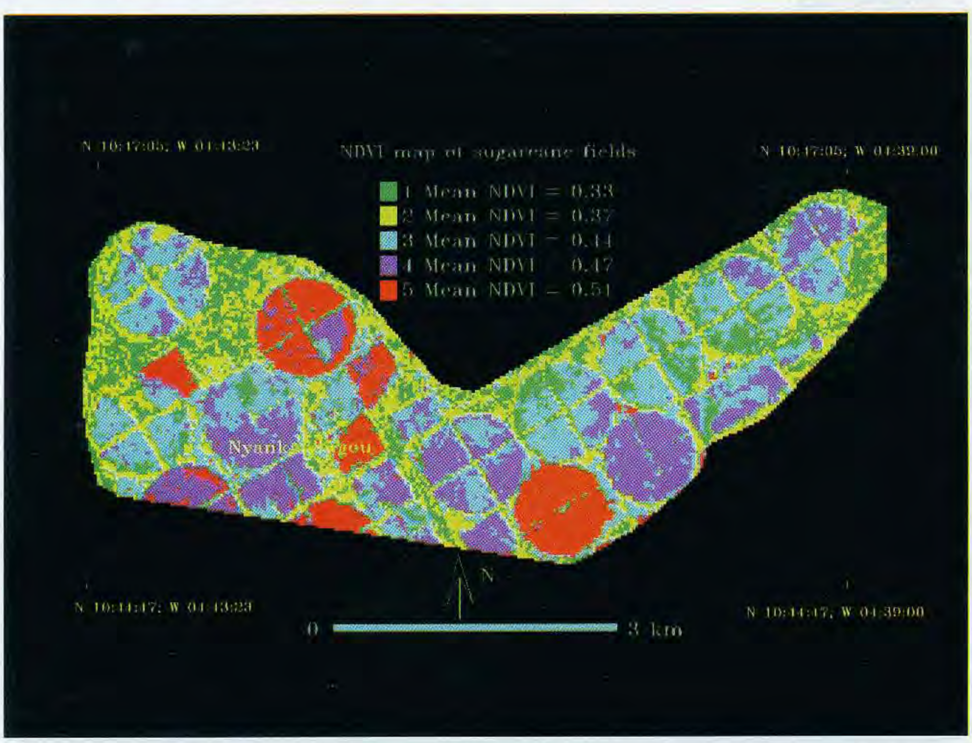

Plate 10 Normalized difference vegetation index (NDVI) map of sugarcane fields in a sub-area (Nyankadougou, South-west of Bobo-Dioulasso) of Landsat Path: 197, Row: 52. The higher the NDVI, the greater is the biomass and vigour, leading to a greater production in yield

Plate 11 Spatial distribution of areas of significant upland cultivation (see white color) in the entire study area of Landsat TM path: 197, row: 52. Areas inside the polygons indicates insignificant cultivation

Plate 12 Spatial distribution of areas of significant cultivation (see white color) in inland valleys (valley bottoms plus valley fringes) in the entire study area of Landsat TM path: 197, row: 52. Areas inside the polygons indicates insignificant cultivation

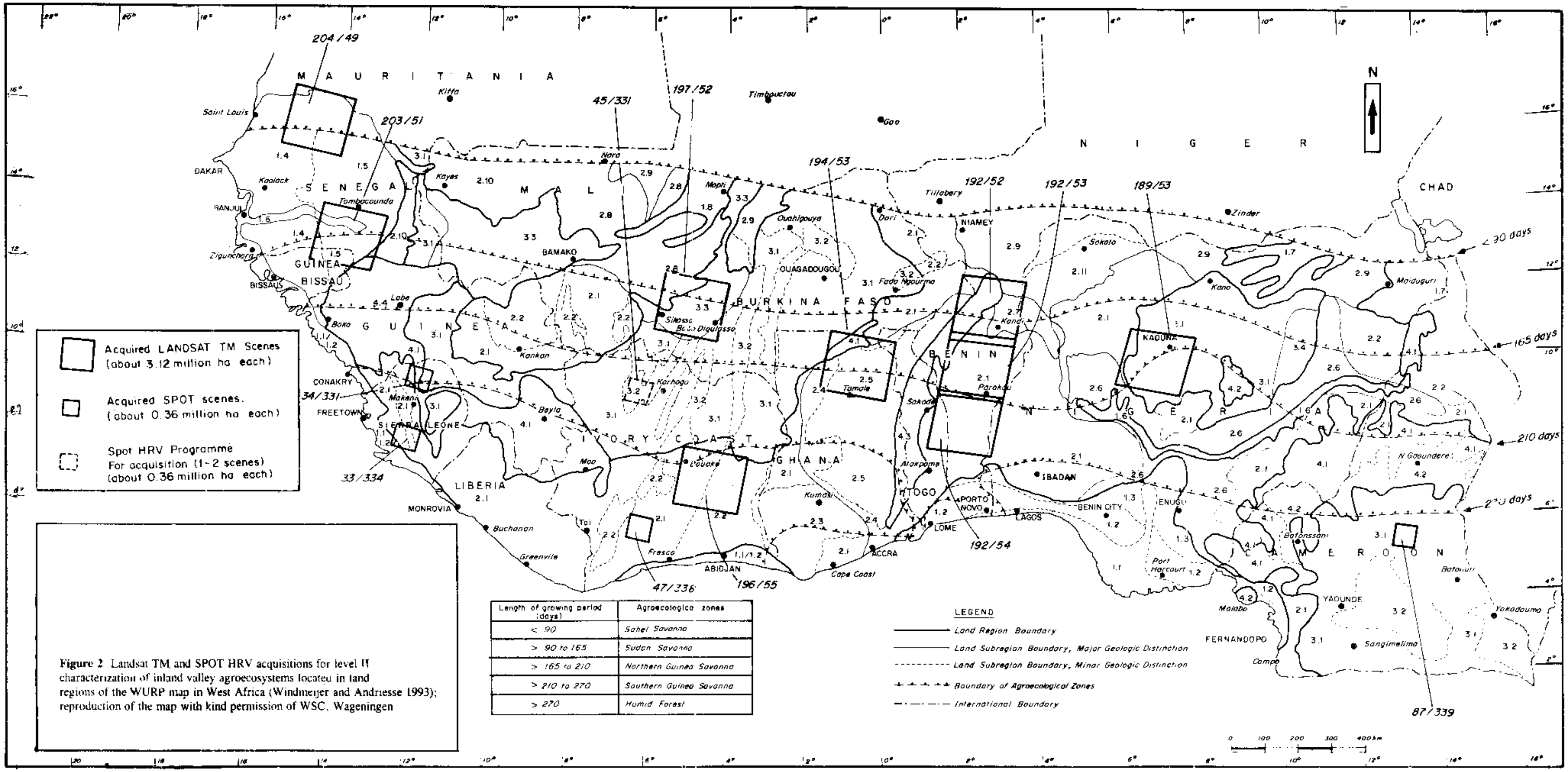

Figure 2 Landsat TM and SPOT HRV acquisitions for level II characterization of inland valley agroecosystems located in land regions of the WURP map in West Africa (Windmeijer and Andriesse 1993); reproduction of the map with kind permission of WSC, Wageningen

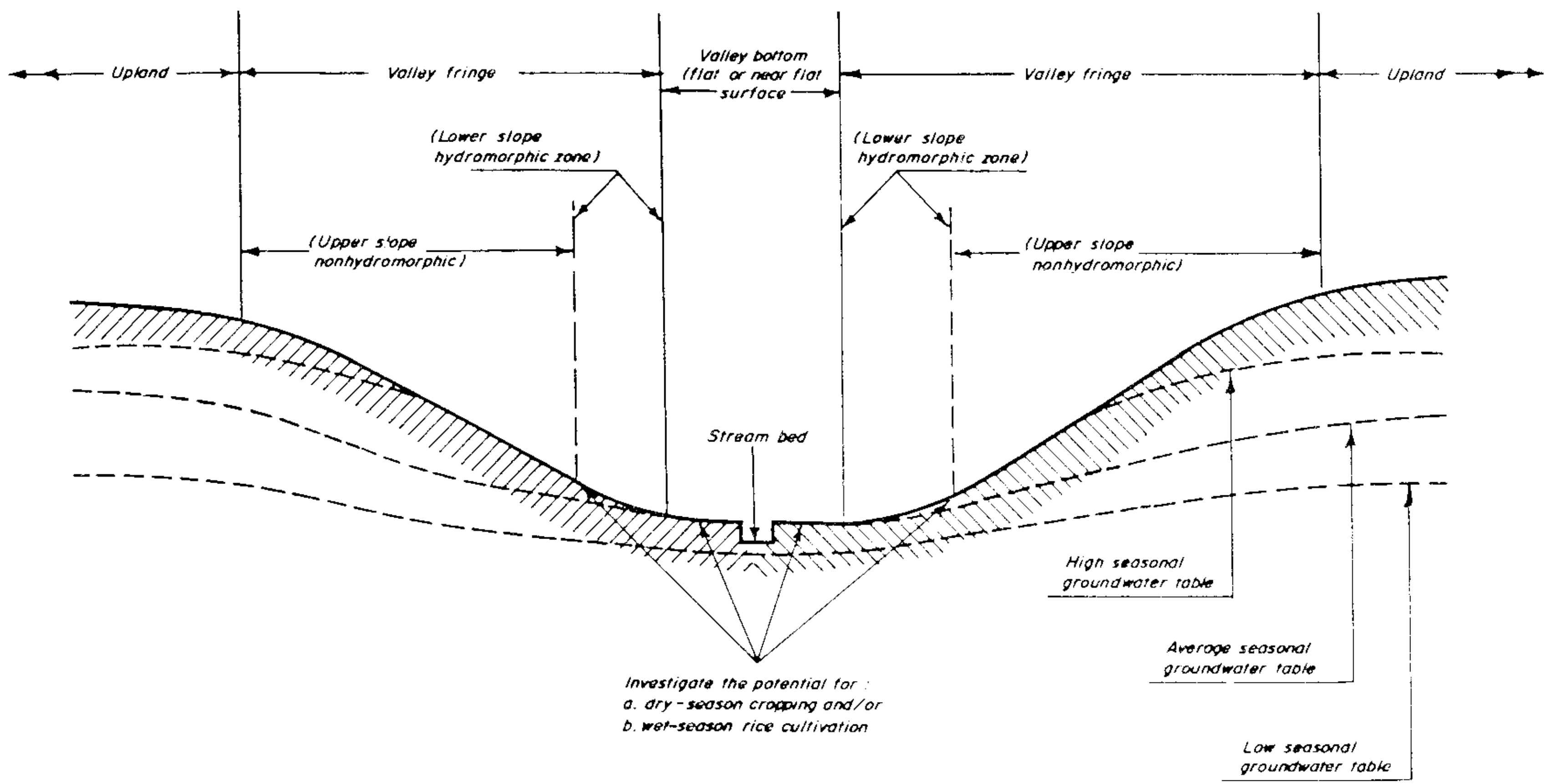

Figure 3 Cross-section showing a model inland valley as defined in this study

II

Study Area and Satellite Data Characteristics

The results of each study area are published in the Inland Valley Characterization Report series. Each publication addresses the envisaged common objectives and adopts a consistent approach and methodology as presented in the monograph by Thenkabail and Nolte (1995a). This study was conducted in parts of Burkina Faso and Mali covered by Landsat-5 TM path:197, row:52 of Landsat's world reference system (see figure 4 for location and geographic co-ordinates). The study area covers about 3.13 million ha. The major settlements in the study area are Bobo-Dioulasso, Orodara, Koloko, Toussiana, Koudougou, Kouka, and Faramana in Burkina Faso; and Sikasso, Kle'la, Koutiala, Karangana and Kouri in Mali (figure 4).

2.1 Macroscale zones covered by the study area

The regional (level II) characteristics are reported with respect to two macroscale zones:
a. IITA's level I agroecological and soil zones (see figure 1 and figure 5);
b. land regions of the WURP report (see figure 2 and figure 6).

Agroecological and soil zones were derived from stratifying West and Central Africa according to two agroecological parameters:
1. IITA's mandate agroecological zones, namely northern Guinea savanna, southern Guinea savanna, derived savanna, and humid forest, which were developed by the Agroecological Studies Unit at IITA (Jagtap, personal communication); the major factor determining a zone is the length of growing period; and
2. soils based on a digitized version of the soil map of the world FAO/UNESCO (1977); the 106 soil units of FAO/UNESCO (1974) had been merged to 23 major soil groupings (e.g., Acrisols, Luvisols, etc.).

These data of agroecological zones and soils were manipulated using a geographical information system (GIS) which resulted in 18 zones, constituting the level I map (figure 1, table 1). Each zone portrays a specific combination of these two factors and represents an area of over 10 million ha in West and Central Africa (see table 1). This study area covers two agroecological and soil zones (AEZs) (see figure 5): AEZ 1 and 2; the rest of the area is not covered by the level I map. The characteristics of AEZ 1 and 2 are given in table 1. The major soil grouping throughout the study area is Luvisols according to the FAO soil classification system of 1974 (FAO/UNESCO 1974). The following land regions are covered by the study area (see table 2):
a. land region 2.8 - Interior Plains with sedimentary deposits as geologic formation
b. land regions 3.1 and 3.2 - Plateaux region with basement complex as geologic formation
c. land region 3.3 - Plateaux region with sedimentary deposits as geologic formation

The process of deriving geologically and geomorphologically determined land regions in West Africa is explained in Hekstra et al. (1983). For a detailed description of these land regions see Windmeijer and Andriesse (1993). The mean population densities in this study area as determined from the WURP report (Hekstra et al. 1983) vary between 5 to 15 (see table 3 and figure 4).

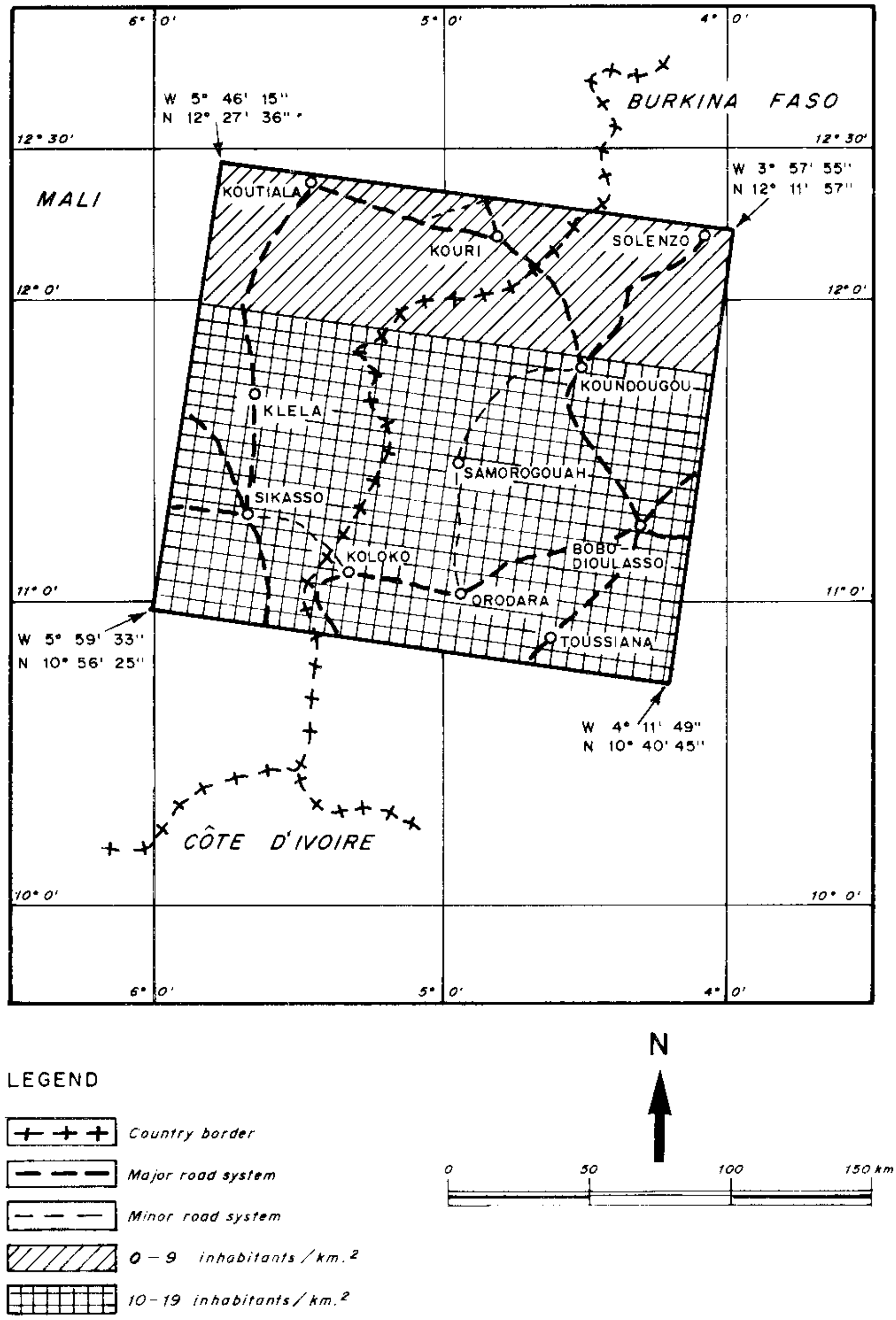

Figure 4 Population density in the study area

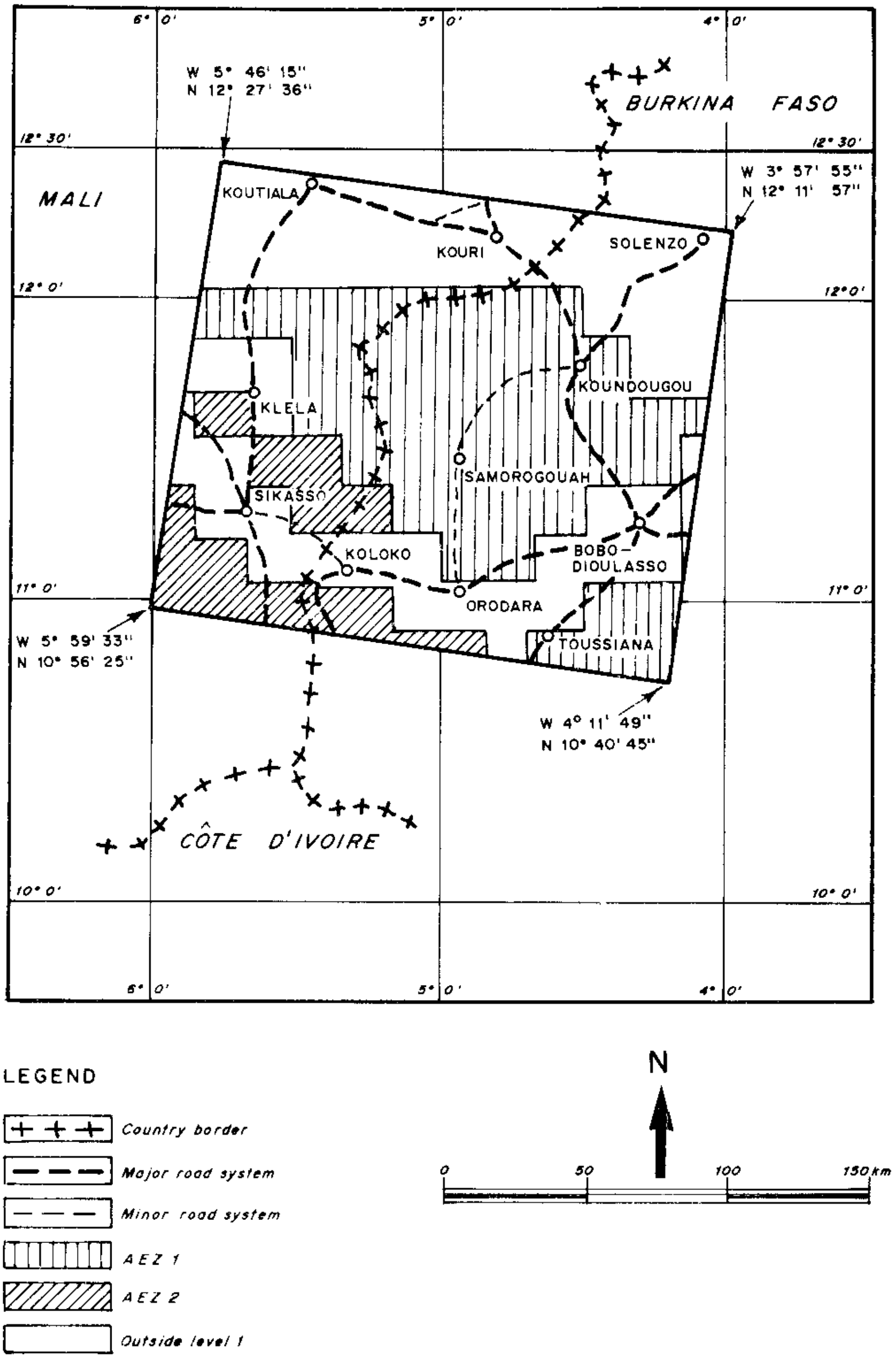

Figure 5 Location of the study area and IITA level I zone

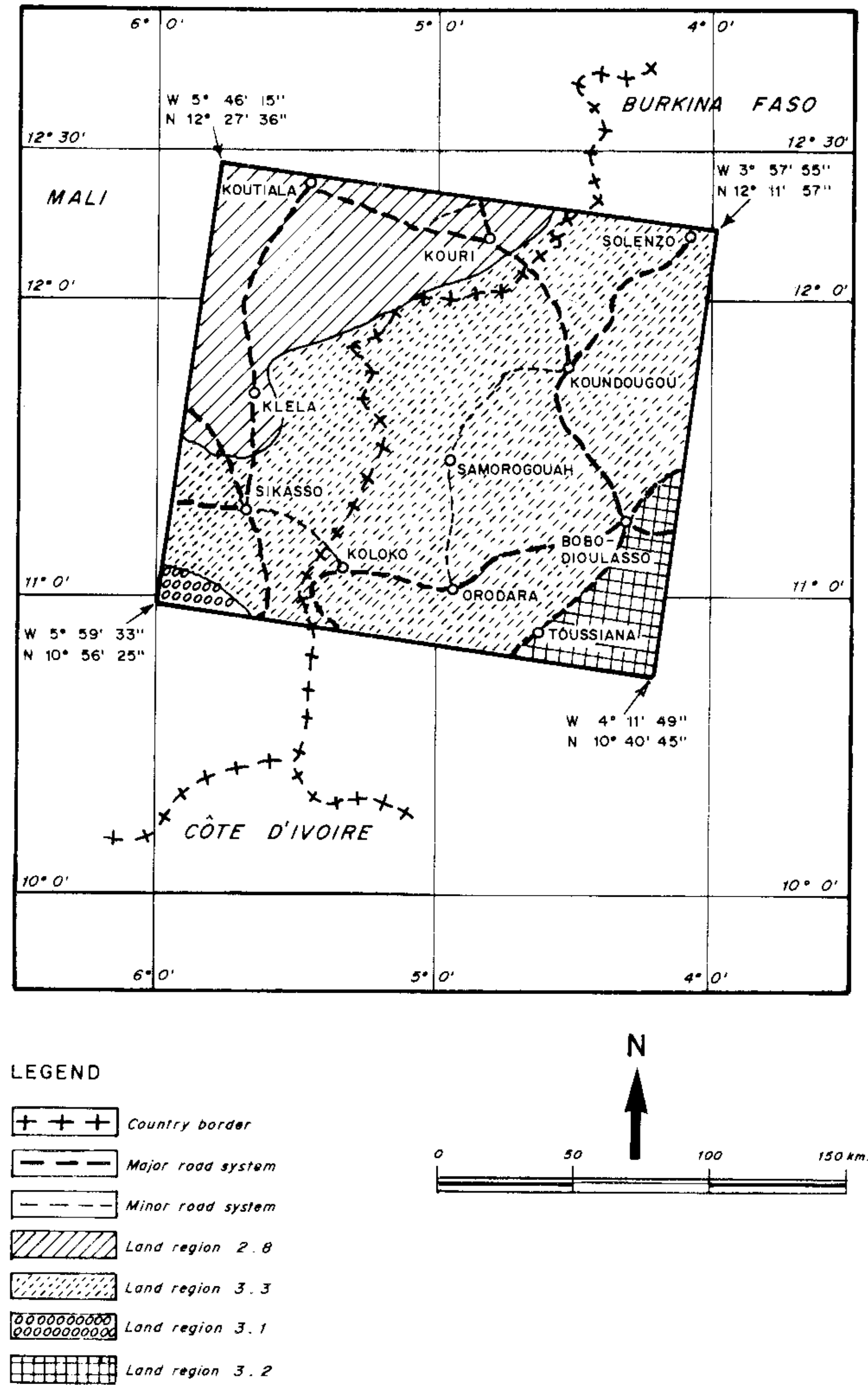

Figure 6 Spatial distribution of the WURP land regions in the study area

Table 2 Legend to the land-regions map of the WURP report - see figure 2 (adapted from Windmeijer and Andriesse 1993)

Map Unit	Geology	Geomorphology	Area (mha)
1.	Land region : COASTAL AND ALLUVIAL PLAINS		
1.1	recent coastal sands + alluvial silts and clays	nearly level to gently undulating	39.7
1.2 to 1.5	tertiary sedimentary deposits	nearly level to gently undulating	
2.	Land region : INTERIOR PLAINS		
2.1	basement complex – lower pre-cambrian: granites, migmatites, gneisses	slightly dissected, with inselbergs, mesas	
2.2	basement complex – middle pre-cambrian: metamorphic rocks	slightly dissected, with inselbergs, mesas	85.2
2.3	basement complex – upper pre-cambrian; metamorphic, sedimentary and volcanic rocks	highly dissected, rolling to steep	
2.4	sedimentary deposits – paleozoic sandstones	dissected and upwarded, gently rolling	
2.5	sedimentary deposits – paleozoic sandstones, shales, mudstones, conglomerates	slightly dissected, nearly level	
2.6	sedimentary deposits – mesozoic sandstones, shales	nearly level to gently undulating	
2.7	sedimentary deposits – mesozoic sandstones, conglomerates	steeply dissected, undulating	66.3
2.8	sedimentary deposits – paleozoic sandstones, tillites	nearly level to gently undulating	
2.9	sedimentary deposits – tertiary sandstones, mudstones, conglomerates	nearly level to gently undulating	
2.10	sedimentary deposits – paleozoic schists, quartzites, sandstones	slightly dissected, with doloritic hills, and mesas	
2.11	sedimentary deposits – sandstone, shales, conglomerates, marls and limestone of different age	dissected, with mesas	
3.	Land region : PLATEAUX		
3.1	basement complex – lower pre-cambrian granites, migmatites, gneisses	slightly dissected, with inselbergs, mesas	74.5
3.2	basement complex – middle pre-cambrian metamorphic rocks	slightly dissected, with inselbergs, mesas	
3.3	sedimentary deposits – paleozoic sandstones	dissected, level to gently rolling	13.1
3.4	sedimentary deposits – tertiary sandstones	dissected, undulating to rolling	
4.	Land region : HIGHLANDS		
4.1	basement complex – lower pre-cambrian undifferentiated granites, migmatites	very steep mountain ranges	
4.2	basement complex of older (pre-cambrian) + younger (jurassic) rocks	rugged, rolling high plateaux	27.2
4.3	basement complex – middle + terminal pre-cambrian; and sedimentary / extrusive formations	strongly faulted	
4.4	sedimentary deposits – paleozoic sandstones, shales	steeply dissected	7.7

Note: Area figures are in million ha; for details refer to Windmeijer and Andriesse (1993), and Hekstra et al. (1983)

Table 3 Population, settlements, and road network in the study area of Landsat TM path:197, row:52 (Bobo-Dioulasso, Burkina Faso; and Sikasso, Mali) with respect to IITA and WURP level I zones

Macroscale zones	Population density (no./km²)	Major settlement (TM data)		Major road network (TM data)	
	WURP[c]	No. of major settlements	Major settlement presence and name (yes/no)	Presence or absence (yes/no)	Density of road network (km/km²)
A. AEZ 1[a]	12	24	Yes. Koundougou, Toussiana	Yes	0.027
B. AEZ 2	15	9	Yes. Klela	Yes	0.022
C. land region 3.3[b]	12	60	Yes: Bobo-Dioulasso, Sikasso, Orodoura Koloko, Kouka, Koudougu	Yes	0.031
D. land region 2.8	7	10	Yes: Klela, Koutiala, Kouri	Yes	0.040
E. Entire study area	11	70	Yes: Bobo-Dioulasso, Sikasso, Orodara, Koloko, Koudougou, Kouka, Faramana, Klela, Kouliala, Kouri	Yes	0.035

Notes:

a. Level I agroecological and soil zones (see figure 1)

b. Geological and geomorphological land regions in West Africa according to Hekstra et al. (1983) and Windmeijer and Andriesse (1993) (see figure 2)

c. Wetland utilization research project (WURP), see Hekstra et al. (1983)

The results and discussions will be presented and discussed for the following zones (see table 4 and figures 5 and 6):

1. Level I zones: AEZ 1 (45% of the study area) and AEZ 2 (12%); and
2. WURP land regions: land region 3.3 (68%) and land region 2.8 (24%); other land regions occupied very low percentages of the overall study area: land region 3.1 (2%) and land region 3.2 (6%), and hence characteristics relative to these two zones were not reported.

The study area comprises two zones with different lengths of growing period: the northern Guinea savanna with 151–180 days and the southern Guinea savanna with 181–210 days (see figure 5 and table 1). Land region 3.3 falls in this study area predominantly in the northern Guinea savanna (figures 5 and 6). The mean vegetation densities were nearly uniform across the different macrozones in the study area (table 5). The Normalized Difference Vegetation Index (NDVI) values of 0.34 to 0.39 (table 5) are indicative of fairly vigorous vegetation. This was mainly due to the date of data acquisition (27 September 1991) which is the peak rainy season in the region with crops in vegetative or critical growth phases. Other vegetation, such as grasses and shrubs, is vigorous to very vigorous in growth.

2.2 Physical characteristics of the study area

2.2.1 Parent material. The study area covers four different land regions (LR) of the WURP map (see figure 2 and table 2, and figure 6). However, two land regions occupy only 2% and 6% of the study area, whereas the major part falls into land region 3.3 (68%), the Plateaux region with sedimentary deposits (paleozoic sandstones) as geological formation. In the northwestern part of figure 6 land region 2.8 occurs (24% of the overall study area). It is part of the Interior Plains region of West Africa with sedimentary deposits (paleozoic sandstones, tillites) as parent material. The geological formations constituting the region are given in figure 7. Much of the study area is covered by sandstones and tillites of Cambrian age. About 90% of the ground-truth sites were located here. According to Simpara (1995) a northwest-southeast axis divides the geologic formations of that region. The sandstone south of Sikasso is of a hard nature whereas north of Sikasso a soft sandstone occurs. Blanchet (1992) sees these changing sandstone characteristics as a major reason for independently circulating subsurface groundwater levels in the region which affects the hydrologic dynamic in inland valleys. The study area is predominantly sandstone with recent alluvial deposits along certain valleys (figure 7). The recent alluvial deposits in the valleys are as a result of periodic flooding in the area. The flooding deposits fertile soil and makes cultivation of rice and other crops extremely attractive.

2.2.2. Soils. According to the classification of the level I map, Luvisols are to be found as the major soil grouping in the study area (see figure 1 and table 1). In reality, the study area is characterized by very heterogenous soil conditions on uplands and the nonhydromorphic part of inland valley fringes. Figure 8 displays the areal spread of 24 map units as given on the soil map of the world (FAO/UNESCO 1977) for that area. Their composition is listed in table 6. Based on the composition rules of FAO (1978) the following distribution of soil units was calculated:

- 56% Luvisols, with 61% gleyic and 37% ferric Luvisols
- 17% Nitosols, with 95% distric and 5% eutric Nitosols
- 11% Regosols, with 87% eutric Regosols
- 9% Lithosols
- 7% Others (Gleysols, Cambisols, Vertisols, Fluvisols, Acrisols)

2.2.3 Vegetation. Vegetation in the study region is mostly part of the shrub savanna in the Sudan-Guinea savanna transition zone. Albergel et al. (1993) report *Buryospremum parkii (Karité), Terminalia macroptera, Pterocarpus erinacerus, Cordia africana, Parkia biglobosa, and Khaya senegalensis* as dominating species to be found. At the lower part of inland valley fringes, a tree-savanna-type canopy (gallery forest) occurs.

2.2.4 Farming systems. The agricultural systems are as diverse as the soils in the study area. Manyong et al. (in preparation) characterized farming systems in the middle belt of that area as market-driven and being in the intensification phase (figure 9). The influence of market access and good infrastructure on farming systems is also obvious in the area around Sikasso and between Bobo-Dioulasso and Toussiana. Farming systems here are in the market-driven expansion and early intensification phases, respectively. That means infrastructure, such as road networks, has reached a level sufficient enough to enable farmers to grow at least one cash crop as a major objective of farm households. Between these two regions, around Koloko on the Burkina Faso site, lies a region where population density is still the major driving force for farming systems but land availability is increasingly scarce. Therefore, Manyong et al. (in preparation) classified that region as population driven expansion phase (figure 10). Market factors mainly drive the farming (figure 9) with cotton and sorghum being the main upland crops (see their spatial distribution in figure 10) and rice being the main lowland crop.

Table 4 Level I agroecological and soil zones and land regions of the WURP map (Hekstra et al. 1983; Windmeijer and Andriesse 1993) covered by Landsat TM path:197, row:52 (Bobo-Dioulasso, Burkina Faso and Sikasso, Mali)

Macroscale zones	Area (ha)	Percentage of entire study area[a]
A. agroecological and soil zone (AEZ)		
AEZ 1	1,418,302	45
AEZ 2	389,234	12
outside level I zone[b]	1,328,110	43
entire study area	3,135,856	100
B. WURP land regions[c]		
land region 2.8	761,281	24
land region 3.1	44,270	2
land region 3.2	191,926	6
land region 3.3	2,138,169	68

Notes:

a. percentages are "rounded-off" to nearest integer

b. results for the area "outside level I" are not reported

c. geological and geomorphological land regions in West Africa according to Hekstra et al. (1983) and Windmeijer and Andriesse (1993)

Table 5 Thematic Mapper (TM) vegetation indices for the macroscale zones in the study area

Macroscale zones	Percentage of the entire study area	Vegetation indices			
		Ratio VI[d] = TM4/TM3	Normalized VI = (TM4-TM3)/(TM4+TM3)	Midinfrared VI1 = TM4/TM5	Midinfrared VI2 = TM4/TM7
AEZ 1[a]	45	2.27	0.39	1.10	3.31
AEZ 2	12	2.19	0.37	1.01	2.76
entire study area[b]	100	2.27	0.39	1.07	3.05
land region 3.3[c]	68	2.21	0.38	1.00	2.89
land region 2.8	24	2.01	0.34	1.02	2.86

Notes:

a. Level I agroecological and soil zone (see figure 1 and table 1)

b. Study area covered by full scene of Landsat-5 path:197, row:52

c. Geological and geomorphological land regions in West Africa according to Hekstra et al. (1983) and Windmeijer and Andriesse (1993) (see figure 2)

d. VI = vegetation index

Table 6 Distribution of soil units in the study area (according to FAO/UNESCO 1977)[a,b]

Map unit[c]	FAO-symbol	Extension in study area(ha)	Dominant soil	%[d]	Associated soils	%[d]	Inclusions	%[d]
1	Lf 41–2a	606183	Lf	60	Lg I	20 20		
2	Lg 5–2a	850560	Lg	60	Lf Re	20 20		
3	Lg 10	298331	Lg	60	Bv Re	20 20		
4	Nd 1	453844	Nd	100				
5	Lg 13	60301	Lg	60	Nd Rd	20 20		
6	Be 26	6347	Be	70	Bf	30		
7	G 2–3a	95212	G	70	J	30		
8	I–Re–b	63475	I-Re	100				
9	Lg 7	117428	Lg	70	Vp	30		
10	Lg 11	6347	Lg	90			Gh	10
11	Ne 18	38085	Ne	60	I Nd	20 20		
12	Lg 3–2a	57127	Lg	70	Re	30		
13	Lg 7–3a	6347	Lg	70	Vp	30		
14	Re 33–1a	19042	Re	60	I Lf	20 20		
15	Lf 18	38085	Lf	70	Re	30		
16	Re 33	69505	Re	60	I Lf	20 20		
17	Lg 1	19042	Lg	100				
18	Lg 12	31737	Lg	60	Ne Re	20 20		
19	I-Rd	60301	I-Rd	100				
20	Lp 8	41259	Lp	70	Ap	30		
21	Lp 10–1a	6347	Lp	60	Lg Nd	20 20		
22	Lf 38	66648	Lf	60	Lg Nd	20 20		
23	Rd 7	12695	Rd	50	Lg Rd	20 20	Be	10
24	Lf 39	31737	Lf	60	Lg Rd	20 20		

Notes:

a. This table is a legend for figure 8

b. Names of soil units according to FAO (1974); abbreviations:

A = Acrisols	J = Fluvisols	V = Vertisols	g = gleyic
B = Cambisols	L = Luvisols	d = distric	h = humic
G = Gleysols	N = Nitosols	e = eutric	p = plinthic
I = Lithosols	R = Regosols	f = ferric	v = vertic

c. Soils in map unit number 1, 11, 14, 21, and 24 have a petric phase; soils in map unit number 2, 16, 20, and 23 have a petroferric phase

d. Percentages according to the algorithm of FAO (1978); areas derived by planimeter measuring

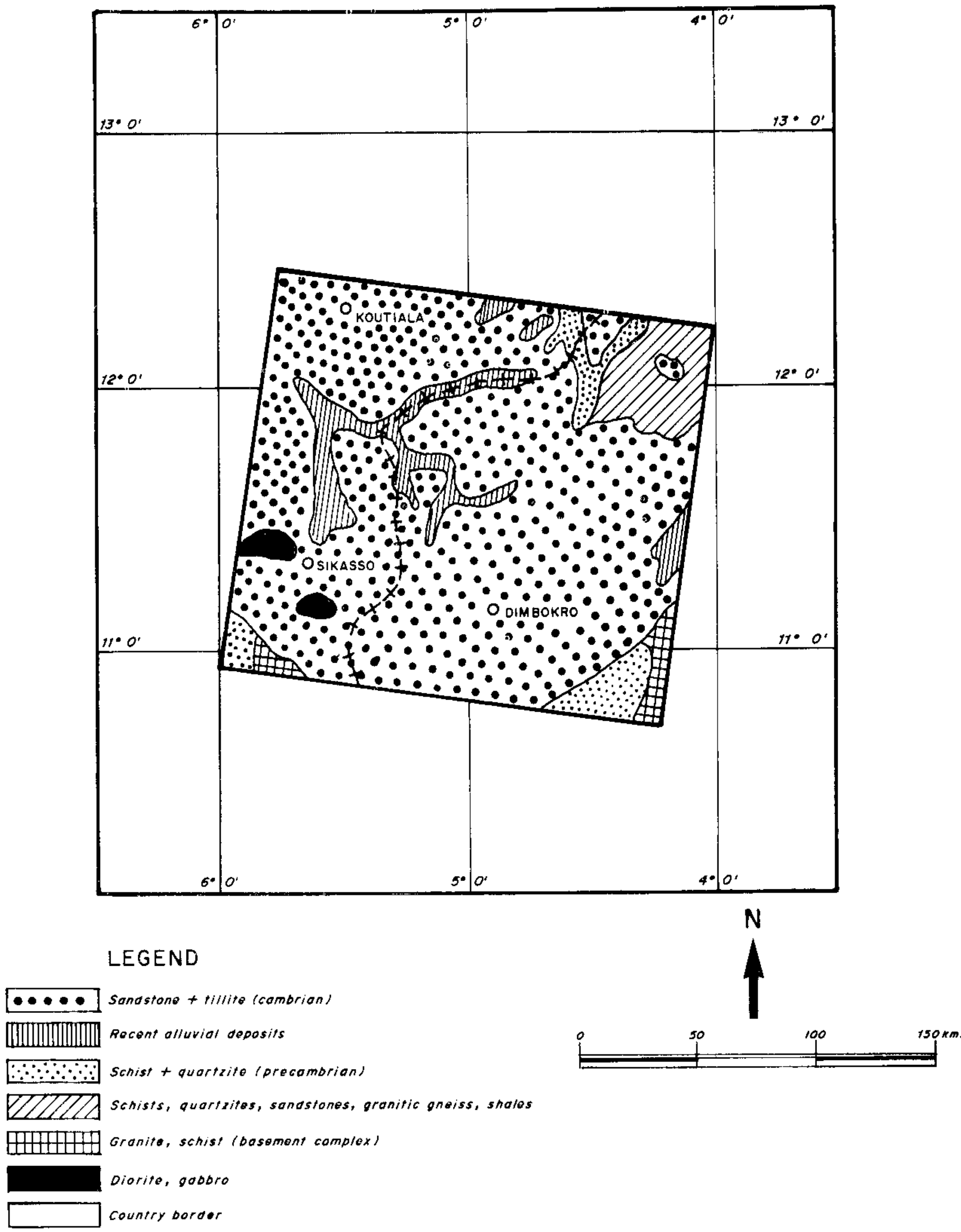

Figure 7 Geological formations in the study area

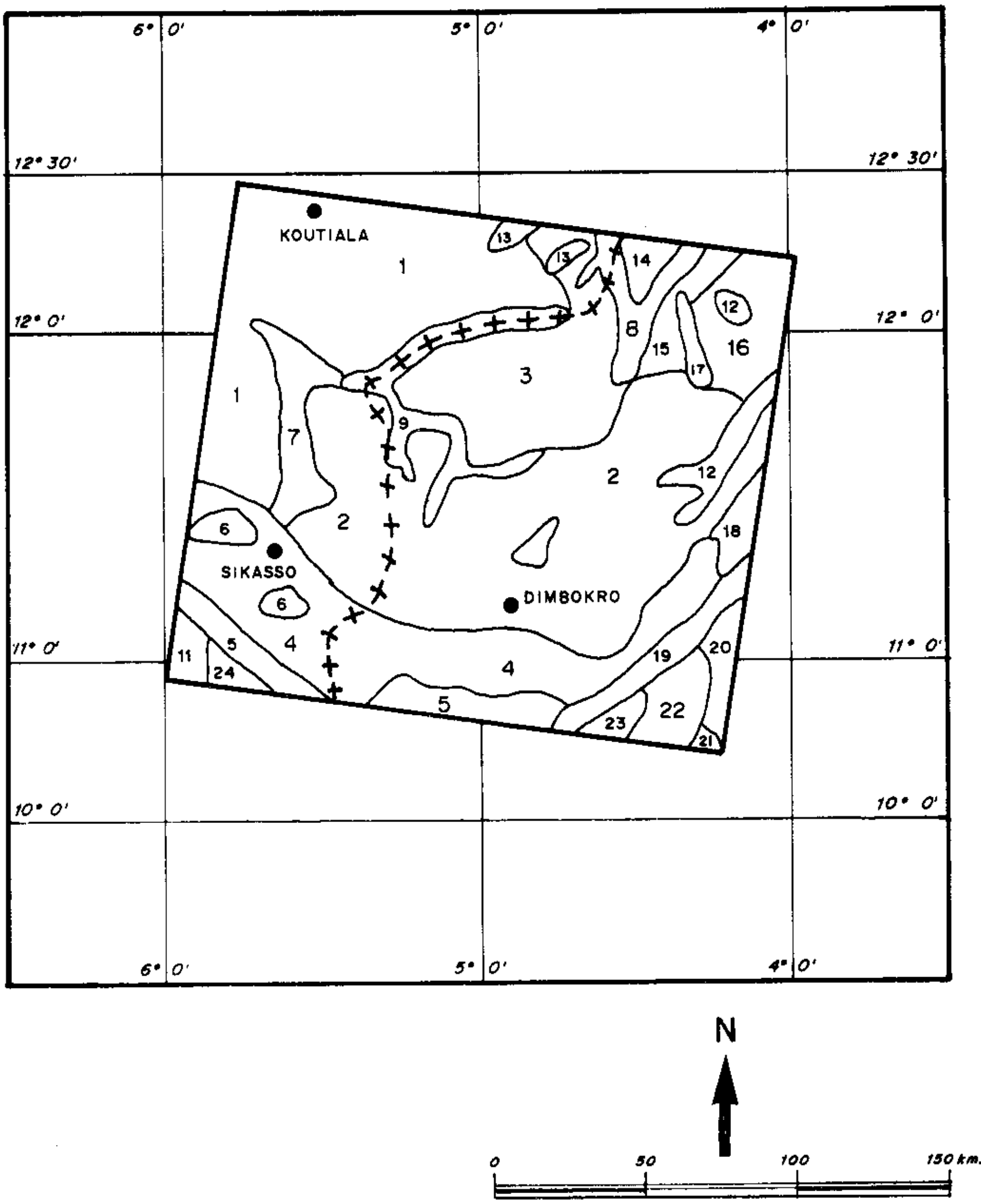

Figure 8 Soil distribution in the study area

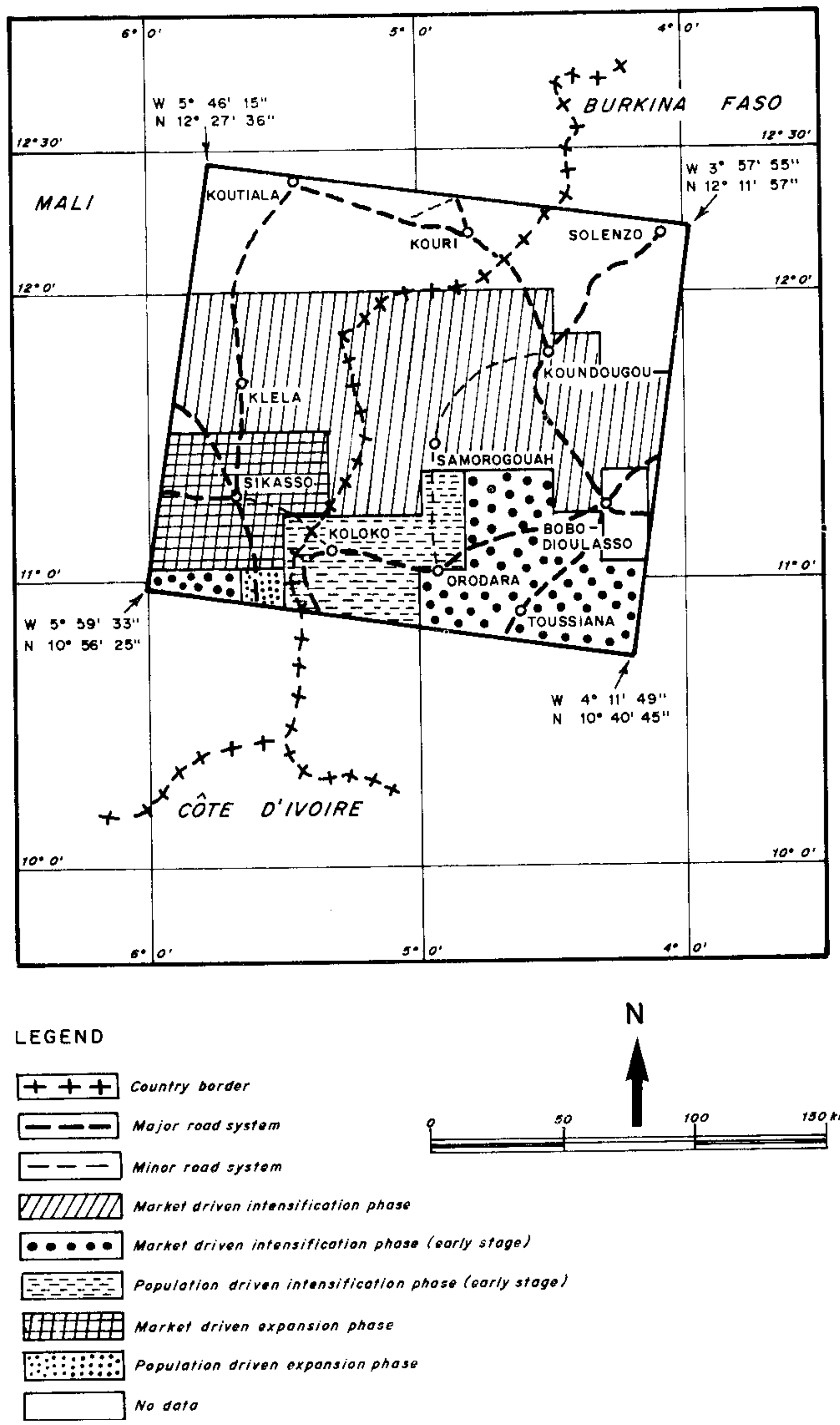

Figure 9 Characterization of agricultural systems in the study area

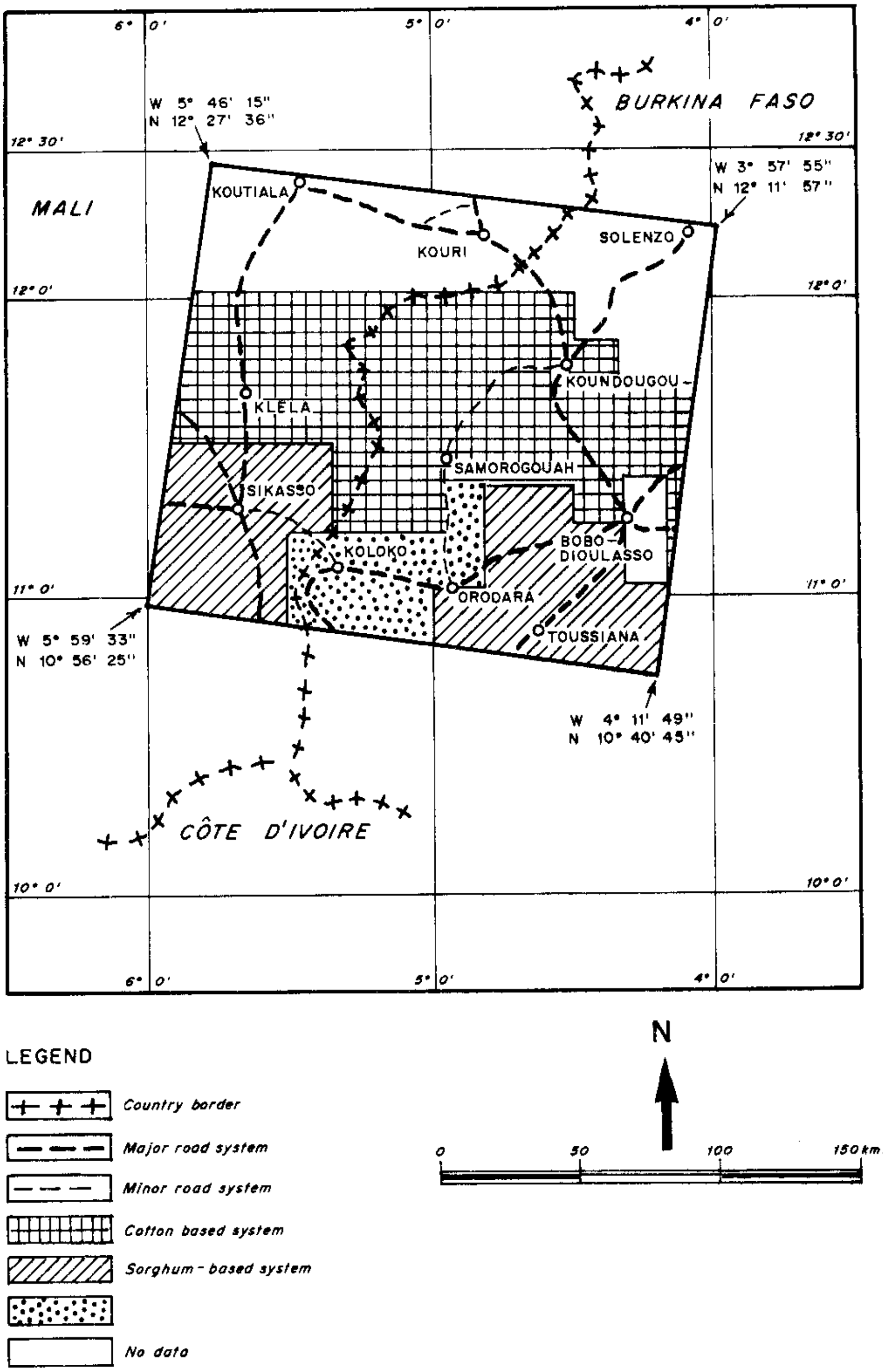

Figure 10 Characterization of cropping systems in the study area

2.3 Rainfall and hydrology

Rainfall in the study area shows a monomodal pattern with 80% of the annual amount falling in four months, between June and September (figure 11). The annual total varies at stations in the study area among 832 mm (Koundougou/Kouka in the northeast), 987 mm (Koutiala in the northwest), 1072 mm (Sidéradougou in the southeast, at the lower right corner of the study area), and 1310 mm (Sikasso in the southwest). Evapotranspiration around Sikasso is around 1800 mm (Blanchet 1992). The long-term spatial distribution of the rainfall in the study area varies between 1000 mm to 1250 mm, with rainfall decreasing towards the northern portion of the study area. Most of this rainfall occurs between the months of May and September.

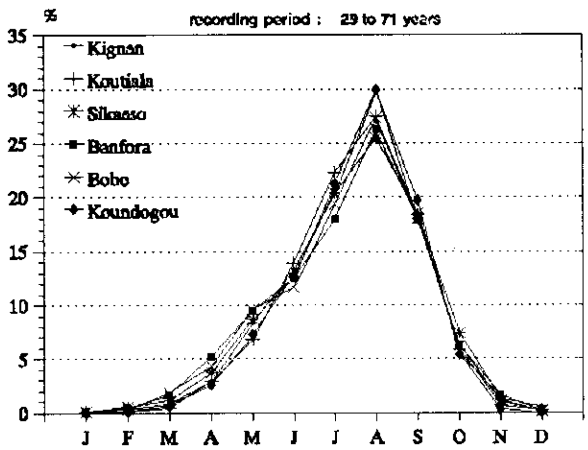

Figure 11 Monthly rainfall in 6 stations in the study area expressed as percentage of annual total [Sivakumar et al. (1984), Sivakumar and Gnoumou (1987)]

2.3.1 Hydrology with respect to the water dynamic in inland valley systems. The hydrological dynamics is best understood with a knowledge of the topographical or terrain features in the study area. The inland valley systems are, typically, characterized by large bottom and fringe widths with gentle transversal slopes of 0–2 degrees. Mild to very mild longitudinal slopes along with flat to near-flat valley bottoms in the first- to fourth-order streams do not facilitate quick drainage of water downstream. This results in shallow water being spread across inland valley bottoms of third- and fourth-order streams (which often exceed 500 m in width) as the water drains off from the first- and second-order streams. The inundation will last for several months during the peak rainy season (July through October). These characteristics are generally found in the whole of the study area and are best exemplified in plate 4: (i) the area between Niaminasso and Nougoussouala north of Sikasso, Mali, (ii) the area between Bama and Desso, north of Sikasso, Mali, and (iii) the area in the immediate vicinity of Sikasso, Mali. These areas are very well suited for inundated rice cultivation.

Blanchet (1992) determined in the Peniasso watershed near by Sikasso in 1991 runoff coefficients (surface runoff in percent of rainfall) between 3.2% and 13.0% for eight events. The runoff coefficients were calculated to be 8–13% at the beginning and in the middle of the rainy season whereas at the end of the rainy season (September) they come down to 6% (Blanchet 1992). Runoff as a percentage of total discharge (defined as surface runoff [*ruissellement*] + base flow [*écoulement de base*] was determined to be > 60% at the start of the rainy season and between 30 and 50% at the end.

III

Ground-Truth Data

Ground-truth data were collected from 25 valley bottoms, 17 valley fringes, and 36 upland plots. In valley fringes, 17 sample plots were located at the upper, nonhydromorphic part and 8 sample plots at the lower hydromorphic part. Ground-truthing took place between 25 September and 1 October 1993 to correspond seasonally with the satellite overpass date of 27 September 1991. The locations of ground-truth sites are shown in figure 12. At each location (where a GPS reading was taken) there were 1 - 2 plots with the GPS location reading being taken on the center of the road and the plots falling on either side of the road. The time frame of the project necessitated a heavy reliance on archived (or historical) satellite data. Real-time or near-real-time ground-truthing is not a feasible proposition due to numerous difficulties involved, such as a high uncertainty in obtaining a good quality real-time satellite image as a result of cloud and harmattan problems, and difficulties in planning ground- truthing activities across several study areas of West and Central Africa at short notice. A consideration of such data collection procedures has been discussed in the monograph by Thenkabail and Nolte (1995a). The data collection strategy, parameters measured or observed, and the methods and procedures used to collect and analyze parameters remain the same across study areas. These are described in the same monograph. A comprehensive inland valley database has been developed by Ofodile et al.(in press). Only a shortcut of the parameters measured is presented in the following paragraph.

The location of each ground-truth site was determined using a global positioning system (GPS) Garmin 100-SRVY^{R}. Locations noted were geographic co-ordinates (latitude/longitude) in degree, minutes, and seconds and universal transverse mercator (UTM) co-ordinates (x,y) in meters. The accuracy of these GPS readings was usually within $\pm$ 30 m. GPS was also used to collect ground-control points to georeference the satellite image. A total of 21 ground-control points in prominent locations, such as a road crossing a river (over the center of the bridge) and a road crossing a railway line were recorded. These ground-control points were well spread across different portions of the image.

Land-use measurements were made along a transect in a 90 m by 90 m plot in valley bottoms, at valley fringes (hydromorphic and nonhydromorphic), and on uplands. GPS-location readings were taken at the center of the valley bottoms. Leaf area index (LAI) of the canopy was measured in the same 90 m by 90 m plot of valley bottoms and uplands. Land-cover types recorded at each site were trees, shrubs, grasses, cultivated farms, barren farms, barren lands, built-up areas or settlements, roads, and others. Different combinations of these land-cover types led to specific land-use categories (see tables 7, 8, and 9).

Several other characteristics recorded at each inland valley site included: valley bottom width (m), valley fringe width (m), transversal slope (degree), stream order (number), and qualitative observations, such as occurrence of a central stream in the bottom, nature of the water discharge, status of water management systems, and soil moisture conditions (see Thenkabail and Nolte 1995a).

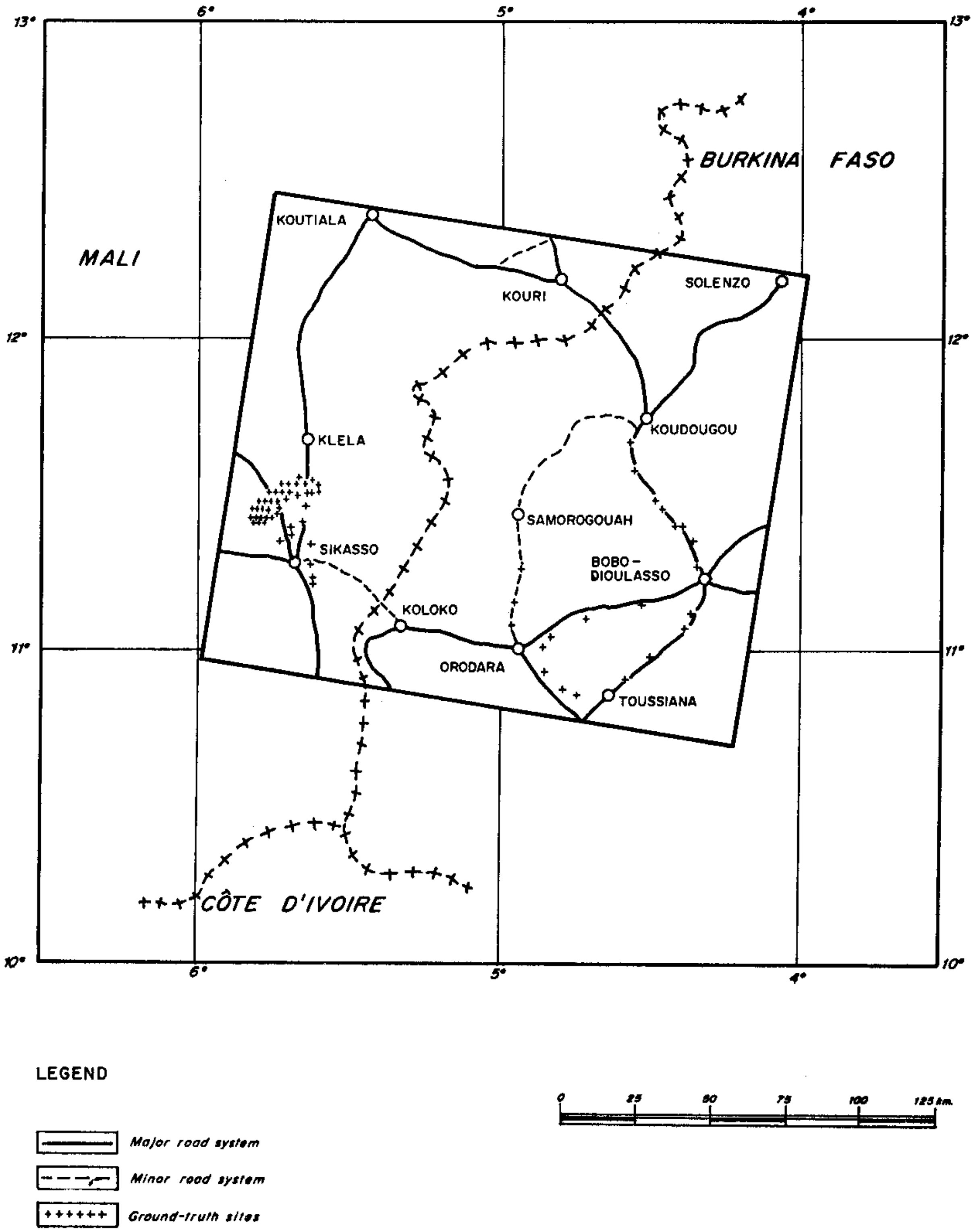

Figure 12 - Ground-truth site location

Table 7 Land-use categories, their vegetation distribution and description in valley bottoms, at valley fringes, and on uplands in regions of Bobo-Dioulasso, Burkina Faso and Sikasso, Mali (Landsat path:197, row:52)

Spectral class no.	Land-use category	Vegetation description and distribution[a,b,c]
	Uplands	
1	significant farmlands	total farmlands dominates in this area; trees (8), shrubs (6), grasses (19), cultivated farms (63), barren farms (3), barren lands (1)
2	scattered farmlands	savanna with significant farmlands; trees (11), shrubs (23), grasses (35), cultivated farms (18), barren farms (4), and barren lands (6)
3	savanna vegetation	savanna with sparse or insignificant farmlands; trees (9), shrubs (24), grasses (48) cultivated farms (5), barren farms (4), barren lands (6)
4	wetland/marshland	short shrub dominant with moist soils and/or flood plain; marshy vegetation; trees (5), shrubs (16), grasses (55), cultivated farms (9), barren farms (1), and barren lands (10)
5	dense forest	dense lush-green vegetation, mostly forest type; trees (41), shrubs (20), grasses (17), cultivated farms (14), barren farmlands (5), and barren lands (2)
6	very dense forest	very dense lush-green forest vegetation dominated by trees; rarely other very dense lush-green vegetation; trees (45), shrubs (31), grasses (12), cultivated farms (6), and barren farms (3)
	Valley fringes	
7	significant farmlands	region with significant cultivation in valley fringes; trees (14), shrubs (13), grasses (21), cultivated farms (40), barren farms (8), and barren land (4)
8	scattered farmland	savannah with significant cultivation in valley fringes; trees (15), shrubs (25), grasses (31), cultivated farms (17), barren farms (7), and barren lands (5)
9	insignificant farmlands	low cultivation in valley fringes; trees (10), shrubs (38), grasses (33), cultivated farms (2), barren farms (0), and barren land (17)
	Valley bottoms	
10	significant farmlands	region with significant cultivation in valley bottoms; trees (8), shrubs (9), grasses (14), cultivated farms (59), barren farms (6) and barren land (4)
11	scattered farmlands	savannah with sparse or no cultivation in valley bottoms; trees (17), shrubs (20) grasses (35), cultivated farms (23), barren farms (0) and barren land (5)
12	insignificant farmlands	low or no cultivation; trees (12), shrubs (22), grasses (51), barren farms (3) and barren land (0)
	Others	
13	water	water (100)
14	built-up area/settlements	small and large settlements; includes villages and townships (100)
15	roads	major and minor roads; includes most motorable roads (100)
16	barren/desert area	open areas with rocks, sand, barren soil, etc. (99)

Notes:

a. Percentage of land-cover types for each spectral class was derived based on ground-truth data

b. Cultivated farms mean cultivation during dry season (satellite data acquisition date and ground-truth data collection dates were during dry season); barren farms mean the agricultural lands left barren during dry season (again refers to the time of satellite data acquisition and ground truthing), but cultivated in the rainy season; total farmlands = cultivated farms + barren farms

c. When the total percentage of land use for each land-use class is less than 100%, then the rest constitute other classes such as rocks, sand, and quarry

Table 8 Land-cover types identified in this study

Code	Land-cover type description	Code	Land-cover type description
1	water	6	barren farms
2	trees	7	barren lands
3	shrubs	8	built-up area/settlement
4	grasses	9	roads
5	cultivated farms	10	others

Table 9 Percentage distribution of land-cover types in the 16 land-use classes for Landsat TM path:197, row:52 covering the regions of Bobo-Dioulasso, Burkina Faso and Sikasso, Mali

Code of land-use classes	Code of land-cover types									
	1	2	3	4	5	6	7	8	9	10
1		8	6	19	63	3	1			
2		11	23	35	18	4	6			3
3		9	24	48	5	4	6			4
4		5	16	55	9	1	10			4
5		41	20	17	14	5	2			1
6		45	31	12	6	3	3			
7		14	13	21	40	8	4			
8		15	25	31	17	7	5			
9		10	38	33	2	0	17			
10		8	9	14	59	6	4			
11		17	20	35	23	0	5			
12		12	22	51	3	0	12			
13	100									
14								100		
15									100	
16		3	27	23	3	0	43			

Note:
Table 13 provides the exact cultivated areas for different components of the toposequence

IV

Results and Discussion

The first step in establishing the characteristics of inland valleys in the study area involved georeferencing the satellite image to Universal Transverse Mercator (UTM) coordinates. This was done using 19 of the 21 GPS-location data points gathered at different prominent locations of the image during the ground-truthing. The image was georeferenced with an accuracy of about 2 pixels (about 60 m). This precise georeferencing made possible an accurate study of inland valley characteristics, such as their land use and cultivation intensities in different components of the toposequence (valley bottoms, valley fringes, and uplands).

4.1 Mapping valley bottoms and valley fringes

The study region is characterized by valleys with large bottom widths as exemplified in a subarea around Sikasso, Mali (plate 1). The characteristics of this image include:

1. a false color composite (FCC) image of band TM4 (red), TM3 (green), and TM5 (blue) surrounding Sikasso, Mali;
2. an image displayed with an magnifying factor of 1; and
3. an image that highlights the flat or near-flat bottoms which are seasonally inundated.

Inland valley bottoms were distinguished from neighbouring fringes and uplands through image enhancement and display techniques such as the ratio RGB image of TM4/TM7 (red), TM4/TM3 (green), and TM4/TM2 (blue) (plate 2). These highlighted valley bottoms were delineated through digitizing. The illustration in plate 2 demonstrates:

1. an enhanced image, obtained by using a ratio red-green-blue (RGB) image of Landsat TM bands TM4/TM7, TM4/TM3, TM4/TM2; as a result, valley bottoms showed up in a white or cream colored network of streams, very easily distinguished from their fringes and surrounding uplands; and
2. an image, displayed with a magnification factor of 2, to highlight inland valley bottoms, clearly distinguished from other features; thereby, valley bottom boundaries could be easily and exactly digitized directly off the screen.

The resulting valley bottoms in the entire study area of 3.12 million ha are shown in plate 3 along with their land-use classes (to be discussed later in this report). Plate 3 provides the spatial distribution of inland valley bottoms, their densities, and land-use characteristics.

Following the definition in Thenkabail and Nolte (1995a), inland valleys comprise valley bottoms and valley fringes (hydromorphic and nonhydromorphic parts) (see figure 3).

Valley fringes adjoin valley bottoms and were mapped by a combination of image processing and GIS techniques as explained in the monograph of Thenkabail and Nolte (1995a). The mean widths of the valley fringes, measured during the ground-truthing, were used to "spread" on either side of valley bottoms and "mask" the image area other than that within this "spread" width. This results in "masking" the valley bottoms and the uplands in order to highlight only the valley fringes. The outcome is illustrated for sample areas in earlier reports of Thenkabail and Nolte (1995b and 1995c). The same technique was adopted to map the valley fringes of the entire study area of Bobo-Dioulasso, Burkina Faso and Sikasso, Mali.

4.2 Mapping settlements and the road network using TM data

The following parameters were determined using the TM data for each of macroscale zones covered by the study area (table 3):

1. presence or absence of major settlements;
2. number of major settlements;
3. presence or absence of major road network; and
4. density of road network (km/km^2).

All the zones had one major settlement or more than one (table 3). The biggest settlements were Bobo-Dioulasso (about 3050 ha) in Burkina Faso and Sikasso (about 835 ha) in Mali. All other settlements were much smaller (between 15 ha and 490 ha). A total of 70 major settlements were mapped. The location of these settlements with respect to the macroscale zones are given in table 3 (even though these settlements exist in plate 4, the scale of the map makes it impossible to notice smaller settlements). All macroscale zones in the study area have a major road system. The density of the road network was lowest in AEZ 2 with 0.022 km/km^2 compared with the other zones which have road-network densities between 0.027 and 0.040 km/km^2 (table 3).

4.3 Land-use characterization of valley bottoms, valley fringes, and uplands

Land-use characteristics were mapped separately for valley bottoms, valley fringes and uplands. This involved using the CLUSTR unsupervised classification algorithm of Earth Resources Digital Analysis System (ERDAS) and incorporating ground-truth information to arrive at the desired land-use themes and classes (see Thenkabail and Nolte 1995a for an extensive discussion of the methodology). Six nonthermal bands of TM were used in the classification process. The GPS data and the land-use and land-cover data were used along with the spectral vegetation indices to identify the spectral classes of unsupervised classification. An initial 50 spectral classes of unsupervised classification were reduced to the final 16 land-use information classes (table 7, and figures 13a and 13b) which were then mapped uniformly across the study area. Each of these classes has a varying percentage of 10 land-cover types (table 8). The 16 land-use classes (table 7) were displayed against the 10 land-cover types in a matrix format in table 9. For example, the class "significant farmlands of valley bottoms" (land-use class 10) contains 65% farmlands (59% barren farms plus 6% cultivated farms), 8% trees, 9% shrubs, 14% grasses, and 4% barren lands (table 9). This proportion of land-cover types will vary depending on the season. For example, in the dry season many of the farmlands are expected to be barren. However, the land-use class will remain the same. The varying proportion of land-cover types for a land-use class is a result of the heterogeneity of the information classes even within a single pixel (28.5 m by 28.5 m) and due to aggregating different spectral classes to a few predecided land-use classes. As mentioned earlier, in this study the original 50 spectral classes from unsupervised classification were aggregated to 16 land-use classes (table 6). Pure land-use classes (having a single land-cover type that occupies 100% of its area) are water, settlements, and roads.

The 50 original spectral classes were reduced to 16 land-use classes by integrating the ground-truth, GPS, and ancillary data. The final mean spectral characteristics of the 16 land-use classes are provided in table 10 and figures 13a and 13b. The vegetation during the satellite overpass date (27 September 1991) was lush green as it was still the rainy season in the region. This results in relatively high vegetation indices for each class. The distinct clusters of each class are obvious from figures 13a and 13b. Settlements (class 14) and roads (class 15) showed high reflectance in thematic mapper band 3 (TM3) resulting in their clustering at the extreme right side of the plot. Absorption in the TM3 and TM4 wavebands resulted in a single very distinct cluster for water (class 13). Upland forest classes - class 6 (very dense forest) and class 5 (dense forest) - predominantly consisted of trees (see table 7).

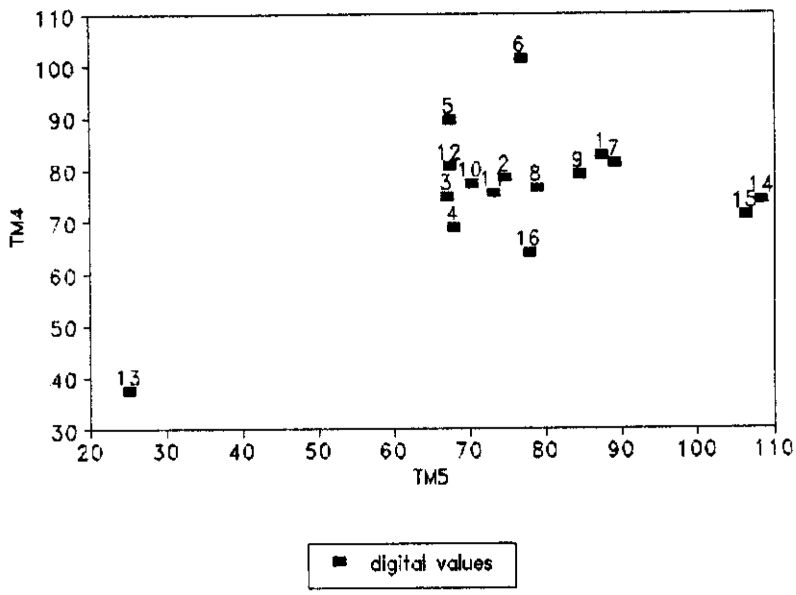

Figure 13 Bispectral plots of the mean digital values for the final 16 land-use classes of Landsat TM band (a) TM4 versus TM3

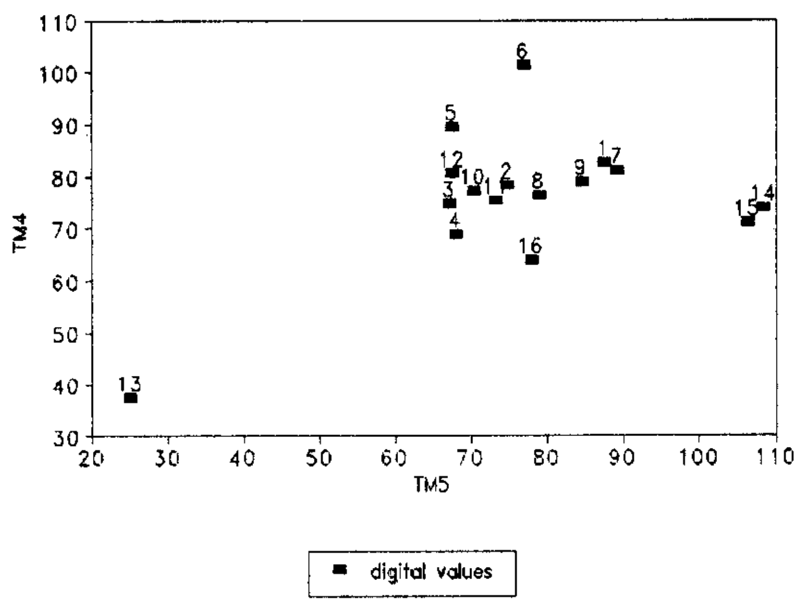

Figure 13 Bispectral plots of the mean digital values for the final 16 land-use classes of Landsat TM band (b) TM4 versus TM5

These classes also comprise gallery forests along the fourth- or higher-order streams. All these classes have high reflectance in TM4 (near infrared waveband) and low reflectance in TM3 (the red waveband). As a result, the vegetation indices for these classes are amongst the highest (see table 10). The uncultivated valley fringes (class 9) were significantly different in spectral characteristics compared to the other two classes for uncultivated areas (class 3 for uplands and class 12 for bottoms). This was mainly due to the higher vigor and greater density of valley-bottom vegetation relative to that of fringes and uplands. Gallery forest (lush green trees and shrubs) is mainly concentrated along the valley bottoms. This was also due to a higher percentage of sparse and short shrubs at the fringes (class 12) compared with the bottoms. The clusters of classes 2, 8, and 11 are very close in figure 12 because they both have a remarkably similar land-cover distribution (table 9).

The classes showing significant farmlands at the fringes (class 7) and on the uplands (class 1) have similar spectral characteristics, but their clusters are notably different in position, illustrating significant farmlands in valley bottoms (class 10). This was mainly due to the cultivation of inundated rice (swamp rice) in the valley bottoms versus cropping of sorghum and cotton at the fringes and on the uplands. The presence of water in these valley bottoms caused a high absorption in the water absorption band TM5, resulting in low values of TM5 (figure 13b). Therefore, the midinfrared simple vegetation index one (MSVI1 = data of TM4 divided through data of TM5) discriminates better between class 10 and class 1 or 7, respectively, than the ratio vegetation index (RVI = data of TM4 divided through data of TM3).

Class 16 (barren land) shows up as a wetland in these bispectral plots mainly due to a high soil moisture status because of rains during the date of overpass.

The 16 land-use classes obtained for this study area (Landsat TM path:197, row:52) are shown in plate 4. These land-use classes were grouped as follows (table 7):

1. 7 classes of uplands (classes 1, 2, 3, 4, 5, 6, and 16);
2. 3 classes of valley fringes (classes 7, 8, and 9);
3. 3 classes of valley bottoms (class 10, 11, and 12); and
4. 3 classes of others (class 13, 14, and 15).

Three land-use classes were synonymous for each component of the toposequence (table 7):

a. significant farmlands (classes 1, 7, and 10): farmlands (cultivated farms + barren farms) constitute > 30 % of the total land area of this class;
b. scattered farmlands (classes 2, 8, and 11): farmlands constitute > 10 % but ≤ 30 % of the total land area of this class; and
c. insignificant farmlands (classes 3,9, and 12): farmlands constitute ≤ 10 % of the total land area of this class.

The areas occupied by each of these 16 land-use classes have been presented with respect to the WURP land regions in table 11 and to the agroecological and soil zones of IITA in table 12. The land-use classes in plate 4 compress an area of 3.13 million ha. This plate is useful in getting a spatial view of land-use distribution in a region. Land-use maps for "windows" within this region of study provide excellent details (see, for example, plate 5).

Land-use class 3 represents areas with savanna vegetation. It comprises $\leq$ 10% (insignificant) farmlands. The percentage area relative to the total geographic area occupied by this class varies between 6.5% (for land region 2.8) to 28.7 % (for AEZ 1) (see tables 11 and 12). The entire study area had 23.2%. area of class 3. Land-use class 2 (for uplands), 8 (for valley fringes), and 11 (for valley bottoms) are also predominantly savanna vegetation with 10% to 30% of the area being farmlands. The percentage areas covered by these predominantly savanna land-use classes, in each agroecological zone, were generally high. For example, in AEZ 1 the percentage areas covered by these classes were 25.9% for class 2 (uplands), 6.7% for class 8 (valley fringes), and 4.2% for class 11 (valley bottoms). The overall percentage areas for savannas should include the percentages of the

"pure" savanna class (class 3) and predominantly savanna classes (classes 2, 3, 8, and 11). Thereby, the overall savanna percentage areas were 65.5% (class 2, 3, 8, and 11) for AEZ 1, 70.4% for AEZ 2, 65.4% for the entire study area, 67.1% for land region 3.3, and 61.6% for land region 2.8. Dominance of these classes in land regions 3.3 and 2.8 (table 11); and AEZ 1, 2, and entire study area (table 12) are characteristics of this study area in the transition of northern Guinea savanna and Sudan savanna. On average, land-use class 3 consists predominantly of grasses (48%) followed by shrubs (24%), trees (9%), farmlands (9%), barren land (6%) and others, (4%) (see table 6).

The forest classes 5 and 6 represent about 4% in different macroagroecological zones (table 11 and 12) as may be expected in this transition zone of the northern Guinea savanna and Sudan savanna study area. It has to be noted that, even within this area, a significant portion is gallery forests (trees along river banks) for higher-order streams (fifth-order or higher) (see these characteristics depicted in plate 4). The gallery forests along the fourth- or lower-order streams fall into the class "uncultivated valley bottoms" (land-use class 12) or part into the class "uncultivated valley fringes" (land-use class 9).

Table 10 TM-derived vegetation indices for the final land-use classes in Landsat TM path:197, row:52, covering the regions of Bobo-Dioulasso, Burkina Faso and Sikasso, Mali[a]

Land-use classes	MEAN VALUES				
	TM3	TM4	TM5	RVI[b]	MSVI1[c]
1	39.75	82.75	87.50	2.10	0.96
2	38.26	78.36	74.89	2.12	1.10
3	33.00	74.82	67.18	2.27	1.11
4	38.00	69.00	68.00	1.82	1.01
5	33.50	89.50	67.50	2.67	1.33
6	33.50	101.40	77.00	3.03	1.32
7	40.25	81.33	89.33	2.05	0.94
8	36.67	76.42	79.00	2.09	0.97
9	38.75	79.13	84.63	2.06	0.95
10	38.90	77.30	70.20	2.01	1.15
11	35.50	75.50	73.38	2.13	1.04
12	32.78	80.67	67.56	2.48	1.19
13	29.70	37.50	25.00	1.26	1.50
14	50.20	74.10	108.40	1.48	0.68
15	53.10	71.20	106.30	1.45	0.67
16	39.00	64.00	78.00	1.64	0.82

Notes:

a. Data were obtained from 10 sample subareas (n = 10), each of 200 pixel by 200 pixel area, for each of the 16 land-use classes; this was done using MASK and BSTATS options of ERDAS

b. RVI = ratio vegetation index; data of TM band 4 are divided through data of TM band 3

c. MSVI1 = midinfrared simple vegetation index one; data of TM band 4 are divided through data of TM band 5

It is important to note that the areas of each land-use class in tables 11 and 12 contain a varying degree of land-cover types as defined in table 9. Land use is an identity name for varying combinations of land-cover types. Thereby, exact cultivated areas, for example, should be derived from tables 11 or 12 based on the distribution pattern of land cover provided in table 9. The results of exact cultivated areas are presented in table 13. For example, the exact cultivated areas of the valley bottoms for AEZ 1 are calculated as follows.

a. The areas of valley bottoms for AEZ 1 were (table 12):
   class 10 (valley bottoms with significant farmlands) with 7,717 ha;
   class 11 (valley bottoms with scattered farmlands) with 59,062 ha; and
   class 12 (valley bottoms with insignificant farmlands) with 62,045 ha.

Adding up these three classes gives a total valley bottom area of 128,824 ha.

Table 11 Land-use distribution in the different land regions of the WURP map (Hekstra et al. 1983, Windmeijer and Andriesse 1993) determined using Landsat TM of path:197, row:52 in the regions of Bobo-Dialousso, Burkina Faso and Sikasso, Mali

No.	Land-use category	Land region 3.3		Land region 2.8	
		area (ha)	% of total land region	area (ha)	% of total land region
	Uplands				
1	significant farmlands	144,642	6.4	124,549	17.8
2	scattered farmlands	588,800	26.0	275,227	39.3
3	savanna vegetation	648,320	28.5	45,760	6.5
4	wetlands/marshland	77,905	3.4	6,011	0.9
5	dense vegetation	72,326	3.1	4,969	0.7
6	very dense vegetation	10,950	0.5	6,905	1.0
	Valley fringes				
7	significant farmlands	58,423	2.6	38,874	5.6
8	scattered farmlands	196,267	8.7	63,776	9.1
9	insignificant farmlands	206,119	9.1	23,639	3.4
	Valley bottoms				
10	significant farmlands	13,898	0.6	6,788	1.0
11	scattered farmlands	87,115	3.9	46,755	6.7
12	insignificant farmlands	84,384	3.7	9,530	1.4
	Others				
13	water	12,093	0.5	183	0.0
14	built-up area/settlements	4,787	0.2	1,056	0.2
15	roads	4,941	0.2	1,577	0.2
16	barren/desert area	57,237	2.5	44,766	6.4

Note:
For the composition of land-cover types and their distribution in each land-use class, see tables 8 and 9.

Table 12 Land-use distribution in the different agroecological and soil zones (AEZ) determined using Landsat TM of path:197, row:52 in the regions of Bobo-Dialousso, Burkina Faso and Sikasso, Mali

No.	Land-use category	AEZ 1		AEZ 2		Entire study area	
		area (ha)	% of total AEZ	area (ha)	% of total AEZ	area (ha)	% of total AEZ
	Uplands						
1	significant farmlands	105,468	7.4	32,124	8.3	280,990	9.0
2	scattered farmlands	367,370	25.9	141,550	36.4	901,130	28.7
3	savanna vegetation	406,472	28.7	63,360	16.3	727,987	23.2
4	wetlands/marshland	46,023	3.2	3,433	0.9	85,202	2.7
5	dense vegetation	51,818	3.7	12,078	3.1	79,955	2.6
6	very dense vegetation	10,797	0.8	1,172	0.3	18,175	0.6
	Valley fringes						
7	significant farmlands	31,561	2.2	17,789	4.6	104,879	3.3
8	scattered farmlands	95,177	6.7	52,260	13.4	282,455	9.0
9	insignificant farmlands	126,930	8.9	29,363	7.5	254,088	8.1
	Valley bottoms						
10	significant farmlands	7,717	0.5	4,863	1.2	21729	0.7
11	scattered farmlands	59,062	4.2	16,792	4.3	139,758	4.5
12	insignificant farmlands	62,045	4.4	8,726	2.2	107,519	3.4
	Others						
13	water	9,750	0.7	544	0.1	12,570	0.4
14	built-up area/settlements	299	0.0	82	0	5,849	0.2
15	roads	2,170	0.2	498	0.1	6,585	0.2
16	barren/desert area	35,643	2.5	4,600	1.2	106,985	3.4

Note: For the composition of land-cover types and their distribution in each land-use class, see tables 8 and 9

b. the cultivated areas of land cover for the corresponding land-use classes (class 10, 11, and 12) were defined in table 8 to be 65% (59% cultivated farmlands plus 6% barren farmlands) for class 10, 23% for class 11, and 3% for class 12;
c. the resulting cultivated area is 20,462 ha (7717*0.65 + 59062*0.23 + 62045*0.03); and
d. the valley bottom area cultivated (20,462 ha) as a percentage of total valley bottom area (128,824 ha) is 15.9% (table 13).

The land-use characteristics mapped for the entire study area of 3.13 million ha is depicted in plate 4. This plate provides an excellent spatial depiction of land use in a regional context. For example, the areas with little or no cultivation are shown in violet (upland savannas), rose, and red-orange (upland forest), red (predominantly valley-fringe savannas and/or forest), and magenta (predominantly valley-bottom forest and/or savannas). These colors are dramatically seen in plate 4 and show up to occupy over 50% of the area. These colors contrast with those of significant cultivation (shown in gray for uplands, white for fringes, and cyan for bottoms) and scattered cultivation (seafoam for uplands; pine-green for fringes; and yellow for bottoms) mainly along roads and settlements (see roads and settlements in plate 8 and compare the distribution of significant and scattered cultivation in plate 4).

The detailed land-use characteristics are depicted forsub areas near two major settlements: Bobo-Dioulasso, Burkina Faso (plate 5), and Sikasso, Mali (plate 6). Plate 5 illustrates the high cultivation intensities across the toposequence in areas nearer to settlement and road networks. In the immediate vicinity of Sikasso there is intense cultivation in valley bottoms (mostly inundated rice) and valley fringes and uplands (mostly sorghum) (plate 6). In areas to the east of Sikasso, in the Farako forest reserve, the land use dramatically changes to savannas (see dramatic differences in land use depicted for forest versus nonforest areas in plate 6).

4.4 Inventory of inland valleys and cultivation intensities across the toposequence

The area of inland valleys (valley bottoms plus valley fringes) is a function of the density of valleys and their characteristics, such as their bottom width and fringe width. An inventory of inland valleys was made possible by this process of highlighting and mapping (see section 4.1). Using the same technique as enumerated in section 4.1 and illustrated in plates 1 through 3, inland-valley bottoms were mapped for the entire study area of 3.13 million ha (plate 3). The sparse network of inland-valley systems in the entire study area (plate 3) is obvious from their spatial distribution. A quantitative assessment indicated low drainage densities (ratio of the length of the streams to the area encompassed by them in km/km^2) and coarse stream frequencies (ratio of length of the streams to the area encompassed by them in number/km^2) (table 14). The drainage densities varied between 0.35 km/km^2 and 0.48 km/km^2 and stream frequencies varied between 0.48 number/km^2 and 0.69 number/km^2. Although the spatial coverage of inland valleys is sparse, this study area is characterized by large valley-bottom and valley-fringe widths (table 15). The large bottom widths are evident in plate 1. These large valley bottom and valley fringe widths account mainly for the considerable percentage of area covered by inland valleys (table 13) in spite of the coarse stream frequency (table 14) in all the different macroscale zones studied.

The mapping strategy conceptualized for use with remotely sensed data, as outlined in detail in Thenkabail and Nolte (1995a), is to map consistently all valleys as inland valleys along fourth- or fifth-order streams. The decision where to draw the line between inland valleys and floodplains (usually at fourth- or fifth-order streams) is based on ground-truth data. However, not all valleys below, say, fourth-order when mapped as inland valleys are actually likely to be inland valleys.

Table 13 Distribution of valley bottoms, valley fringes, and uplands and their cultivation status in the study area

Study area	Percentage of entire study area	VALLEY BOTTOM AREA		VALLEY FRINGE AREA		UPLAND AREA	
		as a % of total geographic area	cultivated as a % of total valley-bottom area	as a % of total geographic area	cultivated as a % of total valley-fringe area	as a % of total geographic area	cultivated as a % of total upland area
AEZ 1[b]	45	9.1	15.9	17.8	16.0	72.2	20.5
AEZ 2	12	7.7	24.0	25.5	21.8	66.5	24.1
land region 2.8[c]	24	9.1	21.0	18.1	27.0	72.6	29.6
land region 3.3	68	8.2	17.0	20.4	16.7	70.5	19.2
Entire study area	100	8.6	18.4	20.4	19.2	70.2	21.9

Notes:

a. When valley bottoms + valley fringes + uplands are not equal to 100%, the rest of the area falls in water body, roads and settlements or "round-off" errors

b. Level I agroecological and soil zones (see figure 1)

c. Geological and geomorphological land regions in West Africa according to Hekstra et al. (1983) and Windmeijer and Andriesse (1993) (see figure 2)

Table 14 Inland valley morphometric characteristics determined using Landsat TM data of path:197, row:52 (Bobo-Dioulasso, Burkina Faso, Sikasso, Mali)[a,b]

	Characteristics of inland valley watersheds						
	AEZ 1	AEZ 2	entire study area	land region 3.3	land region 3.1	land region 2.8	land region 3.2
Mean drainage density (km/km^2)	0.42	0.48	0.40	0.43	-	0.35	-
Mean stream frequency ($no./km^2$)	0.51	0.69	0.61	0.65	-	0.48	-

Notes:

a. Hekstra et al. (1983) classified:

1. drainage densities (km/km^2) as: very low (0–03); low (0.3–0.6); medium (0.6–1.2); high (1.2–2.4); and very high > 2.4; and
2. stream frequencies ($number/km^2$) as: very coarse (0–0.5); coarse (0.5–1.0); medium (1-2); fine (2–3); and very fine (> 3)

b. When the subarea was too small such as for land region 3.1 (2% of total study area), stream densities and frequencies were not calculated and hence were marked "-"

Some of them are floodplains. This is due to the high variation encountered in characteristics such as bottom widths and flooding regime. Since floodplains have a different hydrological regime, soil conditions (Raunet 1985), and cropping patterns, they are to be distinguished from inland valleys. However, a strict distinction is not possible due to practical reasons and hence all valleys of fifth-order and below have been mapped as inland valleys. The inland valley frequencies and densities were higher in (1) AEZ 2 compared to AEZ 1; and (2) Land region 3.3 compared to land region 2.8 (see table 14). However, as a result of the presence of valleys with larger bottom widths in AEZ 1, the percentage area of valley bottoms in AEZ 1 (9.1%) exceeded that of AEZ 2 (7.7%) (as area is also a significant function of bottom width). For the same reason, the valley bottom area of land region 2.8 (9.1%) exceeded that of land region 3.3 (8.2%).

As a result of the methodology used in this study (see Thenkabail and Nolte 1995a for details) valley fringe area is a direct function of valley frequencies and densities. As a result, the zones with higher frequencies and densities (AEZ 2 in comparison to AEZ 1; land region 3.3 in comparison to land region 2.8; see table 14) had a higher percentage of valley fringe area (25.5% for AEZ 2 in comparison to 17.8% for AEZ 1; and 20.4% for land region 3.3 in comparison to 18.1% for land region 2.8; see table 13). Both land regions have similar geology-sedimentary deposits (Cambrian sandstone, figure 7). Cultivation intensities (table 13) in the valley bottoms were highest for AEZ 2 (24%) as a result of nearness of this area to the major settlement of Sikasso, and conditions market-driven expansion phase (see figure 9). Rice is the major crops in the bottoms. The highest intensities of upland (29.6%) and valley-fringe (27%) cultivation was in land region 2.8 as a result of market-driven conditions and with well connected road network and with cotton as the major crop.

Due to significant differences in the geographical areas studied (45% of the entire study area for AEZ 1, 12% for AEZ 2, 24% for land region 2.8, and 68% for land region 3.3, see table 12) a direct and realistic comparison of results across zones was not feasible. In a more regional context,

in the entire study area, valley bottoms were 8.6% (see plate 3) valley fringes 20.4%, and uplands 70.2% (table 13). The cultivation intensities in the entire study area were nearly constant across the toposequence with around 20% (18.4% for valley bottoms, 19.2% for valley fringes, and 21.9% for uplands). The significant cultivation across the toposequence was as a result of:

1. cotton + sorghum-based (figure 10) market-driven intensification or expansion phase (figure 9);
2. market-driven cultivation in lowlands (mainly rice) (see plate 7, for example).

4.4.1 Intensity and distribution of rice cultivation. Rice cultivation forms an important component of inland valley cultivation in the rainy season in the entire study area, especially in the valleys surrounding Sikasso, Mali. The broad and flat or near-flat valley bottoms offer an excellent opportunity for paddy rice cultivation during the rainy season as demonstrated in several valleys around Sikasso, Mali (see plate 7 for the spatial distribution of rice cultivation in valley bottoms near Sikasso and its surroundings). A total of 269,006 ha constitute valley bottoms in the entire study area, of which 18.4% (49,497 ha) are cultivated (tables 12 and 13). Of the cultivated inland valleys, 42% of the area (20,789 ha) had rice crop. Inland valleys with rice are primarily to be found in a large area near Bama, northwest of Bobo-Dioulasso (see plate 4) and in the vicinity of Sikasso (see plate 7). Potential inland valleys for paddy rice cultivation exist, especially valleys that have wide bottom width (typically second- and higher-order), and significant water submergence as shown near Niaminasso, Nougoussouala, and Sikasso (see plate 7). These valleys, however, would require appropriate technologies, such as low-cost water control measures (e.g., channels, levies, and bunding) and rice varieties adapted to inundated conditions.

4.5 Cultivation intensities with respect to distance from settlements and the road network

Cultivation intensities of valley bottoms, valley fringes, and uplands were calculated relative to their distance from major settlements and major road networks through manipulation of relevant GIS spatial data layers, using such techniques as boolean logic interpolation and contiguity analysis. Cultivation intensities of valley bottoms, valley fringes, and uplands at various distance limits (0–2 km, 2–4 km, 4–5 km, and > 5 km) from major settlements and major road networks in the different level I zones are presented in table 15. Five km was considered the greatest distance for farmers to commute on foot to their farms on any given day; and hence the maximum distance limit was set at 5 km.

Generally, the cultivation intensities decreased with increasing distance from settlements and the road network for each component of the toposequence (table 15). However, in several cases such a fall in cultivation intensity between two distance limits was only marginal (within 1 or 2%). This is obvious from uplands in land region 2.8 where the cultivation intensity remained virtually constant. According to Manyong et al. (in preparation) this area is characterized by market-driven agricultural systems with cotton as the major cash crop which is likely to account for that effect. In most cases, however, the cultivation intensities were about 3% higher for distance limits within 0–5 km as compared to those beyond 5 km.

4.6 Study of the cultivation pattern across the toposequence in the entire study area

Significantly cultivated areas at each component of the toposequence are spatially illustrated for the entire study area of 3.13 million ha for uplands (plate 11), valley fringes, and valley bottoms (plate 12). The polygons 1 and 2 were drawn for regions with insignificant cultivation. The regions with insignificant upland cultivation (areas within polygon 1 in plate 11) also had insignificant inland valley (valley bottom plus valley fringe) cultivation (areas within polygon 1 in plate 12). Similarly, regions with significant upland cultivation (several areas outside polygon 1 in plate 11) also have significant inland valley cultivation (several areas outside polygon 1 in plate 12). It is obvious from these

figures that in dominant portions of the study area a high correlation exists between cultivation patterns on the uplands and in inland valleys. This proves one of the hypotheses of Izac et al. (1991) that the degree of upland cultivation has a strong influence on the degree of inland valley cultivation. These results further confirmed the findings of Thenkabail and Nolte (1995b) in the Save study area. The cultivation intensities were strongly influenced by the presence of settlements and the road network (see plate 4 along with roads and settlements shown in plate 8). Data of cultivation intensities across the toposequence are summarized in Table 16.

4.7 Morphological characteristics of inland valleys derived from ground-truth data

Data of measurements of some morphological characteristics of inland valleys gathered during ground-truthing are highlighted in table 16. Only the data for areas with (Cambrian) sandstone as parent material (see figure 7) are illustrated since descriptive statistical analyses were only possible in these areas with enough ground-truth sites per respective stream orders. Due to the small number of observations per stratum, no statistical test was performed. However, data in table 16 show a clear trend that the bottom and fringe widths increase considerably with increasing stream order. At the same time, the data illustrate a high variation in measurements of bottom and fringe widths at each stream order. About 50% of the area (shape ratio of 0.49, table 16) of the valleys along first- and second-order streams constitute the bottom. The lower-order valleys also have 0.5 or 0.8 degree transversal slopes with almost flat or near-flat fringes. Fourth- and fifth-order valleys had mean bottom widths of 495 m and 978 m, respectively. As mentioned in section 4.4 some of the higher-order valleys are to be considered as floodplains. All the valleys (100%) investigated were U-shaped. In this wet season investigation (last week of September) 69% of the valley bottoms had wet soil conditions, 21% were moist, and 10% had dried-out soils.

4.8 Determining the cropping pattern of inland valley systems from ground-truth data

The ground-truth land cover data provided the following important inferences (table 17):

1. The nonhydromorphic valley fringes had significantly more shrubs (27.8%) when compared with valley bottoms (14.5%) and uplands (17%); and
2. Uplands had significantly more grasses (38.3%) when compared with valley fringes (27.5% for hydromorphic and 27.9% for nonhydromorphic) and valley bottoms (26.1%).

The valley bottoms were distinguishable through:

1. Significantly higher cultivation intensities (37.5%) in comparison to valley fringes (17% for nonhydromorphic and 26.2% for hydromorphic fringes); and
2. Significantly fewer trees + shrubs + grasses (50.2%) compared to nonhydromorphic fringes (69%), and uplands (63.9%).

However, the cultivation intensities based on ground-truth data were highly overestimated (table 17) when compared with the same figures from satellite data (table 13). For example, the cultivated areas for valley bottoms were 37.5% using ground-truth data compared to only 18.4% estimated by satellite data. This is due to factors such as:

1. dependency along road networks for ground-truthing;
2. possible bias in stopping for readings at more cultivated valleys rather than relying on selecting valleys on a purely random basis; and
3. the fact that the valleys along road networks are more likely to be cultivated than valleys away from them.

Table 15 Cultivation pattern of valley bottoms, valley fringes and uplands with respect to distance from settlements and the road network for different level I zones of Landsat path:197, row:52

Distance limit (km)	Valley Bottom				Valley Fringe				Upland			
	Cultivated area as percentage of total valley bottom area within the corresponding distance limit				Cultivated area as percentage of total valley fringe area within the corresponding distance limit				Cultivated area as percentage of total upland area within the corresponding distance limit			
	AEZ 1	AEZ 2	land region 3.3	land region 2.8	AEZ 1	AEZ 2	land region 3.3	land region 2.8	AEZ 1	AEZ 2	land region 3.3	land region 2.8
Distance from settlements												
0–2	18.9	31.9	15.6	25.0	17.2	26.3	21.4	30.3	24.7	29.4	24.7	30.7
>2–4	18.3	27.0	14.6	22.5	16.4	26.7	18.2	27.1	21.4	26.1	20.6	27.7
>4–5	14.7	26.2	12.7	22.3	16.7	22.9	15.9	26.7	18.9	27.2	18.2	27.5
>5	15.8	23.0	13.9	20.4	16.4	20.8	16.4	26.8	20.5	23.4	18.3	30.3
Distance from road network												
0–2	16.5	25.8	14.7	23.5	17.2	26.4	19.6	27.9	21.3	30.3	21.8	29.2
>2–4	16.4	27.1	13.7	22.7	17.0	25.7	17.4	27.5	24.7	27.5	18.8	29.5
>4–5	14.6	25.4	12.7	23.2	15.7	22.6	16.3	27.5	17.9	26.8	17.8	29.2
>5	15.9	23.1	13.9	18.9	16.4	21.0	15.9	26.3	21.1	23.9	18.2	30.0

Table 16 Morphological characteristics of inland valleys in the regions of Bobo-Dioulasso, Burkina Faso and Sikasso, Mali

Subarea	Stream order	Transversal slope		Bottom width[a]			Nonhydromorphic fringe width			Shape ratio[b]		TM data: Bottom width (m)[a]	
		n[c]	avg[c] s.e.[c] (degree)	n	avg (m)	s.e. (m)	n	avg (m)	s.e. (m)	n	avg	avg	n
Sandstone[d]	1/2		0.5	4	107	17.7	4	2241	31.1	4	0.49		
	3		0.8	5	129	61.5	4	302	177	4	0.53		
	4			6	495	178	1	2150	-				
	5			4	978	211	2	755	771				

Notes:
Database did not provide enough sample points per subarea and stream order for statistical analyses
a. r^2 value for bottom widths measured on the ground and with TM data is ... (n = ..., α = 0.01)
b. shape ratio = bottom width ÷ fringe width
c. n = number of observations; avg = average; s.e. = standard error
d. see figure 8; 90% of the ground-truth sites fall into land region 3.3 (figures 4 and 7)

Table 17 Relative distribution of land-use patterns within a 90 by 90 m plot at different toposequential components in the Bobo-Dioulasso, Burkina Faso and Sikasso, Mali study area

Toposequence	Observation	Uncultivated and fallow land				Farmland			Barren land and others	Total
		trees (%)	shrubs (%)	grasses (%)	sub total (%)	cultivated (%)	barren (%)	sub total (%)	(%)	(%)
A. Inland-valley bottom	28	9.6	14.5	26.1	50.2	37.5	3.2	40.7	9.0	100
B. Hydromorphic fringe	8	10.6	20.0	27.5	58.1	26.2	10.1	36.3	5.6	100
C. Nonhydromorphic fringe	16	13.3	27.8	27.9	69.0	17.0	3.0	20.0	11.0	100
D. Upland	37	8.6 (1)	17.0 (2)	38.3 (3)	63.9 (4)	27.7 (5)	4.5 (6)	32.0 (7)	4.1 (8)	100

1. C and D (0.10)
2. A and C (0.01), C and D (0.05)
3. A and D (0.05)
4. A and C (0.10), A and D (0.10)
5. A and B (0.05), A and C (0.05), A and D (0.05)
6. A and B (0.10)
7. A and C (0.05)
8. A and D (0.05), C and D (0.01)

Significant differences between any 2 groups (e.g., valley bottom versus uplands) were reported for each parameter (e.g., trees, shrubs) at 0.01, 0.05, and 0.10 levels. For example, grasses were significantly different at 0.05 level between valley bottom (26.1%) and uplands (38.3%); this has been reported as A and D (0.05)

The bias becomes more prominent when one considers the low density of road network in the region (see plate 8, for example).

In addition to the above points, it is important to note that the ground-truth data depends on plot measurement in each location. The diversity and variability even within a given valley are typically overwhelming. This is so because a timely representative plot exists only in theory. In practice (in the field) one hardly gets a clear view of variability due to accessibility and time factors.

The above-mentioned difficulties with ground-truth data can be overcome through the spectral capability of remotely sensed data. This capability will enable a proper characterization of spatial variabilities that occur within and between valleys or uplands.

Similar large differences were found between ground-truth and remotely sensed estimates of cultivation in another study area in Gagnoa, Côte d'Ivoire (Thenkabail and Nolte 1995c). Due to the season (last week of September) of ground-truthing (main cropping season with most crops in vegetative to critical growth phases) 72–92% of farms were cultivated in different components of the toposequence (table 18). Grasses were the most dominant characteristic land-cover feature of uncultivated and fallow lands, irrespective of the toposequence (table 18). Valley bottoms were dominated by rice and closely followed by sorghum or maize (table 19). All other components of toposequence (nonhydromorphic and hydromorphic fringes and uplands) were dominated by sorghum and maize fields. One surprising aspect of these results were that the numbers of cotton fields were very low or nonexistent an observation which contradicts data from Manyong et al. (see figure 10).

Table 18 Relative distribution of land-use types within a cropping pattern at different toposequential components in the Bobo-Dioulasso, Burkina Faso and Sikasso, Mali study area

Toposequence position		Uncultivated and fallow land				Farmland		
	n	trees (%)	shrubs (%)	grasses (%)	sub-total (%)	cultivated (%)	barren (%)	sub-total (%)
A. Inland valley bottom	28	19	29	52	100	92	8	100
B. Hydromorphic fringe	8	18	34	48	100	72	28	100
C. Nonhydro-morphic fringe	16	19	40	41	100	85	15	100
D. Upland	37	14	27	59	100	86	14	100

Note:
n = number of observations

Table 19 Farmland cropping pattern in bottoms and at hydromorphic and nonhydromorphic fringes of inland valleys and on uplands in the regions of Bobo-Dioulasso, Burkina Faso and Sikasso, Mali

Toposequence position	n	Farms	Rice	Cassava or yam	Sorghum or maize	Cotton	Vegetables	Plantation	Barren
Observations in absolute figures									
A. Bottom	28	22	11	1	10	1	3	7	7
B. Hydromorphic fringe	8	8	0	0	6	0	2	2	6
C. Nonhydromorphic fringe	16	9	0	1	7	0	2	2	6
D. Uplands	37	19	0	0	12	2	2	5	5
Observations in relative figures (%)									
A. Bottom		79	50	5	45	5	14	32	32
B. Hydromorphic fringe		100	0	0	75	0	25	25	75
C. Nonhydromorphic fringe		56	0	11	78	0	22	22	67
D. Upland		51	0	0	63	11	11	26	26

Note:
n = number of observations

V

Benchmark Area or Watershed Selection for Technology Development

The output spatial data layers of this study obtained from remotely sensed data (land use of valley bottoms, land use of valley fringes, land use of uplands, road networks, and settlements) were used for GIS modeling to select likely benchmark sites for technology development research. The data obtained from ground-truthing were incorporated into the above datalayers. The position data of each ground-truth site and the ground-control point data for georeferencing form integral components of the above datalayers.

Expert opinion was sought to rate each of the above spatial datalayers on a scale of 1 to 5 (5 being the best). This was done by weighing each factor of each datalayer according to their impact on inland valley cultivation as conceived by the expert. This procedure has been discussed in detail by Thenkabail and Nolte (1995a). These data were sought in standard forms from members of the Inland Valley Consortium. Four international research centers (IITA, WARDA, CIRAD, Winand Staring Centre and Wageningen Agricultural University) and seven national research systems from Republic of Benin, Burkina Faso, Côte d'Ivoire, Ghana, Mali, and Nigeria constitute the Inland Valley Consortium. Thirty scientists with considerable experience and knowledge in inland valley agroecosystems and diverse background were requested to respond to the questionnaire. These scientists represented five international agricultural research centers (IITA/Nigeria, WARDA/Côte d'Ivoire, Winand Staring Centre and Wageningen Agricultural University/The Netherlands, CIRAD/France, and IMMI/Niger) and seven national research institutions (Sierra Leone, Côte d'Ivoire, Mali, Burkina Faso, Ghana, Benin, and Nigeria). Twelve persons responded.

The modal value of each variable pertaining to a spatial datalayer was taken and incorporated into GIS modeling using the GISMO routine of ERDAS. The expert opinion indicated the following:

1. Significantly cultivated valley bottoms ($\geq$ 30% of the total area is cultivated), valley fringes (hydromorphic and nonhydromorphic part), and uplands at present will drive further exploitation of the lands still left in the same valley system and/or in neighboring valley systems.
2. Inland valleys that are near already cultivated uplands have the best chance of being exploited for cultivation; the greater the degree of cultivation in the uplands, the greater are the chances of inland valley cultivation.
3. The nearer the settlements and road networks are to inland valleys, the greater are the chances of those valleys being exploited; proximity to settlements has a greater influence than proximity to road systems.
4. Inland valley utilization for agriculture is likely to peak when population density rises above 30 persons/km^2;
5. The zones with a shorter length of growing period (e.g., northern Guinea savanna) are relatively more likely to have inland valleys utilized for agriculture compared to zones with a greater length of growing period (e.g., equatorial forest).

Based on the above expert input to various spatial datalayers, the GIS modeling highlighted the areas that are potentially the best locations for technology development research activities (plate 8). These benchmark research areas of these spatial datalayers or benchmark research watersheds are highlighted with filled circles in plate 8. The best inland valley systems are those which represent the greatest potential for development. Several of the potential location areas suggested in plate 8 are mapped in detail showing information such as the valley system, the road network, and the land-use classes (see, for example, plate 9); and additional information from remote sensing for these sites such as vegetation density and vigor (see the NDVI map in plate 10); and information from any other sources (e.g., experts, maps). The final selection of a research area or watershed for technology development research activities will be based on a rapid appraisal through visits to selected areas with all available information. This would involve appraisal of additional factors such as social, ethnic, environmental, and economic issues as well as the interests of NARS collaborators in the potential areas or watersheds of interest.

VI

Summary and Conclusions

This inland valley agroecosystem research report presents and discusses the results of a level II (regional or semidetailed or meso-) characterization study of inland valley agroecosystems in the Sikasso and Koutiala regions of Mali; and Bobo-Dioulasso, and Kouka regions of Burkina Faso. The total study area is about 3.13 million ha covered by Landsat-5 Thematic Mapper (TM) path:197, row:52. (See the exact co-ordinates in figure 4.) The study adopted the methodology recommended by Thenkabail and Nolte (1995a) which involved digital image analysis and integration of the remotely sensed data with GPS and ground-truth data in an GIS framework.

One hundred percent of the inland valleys that were studied were U shaped, 74% were *fadamas* (that is, inland valleys with potential for dry-season cropping). At the time of ground-truthing 69% of the inland valleys were wet, 21% were moist, and 10% were dry. The mean transversal slopes were generally mild with about 1.5 degrees for the first-, to third-order inland valley streams, and about 0.5 degrees for the fourth-order inland valley streams.

The total study area (3.13 million ha) comprised 8.6% valley bottoms (see plate 3), 20.4% valley fringes, and 70.2% uplands. Water bodies, roads, and settlements comprised the other 0.8% area. The valley-bottom distribution was sparse (see plates 2 and 3). The drainage density of 0.4 km/km^2, and stream frequency of 0.61 number/km^2 obtained in the study area were classified as low (0.3–0.6 km/km^2), and coarse (0.5–1.0 number/km^2), respectively, by WURP (1983). In spite of the low and coarse drainage densities, and stream frequencies in the study area, the percentage area of inland valleys (valley bottoms plus valley fringes) was significant mainly as a result of the large valley-bottom and fringe widths of the inland valley streams (first- to fourth-order streams). The mean bottom widths for the first- to third-order streams were about 90 m, and increased dramatically for the fourth-order to about 400 m. Valleys with typically large bottom widths are illustrated in plate 1. The mean valley fringe (hydromorphic plus nonhydromorphic) widths were about 200 m for the first three inland valley streams and for the fourth-order stream about 920 m. Hence, even though the stream frequencies and stream densities were coarse and low respectively, the large sizes of the valley bottoms and valley fringes led to their significant percentages.

Due to significant differences in the geographical areas studied (45% of entire study area for AEZ 1, 12% for AEZ 2, 24% for land region 2.8 and 68% for land region 3.3 see tables 11 and 12) a direct and realistic comparison of results across zones was not feasible. However, it may be noted that the valleys in AEZ 1 had greater bottom widths than valleys in AEZ 2, resulting in a higher percentage area of valley bottoms in AEZ 1 (9.1%) compared to AEZ 2 (7.7%). For the same reason, the percentage valley bottom area in land region 2.8 (9.1%) exceeded that of land region 3.3 (8.2%).

The study mapped 16 land-use classes (table 11) which were derived from the various combinations of the land-cover types (table 8). The spatial distribution of the 16 land-use classes in the entire study area of 3.13 million ha (plate 4) dramatically highlights regions with insignificant or no cultivation (violet, red, magenta, rose, and red-orange) in comparison to regions with significant cultivation (gray, white, cyan). The seafoam color is the region with scattered farming. The characteristics of land use are best depicted when mapped in a smaller scale for subareas such as in plates 5 and 6. The spatial distribution of land use and cultivation patterns relative to road networks and settlements is

available from plates 5 and plate 6. Forest and nonforest boundaries are dramatically highlighted in plate 6. Several characteristics of the inland valley agroecosystems can also be inferred from the land-use maps of the subscenes. For example, significant cultivation, mainly with rice crop, is seen mostly in the third- and fourth-order valley bottoms in the vicinity of Sikasso (plate 6). These valley bottoms are, typically, broad and flat and are often flooded and have recent deposits of fertile alluvium.

The grassland dominant savannas are most extensive in the study area. The overall savanna percentage areas were 65.5% for AEZ 1, 70.4% for AEZ 2, 67.1% for land region 3.3, 61.6% for land region 2.8, and 65.4% for the entire study area. The forest classes are predominantly trees along the river banks and were about 4% for all level I zones within the study area. This very low percentage of forest cover was only to be expected in the study area as it falls in the northern Guinea savanna and Sudan savanna. Compared to other level I zones studied, barren areas of the Sudan savanna were most extensive with 6% area of the respective level I zone.

The cultivation intensities were nearly the same across the toposequence with 18.4% for valley bottoms, 19.2% for valley fringes, and 21.9% for uplands. The significant cultivation across the toposequence was mainly attributed to the market-driven conditions. In most cases, cultivation intensities were about 3% higher for distance limits within 0-5 km from the road network and settlements compared to those areas beyond 5 km.

The valley bottoms in the study area were characterized by flat or near-flat surfaces (see plate 1 for example) that have shallow flooding all through the rainy season. Rice cultivation forms an important component of lowland rainy-season cultivation in the entire study area, especially in the valleys surrounding Sikasso, Mali (plate 6). These broad and flat or near-flat valley bottoms of the study area offer an excellent oppurtunity for inundated rice cultivation during the rainy season as successfully demonstrated in several valleys around Sikasso, Mali. (See plate 7 for spatial distribution of rice cultivation in the valley bottoms near Sikasso and surroundings.) However, the area of valley bottoms available for cultivation far exceeds their current utilization. A total of 269,006 ha constitute valley bottoms in the entire study area, of which only 18.4% (49,497 ha) was cultivated. Of the cultivated inland valleys, 42% (20,789 ha) had rice cultivation.

Except for a few inland valleys such as the large farm near Bama, northwest of Bobo-Dioulasso (see plate 4), and in the area surrounding Sikasso (plate 7), there is very little rice cultivation and/or only partial exploitation of inland valley systems for rice cultivation in the study area. However, an extensive potential for rice cultivation exists, especially in the inundated valleys of third- and fourth-order streams such as those near Desso and Laranfiara in Burkina Faso (see plate 9, for example); Banankoni and Lotio watersheds surrounding Sikasso, Mali (see plate 3 and 7); and Niaminasso and Nougoussouala, north of Sikasso, Mali (plates 3 and 7). These valleys, however, require appropriate technology such as low-cost water control measures (e.g., channels, levies, and bunding), and appropriate rice varieties for inundated conditions.

The study showed a strong relationship between upland cultivation (plate 11) and inland valley cultivation (plate 12) proving one of the hypotheses of this study.

The study highlighted the strengths of remotely sensed data in the proper inventorying of parameters such as percentage of cultivated areas. Such estimates based purely on ground-truth data provided significant overestimates of cultivated areas. For example, the cultivated valley-bottom areas estimated purely based on ground-truth data were 37.5% compared to 18.4% provided by Landsat TM data.

Similar differences were observed in another study area in Gagnoa, Côte d'Ivôire using SPOT HRV data (Thenkabail and Nolte 1995c).

Information from the different georeferenced spatial datalayers generated mainly from Landsat TM data (e.g., land use of different components of the toposequence, cultivation intensities of inland valleys with respect to road network and settlements) was used in conjunction with expert knowledge, through GIS modeling, to determine the potential sites for technology development research activities. This led to a map of potential benchmark research sites in the study area (plate 8). These potential benchmark research sites were characterized by: (a) near-flat valley bottoms; (b) large valley bottom widths (about 100 m for first- to third-order valleys; and about 400 m for the fourth-order valleys); (c) well connected road networks (typically, within 6 km); (d) proximity to settlements (typically, within 6 km); (e) rainy-season shallow inundation of flood water in valley bottoms; (f) mild to very mild transversal slopes (mean of about 1.5 degrees for first- to third-order valleys; and a mean of about 0.5 degrees for the fourth-order valleys); (g) large fringe widths (about 200 m for first to third-order valleys; and about 920 m for fourth-order valleys). A final selection of the research sites should involve a visit to the several potential sites shown in plate 8 by a team of scientists of diverse expertise for a quick reconnaissance, interviews with farmers, and interaction with NARS. Detailed maps of each of the interested potential locations that are shown in plate 8 should be drawn to be taken to the field (see one such example in plate 9).

The study resulted in digital georeferenced data bases for the land use of uplands, valley bottoms, and valley fringes; inland valley bottom areas; inland valley fringe areas; upland areas; rice cultivation areas; and benchmark research area locations.

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LIST OF INLAND VALLEY CHARACTERIZATION REPORTS

1. Regional Characterization of Inland Valley Agroecosystems in Save, Bante, Bassila, and Parakou Regions in South-Central Republic of Benin through Integration of Remote Sensing, Global Positioning System, and Ground-Truth Data in a Geographic Information Systems Framework. Prasad S. Thenkabail and Christian Nolte, 1995.

2.Regional Characterization of Inland Valley Agroecosystems in Gagnoa, Côte d'Ivoire through Integration of Remote Sensing, Global Positioning System, and Ground-Truth Data in a Geographic Information Systems Framework. Prasad S. Thenkabail and Christian Nolte, 1995.

3. Regional Characterization of Inland Valley Agroecosystems in Sikasso, Mali and Bobo-Dioulasso, Burkina Faso through integration of Remote Sensing, Global Positioning Systems and Ground-Truth Data in a Geographic Information Systems Framework. Prasad S. Thenkabail and Christian Nolte, 1995.

About IITA

The goal of the International Institute of Tropical Agriculture (IITA) is to increase the productivity of key food crops and to develop sustainable agricultural systems that can replace bush fallow, or slash-and-burn, cultivation in the humid and subhumid tropics. Crop improvement programs focus on cassava, maize, plantain and banana, cowpea, soybean, and yam. Research findings are shared through international cooperation programs, which include training, information, and germplasm exchange activities.

IITA was founded in 1967. The Federal Government of Nigeria provided a land grant of 1,000 hectares at Ibadan, for a headquarters and experimental farm site, and the Rockefeller and Ford foundations provided financial support. IITA is governed by an international Board of Trustees. The staff includes around 180 scientists and professionals from about 40 countries, who work at the Ibadan campus and at selected locations in many countries of sub-Saharan Africa.

IITA is one of the nonprofit, international agricultural research centers currently supported by the Counsultative Group on International Agricultural Research (CGIAR). Established in 1971, CGIAR is an association of about 50 countries, international and regional organizations, and private foundations. The World Bank, the Food and Agriculture Organization of the United Nations (FAO), and the United Nations Development Programme (UNDP) are cosponsors of this effort.

About Inland Valley Consortium

The broad objectives of the Inland Valley Consortium (IVC) are: (i) to improve the competitiveness of crop production in sub-Saharan Africa; (ii) to reduce pressure on the fragile uplands by making it possible for farmers to intensify production in the more robust lowlands; (iii) to minimize environmental costs as inland valleys are brought into cultivation; and (iv) to strengthen the capacity of national research programs through collaboration, and technical, and financial assistance.

Three major research themes are adopted:
- Multiscale agroecological characterization
- *Aménagement* (development of low-cost water management systems)
- Transfer and testing of agronomic technologies

IVC was established in 1994. The present members of the Consortium are national institutes of Benin, Burkina Faso, Côte d'Ivoire, Ghana, Mali, Nigeria, and Sierra Leone, and five international research institutions, West African Rice Development Association (WARDA), International Institute for Tropical Agriculture (IITA), Winand Staring Center (SC-DLO), Wageningen Agricultural University (WAU), and Centre de Coopération Internationale en Recherche Agronomique pour le Dévelopement (CIRAD). New members are expected in the near future because the Consortium is an open structure for cooperation. The Consortium is based in Bouaké, Côte d'Ivoire, at WARDA headquarters.