Maintenance and improvement of soil productivity in the highlands of Ethiopia, Kenya, Madagascar and Uganda

An inventory of spatial and non-spatial survey and research data on natural resources and land productivity

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Contents

1 Introduction

Demographic maps of eastern and central Africa clearly show how strongly human settlement in the rural areas is concentrated in the highlands, where living conditions are relatively favourable and soils are relatively fertile. A huge percentage of land is now occupied by farmers who have developed an intricate pattern of agroecosystems. Ever-increasing population pressure has rendered much of the land prone to different land-degradation processes, such as erosion, landslides, loss of soil fertility, deterioration of soil physical and hydrological properties, and loss of ecological functions. Marginal parts of the highlands are now also under cultivation. Although there are some encouraging examples where increased population pressure has been a stimulus to land husbandry, more often it leads to land degradation and decline in productivity.

The overall goal of the African Highlands Initiative (AHI) is to help communities in the densely populated and intensively cultivated highlands of eastern and central Africa combat poverty resulting from land degradation by enhancing knowledge and dissemination of sustainable systems of agricultural production and natural resources management. It will review and incorporate traditional technologies employed by farmers, to maintain a reasonable level of land productivity using affordable and locally available inputs and to facilitate a community-based approach to conserving natural resources (Wang'ati 1994). A major AHI research theme is Maintenance and Improvement of Soil Productivity (MISP), to which the present report relates.

The International Centre for Research in Agroforestry (ICRAF) contracted the Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO), based in Wageningen, The Netherlands, to carry out a review of survey and research materials that relate to the MISP theme. The present synthesis gives a state-of-the-art report on MISP for the 4 AHI pilot countries: Ethiopia, Kenya, Madagascar and Uganda. It is intended as a resource document to the MISP Technical Advisory Panel and scientists in the region to help them readily access the results of previous research. The synthesis is also meant to avoid 'reinventing wheels' and should assist in further MISP priority setting by identifying critical knowledge gaps.

Section 2 provides the information that is spatially correlated. Section 2.1 presents an overview of natural resources, land use and demography. In sec. 2.2, these datasets are used to translate basic attributes into MISP 'soil productivity indicators'. Section 2.3 deals with the spatial scale at which these indicators were collected and issues such as extrapolability.

Section 3 provides research results that are not spatially correlated as such. As much as possible, a quantitative review is given for each country on MISP-related research. For each country there is (1) an introduction to soil productivity research; this is followed by topics such as (2) soil physical, (3) soil chemical and (4) soil biological properties and processes, (5) runoff and soil erosion, (6) nutrient budgets, (7) technologies for MISP, (8) modelling approaches, (9) long-term experimentation, (10) farming systems research and (11) technology adoption.

This work is summarized and synthesized in sec. 4 with special attention to some of the highlights. General and specific conclusions are made, followed by an evaluation of critical knowledge gaps.

Given the huge amount of old and grey information, in part inaccessible, the editors do not pretend that the study has been exhaustive. Yet the hope is expressed that the report will help to put the major issues on the table and will effectively set the stage for relevant future research and development of the African highlands.

2 Spatial presentation, interpretation of natural resources

2.1 Information base

2.1.1 Where are the 'highlands'?

Several definitions exist on the highlands of eastern and central Africa. When ICRAF studied the potential for agroforestry in these highlands (Djimde and Hoekstra 1988), the limits included annual rainfall above 1000 mm and an altitude range of 1000–2500 m. A CGIAR/NARS task force on natural resources management research then defined highlands as the land above 1500 m in altitude with an average annual rainfall of at least 1000 mm. AHI adopted the CGIAR/NARS definition, but it was later felt that the altitude criteria had to be broadened to begin at 1000 m to include certain agricultural lands in Uganda where land-use systems and resource-management problems are similar to those in other highlands (Wang'ati and Kebaara 1993). For altitude, 1200–3300 m was eventually chosen as a compromise of earlier definitions (Wang'ati 1994), while the rainfall requirement was further specified to include only areas that have more than 400 mm in 5 consecutive months (Hoekstra and Corbett 1995). The area of land resources for the 4 pilot countries in this study is presented in table 2.1.

2.1.2 GIS database

In this section an overview is given of rainfall, altitude, population, soil classification and soil pedon data for the highlands of Ethiopia, Kenya, Madagascar and Uganda—these data have all been entered into a geographic information systems (GIS) database. Later sections describe climate, altitude, soils and land use for each country and show which data are available at larger scales.

Rainfall. Rainfall data collected by meteorological departments and other institutes were used to analyse the climate in a grid database for the highlands of the Horn of Africa. These data were interpolated spatially using thin-plate smoothing splines (Hutchinson and Corbett 1993). The climate surface data have a resolution of 3 arc-minutes, which correspond with grid cells of approximately 25 km^2. In the database 4 rainfall classes were defined: (1) 400–600 mm, (2) 600–800 mm, (3) 800–1000 mm and (4) >1000 mm rainfall in 5 consecutive months. Map 1 presents the rainfall distribution in 5 consecutive wet months for the highlands of Ethiopia, Kenya and Uganda, while for Madagascar this is presented on map 2. Table 2.2 shows the extent of the areas concerned and shows that the highlands of Ethiopia and Madagascar are wetter than those of Kenya and Uganda. The highlands of Uganda are driest, with 64% of the area having only 400–600 mm rainfall in 5 consecutive months.

Altitude. Data were used from the Centre for Resources and Environmental Sustainability (CRES) and differentiated into a grid surface using classes of 300 m each. The resolution of these data is 3 arc-minutes, like the rainfall grid surface. For the highlands of the 4 MISP countries, 7 classes were distinguished: (1) 1200–1500 m, (2) 1500–1800 m, (3) 1800–2100 m, (4) 2100–2400 m, (5) 2400–2700 m, (6) 2700–3000 m and (7) 3000–3300 m. Map 3 presents altitude

Table 2.1 Land resources in the highlands of Ethiopia, Kenya, Madagascar and Uganda

Country	Total (km²)	Highlands (km²)	Highlands (% of country total)	Highlands (% of total highlands)
Ethiopia	1 246 950*	446 928	36	66
Kenya	589 410*	102 955	17	15
Madagascar	592 000**	64 869	11	10
Uganda	242 130*	66 536	27	10
Total	2 670 490	681 288	26	

* Hoekstra and Corbett (1995); ** Oldeman (1992)

Table 2.2 Distribution of rainfall in the 5 consecutive wettest months for the highlands of Ethiopia, Kenya, Madagascar and Uganda

Rainfall	Ethiopia		Kenya		Madagascar		Uganda		Total	
(mm)	(km²)	(%)	(km²)	(%)	(km²)	(%)	(km²)	(%)	(km²)	(%)
400–600	128 932	29	50 774	49	198	0	42 298	64	222 202	33
600–800	105 412	24	43 723	42	2 527	4	20 781	31	172 443	25
800–1000	78 359	18	8 334	8	4 006	6	3 457	5	94 156	14
> 1000	134 225	30	124	0	58 138	90	0	0	192 487	28
Total	446 928		102 955		64 869		66 536		681 288	

for the highlands of Ethiopia, Kenya and Uganda, while for Madagascar this is presented on map 4. Table 2.3 shows that in Kenya and Ethiopia, the highlands are distributed evenly throughout the elevation classes. Uganda and Madagascar have 'low' highlands with 89 and 93% of the surface area between 1200 and 1800 m.

Population. The eastern African highlands are productive and have a long history of agricultural use by Bantu, Nilotic and Semitic populations. Population data for Ethiopia, Kenya, Madagascar and Uganda were retrieved from a recently established database for Africa (Deichmann 1994). The reference years for Ethiopia, Kenya, Madagascar and Uganda were 1984, 1989, 1990 and 1991 respectively. This population database provides the opportunity to link areas with a high population density to certain climatic characteristics, altitude and soil productivity parameters. A population density classification gave the following groupings: (1) 0–25 km^{-2}, (2) 25–75 km^{-2}, (3) 75–175 km^{-2} and (4) >175 km^{-2}. Map 5 presents population densities for the highlands of Ethiopia, Kenya and Uganda, while for Madagascar this is presented in map 6. Remarkable differences in the population density distribution, shown in table 2.4 include the high percentage of Kenyans in the highlands (34%) living in very densely populated areas (> 175 km^{-2}) in contrast to the high percentage of people in Madagascar (not less than 45%) living in low-density areas (0–25 km^{-2}). The total population of the 4 MISP countries living in the highlands is given in table 2.5. Ethiopia has a high percentage of its total population (81%) in the highland area, which comprises only 36% of the country (table 2.1). In Kenya this situation is just as extreme, with 64% of the population in the highlands, which comprise a mere 17% of the country. In Uganda, the situation looks less tense with 37% of the population living in the highlands, which encompass 27% of the country.

Soils. Soil maps for the 4 MISP-countries at an exploratory scale all have a different origin. Survey methods used in Ethiopia, Kenya, Madagascar and Uganda were and are very different, and maps were produced in different time periods. The most complete country map was produced in Kenya at 1:1 000 000 by the Kenya Soil Survey (KSS, Sombroek and others

Table 2.3 Altitude ranges in the highlands of Ethiopia, Kenya, Madagascar and Uganda

Altitude (m)	Ethiopia (km²)	(%)	Kenya (km²)	(%)	Madagascar (km²)	(%)	Uganda (km²)	(%)	Total (km²)	(%)
1200–1500	92 030	21	29 096	28	42 509	66	48 514	73	212 149	31
1500–1800	116 387	26	27 106	26	17 531	27	10 683	16	171 707	25
1800–2100	104 532	23	21 406	21	4 124	6	3 384	5	133 446	20
2100–2400	72 035	16	14 906	14	675	1	2 769	4	90 385	13
2400–2700	37 311	8	6 981	7	30	0	717	1	45 039	7
2700–3000	16 146	4	2 495	2	0	0	204	0	18 845	3
3000–3300	8 489	2	950	1	0	0	264	0	9 703	1
Total	446 930		102 940		64 869		66 536		681 274	
Error (%)	0.0		0.0		0.0		0.0		0.0	

Table 2.4 Population density distribution in the highlands of Ethiopia, Kenya, Madagscar and Uganda

Population density (persons km⁻²)	Ethiopia (km²)	(%)	Kenya (km²)	(%)	Madagascar (km²)	(%)	Uganda (km²)	(%)	Total (km²)	(%)
0–25	77 369	17	9 382	9	29 479	45	17 432	28	133 662	20
25–75	136 195	30	30 728	30	16 616	26	11 655	18	195 194	29
75–175	179 268	40	27 343	27	14 087	22	30 164	45	250 862	37
> 175	54 101	12	35 502	34	4 688	7	7 282	11	101 573	15
Total	446 933		102 955		64 869		66 533		681291	
Error (%)	0.0		0.0		0.0		0.0		0.0	

Table 2.5 Population (1994) in the highlands of Ethiopia, Kenya, Madagscar and Uganda

Country	Total population* ('000s)	Population in highlands ('000s)	Population in country's highlands (%)	Population in MISP highlands (%)
Ethiopia	53 143	43 200	81	60
Kenya	25 835	16 624	64	23
Madagascar	13 047	4 809	37	7
Uganda	18 144	6 956	38	10
Total	110 169	71 589		100

* Deichmann (1994)

1982). In Ethiopia a very broad reconnaissance survey (1:1 000 000) was done by FAO (FAO/UNDP 1984a), while in Madagascar, Riquier (1968) produced a 1:1 000 000 soil map using the French classification system. In Uganda, a countrywide reconnaissance survey was carried out in the early 1960s at a scale of 1:250 000 (Chenery 1960). Both the Kenyan and the Ethiopian maps are available in digital format at ICRAF's GIS laboratory. However, the Madagascar and Ugandan maps were digitized as part of this study. Further explanation of the structure of the soil maps is given for Ethiopia in sec. 2.1.3, for Kenya in sec. 2.1.4, for Madagascar in sec. 2.1.5 and for Uganda in sec. 2.1.6.

Soil pedons. Representative soil profiles that could be linked to mapping units of the soil maps were found for all MISP countries except for Ethiopia. In Kenya, use was made of the KENSOTER (Kenya Soils and Terrain Digital Database) database that was developed in a joint KSS/UNEP/ISRIC (United Nations Environmental Programme/International Soil Reference and Information Centre) project. For Uganda, representative profiles were used from the 'memoirs' that go with the 1:250 000 soil map. In Madagascar, the local expert team managed to collect recent soil pedon data that could be linked to the soil map. Further explanation on the use of the specific country soil pedons is given in sec. 2.2.

2.1.3 Ethiopia

Climate and altitude. Ethiopia is unique in Africa for its vast area of cool tropics and high altitudes. However, great variations in climate occur across Ethiopia, which are to a large extent responsible for the country's widely varying soils (UNDP/FAO 1984a) and for the great variation in agricultural systems (Amare Getahun 1989). The main influences on circulation in Ethiopia are the intertropical convergence zone (ITCZ), the northeast trade winds and the southwest monsoon. Precipitation is in turn strongly influenced by the relative movement of these circulation systems over the Ethiopian land mass. In January, for example, the southern position of the inter-tropical convergence zone brings most of the country under the influence of the northeast trade winds, resulting in an extensive dry season (Hurni and Stähli 1982). The northward movement of the intertropical convergence zone over Ethiopia in the period March to June encourages the progressive movement from the southwest of moisture-laden monsoonal air masses. By July, most of the country is under the influence of the southwest monsoon, which brings about the onset of the main rainy season *(krempt)* over much of the Ethiopian land mass. A short rainy season *(belg)* results from the movement of a high pressure system over the Arabian Peninsula and from the southwestern winds over the Indian Ocean (Hurni and Stähli 1982). The belg precedes the main rainy season in the south and southwestern highlands of Ethiopia. Rainfall amounts vary widely throughout Ethiopia and are principally determined by (1) the direction of moisture-bearing seasonal air currents and (2) the elevation (Gamachu 1977). Map 1 shows that the highest amounts of rainfall over 5 consecutive months are concentrated in the western part of the country. Although the western part of Ethiopia is relatively wet, part of this area is out of the highlands because of the altitude criterion. Temperature is greatly influenced by altitude. A high correlation ($r^2 = 0.9$) was found between altitude and mean daily temperature during the growing period for Ethiopia (excluding the southeastern lowlands and the Ogaden), which allows a definition of thermal zones according to contours (UNDP/FAO 1984a). In table 2.6, altitude ranges are presented with corresponding mean daily temperature ranges during the growing period.

Table 2.6 Thermal zones of the highlands of Ethiopia

Thermal zone no.	Altitude (m)	Temperature (C)
3	3000–3400	10.0–12.5
4	2600–3000	12.5–15.0
5	2200–2600	15.0–17.5
6	1700–2200	17.5–20.0
7	1300–1700	20.0–22.5

Source: UNDP/FAO (1984a)

Soils. In Ethiopia, soils have been mapped at various scales with varying approach and quality. Data for over 3500 point samples exist (so far these are unavailable for use in ICRAF's GIS database), while 30% of the country has been surveyed and mapped at a reconnaissance level. The most recent soil surveys have been carried out by the joint UNDP/FAO assistance to land-use planning project. This project produced a 1:1 000 000 geomorphology and soils map (UNDP/FAO 1984a), and based on that a 1:2 000 000 soil association map was made. Furthermore at reconnaissance level (1:250 000) 3 areas were surveyed (table 2.7) and 3 more at semi-detailed level (1:50 000). For the current study, the 1:1 000 000 geomorphology and soils map (UNDP/FAO 1984a) has been used for a general overview of soil productivity in the highlands. This map is present at ICRAF in digital format with an extensive legend. In Addis Ababa, the Soil Conservation Research Project (SCRP) and the Woody Biomass Inventory and Strategic Planning Project (WBISPP) have GIS facilities. With help of Berne University, SCRP is also digitizing the geomorphology and soils map, while at WBISPP, GIS facilities are used for an inventory of the availability of fuelwood in southwestern Ethiopia. At WBISPP there are a large number of maps available in digital format, among which are the 1:1 000 000 Geomorphology and Soils and the 1:2 000 000 Soil Association map.

The Geomorphology and Soils map (UNDP/FAO 1984a) was put together through the use of Landsat satellite imagery interpretation, field surveys and agroclimatic data. Major complex map units are referred to as land systems or landscape units. These are made up of several land facets, which correspond with the soil classification orders. The characteristics of a land facet include classification (FAO-Unesco 1974), effective depth (cm), pH-H_2O, organic matter (g kg^{-1}), cation-exchange capacity (cmol kg^{-1}) and P-Olsen (mg kg^{-1}).

In the highlands of Ethiopia, the major soils (FAO-Unesco 1974) are Cambisols (23.9%), Nitosols (21.8%), Lithosols (14.2%), Vertisols (13.5%) and Luvisols (10.0%). These 5 major soil orders cover 83% of the highlands. The total picture for the highlands is presented in table 2.8. Map 7 presents the major soils for each predominant land facet. Based on this map one can define a global distribution of the 5 major soil orders. The Cambisols occur spread over the country, but mainly they border the large areas of Nitosols in the western highlands and Lithosols in the Harerge highlands, and a large patch in the northeast.

Table 2.7 Land resources maps for Ethiopia (different scales)*

Serial no.	Title/area	Year	Scale
FD3	Geomorphology and Soils (Ethiopia)	1984	1:1 000 000
TR1	Land resources map (Ethiopia)	1984	1:1 000 000
FD6	Soil association map (Ethiopia)	1984	1:2 000 000
TR5	Land suitability map (Ethiopia)	1984	1:2 000 000
FD29	Soils of Menagesha Awraja (Shewa)	1984	1:250 000
FD37	Reconnaissance soil survey of Haykoch & Butajira (Shewa)	1984	1:250 000
FD43	Reconnaissance soil survey of Yerer & Kereju (Shewa)	1984	1:250 000
FD7	Soil survey of Borkena study area	1984	1:50 000
FD10	Soils of Bichena study area	1984	1:50 000
FD1	Soils of Hosaina study area	1984	1:50 000

* available at the Land Use Department, Ministry of Agriculture (see appendix 2)

Table 2.8 Distribution of soils in the highlands of Ethiopia

Soil classification (FAO-Unesco 1974)	Total area		Area with population density > 175 persons km^{-2}		Area with population density < 75 persons km^{-2}		Area with population density < 25 persons km^{-2}		Area with rainfall in the 5 consecutive wettest months > 800 mm		Area with altitude <2400 m	
	(km^2)	(%)	(km^2)	(%)*	(km^2)	(%)*	(km^2)	(%)*	(km^2)	(%)	(km^2)	(%)*
Acrisols	13 947	3.1	353	3	9 882	71	2 830	20	12 000	86	13 312	95
Andosols	5 735	1.3	1 920	33	1 248	22	435	8	0	0	5 734	100
Arenosols	5 403	1.2	156	3	3 262	60	743	14	790	15	5 302	98
Cambisols	107 979	23.9	11 856	11	52 185	48	23 157	21	38 447	36	92 148	85
Chernozems	1 021	0.2	0	0	114	11	0	0	0	0	632	62
Fluvisols	13 435	3.0	1 413	11	7 438	55	3 009	22	5 470	41	12 211	91
Gleysols	3 318	0.7	94	3	1 679	51	308	9	2 602	78	2.983	90
Histosols	39	0.0	0	0	39	100	5	13	4	10	7	18
Lithosols	64 266	14.2	9 478	15	26 994	42	10 536	16	21 273	33	52 331	81
Luvisols	45 453	10.0	8 206	18	19 214	42	6 336	14	18 013	40	35 505	78
Nitisols	98 517	21.8	8 491	9	58 233	59	16 646	17	77 764	79	89 741	91
Phaeozems	3 444	0.8	410	12	1 824	53	620	18	1 295	38	3 288	95
Regosols	5 469	1.2	1 003	18	2 343	43	962	18	1 130	21	4 360	80
Rendzina	8 408	1.9	1 354	16	3 231	38	1 999	24	2 733	33	8 081	96
Solonchaks	1 117	0.2	6	1	130	12	66	6	0	0	200	18
Vertisols	60 828	13.5	7 953	13	22 904	38	9 562	16	28 437	47	51 424	85
Xerosols	122	0.0	21	17	102	84	102	84	0	0	117	96
nda	13 139	2.9	1 631	12	5 297	40	1 804	14	5 178	39	11 622	88
Total	451 64		54 345		216 119		79 119		215 137		388 997	
Error (%)	1.0		0.5		1.2		2.3		1.2		1.0	

* percentage of total area (1st column) per soil type

Luvisols are concentrated around Lake Tana and the Rift Valley area, whereas Vertisols occur in patches throughout the country. Apparent from the map is also the occurrence of Acrisols in the large Nitisol area in the west and Andosols in the Rift Valley area.

Table 2.8 also shows the combination of soil order and population density, so as to see if there is still some room for expansion. The highest population density class (table 2.4) represents 12% of the Ethiopian highlands. In table 2.8 one can see that Andosols have a fairly high extent (33%) in these areas. Remarkably low is the extent of Acrisols (3%). In less densely populated areas (below 75 km^2), comprising 37% of the Ethiopian highlands, Acrisols (71%), Cambisols (48%) and Fluvisols (55%) are more common. The last 2 columns in table 2.8 present the major soils in areas with rainfall in the 5 wettest months exceeding 800 mm (38% of the highlands) and areas with an altitude less than 2400 m (86% of the Ethiopian highlands).

Land use. The most important food crops are grown in the Ethiopian highlands; they are tef *(Eragrostis tef)*, barley *(Hordeum vulgare)*, wheat (*Tristicum* spp.), sorghum *(Sorghum bicolor)*, maize (*Zea mays*), noug *(Guzotia abyssinia)* and enset *(Ensete ventricosum)* (table 2.9). Tef, noug and enset are unique to Ethiopia. Tef is a very small-seeded cereal, noug an edible oil and enset a member of the banana family in which starch is extracted from the corn and pseudostem. Coffee (*Coffea* spp.) is the most important export crop. Land use is mainly governed by climate, terrain and population (UNDP/FAO 1984b). The latter has changed land use dramatically over the past 10 years. Large areas in the north with high population densities were already devoid of any vegetal cover outside the cropping period at the time of the UNDP/FAO survey. Some areas had no soil cover left because of previous overexploitation, which resulted in massive soil erosion and exposure of bedrock. The study on land use, production regions and the farming systems inventory by the Assistance to Land-Use Planning Project (UNDP/FAO 1984b) is now rather old and partly obsolete. Yet it is the most comprehensive work on land use in Ethiopia. The 1:1 000 000 map that was produced is also available in digital format at ICRAF's GIS lab. Table 2.10 gives the distribution of land-use types for the whole country. One could say that land use in the highlands is mainly made up of classes 2, 3, 4 and 5.3. This covers an area of approximately 310 000 km^2 (25% of the country).

In a recent study for the IGADD (Inter-Governmental Authority on Drought and Development) region (Van Velthuizen and Verelst 1995), crop production system zones (CPSZS) have been defined representing homogeneous zones in terms of agroecological conditions and current distribution of land use. The most important zones for the Ethiopian highlands are the tef–barley–maize zone and the barley/wheat–tef–pulses zone in the northern and central highlands, and the maize–coffee–tef zone and the enset–maize–barley zone in the southwestern highlands. The eastern highlands are dominated by the barley/wheat–chat *(Catha edulis)* zone. In farming systems research (FSR) in Ethiopia, Franzel and van Houten (1992) characterized land use in Ethiopia into 24 zones, not all of which are in the highlands. These are discussed in the FSR part of sec. 3.

Table 2.9 Major agricultural activities in Ethiopia, Kenya, Madagascar and Uganda

	Ethiopia	Kenya	Madagascar	Uganda
Major food crops	tef barley wheat sorghum maize noug enset	maize wheat rice beans sorghum sugarcane	rice cassava maize beans sweet potatoes horticulture	banana[1] millet sorghum maize cassava sugarcane
Major cash crops	coffee	coffee tea pyrethrum horticulture	coffee vanilla cloves pepper	coffee cotton tobacco tea
Other activities	livestock	dairy	fish forestry	fish

[1] including plantains

Table 2.10 Land use in Ethiopia

Major land-use classes	Sub-units	Area (km²)	Area (%)
1. Urban or built-up land		610	0
2. Cultivated land	2.1 State farms	740	0
	2.2 Intensively cultivated land	127 904	10
	2.3 Moderately cultivated land	135 812	11
	2.4 Perennial crop cultivation	19 694	2
3. Afro-alpine and sub afro-alpine vegetation		2 000	0
4. Forest land	4.1 Dense coniferous high forest	1 430	0
	4.2 Dense mixed high forest	28 600	2
	4.3 Disturbed high forest	25 022	2
5. Woodland	5.1 Dense woodland	11 406	1
	5.2 Woodland	19 164	2
	5.3 Eucalyptus woodland	350	0
6. Riparian woodland or bushland		7 990	1
7. Bushland	7.1 Dense bushland	45 554	4
	7.2 Open bushland	12 814	1
	7.3 Lowland bamboo bushland	5 506	0
8. Shrubland	8.1 Dense shrubland	78 130	6
	8.2 Open shrubland	124 666	10
9. Grassland	9.1 Open grassland	153 742	12
	9.2 Bushed shrubbed grassland	173 708	14
	9.3 Wooded grassland	53 672	4
10. Swamp and marshes	10.1a Perennial swamp	5 990	0
	10.1b Seasonal swamp	1 300	0
	10.2a Perennial marsh	1 860	0
	10.2b Seasonal marsh	686	0
11. Salt flats, exposed rock or sand surface	11.1 Exposed rock surface	18 880	2
	11.2 Salt flats	6 050	0
	11.3 Exposed sand soil surface	38 870	3
	11.4 Exposed sand soil surface with scattered scrub and grass vegetation	55 180	4
	11.5 Exposed rock surface with scattered scrub and grass vegetation	84 790	7
12. Water body		6 830	1

Source: (UNDP/FAO 1984b)

2.1.4 Kenya

Climate and altitude. As in the Ethiopian highlands, climate patterns in the Kenyan highlands are influenced by the intertropical convergence zone, although mountains, plateaux and larger lake basins can distort the airflow and modify the rainfall distribution. This complicated nature of rainfall distribution in the Kenyan highlands is reflected in extreme areal variation of annual rainfall (Davies and others 1985). In the highlands of Kenya there are 2 major rainfall seasons, and in the western part of Kenya there is a 3rd season (Kenworthy 1964). The first occurs in March–May; from July to September there is a wedge-shaped maximum stretching from the northwest that is particularly strong in August around the Lake Victoria and Mt Elgon areas and protruding around Mt Kenya; the 3rd rainy season is from October to December. Hills (1979) suggested that the July–September rainfall in western Kenya is caused by the westerlies, in contrast to the main season's rainfall.

For Kenya an agroclimatic zone map at 1:1 000 000 (Sombroek and others 1982) was produced as a tool to assess which areas are climatically suitable for various land-use alternatives, with particular emphasis on the suitability for crops. A relationship between the average annual temperature and altitude was developed by the East African Meteorological Department (1970), which was found to be suitable for the highlands (X in m):

$$T_{mean}\ (^\circ C) = 30.2 - 0.00650 * X \qquad \text{Eq. 2.1.1}$$

Sombroek and others (1982) used eq. 2.1.1 to define temperature zones (table 2.11). A well-known follow-up was the work by Jaetzold and Schmidt (1982) and their farm management handbooks for western, central and eastern Kenya. The handbooks contain information on climate, agroecological zones, soils and land use per district, and specifically deal with seasonality and probability of rainfall.

Soils. Soil survey activities started in full swing in the early 1970s, at the inception of the KSS project. The Exploratory Soil Map by Sombroek and others (1982) incorporates all the information available up to the end of 1979.

Table 2.11 Temperature zones for the highlands of Kenya

Zone	Mean annual temperature (°C)	Altitude (m)
8	10–12	2750–3050
7	12–14	2450–2750
6	14–12	2150–2450
5	16–18	1850–2150
4	18–20	1500–1850
3	20–22*	1200–1500

Source: Sombroek and others (1982)

* These are averages for the whole country; for areas in and west of the Rift Valley the temperature range is one degree warmer and for areas east of the Rift Valley one degree colder than indicated.

Next to this map, which is used for this report, several maps were produced by KSS at reconnaissance level (1:250 000 and 1:100 000; table 2.12).

The soils pattern in the Kenyan highlands is intricate because of large differences in altitude, landforms, geology and climate. The legend of the exploratory soil map reflects landforms at the highest level, geology and lithology at the 2nd level, and descriptions of individual soil mapping units at the 3rd level. At the exploratory level, the individual mapping units rarely comprise a single soil, but they usually consist of one main soil with minor associates. When the various soils of a mapping unit occur in a recognizable geographical pattern in defined proportions, they constitute a soil association; if such a pattern is absent, they form a soil complex.

Kenya had earlier been selected as a pilot country for a world Soils and Terrain Digital Database (SOTER) according to procedures defined by Van Engelen and Wen (1995). In an attempt to select representative soil profiles for mapping units in this current study, KENSOTER has proven to be the best option. The KENSOTER database is structured at the highest level with terrain component information, which is split into 2 tables: (1) the terrain component table, which indicates the SOTER unit to which the terrain component belongs and the proportion that it occupies within that unit, and (2) the terrain component data table, which holds all specific attribute data for the terrain component. At a 2nd level the soil component is stored in 3 tables: (1) the soil component table, which holds the proportion of each soil component within a SOTER unit/terrain component combination and its position within the terrain

Table 2.12 Soil maps of the highlands of Kenya

Serial no.	Title/area	Year	Scale
E1	The Exploratory Soil Map and Agro-climatic Zone Map of Kenya	1982	1:1 000 000
R1	Soil of the Kindaruma area (quarter degree sheet 136)	1975	1:100 000
R2	Soil of the Kapenguria area (quarter degree sheet 75)	1976	1:100 000
R4	Soil of the Kisii area (quarter degree sheet 130)	1982	1:100 000
R8	Soil of the Busia area (quarter degree sheet 101)	1996	1:100 000
R10	Soil of the Bondo area (quarter degree sheet 115)	in prep	1:100 000
R12	Soil of the Mount Kulal area (quarter degree sheet 112)	1986	1:250 000
R13	Soil of the Transmara-Kichancha area (quarter degree sheet 144)	in prep	1:100 000
R15	Soil of the Narok area (quarter degree sheets 145, 146, 158 and 159)	in prep	1:250 000
R16	Soil of the Chuka area (quarter degree sheet 122)	in prep	1:100 000
–	Reconnaissance soil map of the Lake Basin Development Authority area (Andriesse and van der Pouw 1985)	1982	1:250 000

component, (2) the profile table, which holds all attribute data for the soil profile as a whole, and (3) the horizon table, which holds data for each individual soil horizon. One disadvantage of this structure is that one profile (including all values for several parameters) represents a whole mapping unit.

Based on the KENSOTER database, the extent of the highland soil orders was determined (table 2.13). In Kenya, the soils classified by FAO-Unesco as Nitosols have been more strictly defined as Nitisols in view of their extent and their importance for agricultural production (Sombroek and others 1982). The major soils in the highlands are Nitisols (17%), Cambisols, (12%), Phaeozems (12%), Andosols (10%) and Ferralsols (8%). From map 8, one can also detect the major FAO-Unesco soil units as presented in table 2.13, although the map presents only the major soil order for each mapping unit and no associated soil orders. Nitisols are found at the lower slopes of Mt Kenya, Mt Elgon, the Aberdares, and in the Nandi Hills and Kericho area (map 8). Cambisols are mainly found in the area north of Kitale, while Phaeozems are concentrated in the relatively dry highland areas of Narok and Laikipia. Andosols are found at the higher slopes of Mt Kenya, the Aberdare range, and on the Chyulu Hills and Mau Escarpment. A large concentration of Ferralsols is found between Eldoret and Kitale, and Acrisols are to the west of Kakamega.

In table 2.13, the highlands soils are shown in relation to population density, rainfall and altitude. The table shows that 65% of the Acrisols and 64% of the Nitisols are in zones with more than 175 inhabitants km^{-2} (see also table 2.4).

Land use. As is the case in Ethiopia, in Kenya most food crops are grown in the highlands, with the important food crops being maize *(Zea mays)*, wheat *(Triticum aestivum)*, rice *(Oryza sativa)*, field bean *(Phaseolus vulgaris)* and sugarcane (*Saccharum* cvs). Important export crops such as coffee *(Coffea arabica)*, tea *(Camellia sinensis) and*, pyrethrum *(Chrysanthemum cinerariafolium)* and horticultural crops are also grown in the highlands (table 2.9).

Land use for Kenya was last mapped (1:1 000 000) in 1981 by the Kenya Rangeland Ecological Monitoring Unit (KREMU). The map was compiled from remote-sensing data of 1972–80; the legend is very broad. The main mapping units are (1) settlement and associated non-agricultural areas, (2) horticulture and market gardening, (3) perennial cropland, (4) arable cropland, (5) improved grazing land, (6) unimproved grazing land, (7) woodlands and forests, (8) water bodies and (9) bad or barren land. This map has not been used for this report as it was considered too broad and largely obsolete. However, it is available at ICRAF's GIS laboratory in digital format.

In the more recent study for the IGADD region (Van Velthuizen and Verelst 1995), crop production system zones have been defined representing homogeneous zones in terms of agroecological conditions and current distribution of land use. The most important zones for the Kenyan highlands are the maize–field bean–potato zone (Rift Valley), the maize–field bean–coffee zone (Mt Elgon and the area between Nairobi and Mt Kenya), and the maize–field bean–tea zone (Kericho and Kakamega). The region around Lake Victoria is defined as the finger millet–cassava–maize zone.

2.1.5 Madagascar

Climate and altitude. Three main weather systems affect Madagascar (Donque 1973, Williams 1985): (1) the trade winds from the southeast, (2) the monsoons, moving in from the northwest when the trade winds are weak, and (3) the west-to-east-moving anticyclones, that pass to the south of the island, pushing fronts northwards into Madagascar. In the highlands, there is an interaction of all 3 weather systems, and the cool climate is characterized by wet and dry seasons. Thus, depending on whether an area is on the windward or leeward side of the dorsal mountain chain, it will find pronounced dry and wet seasons or seasons with less pronounced dry periods. Long-term weather data (1930–60) for the highlands (Oldeman 1990) indicate that mean annual precipitation ranges from 1200 to 1500 mm, with monthly totals exceeding 200 mm in the period December until March. In the southern parts of the highlands, the rainy season is shorter, March already having less than 200 mm of rain. Oldeman (1990) also developed regression equations for the mean annual maximum and minimum temperatures of Madagascar. As in Ethiopia and Kenya, a correlation with altitude was found. However, as there are differences between the west coast

Table 2.13 Distribution and characteristics of soils in the highlands of Kenya

Soil classification (FAO-Unesco 1974)	Total area		Area with population density > 175 persons km^{-2}		Area with population density < 75 persons km^{-2}		Area with population density < 25 persons km^{-2}		Area with rainfall in the 5 consecutive wettest months > 800 mm		Area with altitude < 2400 m	
	(km^2)	(%)	(km^2)	(%)*	(km^2)	(%)*	(km^2)	(%)*	(km^2)	(%)	(km^2)	(%)*
Acrisols	7 019	6.9	4 575	65	1 286	18	703	10	1 512	22	6 898	98
Andosols	9 837	9.6	2 107	21	2 942	30	300	3	383	4	5 547	56
Arenosols	599	0.6	84	14	123	21	76	13	42	7	599	100
Cambisols	11 722	11.5	2 513	21	6 368	54	2 932	25	411	4	10 367	88
Chernozems	138	0.1	0	0	42	30	42	30	0	0	138	100
Ferralsols	8 605	8.4	3 440	40	1 159	13	316	4	1 105	13	8 576	100
Fluvisols	916	0.9	365	40	465	51	131	14	142	16	910	99
Gleysols	1 952	1.9	1 521	78	39	2	0	0	308	16	1 949	100
Greyzems	690	0.7	143	21	547	79	0	0	0	0	690	100
Histosols	293	0.3	236	81	1	0	0	0	48	16	12	4
Kastanozems	11	0.0	0	0	11	100	11	100	0	0	11	100
Lithosols	7 091	6.9	780	11	4 978	70	1 079	15	163	2	6 697	94
Luvisols	4 797	4.7	1 210	25	2 641	55	1 243	26	516	11	4 312	90
Nitisols	17 606	17.3	11 252	64	1 568	9	180	1	2 951	17	15 601	89
Phaeozems	11 784	11.5	2 775	24	7 239	61	467	4	425	4	11 093	94
Planosols	7 396	7.2	1 832	25	4 492	61	83	1	83	1	6 699	91
Regosols	4 301	4.2	57	1	3 191	74	1 000	23	9	0	4 253	99
Rendzina	22	0.0	0	0	14	64	14	64	0	0	22	100
Solonchaks	110	0.1	6	5	26	24	26	24	0	0	52	47
Solonetzes	483	0.5	84	17	230	48	79	16	0	0	457	95
Vertisols	3 140	3.1	709	23	1 433	46	254	8	10	0	3 120	99
Xerosols	27	0.0	0	0	27	100	27	100	0	0	24	89
No data avail.	2 882	2.8	1 090	38	1 014	35	432	15	276	10	2 693	93
No soil	610	0.6	0	0	162	27	129	21	0	0	610	100
Total	102 031		34 780		39 997		9 524		8 384		91 332	
Error (%)	0.9		2.0		0.3		1.5		0.9		1.3	

* percentage of total area (1st column) per soil type

and the east coast, 2 equations exist (X in m):

West coast:

$T_{max} = 34.7°\mathrm{C} - 0.0074\,X$ Eq. 2.1.2

$T_{min} = 20.4°\mathrm{C} - 0.0063\,X$ Eq. 2.1.3

East coast:

$T_{max} = 29.5°\mathrm{C} - 0.0047\,X$ Eq. 2.1.4

$T_{min} = 18.6°\mathrm{C} - 0.0054\,X$ Eq. 2.1.5

It should be noted that these equations are not to be used for the coastal regions themselves, because of the effect of latitude on temperature.

Soils. The island of Madagascar is characterized by a dorsal crystalline mountain range with 3 isolated massifs, Tsaratanana in the north with its highest peak at 2876 m, Ankaratra in the central part of the island (2643 m) and Andringitra in the south (2658 m). The shape of this ridge is asymmetrical in the centre and south of the island. Slopes and escarpments east of this ridge (such as the Angavo escarpment) are steep. The western side of the mountain chain is gently sloping but severely dissected in many places because of water erosion. Several basins can be recognized in the highlands of Madagascar, such as the Alaotra basin and the smaller basins around Antananarivo, Antsirabe and Ambalavao. These depressions are former lakes, gradually filled up with peat and colluvial material washed away from surrounding hills. In Alaotra, a small, shallow lake still exists, while the Antananarivo basin is flooded annually. The major rivers of Madagascar—Betsiboka, Ikopa, Tsiribirina, Mangoky and Onilay—all flow in westwards and have severely dissected the landscape. Deforestation of the mountain sides by humans has increased erosion (Oldeman 1990).

The soils of Madagascar were mapped by Riquier (1968) at a scale of 1:1 000 000 according to the French classification system. A more systematic countrywide survey at a scale of 1:200 000 was started in 1991 but was completed for only 2 sheets (Antananarivo and Antsirabe). More detailed surveys were carried out in the late 1980s by FOFIFA (Centre national de la recherche appliquée au développement rural [table 2.14]). The legend of Riquier's map for the highland soil units and the corresponding major soils classified according to FAO-Unesco (1974) are given in table 2.15. Four mapping units in the highlands turned out to be soil associations or 'juxtapositions'. The mapping units of which they consist are given in table 2.16, in case they do not constitute an independent mapping unit in the highlands (which would put them in table 2.15).

The major soil orders in the highlands are the *sols ferrallitiques* (Ferralsols), Lithosols, Cambisols and the *sols hydromorphes* (Gleysols). Ferralsols, occupying the largest portion of the highlands (65%), were formed on the basal crystalline parent material under a perhumid climate. These soils are very deep and may reach a thickness of up to 30 m when not eroded. They are characterized by an oxic horizon, have a very low adsorption complex and are strongly leached. Lithosols and Cambisols occupy a smaller portion of the highlands, 18 and 10% respectively (table 2.17). Although the Gleysols occupy only a small percentage of the highlands (1.6% according to the 1:1 000 000 soil map), they are very important, intensively used soils as most of the lowland rice is grown on them. As they are so widespread, but yet unmappable at a scale of

Table 2.14 Soil surveys for Madagascar at different scale levels

Title/area	Year	Scale
Carte pédologique de Madagascar à 1:1.000.000e (Riquier 1968)	1968	1:1 000 000
Carte des ressources en sols–Antananarivo	1991	1:200 000
Carte des ressources en sols–Antsirabe	1991	1:200 000
Etude pédologique de la plaine de Soavina (Ambatofinandrahana)	1982	1:10 000
Etude pédologique de la plaine d'Ambohibary-Sambaina	1986	1:10 000
Etude pédologique de la plaine d'Iandratsay (Betafo)	1986	1:10 000
Etude pédologique de la plaine de Manandona	1986	1:10 000
Etude pédologique de la plaine de Vinaninony	1986	1:10 000
Etude pédologique du plateau d'Ankazobe	1986	1:20 000
Etude morpho-pédologique: (1) Basse Ankona Ambohimahasoa, (2) Alakamisy Ambohimaha (Fianarantsoa), (3) Iboaka (Fianarantsoa), (4) Sahambavy (Fianarantsoa)	1989	1:10 000

Table 2.15 Legend for highland mapping units of the Soil Map of Madagscar (Riquier 1968)

Soil mapping unit (Riquier 1968)	Soil class	Soil subclass	Soil group	Soil subgroup	Soil type	Corresponding FAO-Unesco (1974) classification
I1	Sols minéraux bruts	Sols d'origine non climatique	Sols d'érosion	Lithiques	Sur granite	Lithosol
I2	Sols minéraux bruts	Sols d'origine non climatique	Sols d'érosion	Lithiques	Sur gneiss	Lithosol
I2, VIII3, VIII4	Association of I2 VIII3 and VIII4	na	na	na	na	ferric Luvisol/ Lithosol
I3	Sols minéraux bruts	Sols d'origine non climatique	Sols d'érosion	Lithiques	Sur quartzite	Lithosol
I5	Sols minéraux bruts	Sols d'origine non climatique	Sols d'érosion	Lithiques	Sur calcaire ou cipolin	Lithosol
I6	Sols minéraux bruts	Sols d'origine non climatique	Sols d'érosion	Lithiques	Sur basalte ou gabbro	Lithosol
I7	Sols minéraux bruts	Sols d'origine non climatique	Sols d'érosion	Lithiques	Sur rhyolite ou trachyte	Lithosol
I9, II5, X5	Association of I9 II5 and X5	na	na	na	na	Lithosol/humic Gleysol
II1	Sols peu évolués	Sols d'origine non climatique	Sols d'érosion	Rankers lithosoliques	Sols arénacés et rocailleux des régions subhumides	ferralic/chromic Cambisol
II2	Sols peu évolués	Sols d'origine non climatique	Sols d'érosion	Rankers lithosoliques	Sols d'érosion des régions humides	ferralic/chromic Cambisol
II3	Sols peu évolués	Sols d'origine non climatique	Sols d'érosion	Rankers lithosoliques	Sols humifères des forêts ombrophyles	ferralic/chromic Cambisol
II6, X3	Association of II6 and X3	na	na	na	na	humic Gleysol/ferralic Cambisol
VI1	Sols a mull	Sols des pays tropicaux	Sols bruns eutrophes	Peu évolués	Sur cendres volcaniques	eutric Cambisol/Andosol
VIII2	Sols a sesquioxydes	Sols ferrugineux tropicaux	Sols peu ou pas lessivés	Non lessivés en fer (rouges ou jaunes)	Sur matériau régosolique, carapace sableuse, dunes	ferric Luvisol
VIII4	Sols a sesquioxydes	Sols ferrugineux tropicaux	Sols peu ou pas lessives	Rouges	Sur roches acides	ferric Luvisol
VIII6	Sols a sesquioxydes	Sols ferralitiques	Sols faiblement ferralitiques	Modal et ferrisolique non différenciés	Sur roches acides	eutric Nitisol
VIII7	Sols a sesquioxydes	Sols ferralitiques	Sols typiques	Rouges	Sur roches acides	haplic/rhodic Ferralsol
VIII8	Sols a sesquioxydes	Sols ferralitiques	Sols typiques	Rouges	Phase érodée	haplic/rhodic Ferralsol
VIII9	Sols a sesquioxydes	Sols ferralitiques	Sols typiques	Brun-rouge	Sur roches basiques	haplic/rhodic Ferralsol
VIII10	Sols a sesquioxydes	Sols ferralitiques	Sols typiques	Jaune sur rouge (parfois tendance hydromorphe)	Sur roches acides	xanthic Ferralsol
VIII11	Sols a sesquioxydes	Sols ferralitiques	Sols lessivés	En colloides (jaunes)	Sur alluvions anciennes	haplic/rhodic Ferralsol
VIII12	Sols a sesquioxydes	Sols ferralitiques	Sols humifères	Bruns et jaunes	Sur materiau volcaniques ancien	humic Ferralsol
VIII13	Sols a sesquioxydes	Sols ferralitiques	Sols humifères	Noirs	Sur roches volcaniques	humic Ferralsol
VIII14	Sols a sesquioxydes	Sols ferralitiques	Sols indurés concrétionnés ou cuirassés	Jaune/rouge (en general)	Sur roches diverses acides	plinthic Ferralsol
VIII15	Sols a sesquioxydes	Sols ferralitiques	Sols indurés concrétionnés ou cuirassés	Rouges ou jaunes	Sur roches basiques	plinthic Ferralsol
X1, X2, X3, X4	Association of X1, X2, X3 and X4	na	na	na	na	humic Gleysol

na = not applicable

Table 2.16 *Description of mapping units in table 2.15b that are built of of associated soils*

Soil mapping unit (Riquier 1968)	Soil class	Soil subclass	Soil group	Subgroup	Soil type
I9	Sols minéraux bruts	Sols d'origine non climatique	Sols d'apport	Eoliens	Cf: association of soils
II5	Sols peu évolués	Sols d'origine non climatique	Sols d'erosion	Rankers regosoliques	Sols sableux dunaires. Cf. association of soils
II6	Sols peu évolués	Sols d'origine non climatique	Sols d'apport	Modaux (bien drainés)	Cf. association of soils
VIII3	Sols a sesquioxydes	Sols ferrugineux tropicaux	Sols peu ou pas lessivés	Non lessivés en fer (rouges ou jaunes)	Cf. association of soils
X1	Sols hydromorphes	Sols organiques	Sols tourbeux	na	Cf. association of soils
X2	Sols hydromorphes	Sols organiques	Sols semi-tourbeux	na	Cf. association of soils
X3	Sols hydromorphes	Sols minéraux	Sols a gley et pseudogley	na	Cf. association of soils
X4	Sols hydromorphes	Sols minéraux	Sols peu humifères a gley de profonde	na	Cf. association of soils
X5	Sols hydromorphes	Sols minéraux	Sols a mouvement oblique de.la nappe	na	Pseudopodzol de nappe. Cf. association of soils

Table 2.17 *Distribution and characteristics of the major soils (FAO-Unesco 1974) in the highlands of Madagascar*

Soil classification (FAO-Unesco 1974)	Total area		Area with population density > 175 persons km⁻²		Area with population density < 75 persons km⁻²		Area with population density < 25 persons km⁻²		Area with rainfall in the 5 consecutive wettest months > 800 mm		Area with altitude < 2400 m	
	(km²)	(%)	(km²)	(%)*	(km²)	(%)*	(km²)	(%) *	(km²)	(%)	(km²)	(%) *
Cambisols	6 747	10.4	345	5	4 369	65	3 124	46	6 351	94	6 747	100
Ferralsols	42 179	65.1	3 651	9	28 405	67	18 421	44	41 912	99	42 170	100
Gleysols	1 040	1.6	423	41	590	57	490	47	1 031	99	1 040	100
Luvisols	715	1.1	0	0	678	95	515	72	596	83	715	100
Nitisols	2 472	3.8	0	0	2 444	99	2 310	93	648	26	2 472	100
Lithosols	11 601	17.9	266	2	9 564	82	4 594	40	11 491	99	11 580	100
Total	64 754		4 685	7	46 050	71	29 454	45	62 029	96	64 724	100
Error (%)	0.2		0.1		0.1		0.1		0.2		0.2	

* percentage of total area (1st column) per soil type

Table 2.18 Distribution and characteristics of the soils (Riquier 1968) in the highlands of Madagascar

Soil mapping unit (Riquier 1968)	Total area		Area with population density > 175 persons km^{-2}		Area with population density < 75 persons km^{-2}		Area with population density < 25 persons km^{-2}		Area with rainfall in the 5 consecutive wettest months > 800 mm		Area with altitude < 2400 m	
	(km^2)	(%)	(km^2)	(%)*	(km^2)	(%)*	(km^2)	(%)*	(km^2)	(%)*	(km^2)	(%)*
I1	6 724	10.4	163	2	5 025	75	2 401	36	6 620	98	6 707	100
	12	190	0.3	0	0	190	100	20	11	188	99	190
100												
I2, VIII3, VIII4	492	0.8	0	0	492	100	405	82	434	88	492	100
I3	4 152	6.4	57	1	3 867	93	1 998	48	4 155	100	4 155	100
I5	212	0.3	0	0	212	100	92	44	212	100	212	100
I6	82	0.1	0	0	82	100	82	100	82	100	82	100
I7	215	0.3	46	21	169	79	0	0	215	100	215	100
I9, II5, X5	18	0.0	0	0	18	100	0	0	18	100	18	100
II1	255	0.4	0	0	255	100	253	99	9	4	255	100
II2	2 492	3.9	213	9	415	17	309	12	2 493	100	2 494	100
II3	3 536	5.5	0	0	3 372	95	2 487	70	3 390	96	3 538	100
II6, X3	622	1.0	423	68	173	28	123	20	613	99	623	100
VI1	459	0.7	132	29	327	71	75	16	459	100	459	100
VIII10	6 418	9.9	0	0	5 552	87	3 468	54	6 272	98	6 423	100
VIII11	630	1.0	242	38	85	13	31	5	630	100	630	100
VIII12	1 079	1.7	220	20	337	31	59	6	1 080	100	1 080	100
VIII13	265	0.4	44	17	96	36	9	3	265	100	257	97
VIII14	4 297	6.6	0	0	3 821	89	2 971	69	4 300	100	4 300	100
VIII15	553	0.9	0	0	392	71	392	71	554	100	554	100
VIII2	14	0.0	0	0	14	100	14	100	14	100	14	100
VIII4	208	0.3	0	0	171	82	97	46	149	71	209	100
VIII6	2 471	3.8	0	0	2 444	99	2 310	93	648	26	2 472	100
VIII7	7 727	11.9	216	3	5 693	74	3 302	43	7 617	99	7 733	100
VIII8	19 482	30.1	2 542	13	11 854	61	7 812	40	19 497	100	19 497	100
VIII9	1 695	2.6	387	23	574	34	377	22	1 696	100	1 696	100
X1, X2, X3, X4	417	0.6	0	0	417	100	367	88	417	100	417	100
Total	64 704		4 685		46 050		29 454		62 029		64 724	
Error (%)	0.3		0.1		0.1		0.1		0.2		0.2	

* percentage of total area (1st column) per soil type

1:1 000 000, their extent may be considerably larger than indicated here. Gleysols, also characterized as *bas-fonds*, are formed from unconsolidated, alluvial deposits and show hydromorphic characteristics. They have a high spatial variability that is visible from both topsoils and crop stands. As rivers mostly follow fissures and faults, there is a mixture of parent materials in deep alluvia, giving soils different properties over short distances. Their characterization is currently directed by topsoil organic matter content (Roche 1991, PEM/FAO 1992). Major soils and their distribution are given, according to both the FAO classification system (table 2.17 and map 9) and the French system (table 2.18). It is also shown that 41% of the Gleysols are occupied by more than 175 persons km^{-2}, whereas only 7% of the highlands have such a population density. Soils that could potentially accommodate more people are Nitisols, of which 93% support less than 25 persons km^{-2}.

Land use. The most important food crops in the highlands are rice *(Oryza sativa)*, cassava *(Manihot esculenta)*, maize *(Zea mays)*, field bean *(Phaseolus vulgaris)*, sweet potato *(Ipomoea batatas)*, potato *(Solanum tuberosum)*, vegetables and fruits (table 2.9). The main export product is coffee (*Coffea* spp.). Land use in Madagascar is poorly surveyed, with only a 1:4 000 000 map in the *Atlas of Madagascar*. Approximately 47% of the total land area is cultivated, of which 51% is irrigated. Indeed, Madagascar has the 2nd largest area of irrigated crops in the eastern African region after the Sudan (Weijenberg and others 1995). About 21% of the land is covered by forest.

2.1.6 Uganda

Climate and altitude. Jameson and McCallum (1970) indicated that most of Uganda receives between 1015 and 1525 mm of rainfall each year, but the Lake Victoria region and the mountains of Bufumbira, Ruwenzori and Elgon receive higher amounts of over 2000 mm. The troughs near lakes Edward, George and Albert receive less than 1015 mm of rainfall while the arid northeastern part of the country receives less than 510 mm per year. The country is basin shaped, with mountains forming a rim around a central plateau. Altitude varies from below 1000 metres in the Rift Valley areas in the northwest to above 3000 m in the southwest and Mt Elgon in the east. The Uganda Agricultural Task Force (anonymous 1987) made a classification with 4 very broad classes of the agroclimatic zones of Uganda: (1) high-altitude zone, (2) pastoral dry to semi-arid rangelands zone, (3) northern and eastern short-grasslands zone, and (4) southern and western tall-grasslands zone. The 'highlands' in the present study coincide with the high-altitude zone (Kigezi, Sebei, some parts of Ankole, West Nile, Toro and Mbale) and the southern and western tall-grasslands zone (Kampala, Mbarara and Jinja).

Soils. Much of Uganda is situated on a raised plateau between the western and eastern African rifts. Resource inventories were started in 1933 by Martin, and the results are in the *Provisional soil map of East Africa* compiled by Milne (1935b). Between 1935 and 1954 several attempts were made to improve the first map. The first detailed countrywide resource inventories were carried out between 1955 and 1960. The soil surveys were presented in 6 'memoirs': (1) *The introduction to the soils of the Uganda Protectorate* (Chenery 1960), (2) *The soils of the Eastern Province of Uganda* (Ollier and Harrop 1959), (3) *The soils of the Northern Province, Uganda* (Ollier 1959), (4) *The soils and land use of Buganda* (Radwanski 1960), (5) *The soils of Karamoja District, Northern Province of Uganda* (Wilson 1959), and (6) *The soils of the Western Province of Uganda* (Harrop 1960). Memoir 1 (Chenery 1960) shows 138 soil units and their distribution mapped on a scale of 1:500 000. Soil maps attached to the memoirs are in black and white at a scale of 1:500 000, which were later revised to more detailed coloured maps at 1:250 000, adding up to 17 mapsheets. Units on the maps are soil series or soil associations and complexes. It was envisaged that the reconnaissance surveys were followed by detailed surveys of selected areas and further in-depth pedological studies, which, however did not happen.

According to FAO-Unesco (1974) the major soil orders in the highlands are Ferralsols in the Lake Victoria Crescent, and Andosols, Lithosols and Nitosols in the southwestern highlands and the Mt Elgon region. Although soil surveys in Uganda had a head start compared with those in other countries in east and southern Africa, no national exploratory survey was carried out after the work in the 50s and 60s. The need for such a survey was recognized (FAO/UNEP 1992) but so far no funding has been obtained. Yost and Eswaran (1990) attempted to classify the soils of the 18 geomorphic units recognized by Harrop (1970) according to the USDA (United States Department of Agriculture) system but found that the information is in fact insufficient in detail. The authors concur that Uganda serves as a historical source of soils data, since some of the earliest and best information on soils of the tropics emerged from here through the works of Milne, Ollier and others. Milne (1935a and 1935b) developed his catena concept during his work in the eastern Africa region. Yost and Eswaran (1990) further assessed the soil, landscape, climate, vegetation and water resources of Uganda and established the major land resources areas of Uganda.

From the early 1970s onwards detailed soil investigations have been carried out on request for development projects, individuals and government institutions. Institutions covered since the early 1970s are listed in table 2.19.

So far, Ugandan soils have not been classified nationwide according to FAO-Unesco (1974). Therefore, it has not been possible to present a table in this study that shows the distribution of soils in the highlands of Uganda, as was done for Ethiopia (table 2.8), Kenya (table 2.13) and Madagascar (table 2.17).

Land use. A land-use and land-cover classification (consisting of 13 classes) has just been developed by the National Biomass Study (NBS). Maps at a scale of 1:50 000 were developed based on the interpretation of SPOT XS satellite images. A total of 314 map sheets, covering the whole country, is available in paper and digital format. The distribution of land use and land cover is shown in table 2.20.

Farming systems in Uganda exhibit a variability depending on population density, rainfall pattern and elevation. Farmers show

Table 2.19 Soil surveys in Uganda at reconnaissance and detailed level*

Title/area	Year	Scale
Soil map of Uganda (Atlas of Uganda)	1962	1:1 500 000
Soil map of Uganda (5 sheets, black and white)	1960	1:500 000
Colour soil map of Uganda, sheet Arua	1961	1:250 000
Colour soil map of Uganda, sheet Kitgum	1959	1:250 000
Colour soil map of Uganda, sheet Kaabong	1959	1:250 000
Colour soil map of Uganda, sheet Pakwach	1961	1:250 000
Colour soil map of Uganda, sheet Gulu	1959	1:250 000
Colour soil map of Uganda, sheet Aloi	1960	1:250 000
Colour soil map of Uganda, sheet Moroto	1960	1:250 000
Colour soil map of Uganda, sheet Hoima	1965	1:250 000
Colour soil map of Uganda, sheet Masindi	1968	1:250 000
Colour soil map of Uganda, sheet Mbale	1970	1:250 000
Colour soil map of Uganda, sheet Kapenguria	1961	1:250 000
Colour soil map of Uganda, sheet Fort Portal	1965	1:250 000
Colour soil map of Uganda, sheet Kampala	1961	1:250 000
Colour soil map of Uganda, sheet Jinja	1971	1:250 000
Colour soil map of Uganda, sheet Mbarara	1961	1:250 000
Colour soil map of Uganda, sheet Masaka	1960	1:250 000
Colour soil map of Uganda, sheet Kabale	1960	1:250 000
Kawanda Agricultural Research Institute	1973/1988	1:2 500
Serere Agricultural Research Institute	1971	1:2 500
Namulonge Agricultural Research Institute	1975/1988	1:2 500
Kabanyolo (MUARIK)	1988	1:2 500
Mityana D.F.I.	1975	1:2 500
Kamenyamiggo D.F.I.	1975	1:2 500
Mukono D.F.I.	1976	1:2 500
Kiige Citrus Plantation	1976	1:2 500
Bukalasa	1977	1:2 500
Mpigi D.F.I.	1978	1:2 500
Kisindi (Uganda Seed Project Farm)	1985	1:2 500
Mubuku Grain Legume Project Farm	1990	1:2 500
Kalengyere Highlands Centre	1992	1:2 500
Kachwekano D.F.I.	1992	1:2 500

* excluding detailed soil maps from Makerere University

Table 2.20 Land use in Uganda

Land use/cover	Area (km²)	Area (% of total land)	Area (% of total)
Deciduous plantation	193	0.1	0.1
Coniferous plantation	185	0.1	0.1
THF-fully stocked	5 743	2.8	2.4
THF-depleted/ encroached	2 836	1.4	1.1
Woodland	40 991	20.0	16.9
Bush	14 240	6.9	5.9
Grassland	50 822	24.7	21.0
Wetlands	4 872	2.4	2.0
Small-scale farmland	84 514	41.1	34.9
Uniform, large-scale farmland	616	0.3	0.3
Built-up areas	362	0.2	0.2
Impediments (bare rock)	39	0.0	0.0
Total land area	205 414	100	84.8
Open water	36 906		15.2
Total area	242 320		100

Source: National Biomass Study (unpublished data)

themselves to be highly responsive to changes in circumstances, reacting rapidly to external stimuli by adapting their farming systems, particularly as far as cash cropping is concerned. Uganda is a country of small farms with the average farm family managing about 2.5 to 3.0 ha, on which the majority of food crops is produced. High- and medium-potential farming areas have been identified in central, southern and western Uganda and in the Busoga/Bukedi areas of eastern Uganda. The highly productive Lake Victoria Crescent is a major supplier of food for the domestic and export markets, while horticulture is a fast growing sector in this region.

The IGADD study (Van Velthuizen and Verelst 1995), in which crop production system zones have been defined, generally corresponds with earlier work by the Agricultural Task Force (anonymous 1987) and Djimde and Hoekstra (1988). Around Lake Victoria, land use is dominated by banana cultivation, classified as the banana–coffee–maize zone (Van Velthuizen and Verelst 1995), while the Mbarara area is classified as the banana–field bean–maize zone. The area north of Jinja has fewer bananas (finger millet–cassava–maize zone). In the higher altitude zones (Mt Elgon and the south-western highlands) very diverse systems are found. Around Mt Elgon, coffee is produced (coffee–banana–cassava and banana–maize–coffee zones) but in the south-western highlands it is fairly absent (sorghum–field bean–sweet potato zone).

2.2 Translation of basic attributes into MISP indicators

2.2.1 Definitions of soil productivity indicators

Based on the principles of the Fertility Capability Classification (Sanchez and others 1982), indicators of soil productivity are now attached to the spatially correlated information that was collected and discussed in the previous sections. Group discussions and knowledge about the extent of the available information allowed the authors to list the following soil productivity indicators (SPIs):

- organic C content
- N stocks
- N-leaching potential
- NO_3 accumulation at depth
- gaseous losses (denitrification, ammonia volatilization, and so forth)
- P stocks
- 'available' P
- potential P fixation
- potential nutrient supply (N and P)
- acidity
- nutrient balance
- rootable soil depth
- relief (slope gradient, slope length and S x L)
- soil erodibility

Some SPIs do not follow from standard laboratory analysis and need to be determined in a different way. Based on the knowledge of the available pedon data of the 4 countries, it was found that Al was not determined in most cases. For organic C, N stocks, P stocks, 'available' P, acidity, rootable soil depth and relief, basic data were available in all countries at a level that allows classification. For the indicator 'potential nutrient supply' (Janssen and others 1990, Smaling and Janssen 1993), so-called (pedo)transfer functions were applied. These are regression equations, empirically explaining the 'difficult-to-measure' property as a function of independent, related properties that are easy to measure. For P fixation and leaching, classes were established based on existing transfer functions that were all that could be used in some cases because of lack of data. Although erodibility has extensively been described by the Universal Soil Loss Equation (Wischmeier and Smith 1978), insufficient data was found in the 4 countries. Therefore, classes were developed according to the FAO-Unesco (1974) classification system as was done in a case study for Kenya (Kassam and others 1991). Nutrient depletion has been studied at the supra-national level (Stoorvogel and Smaling 1990) using land/water classes. Gaseous losses can potentially form a major loss mechanism in highland systems, but it is hard to describe the processes quantitatively, let alone in a spatially correlated way. Therefore, gaseous losses have not been used as an SPI in this study. This also applies for NO_3 accumulation at depth. This process has not been studied to a large extent so far and no transfer function is available that describes under what circumstances NO_3 accumulation occurs.

Organic C content. The organic matter content of the soil influences many soil properties, including (1) the capacity to supply plant nutrients, (2) infiltration and retention of water, (3) the degree of aggregation and overall structure that affect air and water relationships, (4) cation-exchange capacity and (5) soil colour. Most laboratories do not determine organic matter in their standard analysis but refer to the determination of organic carbon. Page and others (1982) indicate that to get an estimation of the organic matter content of the soil, organic carbon multiplied by a factor of 2 is universally most accepted. The method used in most laboratories in eastern Africa is the wet combustion method of Walkley and Black (1934).

N stocks. The main form of N taken up by plants is NO_3. However, as NO_3 is very dynamic, its suitability as an SPI is not high. Therefore total N is taken as SPI at the present scale, providing an indication of the N stocks in the soil. Laboratories that do not determine 'total N' use a C:N ratio of 10 to determine N stocks. The Kjeldahl method is the one used in most laboratories in eastern Africa.

N-leaching potential. Measuring N leaching is time consuming, and requires monitoring sessions with porous cups or lysimeters. Hence, researchers developed 'transfer functions' as an alternative using field data on N leaching. Transfer functions for N leaching in sub-Saharan Africa were developed by Stoorvogel and others (1993) and Smaling and others (1993) (table 2.21). Based on these functions, a rating system has been established for this study (table 2.22). For instance, if total N > 1.5 g kg^{-1} a rating of 1 is given. The final rating is determined by adding all individual parameter ratings. The N-leaching potential is then classified high at a final rating of 4–5, moderate at 2–3 and low at 0–1. We realize the limitations of this approach. Yet the method described gives an indication that is in line with the scale of the present study.

Table 2.21 Equations to estimate N leaching from the topsoil (20 cm) in the highlands of Kenya

Equation	Criterion	Equation
$LN = (2.1 * 10^{-2} * P - 3.9) * 0.2 * N_{tot} * M * {}^{b}r_{d}$	% clay £ 35	2.2.1
$LN = (1.4 * 10^{-2} * P - 0.71) * 0.2 * N_{tot} * M * {}^{b}r_{d}$	35 < % clay < 55	2.2.2
$LN = (7.1 * 10^{-2} * P - 5.4) * 0.2 * N_{tot} * M * {}^{b}r_{d}$	% clay ≥ 55	2.2.3

LN: N leached (kg ha^{-1}); P: annual precipitation (mm); N_{tot}: total N (g kg^{-1}); M: annual mineralization rate (%); ${}^{b}r_{d}$: dry bulk density (g cm^{-3})
Source: Smaling and others (1993)

Table 2.22 Rating table for an estimation of N leaching potential in the highlands of Kenya

Rating = 1	Parameter	Rating = 0
Total N (g kg^{-1})	0 – 1.5	> 1.5
Clay (%)	> 45	0–45
${}^{b}r_{d}$ (kg cm^{-3})	0–1.2	> 1.2
Rainfall in the 5 consecutive wettest months (mm)	400–800	> 800
Altitude (m)	2700–3300	1200–2700

NO_3 accumulation at depth. NO_3 accumulation at depth is commonly known in western Europe as a result of overfertilization, but bulges of NO_3 were also reported in Uganda in the 1950s and 1960s (Griffith 1951, Mills 1953a, Simpson 1961, Stephens 1962). They can potentially be exploited and may in places be SPIs of importance. Around Maseno in western Kenya, a high accumulation of NO_3 in the subsoil was found (Hartemink and others 1996). One of the main causes of this accumulation is a low uptake of nitrogen by crops, caused by either low P levels or striga incidence or both. Chemical soil characteristics that promote NO_3 accumulation in the subsoil (Roland Buresh, personal communication) are (1) kaolinite in the subsoil, (2) a deeply weathered soil, (3) high organic C content and (4) anion sorption (low pH and the presence of Fe_2O_3). Important climatic characteristics are high rainfall and temperatures that are not too low. Such climatic conditions promote mineralization and therefore can potentially cause a build-up of NO_3. Given the initial stages of revival of this type of research, we have not been able to classify soils that could potentially build up NO_3 in the subsoil. An objective of PhD research by G. Shepherd at ICRAF is to develop boundary conditions under which NO_3 accumulation could take place. In this report the deep accumulation of NO_3 is just mentioned as a potential SPI, which could be mapped.

Gaseous losses. In the humid tropics denitrification is the main mechanism of gaseous N loss. Most measurements have been carried out under artificial conditions, alongside lots of estimates (Hoffmann and Pagel 1979). The factors governing the process of denitrification are well known. Apart from the presence of NO_3, the presence of readily decomposable organic matter as an energy source, the absence of oxygen, and temperatures > 10°C are needed for denitrification to take place at a significant rate. Field data for transfer functions on denitrification in the highlands are very scanty (Lensi and others 1992, Dubey and Fox 1974). Therefore, denitrification is not quantified here as an SPI, although its importance is recognized. The same holds for other gaseous losses from highland soils.

P stocks. P occurs in the soil in both organic and inorganic forms. In depleted tropical soils, organic P almost corresponds with total P. In terms of availability for plant uptake, P can be (1) inert or highly stable, (2) stable, or (3) labile. These 3 forms together present total P, which is used as an SPI. Other phosphorus SPIs, 'available' P and potential P fixation, are described below.

'Available' P. Labile or readily available P is determined by an array of extraction techniques, and there has been a lot of confusion in the past as to which one best describes real availability. Unfortunately for the present study, Uganda used the Truog (1930) method, Ethiopia and Madagascar the Olsen method (Olsen and others 1954), and Kenya the Mehlich method. Data on 'available' P are also highly variable, making it an unreliable SPI with a poor predictive value.

Potential P fixation. In the east African highlands, research on the P-fixing status of soils is scarce. Measurement of P sorption (Fox and Kamprath 1970) is not done routinely in the eastern African laboratories. In general, soils that have a capacity to fix P have a high Fe_2O_3 content, a high clay content and a red colour. As there are no data on Fe_2O_3 content in the east African highlands, clay content and colour will be used to identify potentially P-fixing soils. Next, in the east African highlands, P is strongly fixed in Andosols and soils of the andic subgroup. Therefore the criteria for the SPI are as follows:

- highly P-fixing soils: Andosols (FAO-Unesco 1974)
- moderately P-fixing soils: soils with a percentage of clay > 35 and dominant Munsell 5YR and redder
- low to non P-fixing soils: other soils

Potential supply of N and P. With the QUEFTS model (quantitative evaluation of tropical soil fertility; Janssen and others 1990) maize yields are calculated, based on several soil properties. During model development, the following transfer function was developed for the potential supply of N in the topsoil (eq. 2.2.1):

$$SN\ (\text{kg ha}^{-1}) = 17 * (\text{pH-H}_2\text{O} - 3) * \text{total N}\ (\text{g kg}^{-1}) \qquad \text{Eq. 2.2.1}$$

The transfer function is valid only between the following boundary conditions: (1) pH-H_2O: 4.5–7.0, (2) well-drained deeply rootable soil, and (3) total N < 7 g kg^{-1}.

Because data on P-Olsen were scarce, the potential supply of P in the topsoil was calculated with the transfer function from the calibrated QUEFTS model (Smaling and Janssen 1993; eq. 2.2.2).

$$SP\ (\text{kg ha}^{-1}) = (1 - 0.25 * (\text{pH-H}_2\text{O} - 6.7)^2)\ (0.0375 * \text{total P} + 0.45 * \text{org C}) \qquad \text{Eq. 2.2.2}$$

total P in mg kg^{-1}; org C in g kg^{-1}

$$\text{total P}\ (\text{mg kg}^{-1}) = 25 * \text{org C}\ (\text{g kg}^{-1}) \qquad \text{Eq. 2.2.3}$$

Acidity. Soil acidity problems are associated with pH levels lower than 5.5 and high levels of exchangeable aluminium in the soil (Sanchez 1976). In the absence of sufficient data on Al saturation of the exchange complex, pH classes were used, supplemented by a classification based on cation-exchange capacity that shows how well the soil can buffer acidity. The classification is presented in table 2.23.

Nutrient balance. In a study carried out for 38 sub-Saharan countries (Stoorvogel and Smaling 1990), nutrient balance was calculated for land and water classes. This SPI constitutes an aggregation of a series of input and output processes. When determining the nutrient balance, there is mostly a series of primary data (crop yields, use of manure and fertilizer, crop residues), and there are secondary data. The latter are often calculated on the basis of transfer functions, some of which have been used as individual SPIs (leaching, gaseous losses, erosion hazard). The nutrient balance study by Stoorvogel and Smaling (1990) could not be used in combination with the country databases as the nutrient balance database was not georeferenced to a sufficiently detailed level. However, in sec. 3 the results of the study are given for each country.

Rootable soil depth. Rootable soil depth clearly is an important SPI. For the present study, the following generally used classification is observed: shallow (< 25 cm), moderately shallow (25–50 cm), moderately deep (50–100 cm), deep (100–150 cm) and very deep (> 150 cm).

Relief. Slope gradient (%) and slope length (m) are important factors determining slope processes such as runoff and water erosion. Both factors are used in the Universal Soil Loss Equation, as well as in other erosion models. The factors S and L are defined in eq. 2.2.4 and 2.2.5 according to Mitchell and Brubenzer (1980).

$$S = (0.43 + 0.30 * s + 0.043 * s^2)/6.613 \qquad \text{Eq. 2.2.4}$$

where s = slope gradient (%).

$$L = (d/22.13) \qquad \text{Eq. 2.2.5}$$

where d = slope length (m)

Soil erodibility. The erodibility factor (K) of the Universal Soil Loss Equation is derived from soil texture, organic matter content, soil structure and permeability (Mitchell and Brubenzer 1980). The nomograph, however, tends to overestimate the K factor for east African soils, as many deep volcanic soils showed very stable microaggregation (Ahn 1977). In Ethiopia, Madagascar and Uganda the data necessary to calculate the K factor were not available. In a case study for Kenya, Kassam and others (1991) developed a ranking of soils orders according to their susceptibility to productivity loss with loss of topsoil. This ranking is used in the present study (table 2.24).

2.2.2 Collection of country-specific pedon data

Ethiopia. Although no countrywide pedon database was available for this study, we did have access to soils data published in Geomorphology and Soils (UNDP/FAO 1984a). The legend of the map, however, allows the calculation of only 7 SPIs: (1) organic C content, (2) available P (P-Olsen), (3) potential P fixation, (4) acidity, (5)

Table 2.23 Class specifications for the acidity soil productivity indicator in the highlands of East Africa

Class	Description	$\text{pH–H}_2\text{O}$	CEC at $\text{pH–H}_2\text{O}$ 7.0 (mmol kg^{-1})
I	Acid soils with a high buffering capacity	< 5.5	> 160
II	Acid soils with a low buffering capacity	< 5.5	≤ 160
III	Moderately acid soils with a high buffering capacity	5.5–6.0	> 160
IV	Moderately acid soils with a low buffering capacity	5.5–6.0	≤ 160
V	Non-acid soils	> 6.0	–

Table 2.24 Ranking of soils for soil erodibility

High erodibility	Intermediate erodibility	Low erodibility
Eutric and dystric Nitosol Ferralic Cambisols Ferralsols, except humic Ferralsols Lithosols Planosols Rendzinas Solonchaks Solonetz	Acrisols, except humic Acrisol Cambisols, except ferralic Cambisols Gleysols Greyzems humic Acrisols humic Ferralsols Kastanozems Luvisols mollic and humic Nitosols Nitosols Phaeozems Regosols vitric Andosols Xerosols Yermosols	Arenosols Chernozems Fluvisols Histosols humic and mollic Andosols Vertisols

Source: adapted from Kassam and others (1991)

rootable soil depth, (6) slope and (7) soil erodibility. The SPIs were calculated for each land facet per mapping unit. A large extent of Ethiopia is covered by Lithosols (14.2%; table 2.8). The only parameter that is presented in the legend for this soil order is slope. Hence, gaps on the SPI maps can be expected where Lithosols make out the predominant land facet. Given the data availability, ratings could be developed for the following parameters: organic C content, P-Olsen, potential fixation, soil depth and slope. The classes and their limits are shown in table 2.25, and the soil-specific average rankings in table 2.26.

Kenya. With the relatively ample data available for Kenya (Exploratory Soil Map, KENSOTER, KSS archives), it was possible to calculate 11 SPIs: (1) organic C content, (2) N stocks, (3) N-leaching potential, (4) P stocks, (5) available P (P-Mehlich), (6) potential P fixation, (7) potential nutrient supply (N and P), (8) acidity, (9) rootable soil depth, (10) slope characteristics and (11) soil erodibility. The classes and their limits are shown in table 2.27 and the soil-specific average rankings in table 2.28.

Madagascar. Pedon data were not available in a readily accessible database. However, as there are not many soil orders in the highlands, it was possible to use a number of suitable 'representative' pedons from more detailed surveys than the Riquier survey of 1968. These pedons could not, however, be referenced to Riquier's map. With use of the pedon descriptions, including their French classification, the legend of the soil map (table 2.15) and Oldeman (1992), it was possible to group the pedons into 5 main orders. Problems occurring with respect to the pedons from Madagascar were (1) inconsistent classification, (2) inconsistent *X* and *Y* coordinates, and (3) incomplete pedons. As the pedons could not be georeferenced in the GIS database, it was not possible to add attributes to the digitized soil map. Therefore, it was decided to present average values for soil characteristics for the soil orders for which pedons were available (table 2.29).

Table 2.25 Rating table for soil productivity indicators in the highlands of Ethiopia

Rating	Organic C ($g\ kg^{-1}$)	P-Olsen ($mg\ kg^{-1}$)	P-fixation class	Depth (cm)	Slope (%)
1	0–5	0–5	low to non	< 25	0–2
2	5–10	5–10	moderately	25–50	2–8
3	10–15	10–15	highly	50–100	8–16
4	15–50	15–25	na	100–150	16–30
5	> 50	na	na	> 150	30–50
6	na	na	na	na	> 50

na = not applicable

Table 2.26 Area-specific rating for soil productivity indicators for the major soils in the highlands of Ethiopia

Soil classification (FAO-Unesco 1974)	Organic C	P-Olsen	P fixation	Depth	Slope
Acrisols	3.0	1.0	2.0	3.5	4.5
Andosols	2.9	1.0	3.0	3.7	1.6
Arenosols	1.7	2.1	1.0	2.5	3.0
Cambisols	2.6	1.2	1.1	2.7	3.4
Chernozem	3.0	1.0	1.0	5.0	1.5
Fluvisols	2.9	1.3	1.4	5.0	1.4
Gleysols	3.0	1.0	1.0	5.0	1.0
Histosols	4.0	1.0	1.0	5.0	1.0
Lithosols	nda	nda	1.0	nda	5.4
Luvisols	2.9	1.1	1.7	3.2	3.8
Nitisols	2.9	1.0	2.0	5.0	2.6
Phaeozems	3.0	2.1	1.0	4.1	2.1
Regosols	2.0	1.1	1.0	1.4	3.6
Rendzina	3.0	2.0	1.0	1.6	3.4
Solonchaks	nda	nda	1.0	4.9	1.1
Vertisols	3.0	1.3	1.0	5.0	1.5
Xerosols	1.2	1.8	1.0	2.5	2.3

nda = no data available

Uganda. The 5 memoirs on the soils of Uganda contain 286 soil profiles. These profiles were not classified according to FAO-Unesco (1974), but potentially this could be done. A total of 144 profiles from memoirs 2 (Ollier and Harrop 1959), 3 (Ollier 1959) and 4 (Radwanski 1960) were available at ICRAF in a pedon database format, while 65 selected profiles from memoirs 5 (Wilson 1959) and 6 (Harrop 1960) were entered as part of the present project. These 209 profiles can be used to analyse SPIs for the highlands of Uganda. They are, however, not presented in this report because of time constraints.

2.2.3 Application of soil productivity indicators for the 4 MISP countries

Ethiopia. The extent of the 7 SPIs for the Ethiopian highlands is presented in table 2.30 and on Ethiopia maps 1–7 (for the major land facet). The area with no data available on Ethiopia map 1 presents the Lithosols that have not been analysed for any parameter other than slope. Assuming that the area with no data available (mainly Lithosols) also has very low available P (P-Olsen < 5 mg kg^{-1}), then the availability of P for the Ethiopian highlands classifies as less than 5 mg kg^{-1} for 90% of the country (Ethiopia map 2). The highest class of P fixation, in the Ethiopian highlands exclusively Andosols, occupies 1% of the highlands. The location of these can clearly be distinguished in the Rift Valley on Ethiopia map 3. Soils with a moderate P-fixing potential are in the western highlands. These are mainly Acrisols, Nitosols, a majority of the Luvisols, and some Fluvisols and Cambisols (table 2.26). Ethiopia map 4 shows that the soils in the western highlands (mainly Nitosols and Acrisols) are acid (pH-H_2O < 5.5). This is the area that also has high rainfall in the 5 consecutive wettest months (map 1). Soils in the central part of the country with less rainfall in the 5 consecutive wettest months have moderately acidic soils (pH-H_2O 5.5–6.7), while the Andosols and soils in the dry northeast and Harerge highlands are non-acidic. Nearly 50% of the Ethiopian highland soils are deeper than 100 cm (table 2.30), while approximately 19% are shallow (Ethiopia map 5). Lithosols have the steepest slopes (table 2.26), followed by Acrisols, Cambisols, Luvisols, Regosols and Rendzinas. Flat areas (0–2%) cover 8% of the highlands (table 2.30; Ethiopia map 6). The soil erodibility SPI, calculated per soil type (table 2.24), places many soils in the high (41%) and intermediate class (39%; table 2.30 and Ethiopia map 7). The distribution for land facet 1 shows that highly erodible soils are mainly in the west (Acrisols and Nitosols) and northeast (Lithosols), while the least erodible soils are mainly concentrated in the Rift Valley area.

Kenya. The extent of the 11 SPIs for the Kenyan highlands is presented in table 2.27, and on

Table 2.27 Distribution of soil productivity indicators for the highlands of Kenya

Organic C content			N stocks			P stocks			'Available' P		
					topsoil						
Org C (g kg^{-1})	Area (km^2)	Area (%)	Total N (g kg^{-1})	Area (km^2)	Area (%)	Total P (mg kg^{-1})	Area (km^2)	Area (%)	P–Mehlich (mg kg^{-1})	Area (km^2)	Area (%)
0–5	3 562	3	0–0.5	2 350	2	0–100	3 857	4	0–10	9 642	9
5–10	10 948	11	0.5–1.0	25 139	25	100–300	2 339	2	10–30	10 086	10
10–30	33 862	33	1.0–3.0	17 264	17	300–600	2 385	2	30–100	13 472	13
> 30	12 853	13	> 3.0	16 472	16	> 600	1 311	1	> 100	2 672	3
nda	40 805	40	nda	40 808	40	nda	92 140	90	nda	66 159	65

Potential P fixation			Potential supply of N			Potential supply of P			Acidity		
							topsoil				
Class	Area (km^2)	Area (%)	SN (kg ha^{-1})	Area (km^2)	Area (%)	SP (kg ha^{-1})	Area (km^2)	Area (%)	Class	Area (km^2)	Area (%)
highly	9 837	10	0–50	11 264	11	0–7.5	6 227	6	I	13 252	13
moderately	33 984	33	50–100	9 709	10	7.5–15	18 142	18	II	6 330	6
low to non	20 694	20	100–200	14 531	14	15–30	16 479	16	III	18 055	18
nda	37 517	37	> 200	4 097	4	> 30	6 301	6	IV	4 125	4
			nda	38 730	38	nda	41 654	41	V	18 220	18
			ebc	23 699	23	ebc	13 228	13	nda	42 050	41

				Relief				
Slope (%)	Area (km^2)	Area (%)	Slope (m)	Area (km^2)	Area (%)	S* L (USLE)	Area (km^2)	Area (%)
0–5	50 973	50	0–150	42 483	42	0–3	27 917	27
5–15	26 246	26	150–500	49 191	48	3–10	38 272	38
15–30	17 175	17	500–1000	8 742	9	10–30	22 751	22
> 30	7 592	7	> 1000	1 569	2	>30	13 015	13
nda	83	0	nda	83	0	nda	83	0

N leaching potential			Rootable soil depth			Soil erodibility		
Class	Area (km^2)	Area (%)	Depth (cm)	Area (km^2)	Area (%)	Class	Area (km^2)	Area (%)
high	4 401	4	< 30	13	0	high	34 562	34
moderate	44 669	44	30–50	10 440	10	intermediate	43 673	41
low	8 347	8	50–100	8 246	8	low	20 915	20
nda	44 614	44	100–150	27 228	27	nda	2 882	3
			≥ 150	26 989	26			
			nda	29 116	29			

nda = no data available; na = not applicable (no soil); ebc = exceeds boundary conditions

nda = no data available; na = not applicable (no soil); ebc = exceeds boundary conditions

Table 2.28 Soil characteristics for the major soils of the highlands of Kenya

Soil classification (FAO-Unesco 1974)	Organic C ($g\ kg^{-1}$)					Total N ($g\ kg^{-1}$)					Total P ($mg\ kg^{-1}$)				
	#	av	min	max	sd	#	av	min	max	sd	#	av	min	max	sd
Acrisols	20	12.1	5.6	29.0	6.1	20	1.2	0.6	2.9	0.6	2	90	80	100	10
Andosols	10	34.5	19.2	49.6	10.4	10	3.6	1.9	6.7	1.5	3	360	190	555	150
Arenosols	5	4.2	2.9	5.9	1.0	5	0.4	0.3	0.7	0.2	3	26	26	26	0
Cambisols	33	19.1	6.0	60.0	14.7	33	2.1	0.6	9.0	2.0	11	609	29	1850	559
Ferralsols	14	9.9	1.4	15.8	3.9	14	1.0	0.1	1.7	0.4	5	138	16	240	79
Fluvisols	10	8.1	1.7	29.0	8.0	10	0.8	0.2	2.9	0.8	2	800	800	800	0
Gleysols	12	24.3	3.4	60.2	16.9	12	2.5	0.3	6.5	1.9	3	391	52	560	239
Greyzems	2	34.0	28.0	40.0	6.0	2	3.4	2.8	4.0	0.6	nda	nda	nda	nda	nda
Kastanozem	1	196.0	196.0	196.0	0.0	1	19.6	19.6	19.6	0.0	nda	nda	nda	nda	nda
Lithosols	2	18.6	14.1	23.0	4.5	2	2.3	2.0	2.5	0.3	nda	nda	nda	nda	nda
Luvisols	26	10.1	0.3	26.0	6.6	25	1.2	0.2	2.6	0.6	8	317	50	1300	388
Nitisols	21	22.1	8.0	43.2	10.4	21	2.3	0.8	5.4	1.4	1	210	210	210	0
Phaeozems	23	25.0	11.0	50.0	10.0	23	2.6	1.0	5.2	1.2	3	128	85	180	39
Planosols	18	27.7	3.0	123.0	26.2	18	2.8	0.3	9.2	2.3	nda	nda	nda	nda	nda
Regosols	6	7.3	0.9	26.0	8.7	6	0.9	0.1	3.5	1.2	nda	nda	nda	nda	nda
Solonchaks	2	3.8	1.7	5.9	2.1	2	0.3	0.2	0.3	0.1	nda	nda	nda	nda	nda
Solonetzes	6	15.7	1.7	61.0	21.0	6	1.7	0.2	6.1	2.1	1	170	170	170	0
Vertisols	18	12.2	1.2	26.3	6.2	18	1.3	0.1	2.6	0.6	3	94	24	200	76
Xerosols	3	2.2	1.1	3.5	1.0	3	0.2	0.1	0.4	0.1	nda	nda	nda	nda	nda
P-Mehlich ($mg\ kg^{-1}$)						Potential supply of N, SN ($kg\ ha^{-1}$)					Potential supply of P, SP ($kg\ ha^{-1}$)				
Acrisols	9	20	4	78	23	18	47.5	23.8	119.3	24.6	15	8.7	2.7	26.1	6.0
Andosols	6	49	26	102	25	7	207.9	88.1	410.0	108.0	10	41.9	20.0	68.6	16.9
Arenosols	5	124	20	540	208	3	17.3	17.3	17.3	0.0	5	5.4	3.5	7.2	1.2
Cambisols	19	94	0	250	88	15	76.1	37.4	220.2	42.1	27	18.7	6.1	66.4	12.5
Ferralsols	10	11	0	42	11	12	41.4	5.0	75.1	17.7	12	10.0	0.7	20.6	5.2
Fluvisols	5	164	8	246	98	2	33.1	23.8	42.4	9.3	6	5.5	1.6	10.1	2.6
Gleysols	10	12	6	24	6	nda	nda	nda	nda	nda	nda	nda	nda	nda	nda
Histosols	1	10	10	10	0	nda	nda	nda	nda	nda	nda	nda	nda	nda	nda
Lithosols	1	35	35	35	0	nda	nda	nda	nda	nda	1	19.6	19.6	19.6	0.0
Luvisols	14	83	2	252	78	15	63.6	23.8	123.8	30.9	23	11.9	1.8	29.1	7.7
Nitisols	13	22	2	86	27	20	95.5	35.4	251.4	52.3	18	18.0	6.5	44.1	10.3
Phaeozems	10	15	4	41	11	17	117.6	57.8	238.7	48.4	21	22.3	8.9	48.4	10.7

Soil classification (FAO-Unesco 1974)	Organic C (g kg^{-1})					Total N (g kg^{-1})					Total P (mg kg^{-1})				
	#	av	min	max	sd	#	av	min	max	sd	#	av	min	max	sd
Planosols	11	14	4	29	9	nda	nda	nda	nda	nda	2	14.9	13.6	16.2	1.3
Regosols	3	18	3	47	21	nda	nda	nda	nda	nda	3	2.9	0.8	5.9	2.2
Solonchaks	1	36	36	36	0	nda	nda	nda	nda	nda	nda	nda	nda	nda	nda
Solonetzes	4	88	22	250	94	nda	nda	nda	nda	nda	nda	nda	nda	nda	nda
Vertisols	13	40	0	150	49	1	103.4	103.4	103.4	0.0	3	22.8	17.6	33.2	7.4
Xerosols	3	28	7	43	15	nda	nda	nda	nda	nda	nda	nda	nda	nda	nda
Acrisols	26	6.6	1	20	4.8	26	321	50	1500	389	26	11.0	0.8	79.3	20.3
Andosols	17	12.9	1	55	14.5	17	276	100	1000	204	17	45.5	1.6	502.4	118.0
Arenosols	8	7.5	1	20	6.2	8	188	50	500	127	8	5.9	2.3	24.3	7.0
Cambisols	57	8.4	1	45	9.7	57	373	100	1000	330	57	16.2	0.8	143.8	28.8
Chernozem	2	1.5	1	2	0.5	2	300	300	300	0	2	2.0	1.6	2.4	0.4
Ferralsols	21	5.6	1	20	6.0	21	257	100	1000	248	21	5.8	0.5	24.3	7.2
Fluvisols	13	1.5	0	5	1.2	13	358	100	1000	291	13	2.3	0.5	8.1	1.9
Gleysols	13	2.1	0	5	1.8	13	542	50	1000	437	13	4.1	0.2	11.8	3.9
Greyzems	3	2.0	1	3	0.8	3	500	200	1000	356	3	3.4	2.3	5.4	1.4
Histosols	2	15.5	1	30	14.5	2	125	100	150	25	2	25.0	0.5	49.5	24.5
Kastanozems	1	10.0	10	10	0.0	1	150	150	150	0	1	8.0	8.0	8.0	0.0
Lithosols	10	17.8	1	40	11.3	10	200	50	1000	285	10	12.8	4.7	32.8	9.6
Luvisols	39	5.3	1	20	4.9	39	351	100	1500	355	39	5.6	1.1	24.3	5.3
Nitisols	31	9.1	1	30	6.8	31	242	100	1000	219	31	10.2	1.6	33.5	9.7
Phaeozems	39	7.4	1	35	7.6	39	307	100	1000	247	39	12.1	0.8	130.8	23.2
Planosols	28	3.0	0	20	3.6	28	457	50	2000	452	28	4.5	0.5	24.3	5.0
Regosols	8	12.4	3	40	12.5	8	288	100	500	117	8	27.1	1.2	110.5	35.2
Rendzina	1	10	1	1	0.0	1	300	300	300	0	1	1.6	1.6	1.6	0.0
Solonchaks	5	14	1	3	0.8	5	420	100	1000	319	5	2.5	0.5	5.4	1.6
Solonetzes	10	15	0	2	0.7	10	705	250	3000	792	10	3.7	2.0	9.5	2.2
Vertisols	26	1.5	0	5	1.3	26	562	100	1000	357	26	3.6	0.5	8.1	2.4
Xerosols	4	2.5	1	3	0.9	4	325	200	400	75	4	3.2	2.2	4.1	0.9

= profile counts; av = average; min = minimum; max = maximum; sd = standard deviation; nda = no data available

Table 2.29 Average soil characteristics for the major soils of the highlands of Madagascar

Soil classification (FAO-Unesco 1974)	Pedons (no.)	Organic C (g kg^{-1})	total N (g kg^{-1})	P-Olsen (mg kg^{-1})	Potential supply OF N, SN (kg ha^{-1})	Potential supply of P, SP (kg ha^{-1})	P-fixation	Acidity class	Soil Erodibility class
Andosol	1	67.1	4.3	50	219.3	8.7	highly	V	low
Cambisols	2	27.8	2.7	17	127.9	31.0	moderately	IV, V	intermediate
Ferralsols	18	25.1	1.8	26	58.4	12.5	moderately (56%) low to non (44%)	II (72%)	high
Gleysols	7	52.3	4.3	35	ebc	ebc	low	I, II	intermediate
Nitisol	1	25.8	2.2	17	ebc	ebc	low	II	high

ebc = exeeds boundary conditions

Table 2.30 Distribution of soil productivity indicators for the highlands of Ethiopia

Organic C content			'Available' P			Potential P fixation			Acidity		
Org C (g kg^{-1})	Area (km^2)	Area (%)	P-Olsen (mg kg^{-1})	Area (km^2)	Area (%)	Class	Area (km^2)	Area (%)	Class	Area (km^2)	Area (%)
0–5	4123	1	0–5	321 533	71	highly	5 735	1	I	107 293	24
5–15	55 249	12	5–10	32 790	7	moderately	164 336	36	II	1214	0
15–50	312 462	69	10–15	16 964	4	low to non	264 169	58	III	169 732	38
> 50	39	0	15–25	586	0	nda	17 401	4	IV	3027	1
nda	79 769	18	nda	79 769	18				V	89 707	20
									nda	80 674	18

Slope			Rootable soil depth			Soil erodibility		
Slope (%)	Area (km^2)	Area (%)	Depth (cm)	Area (km^2)	Area (%)	Class	Area (km^2)	Area (%)
0–2	34 645	8	< 25	6 898	2	high	185 357	41
2–16	234 693	52	25–50	65 920	15	intermediate	175 193	39
16–30	71 787	16	50–100	86 213	19	low	77 972	17
> 30	109 906	24	100–150	27 227	6	nda	13 139	3
nda	610	0	> 150	188 039	42			
			nda	77 344	17			

nda = no data available

Kenya maps 1–11 for the major soil of a specific mapping unit. From table 2.27, it is obvious that there are quite a number of data gaps. For almost 40% of the highlands there are no data available on chemical soil properties, mainly caused by the absence of representative soil profiles for specific SOTER units.

For the organic C content in the topsoil, 44% of the soils exceed 10 g kg^{-1} (table 2.27), most of which are Andosols, Cambisols, Nitisols, Phaeozems and Planosols (table 2.28 and Kenya map 1). Acrisols, Ferralsols and Luvisols (6.9, 8.4 and 4.7% of the Kenya highlands; table 2.13) are soils with a large extent but fairly low organic C content (table 2.28). The same picture can be drawn for N stocks (table 2.27 and 2.28, Kenya map 2). Data on P stocks (total P) and available P (P-Mehlich) are very scarce (table 2.27). Therefore, these SPIS are not presented on maps. However, based on the pedons in the database, the average total P and P-Mehlich (mg kg^{-1}) are presented in table 2.28. The highly P-fixing soils are situated on the slopes of the Mau Escarpment, the Kinangop Escarpment, the lower slopes of Mt Kenya and in the Chyulu Hills (Kenya map 3), as these are classified as Andosols. They cover 10% of the highlands of Kenya, while 33% of the soils has a moderate P-fixing potential (table 2.27). These soils are situated in the Acrisol, Nitisol and Ferralsol areas (Kenya map 3), have a relatively high clay fraction and are fairly red. Non-acidic soils in the Kenya highlands are situated in the Rift Valley area (Kenya map 4) and occupy 18% of the highlands. Acid soils are found in the western part of the highlands and on the middle slopes of the Aberdare Range and Mt Kenya. Of these acid soils, the buffering capacity is low in part of the Kisii area, west of Kakamega and northeast of Kitale (Kenya map 4).

As the SPI on potential nutrient supply is dependent on more than one basic parameter, there is a large area with no data available (38% for SN and 41% for SP), whereas some profiles exceed the boundary conditions defined for the transfer functions. Nutrient supply is very high (table 2.28 and Kenya maps 5 and 6) in the Andosols of the Mau Escarpment, while Nitisols and Phaeozems also show a reasonably high supply (table 2.28). A low potential nitrogen supply is found in the Machakos area, the area northeast of Nakuru and southwest of Kakamega (Kenya map 5).

The SPI 'rootable soil depth', presented on Kenya map 7 indicates that many soils in the Kenyan highlands are very deep (45%), whereas the few shallow soils are scattered around the Rift Valley. Very steep slopes (> 30%) occur on Mt Longonot, Mt Suswa, in the Machakos area, on the Chyulu range, on the Kerio Escarpment and in the Cherengani Hills (Kenya map 8); less steep slopes are found on the slopes of Mt Kenya, Mt Elgon and the Aberdare Range. Soils with steep slopes are especially Andosols, Lithosols and Regosols (table 2.28). The slope gradient *(S)* and slope length *(L)* factors show a similar geographical distribution (Kenya map 9). Soil erodibility, determined according to table 2.24, is high in the Machakos area, along the Kerio Escarpment, in a large area southwest of Narok, and in a large area to the west of Kakamega and around Eldoret (Kenya map 10).

A large area of the Kenya highlands (44%) does not have enough data from representative soil profiles to classify N-leaching potential (table 2.27 and Kenya map 11). For the major soils, the distribution is presented in Kenya map 11, showing high N-leaching potential near Kakamega, in the Cherangani highlands and in Kisii District, while low N-leaching potential is found between Kisii and Eldoret, west of Siaya, northeast of Nakuru and in some Nitisols around Nairobi.

Madagascar. Table 2.29 presents the SPIS for the major soil orders of the soils of Madagascar. The extent of these soils is presented in table 2.17 and map 9. Ferralsols, representing 65% of the highlands, are the poorest soils of the highlands of Madagascar (table 2.29). All soils are fairly acidic, including most of the Gleysols. The Gleysols (*bas-fonds*) are the rich soils in Madagascar, and this is reflected in their intensive use for rice cultivation. The Andosol is also a fairly rich soil. Given the poor georeferencing and data availability, no country SPI maps could be produced at this stage.

Uganda. Because of the constraints indicated in the previous sections, no country SPI maps could be produced for Uganda during the compilation of the present report.

3 Review of MISP-related research

This section covers MISP-related research in Ethiopia, Kenya, Madagascar and Uganda.

Although we well realize that it is almost impossible to be exhaustive, we hope the majority of research efforts are covered. For each country, an overview is given of the status and setting of soil productivity research (sec. 3.1). This is then followed by an overview of survey and research data on soil physical (sec. 3.2), soil chemical (sec. 3.3) and soil biological (sec. 3.4) properties and processes. In sec. 3.5 runoff and erosion research is presented, whereas sec. 3.6 deals with nutrient cycling and budgets. MISP technologies (sec. 3.7) are partitioned into subsections on mineral fertilizers (MF), mineral soil amendments (MSA), improved, low external-input agroecosystems (ILEIAS), soil and water management and conservation (SWMC) and integrated nutrient management (INM). The section is concluded by an overview of modelling approaches for soil productivity assessment (sec. 3.8), long-term experimentation (sec. 3.9), farming systems research (FSR, sec. 3.10) and technology adoption (sec. 3.11).

Certain areas of research are covered in different paragraphs. In most countries N is discussed in both sec. 3.3 and sec. 3.4. In sec. 3.3 reference is made to the availability of N, while in sec. 3.4 mineralization, decomposition and biological nitrogen-fixation (BNF) are discussed. Consequently BNF is discussed in sec. 3.3 as a process and in sec. 3.7 as an MISP technology to improve yields. The final sections—long-term experimentation (sec. 3.9) and FSR and technology adoption (sec. 3.10 and sec. 3.11)—may cover MISP technologies that were dealt with in sec. 3.7, and therefore some overlap is inevitable.

3.1 Ethiopia

3.1.1 Introduction to soil productivity research

Research on soil productivity in Ethiopia started at the Jima Agricultural Technical High School (1950s), and at Alemaya University of Agriculture (AUA, 1960s). In 1966, the Institute of Agricultural Research (IAR) was founded and is now the main agricultural research centre in the country (Weijenberg and others 1995). Its role in the development of Ethiopian agriculture is outlined by Getinet Gebeyehu and others (1995). Its mandate excludes forestry, fisheries and food technology research. The specific activities of IAR's Soil Science Department included research on crop-specific fertilizer recommendations, the effects of soil burning *(guie)* and Vertisol properties and management. Other ministries, commissions and agencies that carry out soil productivity research include the Awasa Junior College of Agriculture (ACA) and the Ministry of Agriculture (MOA). International Agricultural Research Centres (IARCS) active in this area of research include the International Livestock Research Institute (ILRI) (Mohamed Saleem 1994), the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT), the International Centre for Tropical Agriculture (CIAT) and the International Centre for the Improvement of Maize and Wheat (CIMMYT). Moreover, a review of Ethiopia's research programme management and workforce planning was carried out by the International Service for National Agricultural Research (ISNAR 1987). Country master and strategic plans in Ethiopia are unofficial documents that can not be cited. The long-term objective of development is structural transformation of the economy to increase the importance of industry and service over agriculture. This strategy, known as agricultural-development-led industrialization, primarily focuses on agricultural development. This is to be attained through improvement of productivity in smallholdings and expansion of large-scale farms. Consequently, Ethiopia has also spelled out a fertilizer policy that broadly aims to address farmers' effective demand, supply, distribution and marketing, pricing and subsidies, credit, research and extension, quality control, and environmental and organizational set-up.

In Ethiopia, agricultural research has been well funded, allocations increasing from USD 3.4 million in 1983 to USD 18.4 million in 1989. Salaries accounted for less than 30% of the total annual budget, leaving more than 70% for investment and recurrent costs. In the same period the number of national scientists increased from 235 to 649. By 1992/93 salaries accounted for 60% of a budget of USD 20.2 million (table 3.1.1) covering 928 scientists (USD 21 800 per scientist). By then 94% of the budget was covered by the government. As a result of increased allocations, there have been substantial investments in infrastructure for agricultural research. Therefore, Ethiopia seems to enjoy adequate basic facilities and scientific capacity that now need to be maintained and provided with operating costs (Weijenberg and on both crops is primarily influenced by producer prices, fertilizer prices and credit availability. Mbata (1994), working in Nakuru District, arrives at conclusions that put the social factor first. He obtained data from a cross-section of 133 farmers by using a multistage random sampling technique to purposively select both adopters and non-adopters of fertilizers. The results indicate that fertilizer adoption is more sensitive to sociological and institutional factors such as cooperative membership, literacy level and contact with extension agents than to economic factors such as labour and credit availability.

Pretty and others (1995) describe the history and achievements as to the catchment approach to soil conservation, adopted in 1988 by the Kenyan government. At first seen as a way of concentrating technical effort, this approach has evolved to be interdisciplinary and community mobilizing. Conservation coverage must be complete if it is to be sustainable, and this will only happen if there is full participation at a local level. Catchment committees articulate local priorities and provide a link with external agencies. A self-evaluation conducted in 6 districts found the most significant impact where there has been interactive participation. In these communities, crop yields are increasing, farmers are growing a greater diversity of crops, there are more trees, ground cover has increased, groundwater resources are being recharged, land prices and labour rates are increasing, and communities are actively replicating successes to neighbouring communities.

Laing and Ashby (1993) describe a range of experiences of adoption and non-adoption of conservation practices by resource-poor farmers in developing countries. Six cases are reviewed, from which some overall conclusions are drawn. The cases of successful adoption, whether indigenous and spontaneous or catalysed by external agencies, show that poverty and population pressure on scarce resources do not necessarily or inevitably lead to environmental degradation. On the contrary, the successful cases demonstrate a willingness on the part of resource-poor farmers to make quite significant investments, either individually or through the community (for example, Tiffen and others 1994).

The 2 cases of spontaneous adoption show that extension services to promote conservation practices are not indispensable, but that effective, dynamic promotion of farmer-to-farmer communication can be very important. More details on the successes of soil conservation strategies in Kenya at the grassroots level are provided by Mbegera and others (1992).

ICRAF developed the so-called diagnosis and design method for agroforestry project planning and implementation. It is based on a thorough diagnosis of the land-use systems and their users. Scherr (1990) provides examples for Kenya. Kerkhoff (1990) provides an interesting review of successes and misconceptions in technology transfer of agroforestry. Several projects and government-led attempts to make people grow trees are discussed. In Kenya, ICRAF, the Kenya Woodfuel and Agroforestry Project, and several NGOs, among which is the Green Belt Movement, led by Wangari Maathai, are involved in tree planting. An interesting account on the history of agroforestry in 'Kikuyu land' is given by Castro (1993). He describes modern technology-push practices in the context of the indigenous importance and material and non-material values of trees. Some more work by the KEFRI/KARI/ICRAF project in Maseno on the adoption potential of hedgerow intercropping in maize-based cropping systems is under way. (Shepherd and others 1997, Swinkels and Franzel, 1997).

3.3 Madagascar

3.3.1 Introduction to soil productivity research

Agricultural research in Madagascar was initiated in 1921 when the Institut national de l'agronomie coloniale (INAC) was founded. The country suffered a major setback in agricultural research in 1974 as a result of the abrupt termination of technical and financial assistance from France, but currently CIRAD (Centre de coopération international en recherche agronomique pour le développement) and ORSTOM (Institute francais de recherche scientifique pour le développement en coopération) are operating again. Currently, FOFIFA (Centre national de la recherche agricultural appliquée au développement rural) is the dominant agricultural research institution as it accounts for 80% of the national research capacity in terms of human resources engaged in agricultural research. CNRE has a mandate for soil and water research and FIFAMANOR (Fionpiana, Fambolena [elevage et Agriculture] Malagasy Norvegienne), under the Ministry of Agriculture, is responsible for crops and livestock research. The national AHI consortium consists of (1) FOFIFA, the principal NARS, including the Swiss-funded project Terre-Tany, (2) FIFAMANOR, a research-development organization cofunded by the government, NORAD, the World Bank and other donors, (3) FAFIALA, a Swiss-supported NGO for adaptive research, and (4) ANAE, a national network on natural resources management and rural development. Agricultural research mainly focuses on crops (35%) and forestry (17%), with limited attention for natural resources (2%). About 27% of the research is classified as 'other', which includes FSR, socioeconomic studies and post-harvest technology (Weijenberg and others 1995). In 1993, the country spent 20% of its agricultural research budget (USD 4.8 million) on salaries, at a total budget of USD 30 427 per scientist (Weijenberg and others 1995). The contribution of the government to this budget is up to 37% (table 3.1.1). Agriculture is the most important sector of the economy, contributing about 33% of GDP, and 88% of the population depend on agriculture. Agriculture contributes about 85% of the total exports. Coffee, the major export crop, is responsible for 43% of foreign exchange earnings.

The highlands of Madagascar are characterized by 4 landscape and agricultural subsystems: *l'espace tanety*, the uplands, which have *Eucalyptus* and *Pinus* on the higher slopes and annual crops and pastures on the middle slopes; the vegetable gardens on terraces on the lower slopes; and *l'espace rizicole*, the bottomlands, where rice *(Oryza sativa)* is the dominant crop. Rice being the staple food in the highlands of Madagascar, substantial research efforts went into rice systems in the small inland valleys. With the inception of the Terre-Tany project, however, the approach changed towards the study of complete toposequences. Terre-Tany is a natural resources management, collaborative research project between the University of Bern and FOFIFA. Established in 1989, it has undertaken research in diagnostic and socioeconomic surveys, soil characterization and mapping, and technology development (including agroforestry) for regeneration of acid soils. Since 1992, the project has put emphasis on the inventory of natural resources and the establishment of a methodology for environmental diagnostics (soils, vegetation and water).

Because of the temporary absence of CIRAD and ORSTOM, the current review may not be complete as lots of research data are still suspected to be somewhere in Montpellier archives. Retrieving and summarizing that older literature is outside the scope of the present exercise. The present review was prepared mainly by using 'grey' literature collected by the Malagasy MISP team. Other sources that provided useful information were 2 bibliographies, *Bilan des recherches effectuées à Madagascar avant 1974 en matière de connaissance et d'utilisation des sols* (Kilian 1988) and *Bilan de la recherche agricole à Madagascar* (FOFIFA 1989). Both studies reveal that there are many very site-specific studies with results that are hard to extrapolate. The Silverplatter Soils CD-ROM (1973-07/95) also provided some useful research work that was not found elsewhere.

3.3.2 Soil physical properties and processes

Soil surveys by ORSTOM, CIRAD and FOFIFA provided a good set of soil profile descriptions and laboratory data. For the major soil types *(sols ferallitiques, sols humifères* and *sols hydromorphes* or *bas fonds)*, texture data are available and have been listed in table 3.3.1. Bulk density data are quite scarce. Unfortunately none of the profiles has a complete data set.

Water balance studies were done in catchment areas, mainly by the staff of Terre-Tany. The experiments show that there is a considerable rainfall surplus, concentrated during certain parts of the year. Runoff losses can be high. Grassland plots were compared with plots under *Eucalyptus* forest. The latter was better able to store moisture, and runoff losses were smaller (Terre-Tany unpublished data).

Infiltration tests were carried out by Terre-Tany at different parts of upland slopes and under different vegetation types. 'Ninety-minute' infiltration for topsoils was 4–8 cm h^{-1} under grassland, and 5–48 cm h^{-1} under eucalyptus. Pore volume of the eucalyptus topsoils was 46–61% (Terre-Tany 1995).

3.3.3 Soil chemical properties and processes

Soil nutrient stocks can be derived from the many soil profile descriptions and laboratory data. Organic C, total N, pH and the exchange-

Table 3.3.1 Chemical topsoil properties and texture for the major soils of the highlands of Madagascar

Site	Profile no.	Riquier (1968)	Sand	Silt	Clay	org C	total N	pH-H_2O	Ca	Mg	K	Na	CEC	BS (%)	P–Olsen (mg kg^{-1})	Fe_2O_3 (%)
			%			g kg^{-1}			cmol kg^{-1}							
Andosol																
Antsirabe	M1	VI-1	31	40	11	.67	4.0	6.0	1.4	0.5	0.1	0.0	12.2	17	50	11.1
Eutric Cambisol																
Arivonimamo	TB5	VI-1	6	35	46	44	4.0	6.0	4.3	2.4	0.1	0.0	13.4	51	18	25.9
Est Ambatofinandrahana	M2	VI-1	52	22	20	12	0.9	7.0	10.2	6.6	0.1	0.0	nda	nda	15	7.4
Ferralsols																
Sakay	A5	VIII-7/8	44	19	34	16	1.2	6.0	2.0	0.6	0.1	0.0	7.8	35	9	16.3
Colline d'Andriatsilahy	A6	VIII-7/8	13	20	55	45	4.0	4.2	0.1	0.4	0.2	0.1	14.5	5	17	nda
Ambohitompoina	A3	VIII-7/8	48	13	35	22	1.6	5.0	0.3	0.1	0.1	0.0	7.4	6	3	4.7
Ambohimandroso	18*	VIII-7/8	33	27	40	45	3.0	5.0	nda	nda	nda	nda	50.1	13	7	14.6
Ambatofinandrahana	M16	VIII-7/8	45	11	43	6	0.4	5.0	0.0	0.1	0.0	0.0	6.0	3	18	11.6
Ambohitrila	13	VIII-7/8	58	8	29	23	1.5	5.0	0.4	0.2	0.1	0.0	8.6	9	1	nda
Avaratrambolo	AAS1	VIII-7/8	66	8	26	22	1.6	4.7	1.6	1.2	0.2	nda	3.6	83	nda	nda
Avaratrambolo	AAS5	VIII-7/8	64	6	40	17	1.0	5.0	0.2	0.8	0.1	nda	2.7	42	nda	nda
Avaratrambolo	AAS3	VIII-7/8	60	4	36	12	0.9	5.2	0.4	0.4	0.2	nda	1.6	62	nda	nda
Ankazomiriotra	A9	VIII-7/8	37	18	39	25	1.4	4.5	0.8	0.8	0.1	0.0	9.5	19	13	nda
5 km a Ouest d'Amborompotsy	A13	VIII-7/8	69	10	19	19	1.4	5.0	0.3	0.8	0.3	0.0	6.4	20	11	4.0
15 km au Nord d'Ambatofinondrahana	A14	VIII-7/8	45	11	43	6	0.4	5.0	0.0	0.1	0.0	0.0	6.0	3	nda	11.6
Imerintsiatosika	ANR1	VIII-7/8	nda	nda	23	41	3.0	5.0	1.4	0.2	0.1	0.5	20.7	10	15	33.6
Le lac d'Ambohidratrimo	TC50	VIII-7/8	35	14	53	13	1.0	5.0	0.1	0.1	0.0	0.0	6.0	4	18	nda
Mandalahy	Bo47-13	VIII-10	45	21	23	60	3.0	5.0	0.4	0.3	0.1	0.0	12.6	6	7	nda
Plateau d'Ambatondratsiry	A7	VIII-11	21	27	45	21	1.3	4.5	0.2	0.1	0.1	0.0	14.7	2	10	nda
Ansirabe	ABR3	VIII-9/13	15	40	26	54	4.0	6.0	9.6	3.5	0.3	0.1	28.3	48	220	17.1
Tampoketsa-Ankazobe	M21	VIII-14	33	23	27	6	0.4	6.0	0.1	0.1	0.0	0.0	4.9	4	18	nda
Gleysols																
Ambohimandroso	d20	X-3	25	30	38	41	3.8	5.0	nda	nda	nda	nda	nda	nda	27	nda
Ambohimandroso	d6	X-3	19	30	32	106	10.0	6.0	nda	nda	nda	nda	nda	nda	7	nda
Ranomadia	Bo47-18	X-3	61	12	23	22	2.0	4.0	0.4	0.3	0.1	0.1	5.8	14	6	nda
Antsirabe	ABP8	X-3	6	29	51	62	4.6	5.0	5.9	2.2	0.1	0.0	20.1	41	136	4.9
Ansirabe	ABR15	X-4	32	39	23	17	2.0	5.0	0.9	0.6	0.0	0.0	8.9	17	26	8.4
Buest d'Ambatokombana	ABR12	X-4	16	28	32	67	5.0	5.0	1.5	0.7	0.0	0.0	22.6	10	nda	3.9
Sambavy	MTS34	X-5	90	3	8	51	3.2	5.0	1.4	0.8	0.1	0.0	23.8	10	8	nda
Nitisol																
Sur massif du Tsangana	Bo47-23	VIII-10	56	15	24	26	2.0	4.0	0.8	0.3	0.1	0.0	9.0	14	17	nda

Source: FOFIFA (unpublished data)

* BS = base saturation

able bases are almost always given. A large percentage also has P-Olsen values. Total P is, however, mostly absent. An overview of chemical properties is given in table 3.3.1.

Uplands

Organic C contents of upland topsoils range from 10 to 50 g kg^{-1}. The vast majority, however, has organic C less than 20 g kg^{-1}. N contents in the uplands vary between 0.1 and 2.5 g kg^{-1}, but most soils have N contents of less than 1.0 g kg^{-1}. Not much is known on mineralization rates. The *sols ferralitiques* are strong P fixers, but not much is known quantitatively on the rate of fixation. It is known that application of organic manure helps liberating fixed P. Soil surveys show that Ca levels are always below 1 cmol kg^{-1}, and sometimes even below 0.2 cmol kg^{-1}; Mg levels are at least equal to Ca levels; K levels are often below 0.1 cmol kg^{-1}. Few analyses have been carried out on trace elements. Yet deficiencies have been registered on Zn in *Pinus*, on Mo in leguminous species, on B in wheat *(Triticum aestivum)*, and on S in different plant species (Oliver and others 1974).

Cation-exchange capacity depends on clay and organic C content. In subsoils, cation-exchange capacity varies between 2 and 3 cmol kg^{-1} at clay percentages of 30–50%. In topsoils, cation-exchange capacity varies between 4 and 8 cmol kg^{-1}, because of higher organic C contents. Based on the data, clay has a cation-exchange capacity < 10 cmol kg^{-1}, whereas organic C contributes up to 50–100 cmol kg^{-1}.

Soil pH-H_2O in the uplands generally varies between 4 and 5.5. The soils of the deeply weathered erosional plains are mostly acid and contain appreciable amounts of exchangeable Al. In the *sols ferralitiques fortement désaturés*, the ratio between exchangeable Al and Ca is 1 to 5. Absolute values of exchangeable Al range between 0.5 and 2.5 cmol kg^{-1}. Exchangeable acidity (Al + H) is higher in the topsoil than in the subsoil. The *sols ferralitiques moyennement désaturés* are much less prone to high Al saturation.

Bottomlands

Apart from the soils that are derived from volcanic rocks, most alluvial soils in the highlands are low in fertility. FOFIFA distinguishes 4 classes on the basis of OM content (table 3.3.2). The classification is very useful but does not do justice to an overriding feature, which is the very dynamic hydrological and redox conditions in the different parts of the bottomlands (Vizier and others 1990, Rabeson and Balasubramanian 1992).

Total P, P-fixing capacity and available P are all closely linked with OM content. P-fixing capacity ranges between 1200 and 2000 mg P kg^{-1}, whereas P-Olsen is as low as 8–11 mg P kg^{-1}. P can be regarded as the major limiting nutrient in the bottomlands. Low P content is often associated with Fe toxicity and low base saturation. Cation-exchange capacity is very low (2.9-4.2 cmol kg^{-1}), and so is exchangeable K (around 0.1 cmol kg^{-1}). Al saturation ranges between 14 and 44%, coinciding with a pH range of 5.6 to 4.9. Only the very organic soils have no S deficiency (Roche 1991, Rabeson 1991). The Zn content is low (0.3–1.2 mg Zn kg^{-1}) and decreases with increased OM content. The combination of poor drainage and high OM contents provokes high amounts of mobile Fe, up to levels that are toxic to rice. Low soil fertility and P deficiency further aggravate Fe toxicity (Rabeson and others 1994).

3.3.4 Soil biological properties and processes

Uplands

Although little is known quantitatively about the allelopathic influence of certain species, farmers tend to grow tuber crops such as cassava *(Manihot esculenta)* and potato *(Solanum tuberosum)* after clearing land. It is known that crops like maize *(Zea mays)*, upland rice and to a lesser extent leguminous species do not perform well immediately after land is cleared. *Eucalyptus* has a tendency to create

Table 3.3.2 Organic matter classes for the bottomlands in the highlands of Madagascar

Soil type	OM (g kg^{-1})
Sols hydromorphes minéraux	0–40
Sols hydromorphes moyennement organiques	40–80
Sols hydromorphes organiques	80–140
Sols hydromorphes très organiques	> 140

Source: Roche (1991) and PEM/FAO (1992)

unfavourable chemical and hydrological conditions for other plant species once settled. This is probably the case in those parts of the highlands where *Eucalyptus* has been established, but no research data on this phenomenon are available. *Eucalyptus* is meanwhile seen as a major revenue earner (FOFIFA unpublished data).

Table 3.3.3 shows the C balance for 3 agroecosystems (*Pinus* forest, grassland and annual cropping) in Ankazobe (Raveloarivony 1993). The 3 systems show large differences in C balances, that is, from –3000 kg C ha^{-1} in the annual cropland to +800 kg C ha^{-1} in the forested land. Also remarkable are the large differences in biomass production and availability, that is, from 165 000 kg C ha^{-1} in the forest and 11 500 kg C ha^{-1} in the grassland to a mere 600 kg C ha^{-1} in the annual cropland. Primary production through photosynthesis differs from 1460 kg C ha^{-1} for the cropland to 15 000 kg C ha^{-1} for the forest system.

Soil fauna. Termites are not known to damage farmers' crops. Earthworms are many in uncultivated land or land that is regularly manured. If this is not the case, the earthworm population dwindles rapidly (FOFIFA unpublished data).

Striga hermonthica is not a real problem in the highlands. This parasitic weed is known only in the midwest, especially in maize and upland rice. The midwest is the area between the highlands and the west coast, namely the Sakay area, Kianjasoa and Tsiroanomandidy areas and the Mandoto–Ankazomiriotra areas. Maize and upland rice are threatened by this weed in these areas, but farming systems research using leguminous catch crops (groundnut and soybean) shows promising results. Hence, the danger of striga spreading to other areas exists.

Bottomlands

Nitrogen contents range from 1.6 to 10.6 g kg^{-1} (table 3.3.1). The N mineralization rate in the bottomlands is roughly estimated at 1–3% per year (Rabeson and Balasubramanian 1992). In an experiment with soils from different bottomlands (Antananarivo, Ambohidratrimo/Mahitsy), mineralization ranged between 3 and 14 kg N ha^{-1} in 6 days. The lower values are derived from class A soils, and the higher values from class C soils (table 3.3.4). Recent experiments with labelled azolla showed that 27% and 60% of the N was mineralized after 4 months in soils with high (210 g kg^{-1}) and low (2 g kg^{-1}) OM, respectively (Rabeharisoa 1992).

3.3.5 Runoff and erosion

Randrianarijaona (1983) described the deplorable situation of erosion in Madagascar. He thinks it has both natural causes and those made by humans. He lists measures of the then-government, which have now been reviewed and partly abandoned.

Erosion (plot and catchment level). Potential erosion in the highlands of Madagascar was

Table 3.3.3 C balance (kg ha^{-1}) for 3 agro-ecosystems at Manakazo, Ankazobe, Madagascar

Compartment	Pinus forest	Natural grassland	Annual cropping
Photosynthesis	15 000	4 100	1 460
Above-ground biomass	130 000	5 500	100
Leaffall (A)	6 770	1 100	0
Above-ground litter	15 200	1 120	1 000
Oxidation (B)	5 690	950	0
Humification (A – B)	1 080	17	0
Humus	103 000	90 300	80 650
Oxidation (E	3 100	3 610	3 200
Root humus (C – D)	2 900	1 000	200
Oxidation (D)	5 100	2 000	300
Root litter	8 000	3 000	500
Root biomass	35 000	6 000	500
Root growth (C)	8 000	3 000	500
Losses (E)	3 100	3 610	3 200
Gains (A – B+ C – D)	3 980	1 170	200
Carbon balance	+880	– 2 440	– 3 000

Source: Raveloarivony (unpublished data)

Table 3.3.4 Characteristics of three types of Inland Valley soils in the highlands of Madagascar

	A	B	C
Site	BELANITRA (Plaine d'Antananarivo)	MAHITSY (Ambohidratrimo)	ANIERA (Plaine d'Antananarivo)
Soil type	Sol hydromorphe minéral à gley	Sol hydromorphe moyennement organique à gley	Sol hydromorphe organique (tourbeux)
Soil characteristics			
OM (g kg^{-1})	46	76	297
Organic C (g kg^{-1})	27	44	173
Total N (g kg^{-1})	2.4	4.0	13.3
C/N	11	11	13

Source: Rabeson and Balasubramanian (1992)

estimated at 400–500 t ha^{-1} year^{-1} (FOFIFA 1975) but actual erosion rates of 100–150 t ha^{-1} year^{-1} under dryland cropping and 10 t ha^{-1} year^{-1} under natural grasses were found. Degraded grasslands have erosion rates up to 30 t ha^{-1} year^{-1}, whereas 2-year-old fallow land may lose 60 t ha^{-1} year^{-1}. The larger gullies *(lavaka)* may lose 300 t ha^{-1} year^{-1}. Some researchers put question marks behind the assumption that people cause the gully erosion (Wells and Andriamihaja 1993). Tectonism and climatic aridification are mentioned to be more important in the development of lavaka than human activities such as range burning, forest cutting, and overgrazing, given that many lavaka are a natural part of the landscape's evolution and that some lavaka predate primary (uncut) rain forest.

Runoff (plot level). Bailly and others (1967) registered that land under contour strips, terraces and *Pinus* plantations generally loses less than 5–10% of event rainfall to runoff. Land under traditional annual cropping lost less than 5% of total rainfall to runoff in 34 out of 75 events, but it lost more than 20% of rainfall in 20 cases. Land that had been burned lost more than 20% of event rainfall to runoff in 35 out of 91 cases. Peak runoff values were 90 l s^{-1} ha^{-1} for *Pinus* land, 110 l s^{-1} ha^{-1} for contour stripped land, 125 l s^{-1} ha^{-1} for land under arable crops, and 270 l s^{-1} ha^{-1} for land that had been burned.

Erosivity, erodibility. Some general values for erosivity and erodibility for the highlands (table 3.3.5) are reported by Malvos and others (1976). Erosivity is classified as low at *R*-factor < 380 and medium at *R*-factor of 380–520, while erodibility ranges between very low (0.03) and high (0.24).

3.3.6 Nutrient cycling and budgets

At the national scale, an assessment was made of the nutrient balance of Madagascar, as part of the sub-Saharan Africa study (Stoorvogel and Smaling 1990, Stoorvogel and others 1993). The methodology was described earlier for Ethiopia (see sec. 3.1.5). The total arable land in Madagascar in 1983 was projected to be 31 310 km^2, of which *GR* represents 25% (7760 km^2), *I* (irrigated area) 29% (9080 km^2) and *P* (problem area) 31% (9610 km^2). Figure 3.3.1 shows us that the highland area mainly consists of the classes *GR* (good rainfall) and *P*, with a small area *UR* (uncertain rainfall compare map 4 with figure 3.3.1). Class *I* is not represented on the map because of its low resolution. However, the inland valleys that are irrigated do represent a considerable area and are quite important for Malagasy agriculture. The nutrient balance for class *I* land is only slightly negative for N and K (table 3.3.6). Input through biological N-fixation (IN 4) can be high in wetland rice systems. Nutrient losses are mainly caused by harvested products (N and P), and crop resi-

Table 3.3.5 Erosivity and erodibility for the highlands of Madagascar

Sous région des Hautes Terres	Erosivity R-factor USLE	Erodibility K-factor USLE
Central highlands (Antananarivo)	370	0.16
Southern highlands (Fianarantsoa)	476	0.03
Western highlands	508	0.24
Eastern highlands	385	0.19
Volcanic area (Antsirabe)	359	0.22

Source: CIRAD-CFTF (nd)

dues (K). In class *GR*, nutrient losses are mainly caused by removal of harvested products and erosion.

Table 3.3.6 *Total nutrient balance for land/water classes in the highlands of Madagascar*

LWC	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
GR (good rainfall)	– 28	– 5	– 21
I (irrigated area)	– 1	– 5	– 15
UR (uncertain rainfall)	– 40	– 7	– 28
P (problem area)	– 37	– 4	– 23

Source: Stoorvogel and Smaling (1990)

Table 3.3.7 shows the major flows of biomass and nutrients in different Malagasy agroecosystems (Rakotomavo 1995).

The Terre-Tany project did an interesting catchment-level study into the movement of nutrients from the uplands to the highly valued terraces on the lower slopes. N losses on uplands after slash and burn amounted to 56 kg N ha^{-1} (Rakotondranaly 1995), whereas the terraces received a net amount of 84 kg N ha^{-1}, including farmyard manure and household waste transported from the stables and kraals on the upper slopes minus export of nutrients in crops. For P, the balance was –2 kg ha^{-1} for the higher slopes and +8 kg ha^{-1} for the terraces; for K these values were –29 kg ha^{-1} for the higher slopes and +113 kg ha^{-1} for the terraces. Fertility differences between higher slopes (3–4 years of fallow) and the terraces come out clearly from laboratory analysis (Rakotondranaly 1995). The terraces have a total N of 2.1 g kg^{-1}, P-Olsen is 16 mg P kg^{-1}, and for K, Ca and Mg they have 0.7, 3.2, and 1.6 cmol kg^{-1}, respectively. The corresponding values for the upper slopes are 1.4 g N kg^{-1} (total N), 6 mg P kg^{-1} (P-Olsen), and 0.0, 0.6 and 0.6 cmol K, Ca and Mg kg^{-1}, respectively.

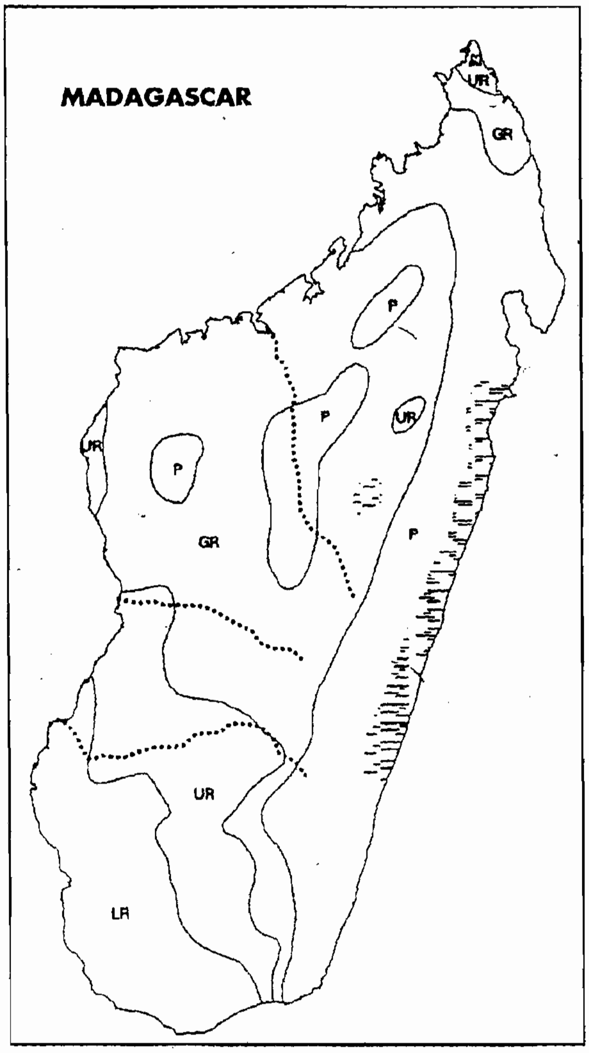

Figure 3.3.1 Distribution of land and water classes for Madagascar: GR = good rainfall; UR = uncertain rainfall; LR = low rainfall; P = problem area (Stoorvogel and Smaling 1990).

3.3.7 MISP technologies

Mineral fertilizers

The use of mineral fertilizers in the uplands is virtually restricted to the terraced fields under vegetables. Compound NPK and urea are both applied. Research revealed that P fertilizers in upland rice have a recovery of 11% at a fertilizer rate of 19.5 kg P ha^{-1} and 10% at a rate of 39 kg P ha^{-1}. Upland rice yields of 1500–2000 kg ha^{-1} were obtained at fertilizer applications corresponding with 45 kg N ha^{-1} and 26 kg P ha^{-1}. The crop is recommended as a component of cassava–maize–upland rice rotations. Old, undocumented fertilizer recommendations for lowland rice are 30–60 kg N ha^{-1}, 26 kg P ha^{-1} and 38 kg K ha^{-1}, with no mention of projected crop yields. Velly (1975) found that rice plants performed better with Si application than without. Velly and others (1967) indicate that P is the most limiting element in the bottomlands. They claim that 85–175 kg P ha^{-1} is needed to obtain 90% of maximum yields. Next, each year maintenance applications of 20–26 kg P ha^{-1} are needed. Rabeson (no date)

Table 3.3.7 Major input (INs) and output (OUTs) flows of Malagasy agroecosystems

Land use	Processes	Exported products and NUTBAL processes*	Imported products and NUTBAL processes*
Eucalyptus forest	production and export of biomass	wood, litter (OUT 1), fodder	nil
Pastures	production and export of biomass	fodder (OUT 1,5), litter with topsoil	nil
Arable dryland crops	production and export of biomass	harvested crops, residues, fodder (OUT 1,2,5)	decaying weeds
Rice fields	production and import of biomass	harvested crops residues, fodder, weeds (OUT 1,2,4)	manure, litter, atmospheric N, sedimentation (IN 2,4,5)
Vegetable terraces	production and import of biomass	harvested crops, residues (OUT 1,2)	manure, fertilizers, litter, sedimentation (IN 1,2,5)
Homesteads	consumption of biomass	ashes	harvested crops
Paddocks/kraals	consumption and modification of biomass	manure	litter, animal droppings and urine
Marketplace	sale of biomass, purchase of mineral fertilizers	wood, harvested crops, animal products	fertilizers

Source: Rakotomavo (1995)
* INs and OUTs are defined † 3.1.5

found that point placement of P was twice as efficient as broadcasting it. Similar conclusions were drawn by Hooper and Rabelolala (no date). In trials carried out by IRAT between 1960 and 1973, local rice varieties gave positive N responses up to 120 kg ha^{-1}, whereas improved varieties under near-optimal water management gave yield responses up to 180 kg ha^{-1}, (IRAT 1970).

Velly (1974) also studied acidification caused by $(NH_4)_2SO_4$ application to maize, cotton *(Gossypium hirsutum)* and groundnut *(Arachis hypohaea)* in the uplands. Decreases in pH and high Al saturation caused major yield reductions. Continuous cropping also lowered pH.

Mineral soil amendments

Rock phosphates are available in the country but are scarcely used in agriculture. Their chemical and mineralogical properties have, however, been well studied in the past (Truong and others 1982). Guano is applied to a limited extent.

Dolomite is locally obtained around Antsirabe, but its use in the uplands is low. Research on dolomite refers to quantities of 250–4000 kg ha^{-1}. It was found that a dose of 500 kg ha^{-1} can already cause considerable yield increases, notably when combined with manure (FOFIFA unpublished data). Celton and others (1973) found that annual applications of dolomite (300 kg ha^{-1}) were needed in the uplands to keep pH above levels that cause Mn and Al toxicity.

Improved, low-external input agroecosystems

Manure is applied to rice fields and on vegetables. Manure use in the uplands is restricted to the droppings of small animals and household waste. Quantities applied are small and applied in 'pockets'.

Crop residues are mainly used as a source of fodder (groundnuts, maize, field beans, potato). They are fed either on the land or in the stable. Whatever is left is burnt or directly incorporated into the soil.

The effects of mulching are known, but mulching is difficult to implement because of the sheer lack of biomass to cover the soil. In the south (Fianarantsoa), town compost is used, which is able to regenerate very unproductive land. Compost derived from *Eucalyptus* leftovers also improved land productivity (Rabeson personal communication).

A potentially interesting organic input is EOB *(engrais organo-biologique)*, which is a waste product of the sisal industry. In experiments in Manjakandriana and Mahitsy, it was found that EOB could be useful as mineral fertilizer up to a certain level (Rakotoarisoa 1988). At control yields of 1000 and 2000 kg paddy ha^{-1} at the 2 sites, 500 kg EOB ha^{-1} increased yields to 1400 and 2600 kg ha^{-1}. Higher amounts of EOB seem to be slightly detrimental, as yields declined somewhat. In a consecutive year, 250 kg EOB ha^{-1} already gave satisfactory yield increases of 500–800 kg paddy ha^{-1}.

Experimentation on agroforestry in the uplands is largely restricted to hedgerow intercropping. Major species used are *Tephrosia* and *Crotalaria*. *Leucaena leucocephala* and *Calliandra calothyrsus* have been used in experiments but with limited success. *Sesbania* spp. can do well but are rarely used because of their poor performance after cutting. Hedges of *Flemengia congesta* do well as shade trees for coffee and produce a lot of biomass, which is used as mulch. It can reportedly be as effective as mineral N fertilizers (FOFIFA, unpublished data).

Natural fallows in the uplands are often based on *Cynodon* and can include *Helichrysum* and *Crotalaria*. It is a problem to get fallows going, as seeds are few and soils are poor. Improved fallows are made up of bushy species *(Crotalaria, Tephrosia)*, green manures (*Mucuna, Trifolium* spp., *Melinis mionutiflora, Chloris gayana, Brachiaria* spp.), or improved pastures (*Melinis, Chloris, Brachiaria, Setaria*, others similar). Effects of different fallow combinations on soils still have to be quantified. Experimentation with cover crops revealed that *Cassia rotundifolia* is the most promising species (FOFIFA unpublished data).

There are many local leguminous plants that are well known and appreciated. Little, however, is known on their–fixing potential. Next, many species have been introduced, among which are the earlier-mentioned woody species *Crotolaria* and *Tephrosia* and the green manures *Mucuna, Trifolium, Pueraria* and *Chloris gayana*, nodulating well with local *Rhizobium* strains. Major N-fixing species are field bean *(Phaseolus vulgaris)*, groundnut and vouandzou. The most widely distributed species is *Acacia dealbata*, but again little is known on its potential to withdraw N from the atmosphere. Rarivoson and Schramm (1988) studied the performance of *Aeschynomene* as green manures in rice cultivation. They found the green manure able to increase yields of a following rice crop by 100%. *Trifolium* spp. and *Vicia sativa* are the green manures that are best adapted in rice-based systems.

Field beans are the most common intercrop. Major associations in the uplands are maize–field bean, cassava–field bean, cassava–maize–field bean, and taro *(Colocasia esculenta)*–field bean. Fruit trees are increasingly interplanted with maize, wheat and field bean, but seldom with tuber crops. Also, rotational systems, including potato or field beans as dry-season *(contre-saison)* crops, generally give higher rice yields than rice alone. Rice gave 3200–3600 kg ha^{-1} after potato and 2600–3100 kg ha^{-1} after field beans. If no 2nd crop is grown, manuring and tillage are needed to secure good rice yields during the following year. Rice after manuring and tillage gave 2800–3100 kg ha^{-1}, whereas the absence of both gave rice yields of 2400 kg ha^{-1} (Rabeson and others 1987).

Double rice cropping has also been tested, but did not give significant yield increases in Manjakandriana. In the more wet and fertile environment of Antsirabe, however, rice gave a good ratoon yield (800–1700 kg ha^{-1}). It is then needed to cut the plant at 7.5 cm height, which gave a significantly better ratoon crop than when cut at 15 cm (Rabeson and others 1987).

In the bottomlands, the potential benefits of azolla have been studied in detail. It was found that 2 kg azolla m^{-2}, corresponding with 20 t ha^{-1}, has the same fertilizing effect as 30 kg N ha^{-1} in fertilizer (Rabeson and others 1987).

Soil and water management and conservation

Scores of techniques have been promoted by the government and are partly adopted by farmers. Currently an extension manual, *Référentiel technique pour la conservation des sols á Madagascar*, is being prepared.

The anti-erosion measures can be grouped as (1) physical and biological blockades, such as stone lines and walls, terraces, water harvesting, hedgerow planting, grass strips, and so forth, (2) land management, such as reafforestation, fencing, no slash and burn, zero-tillage and residue mulching, and (3) soil fertility management, such as improved fallows, fertilizer use, alley cropping, composting, and so forth.

Farmers around Antananarivo use different combinations of anti-erosion measures, including live hedges, fruit tree stands and contour channels (*tatatra*). Pleines (1993) lists 22 woody plant fruiting species and 4 forest tree species that are utilized.

There are many soil conservation projects, and success rates differ substantially. Randriamampianina and Stockli (1992) describe the extension approach in a soil conservation project near Fianarantsoa. Mechanical structures are promoted first, followed by biological measures and improved cropping methods for increased production.

The country has a National Environmental Action Plan (NEAP), but the rural population is so diverse in its decision making that USDA questions the plan's relevance (Larson 1994).

Integrated nutrient management

MF + ILEIAS

Azolla growth is strongly enhanced by the application of mineral P fertilizers. Thirty days after inoculation, a –P treatment gave 370 g azolla m^{-2}, whereas the +P treatment (26 kg P ha^{-1}) gave 3555 g azolla m^{-2}. Rice production in soils without azolla was 1900 kg ha^{-1}, with azolla/–P trials, yields were 2300 kg ha^{-1}, and for azolla/+P trials, yields were 2700 kg ha^{-1} (Rakotoarisoa no date).

ILEIAS

Experiments have also been conducted on the combination of azolla, manures and fish culture (azollarizipisciculture). Although rice alone gave reasonable yields (3100 kg ha^{-1} in the 1st year, 1900 kg ha^{-1} in the 2nd year), the combination of rice with azolla and fish gave higher rice yields and a fish harvest. When the fish was fed farm waste, rice yields reached 3300–3500 kg ha^{-1} in the 1st year and 2700–2900 kg ha^{-1} in the 2nd year. It also turned out to be more economic to combine rice and fish, although the analysis does not take labour cost for azolla incorporation into account (Rakotoarisoa no date).

MF + MSA + ILEIAS

Experiments were conducted in which maize responded best to a combination of 90–60–45 of mineral NPK and 5 t farmyard manure ha^{-1}, yielding 4600 kg ha^{-1}. The control plot did not give any yield at all, the NK plot gave 1400 kg ha^{-1}, and the NPK plot gave 3900 kg ha^{-1}, clearly showing how indispensable P fertilizer was; farmyard manure gave only 800 kg ha^{-1}. With the inclusion of dolomite, bumper harvests of 5800 kg ha^{-1} were realized (90–60–45 of mineral NPK, 1 t dolomite ha^{-1}, and 5 t farmyard manure ha^{-1}) (Rakotoarisoa 1991).

MF + MSA + ILEIAS

Sec. 3.3.9 on long-term experimentation provides data on experiments in both uplands and bottomlands that included mineral fertilizers, lime and organic inputs.

3.3.8 Modelling approaches for soil productivity research

No research data were found.

3.3.9 Long-term experimentation

Uplands

There are few long-term studies on soil fertility development in the uplands, yet it is interesting to note that over the last 20 years farmers have gradually replaced demanding crops, such as maize and groundnuts by less-demanding ones such as cassava and field beans. Medium-term experiments worth mentioning include the development of terraces for vegetables. In Avaratrambolo, terraces in which the subsoils were exposed at the surface received large amounts of fertilizer and farmyard manure. Soil properties after 3–5 years had considerably improved, as is shown in table 3.3.8. A 2nd example is even more interesting. Two full 7-year rotations were studied at Manankazo, according to the schedule presented in table 3.3.9. At the start of the rotational system dolomite (2 t ha^{-1}), farmyard manure (20 t ha^{-1}), P (130 kg ha^{-1}) and K (250 kg ha^{-1}) were applied. The soils were analysed after 2 full rotations (14 years) and show that soil properties improved significantly (table 3.3.10). The results obtained also serve as guidelines for the soil fertility that should be realized in the uplands. Threshold values have been set at Ca ≥ 2 cmol kg^{-1}, K > 0.2 cmol kg^{-1}, Al < 0.6 cmol kg^{-1} and pH-H$_2$0 ≥ 5.5 (Rakotomana, unpublished data).

Bottomlands

Research by Arrivets and Razafindramonjy (1980) revealed that without inputs, rice yields will go down until they stabilize at 1500–2000 kg ha^{-1} for most parts of the bottomlands.

Table 3.3.8 Chemical properties of un-terraced and terraced land at Avaratrambolo, Madagascar

Chemical property	Unterraced land	Terraced land
pH-H_2O	5.2	6.2
Organic C (g kg^{-1})	15	25
Ca (cmol kg^{-1})	0.2	3.2
Mg (cmol kg^{-1})	0.0	0.6
K (cmol kg^{-1})	0.1	0.5
Al (cmol kg^{-1})	1.0	0.2

Source: Rakotondranaly (1995)

Table 3.3.9 Rotation schedule of an experiment at Manankazo, Madagascar

Year	Land use	Input per land use
1	potato	urea
2	maize	NPK–manure–urea
3	soybean	PK
4	maize	NPK–manure–urea
5–6–7	pasture	K and N

Source: Rakotomana (unpublished data)

Table 3.3.10 Effects on chemical properties of the use of a rotation at Manankazo, Madgascar

Chemical property	Untreated land	Land under rotation
pH-H_2O	4.7	5.5
pH-KCl	4.2	4.7
Ca (cmol kg^{-1})	0.4	2.0–2.8
Mg (cmol kg^{-1})	0.2	0.4
K (cmol kg^{-1})	0.1	0.1–0.22
Al (cmol kg^{-1})	1.2	0.2–0.6

Source: Rakotomana (unpublished data)

Between 1950 and 1970, they carried out long-term fertilizer trials on rice. Fertilizer rates and soil, crop and water management were, however, beyond the scope of local farmers.

Since 1985, an IRRI-guided series of trials has been started, both on-station and on-farm, using inputs that are within the financial reach of the farmers. The trials were centred around Mahitsy, Antsirabe and Sambaina, and provided very useful results. Analytical details of the soils at these centres are given in table 3.3.11.

In Mahitsy, factorial trials showed consistently high yields upon application of N and K (4400 kg paddy ha^{-1}). P had been applied in previous trials, and soil P content was already rather high (table 3.3.11). Additions of Zn, S, dolomite or farmyard manure did not provide higher yields. In the farmers' fields, however, P proved to be highly limiting. The NP and NPK treatments gave the highest yields (3300 kg ha^{-1}). Addition of S or farmyard manure increased yields even to 3600 kg ha^{-1}. Control yields also differed considerably, from approximately 3000 kg ha^{-1} on-station to 2100 kg ha^{-1} on-farm. Production functions in on-farm omission trials for N, P and K all showed linearity up to a level of 135 kg of applied nutrient.

In Antsirabe, yields ranged between the already attractive control yields of 3600 kg ha^{-1} and an approximate 4600 kg ha^{-1} in the N, NK and NPK treatments. Addition of Zn did not increase yields any further.

In Sambaina, soils are poor and a mere 1300 kg ha^{-1} was harvested from the control plots, which reportedly also suffered from Fe-toxicity. The NP treatments gave 2200 kg ha^{-1}, and only on application of NPK and farmyard manure at 5 t ha^{-1} were yields of 3000 kg ha^{-1} realized. Production functions in on-farm omission trials for N, P and K all also showed linearity up to 135 kg of applied nutrient (FOFIFA unpublished data).

3.3.10 Farming systems research

Both soils and land use follow toposequential patterns, which have shaped the landscape in

Table 3.3.11 Chemical topsoil (0-20 cm) properties of IRRI sites at Mahitsy, Antsirabe and Sambaina (Madagascar)

Characteristic	Mahitsy	Antsirabe	Sambaina Manjakandriana
Clay (%)	36	37	49
Silt (%)	34	33	21
Sand (%)	30	30	30
pH–H_2O	5.6	5.5	4.9
OM (g kg^{-1})	56	131	57
Total N (g kg^{-1})	3.9	3.5	4.0
Exch. Ca (cmol kg^{-1})	3.4	5.1	0.8
Exch. Mg (cmol kg^{-1})	0.7	1.3	0.2
Exch. K (cmol kg^{-1})	0.1	0.5	0.1
CEC (cmol kg^{-1})	13	30	10
P-Olsen (mg kg^{-1})	11	13	7

Source: Rabeson and Balasubramanian (1993) the highlands. The genesis of these toposequences and associated land use and management has been described at length by Raunet (1989).

A toposequential land-use pattern can be recognized in the uplands. On the highest parts, one finds *Eucalyptus* and *Pinus* forests, on upper slopes, annual crops such as maize and cassava are grown; in this area, one also finds the homesteads and kraals and stables for livestock. On terraced lower slopes, vegetables are grown in a labour-intensive and sometimes also capital-intensive way, and in the bottomlands, one finds rice in places with a 2nd-season contre-saison crop.

In the past, rice cultivation in the bottomlands sufficed to feed the farm family. Because of population increases, however, this is no longer the case. Livestock in the highlands consists mainly of oxen for draught power and, around Antsirabe and Manjakandriana, dairy cows. Poultry and ducks are also important. Average size of a farm holding is 0.2 ha, of which 2/3 is devoted to dryland crops. Tuber crops and field beans are becoming more important of late. This change comes at the expense of the more demanding crops of maize, upland rice and groundnuts. Wetland rice is planted in November–December and harvested in April–May. Late planting means there will be a risk of frost damage. Wheat is often grown as a 2nd-season crop around Antsirabe. It is strongly supported by the local flour factory, which runs below capacity. Potato is another important 2nd-season crop. Crop residues are not generally used as a source of fuel. They are either fed to livestock or left on the surface, burned or incorporated. Most farmers own their land.

Extension has so far been poorly organized in Madagascar. A large World Bank effort to install an extension service is under way. It seems hard, however, to motivate lowly paid extension agents to actually visit and advise farmers.

Nor are farmers very motivated to grow trees. Traditionally, they have slashed and burned grassy vegetation in the uplands with a dual purpose: to provide freshly sprouted grasses for livestock and indirectly to maintain soil fertility and reduce acidity in the bottomlands, receiving eroding materials from above. Government regulations to curb slash and burning of upland areas have proved ineffective, at least up to the late 1980s (Fujisaka 1989).

Water management in the bottomlands is rather poor. Risk of either drought or early inundation by turbulent water looms each year. The combination of rice and fish culture is gaining some momentum. Household waste is not generally much valued as organic fertilizer. It is now increasingly realized by both government and farmers that 'man shall not live by rice alone' (FOFIFA unpublished data).

3.3.11 Technology adoption

Louis (1974) gives 2 main reasons, still valid today, for poor adoption of fertilizer use in Madagascar: poor transport and untimely distribution, and climatic vagaries that make many farmers risk averse. Rice yields can be significantly increased in the bottomlands and farmers are aware how. If used, fertilizers are applied to vegetables in the first place, then to rice, then to leguminous species. Other crops normally do not receive any fertilizer.

The role of azolla in improving wetland productivity is well appreciated by farmers, but it is the labour demand associated with it and its sheer lack of availability that hamper, wider adoption. In erosion control, measures adopted by farmers are traditional and low input, apart from the terraces for vegetables that are constructed on lower slopes (FOFIFA unpublished data).

3.4 Uganda

3.4.1 Introduction to soil productivity research

Since 1937, the soils laboratory at Kawanda has been in charge of soil productivity research, soil surveys, and soil and plant analysis. During the days of the East African Community (1948–1976), the agricultural research centre in Muguga, Kenya, conducted soils research in collaboration with national programmes. Reorganization of agricultural research in Uganda culminated in the formation of the National Agricultural Research Organization (NARO) in 1993. It includes a soils programme with 12 scientists. The other concentration of soil scientists is in the Department of Soil Science of Makerere University (9 scientists). More recently national and international agricultural research centres and NGOs have initiated collaborative projects relevant to soil productivity. These include the CIAT Regional the majority of farmers in Uganda to use chemical fertilizers, mainly because of lack of availability of fertilizers and their cost (Manning and Griffith 1949). The official 'interim' fertilizer recommendations were developed in 1971 but were not very meaningful afterwards because of the changing political situation. Agricultural production in Uganda is now mainly a smallholder affair; these farmers have had no continuous access to fertilizer to date. Hence, widespread use of fertilizer has never taken off and has had no impact whatsoever. A report on the agricultural inputs situation in Uganda (Bank of Uganda 1992) indicated that use of fertilizers on food crops was virtually non-existent and that the little fertilizer imported into the country (2.16 million t in 1991 and 1.0 million t in 1992) was used on estate crops (sugar, coffee and tobacco).

Adoption of soil conservation measures. Prior to 1972, soil conservation was widely practised, and it was taught in schools and enforced by the administration throughout the country. Up to the late 1960s, protection of arable land in Uganda was often good, and soil conservation featured heavily in annual agricultural shield competitions held for many years. After independence the local administration was weakened and so were other systems in society, including soil conservation by-laws. Following the collapse of administrative structures and destabilization in rural areas that started in the early 1970s, soil conservation was practised by only a few progressive farmers. According to Zake (1992) the consequence of all these changes was soil erosion, soil exhaustion, lack of awareness of the necessity for soil conservation, lack of appropriate research, lack of updated land laws, and the use of swamps. Terraces in the hilly areas of southwestern Uganda, including grass strips that served as a source of soil fertility, have collapsed, and along Mt Elgon and the Ruwenzori Mountains extreme erosion has started to result in reduced crop yields.

In Uganda, much research has been donor driven, and according to Zake (1992), farmers have not adopted many research findings to improve soil productivity. Therefore, there is no research into appropriate methods of land clearing and soil tillage, and limited research in the use of local fertilizing materials as substitutes to imported ones. Uganda has deposits of liming materials, phosphate rocks, volcanic and wood ashes (Kisitu 1991), as well as organic materials.

Lastly, land-tenure systems are diverse, leading to great misappropriation of the land (Zake 1992).

Recently the government introduced a new national administrative policy, the Resistance Council system, which once again emphasizes locally centred authorities. Soil conservation could be potentially introduced successfully through the Resistance Councils (Zake 1992). The major limitations to effective soil conservation in Rubanda County of Kabale District were reported to be lack of technical advice, land fragmentation, land shortage and labour scarcity (Kisakye 1992).

4 Summary and highlights

4.1 Summary of georeferenced information

4.1.1 Information base

Georeferenced baseline data on the highlands in the 4 countries included rainfall, temperature, altitude, and population density. The present report includes maps that show their spatial distribution and tables that show the spatial extent. Land use is covered only broadly. In all 4 countries, soil mapping has been undertaken at different spatial scales. The maps that were central to the present study included the 1:1 000 000 Geomorphology and Soils map for Ethiopia (UNDP/FAO 1984a), the 1:1 000 000 Exploratory Soil Map for Kenya (Sombroek and others 1982), the 1:1 000 000 ORSTOM map for Madagascar (Riquier 1968), and the 1:500 000 map of Uganda, made up of several more detailed studies in the late 1950s (Chenery 1960).

The maps all have different legend structures and provide different levels of detail. Accompanying soil profile descriptions and analytical data were unavailable for Ethiopia and Madagascar. This constraint was circumvented by using average map unit data for Ethiopia and profile data from 1:200 000 surveys done by FOFIFA in central Madagascar. For Uganda, a number of 'soil memoirs' exist that provide analytical data. At the time of the present study, all these data were still being processed at ICRAF. The Kenya map is supplemented by a comprehensive set of morphological, physical and chemical soil profile data, which were used for the present study. Most of this data had been structured in the KENSOTER.

4.1.2 Soil productivity indicators

A total of 14 SPIs were considered relevant for the present study. Key to many soil qualities is the content and quality of organic carbon. Next, there are 6 SPIs on nitrogen (total N, potential plant N supply, N balance, N leaching, gaseous N losses, N accumulation at depth), and 5 SPIs on phosphorus (total P, potential plant P supply, P balance, 'easily extractable' P, P fixation). The remaining SPIs are acidity, rootability, relief and erodibility.

An attempt was made in the present study to develop proxies for some of the above SPIs and to portray their values spatially, using the soil property values obtained from the soil maps and the accompanying profile datasets. It was not possible to adequately cover all SPIs for the 4 countries. Most SPIs were calculated for Kenya and are shown on the maps that accompany this report.

The SPIs and their values refer to exploratory scales (1:500 000 to 1:1 000 000). At lower spatial scales, more spatial variability can be shown, and SPI values may be very different. A good example in this respect is the case of bottomlands in Madagascar. These valley floors are many but narrow, and therefore they are only sparsely shown on the 1:1 000 000 soil map (Riquier 1968). However, these bottomlands are extremely important for rice and associated agricultural production. One has to turn to maps produced at smaller spatial scales (1:50 000 and below) to address such land units properly.

4.2 Summary of non-georeferenced information

4.2.1 Theme x country summary

Continuity of MISP research has been greatest in Kenya and Ethiopia, while Kenya also harbours many international research and development institutes. In Ethiopia, political winds of change have rendered some of the work obsolete. Agricultural research in Uganda came to a virtual halt in the early 70s, not to recover until the early 90s. Agricultural research in Madagascar was largely steered by French research institutes until 1974 when they pulled out, to return only in the mid-80s. FOFIFA was established in 1974 but was rather isolated and ill equipped until the late 80s.

There are many research data on agricultural production and natural resources (management) for all countries, of very diverse nature and quality. A considerable percentage of the data are either obsolete or non-conclusive. The vast majority of research data is on crop response to mineral fertilizers; next are data from research on erosion and on soil and water conservation. Great strides have been made to make grey literature visible by comprehensive bibliographies, books and review papers. Combating nutrient depletion in a holistic way is a relatively new area. Elements of it have been studied, but an overall view is lacking. MISP researchers in the 4 countries (1) have been mainly reductionistic in their approach, (2) analysed a lot but synthesized little, (3) hardly attempted to extrapolate research findings to other areas, (4) until recently did not try to link systems and process research, and (5) have only recently been adopting concepts of different spatial and temporal scales as key elements of agricultural and natural resource management research. Integrated nutrient management in its wider meaning, that is, combining different MISP technologies, is slowly gaining some momentum, but it has not yet been embraced as a future, more holistic avenue for farming system and technology research and development.

For each country, a summary of the relative abundance of the information presented in sec. 3 is given in table 4.2.1.

4.2.2 Highlights per country

Ethiopia

- The *P-sorption* capacity among Ethiopian soils varies widely. Sahlemedhin Sertsu and Ahmed Ali (1983) reported that P sorption ranged from 150 to 1500 mg kg^{-1}. Tekalign Mamo and Haque (1987) found very high sorption in a volcanic ash soil (maximum value of 1500 mg P kg^{-1}), while Fluvisols and Regosols had very low sorption values (13–14 mg P kg^{-1}).
- Legesse Wolde-Yohannes and Wehrmann (1975) reported losses of up to 14 t C ha^{-1} and 1 t N ha^{-1} because of *guie* but grain yield increase from 0.3 to 0.9 t ha^{-1} for periods of 1–2 years. Nonetheless grain yields of 3.0 t ha^{-1} annually are possible in unburned soil if mineral fertilization and weed control are applied.
- *Soil erosion* in Ethiopia has been rampant, although some successful cases of indig-

Table 4.2.1 Qualitative ranking of MISP research in the highlands of Ethiopia, Kenya, Madagascar and Uganda; ranking as follows: 0 (no information), 1 (little information: 1or 2 studies), 2 (moderate information), 3 (much information) and 4 (abundant information)

	Ethiopia	Kenya	Madagascar	Uganda
Physical properties and processes	1[a]	2	1	1[o]
Chemical properties and processes	2[b]	4[g]	3[k]	3[p]
Biological properties and processes	3[c]	2[h]	1[l]	3[q]
Runoff/erosion	3	3	2	2[r]
NUTBAL	2	2	2	1
FSR diagnostics	3	2	2	3[s]
MISP tchnologies				
Mineral fertilizers (MF)	3[d]	4[i]	2[m]	2[t]
Mineral soil amendements (MSA)	2	2	1	2[t]
Improved, low external input agroecosystems (ILEIAS)	2[e]	2[j]	2[n]	2[u]
Soil and water management conservation (SWMC)	2[f]	2	1	1
Integrated nutrient management (INM)	1	1	2	1
Adoption	3	2	1	2
Modelling	0	2	0	1
Long-term	0	2	2[m]	1

[a] mainly Vertisol research
[b] mainly P availability and extraction techniques, and 'guie'
[c] mainly *Rhizobia* inoculation
[d] many trials on different crops and pasture; recent work by NFIU, little on fertilizer efficiency
[e] mainly agroforestry
[f] much attention for BBF in Vertisols
[g] KSS and FURP data, and useful data on P sorption and acidification
[h] mainly *Rhizobia* inoculation and BNF, C and N dynamics (1960s), and *Striga*
[i] mainly FURP trials and data from Tea and Coffee Research Foundations; little information on fertilizer use efficiency
[j] mainly mulching and crop residue management, followed by agroforestry
[k] mainly FOFIFA and ORSTOM profile data
[l] one interesting study on C-balance un different (agro)ecosystems
[m] almost exclusively on wetland rice; little information on fertilizer use efficiency
[n] largely on azolla, followed by intercropping systems and agroforestry
[o] largely quantitative soil structure research (1960s)
[p] emphasis on secondary and trace elemants (1960s)
[q] mainly *Rhizobia* inoculation and BNF, root studies, termite activity, and C and N dynamics
[r] almost exclusively trials from the 1960s
[s] lots of recent diagnostic studies
[t] almost exclusively trials from 1960s
[u] emphasis on (improved) fallows, mulching, residue management and green manures

enous technologies have also been reported (several chapters in Rey and others 1996). Losses from 10 t ha^{-1} to complete removal of topsoil are mentioned by the many researchers who dealt with this problem.

- NFIU, with support from FAO, develops *fertilizer recommendations* based on on-farm trials (NFIU 1995). Whereas the old fertilizer recommendations (ADD/NFIU 1990) covered very broad areas using soil colour as a diagnostic criterion, NFIU now improves on that by developing recommendations per region (table 3.1.8), per major soil classification order (table 3.1.9) and per soil colour type (black, brown, grey and red soil) for the 5 main cereals, tef, wheat, barley, maize and sorghum.
- As land preparation on Vertisols requires high draught power, the alternative for smallholders is to use animal-drawn equipment instead of manual labour. It was with this understanding that ILRI and collaborating institutions developed the animal-drawn BBF *for Vertisol areas* (Jutzi and others 1987, Abiye Astatke and Ferew Kelemu 1993). The ox-drawn BBF required considerably less human labour (16 h ha^{-1}) than traditional manual methods (60 h ha^{-1}).
- Although Ethiopia is diverse with many types of *farming systems*, several major constraints have been identified by diagnostic surveys in various agroecological zones. Soil-related problems are high priority across all agroecological zones (Hailu Beyene and others 1992).

Kenya

- Muchena and Kiome (1995), both former senior KSS staff, recently published a valuable *historical picture of soil research in eastern Africa*. In spite of great achievements in terms of accumulation of natural resources survey data, soil science has been poorly integrated with other life sciences.
- In the FURP, established in 1985, fertilizer trials were run throughout the high- and medium-potential areas of Kenya. Sites were chosen such that they represent wider ranges of similar environments (Smaling and Van de Weg 1990). At present, a host of data on soil and plant nutrient contents and crop response to area-specific fertilizer recommendations are available, but partly remain relatively inaccessible and non-interpreted in project archives (Smaling and others 1993, Smaling and Janssen 1993, FURP 1995).
- Ntuma and Ssali (1985) developed *P-sorption* isotherms for 7 Kenyan soils and found the range to be 380 mg P kg^{-1} for a coastal sandy soil to 5357 mg P kg^{-1} for an Andosol in the central highlands. Al-Jabri (1981) found sorption maxima for Luvisols or Ferralsols and 2 Arenosols or Cambisols of 405, 52.6, and 91.7 mg P kg^{-1}, respectively.
- Soils of FURP trials showed clear symptoms of *acidification* after 3 years of continuous application of CAN (FURP 1995, Smaling and Braun 1996). Preparations for a workshop in Trans Nzoia District in 1994 by KSS, approximately 15 years after completing a soil survey (Siderius and Njeru 1976), revealed that soil pH had gone down by approximately 0.5 unit since the time of the survey. Meanwhile, farmers in different parts of western Kenya complain that yield increments as a result of application of DAP are no longer economical. Investigations are ongoing at NARL to unravel the cause, which may well be acidification. Dogo and others (1994) found that soil pH declined significantly with increasing rates of NPKS fertilizer application by as much as 0.3 pH unit over a 4-year period.
- Famous is the work by Birch and Friend (1956) in eastern Africa. On the basis of 570 surface samples, they found very significant relationships between OM content and altitude: each 300 m increase in altitude in eastern Africa is associated with 8 mg kg^{-1} increase in OM. Moreover, OM content was closely linked to rainfall. Each 240 mm of rainfall is associated with an increase of 13 mg kg^{-1} OM.
- *Bean* research by Ssali and Keya (1983, 1986) revealed that application of P to *Phaseolus vulgaris* increased nodulation, dry matter yield, P uptake, tissue N yield, N fixation and seed yield of all cultivars at N rates of both 10 and 100 kg ha^{-1}. High N rates severely reduced nodulation where P was not applied, but severely reduced N fixation occurred at both P levels (0 and 150 kg ha^{-1}). Both papers convincingly show that P availability is of paramount importance in symbiotic BNF by beans.
- A recent, comprehensive review of *agroforestry* achievements so far and challenges ahead has been compiled by Sanchez (1995a). Research needs are grouped under 'competition', 'complexity', 'profitability' and 'sustainability'. Earlier hypotheses on the potential of agroforestry by Young (1989) are revisited. Next to erosion control and benefits of higher amounts of living biomass, deep capture of NO_3 has shown to be another potential benefit of trees.
- Mekkonen (1995) and Hartemink and others (1996) showed in western Kenya that *Sesbania* and weed fallows can explore subsoil water and substantial amounts of mineral subsoil N, as well as topsoil N that would otherwise be leached beyond the root zone of annual crops. Mekkonen (1995) found rooting depths of 120 cm (maize), 240 cm (weed fallow) and 405 cm *(Sesbania)* and substantial N uptake by both weed fallow (22 kg ha^{-1}) and *Sesbania* (10 kg ha^{-1}) from layers inaccessible to maize roots.
- Kenya is the country where *modelling* has gained some foothold as an approach to understanding and simulating processes in the rural environment and their effects. Models used include USLE, SCUAF, QUEFTS, CENTURY, WOFOST and NUTMON.

Madagascar

- Table 3.3.3 shows the *carbon balance* for 3 agroecosystems (*Pinus* forest, grassland and annual cropping). The 3 systems show large differences in C balances, that is, from –3000 kg C ha^{-1} in the annual cropland to +800 kg C ha^{-1} in the forested land. Also remarkable are the large differences in biomass production and availability, from 165 000 kg C ha^{-1} in the forest and 11 500 kg C ha^{-1} in the grassland to a mere 600 kg C ha^{-1} in the annual cropland. Primary production through photosynthesis differs from 1460 kg C ha^{-1} for the cropland to 15 000 kg C ha^{-1} for the forest system.

- Potential *erosion* in the highlands of Madagascar was estimated at 400–500 t ha^{-1} $year^{-1}$ (FOFIFA 1975), but actual erosion rates of 100–150 t ha^{-1} $year^{-1}$ under dryland cropping and 10 t ha^{-1} $year^{-1}$ under natural grasses were found. Degraded grasslands have erosion rates up to 30 t ha^{-1} $year^{-1}$, whereas 2-year-old fallow land may lose 60 t ha^{-1} $year^{-1}$. The larger gullies (lavaka) may lose 300 t ha^{-1} $year^{-1}$.
- The Terre-Tany project did a catchment-level study into the *movement of nutrients from the uplands to terraces* on the lower slopes. N losses on uplands after slash-and-burn amounted up to 56 kg N ha^{-1} (Terre-Tany 1995), whereas the terraces received a net amount of 84 kg N ha^{-1}, including manure and household waste transported from the stables and kraals on the upper slopes minus export of nutrients in crops.
- In the bottomlands, the potential benefits of *azolla* have been studied in detail. It was found that 2 kg azolla m^{-2}, corresponding with 20 t ha^{-1}, has the same fertilizing effect as 30 kg N ha^{-1} in fertilizer (Rabeson and others 1987).
- Long-term studies on soil fertility development in the uplands are few. Yet it is interesting to mention that farmers have, over the last 20 years, gradually *replaced demanding crops* such as maize and groundnuts by less-demanding ones such as cassava and beans.
- Since 1985, an IRRI-guided series of *long-term trials* has been started, both on-station and on-farm, using inputs that are within the financial reach of the farmers. The trials, centred around Mahitsy, Antsirabe and Sambaina, provided very useful results. Analytical details of the soils at these centres are given in table 3.3.11.

Uganda

- There is older work on *N mineralization and build-up*, mainly on ferrallitic soils (Griffith 1949, Griffith and Manning 1949, 1950, Griffith 1951, Mills 1953a, Calder 1957, Simpson 1960, 1961, Stephens 1962). On bare fallows following a cotton crop, NO_3 levels of 500 mg kg^{-1} were recorded. The high levels generally occurred at the beginning of the rainy season but levels reduced towards the end of the season. When soils were mulched, shaded or under grass, NO_3 levels were low (10–50 mg kg^{-1}). NO_3 leaching in bare fallows amounted to up to 400 mg kg^{-1} at 90-cm depth (Mills 1953a). Cropping of millet, maize or sunhemp *(Crotolaria juncea)* reduced soil NO_3 levels.
- Studies on *intercropping* include bananas and 16 cultivars of field bean, sown as sole crops or intercropped with bananas (Wortmann and others 1992). Intercropping reduced field bean yields from 1.11–1.25 to 0.53–0.77 t ha^{-1}. Leaf area index of the field beans was linearly related to yield in the intercrop, suggesting that a plant density higher than the 15 plants m^{-2} used for the intercrop may increase yields. Leaf nutrient concentrations indicated that low K and high Mn availability reduced intercropped field bean yields.
- At Namulonge a *3-year arable,–3-year fallow rotation* was studied. In the fallow crop studies napier grass, *Chloris gayana* and sugarcane were grown; crop rotations included maize, cotton, groundnuts, beans, maize, cotton (Jones 1968). An improvement in all soil properties measured (organic C, pH, N, P, Ca, K and Mg) was found following a rest period.
- The same study revealed that NO_3-N is *accumulated in the subsoil* in the arable phase and this would account for the loss of 480 kg ha^{-1} following an arable period. Jones (1968) suggested that since leaching during rainfall peaks can remove nutrients below the depth of arable roots, rotation with deeper rooting rest vegetation is important for the cycling of nutrients and the maintenance of soil fertility.
- Recently a good number of *diagnostic surveys* on land-use systems, natural resources management by farmers and constraints to production of crops have been carried out by Makerere University, NARO, IARCS (CIAT, ICRAF) and NGOS, for example, CARE-Uganda. These surveys have all been carried out in the southwestern

highlands or in the banana-growing areas of Uganda, coinciding with AHI target areas.

- In 1959, 18 *medium-term experiments* were established at 9 agricultural stations covering central (Buganda) and western Uganda. Details of these experiments and results up to 1965 (3 to 6 years of cropping) are presented by Stephens (1969). The largest responses were of maize and beans to N and of sweet potatoes and cotton to K on frequently cropped, strongly acid ferrallitic soils. Responses to P were smaller, and to Mg or micronutrients usually negligible.
- The failure to maintain soil fertility in simple crop rotations triggered the establishment of the *long-term soil fertility experiment* at Serere in 1935 (Martin and Biggs 1937). A 5-year rotation compared continuous cropping with rotations with rest periods, with and without farmyard manure. Five different resting covers were compared: natural regeneration, undisturbed grass, green manure, grass cut during the 1st cycle and then grazed during the 2nd and 3rd and, lastly, green manure (velvet bean, *Mucuna deringiana*) dug in.

4.3 Major knowledge gaps

In addition to the details given in the previous subsections of this section, and in particular the rankings in table 4.2.1, a number of broader knowledge gaps are given here.

- Georeferenced baseline data at the exploratory level (1:500 000 to 1:1 000 000) are many but incomplete, allowing only partial translation into values for SPIS.
- The present listing of SPIS may well be incomplete (secondary and trace elements, K-h relationship, biological activity). Given the limitations of scale and data availability, these SPIS could not have been quantified anyway. The same holds for some SPIS that were listed (leaching, gaseous losses).
- There is no holistic concept yet of integrated nutrient management (INM). In the present report, every combination of technologies is called INM, but it is never referred to as such in the information accessed.
- Very few studies address particular spatial and temporal scales. Processes have often been studied without much system context. Similarly, issues such as data quality, spatial and temporal resolution and variability, representativeness and extrapolation have hardly been taken into account.
- Most studies are reductionistic, addressing only one or a few components of a larger problem. By doing so, the outcome of research is of limited validity for the generally complex and dynamic farming systems and their exogenous environment.
- Soil profile data are difficult to access and contain many errors. A regional effort is needed to organize pedon data (data sharing, data collection and quality control).
- On phosphorus, there are real crises—on data, their interpretation, and knowledge of available P, total P, properties and effects of rock phosphates, (de)sorption of P, and the relation between available P and crop P uptake.
- The dynamics of soil acidification are still poorly understood.
- Research on erosion is largely restricted to plot-level studies of runoff and sediment transport. Very little, however, exists on catchment and river basin level.
- There is a need to increase the understanding of leaching and gaseous losses by measurement and by the validation of transfer functions. Transfer functions in nutrient balance studies have shown that the 2 processes are potentially important in the eastern African highlands. Few direct measurements have, however, been made. There is evidence for high leaching rates from measurements of subsoil nitrate accumulation under bare fallows, maize and coffee.
- Uganda would be helped considerably by a programme geared towards area-specific fertilizer recommendations as well as by a national soil survey.
- Very few research data were found on source, quantity and quality of organic inputs, and on soil organic matter.
- A specific INM technique, that is, the synchronizing of mineral and organic inputs with crop nutrient demand, looks promising and may need priority.
- There is a need to further prioritize the agroforestry research agenda as proposed by Sanchez (1995a).
- The reports on farming systems research are all merely narrative and hardly surpass the stage of storytelling and listing constraints.

There is a need to establish much better linkages with farm household economists and sociologists, to study differences between farm households that manage to maintain soil productivity very well and those that do not, and to study change and its driving forces.

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Appendix 1

Fertilizer types

$Ca(NO_3)_2$: calcium nitrate

The calcium salt of nitric acid. It is an excellent source of the nitrate form of nitrogen and of water-soluble calcium. The commercial product contains about 150 g N kg^{-1}.

CAN: calcium ammonium nitrate

A mixture of ammonium nitrate and finely pulverized limestone or dolomite, granulated together. It contains 210–260 g N kg^{-1}, half of which is in the form of NH_4-N and the other half in the form of NO_3-N.

DAP: di-ammonium phosphate

This fertilizer grade phosphate $[(NH_4)_2HPO_4]$ contains about 180 g N kg^{-1} and 200 g P kg^{-1}.

DCP: di-calcium phosphate

A product containing not less than 150 g P kg^{-1} citrate-soluble form, which is considered available to plants.

DSP: double superphosphate

A commercial product obtained by treating phosphate rock with sulphuric acid and containing about 190–215 g P kg^{-1}.

MCP: mono-calcium phosphate

A product $[Ca(PO_3)_2]$ obtained by treating phosphate rock with gaseous phosphorus pentoxide (P_2O_5) at high temperature.

$MgSO_4{*}H_2O$: magnesium sulphate

Usually the product known as kiserite. The highly hydrated form, 'Epson salts' ($MgSO_4{*}7H_2O$) is suitable for foliar application.

$(NH_4)_2SO_4$: ammonium sulphate or sulphate of ammonia

Ammonium salt of sulphuric acid containing 206 g N kg^{-1} in ammonical form.

PR: phosphate rock

A natural rock containing one or more calcium phosphate minerals of sufficient purity and quantity to permit its use directly or after concentration in the manufacture of commercial phosphorus fertilizers.

Soda phosphate

Calcinated PR added with Na_2SO_4 (Magadi soda)

SSP: single superphosphate

A commercial product obtained by treating phosphate rock with sulphuric acid and containing about 70–87 g P kg^{-1}, mainly water-soluble, along with calcium phosphate and other products of reaction.

KCl: potassium chloride (muriate of potash)

A potassium fertilizer containing 500–620 g K kg^{-1}.

K_2SO_4: sulphate of potash or potassium sulphate

A potassium fertilizer containing 400g K kg^{-1} and also supplying 170–200 g S kg^{-1}.

TSP: triple superphosphate

A commercial product obtained bt treating phosphate rock with phosphoric acid and containing about 200 g P kg^{-1}, mainly water-soluble.

Urea: $[CO(NH_2)_2]$

A synthetic, non-protein organic compound, crystalline or made into granules or pills for fertilizer use and containing 460 g N kg^{-1}.

Source: FAO (1984)

Appendix 2

List of institutions and individuals in MISP-related research and development

Ethiopia

Regional agricultural research centres

Holetta Research Centre
Institute of Agricultural Research
PO Box 2003, Addis Abeba
Tel. +251-1-511802, Fax. + 251-1-611222
Email: iar@padis.gn.apc.org
Asnakew Woldeab
Asgelil Dibabe
Taye Bekele
Balesh Tulema
Angaw Tsige
Hailu Regasa

Jima Research Centre
Institute of Agricultural Research
PO Box 192, Jimma (Melko)
Tel. +251-7-110367, Fax. +251-7-110575
Paulos Dubale
Zebene Mikru
Tesfu Kebede

Kulumsa Research Centre
Institute of Agricultural Research
PO Box 2003, Addis Abeba
Tel. + 251-2-311422, Fax. +251-1-611222
Yosuf Hassen
Duga Debelle

Mekele Research Centre
Institute of Agricultural Research
PO Box 492, Mekele
Tel. +251-4-402819, Fax. +251-1-611222
Girmay Gebru
Fisseha Hadgu

Werer Research Centre
Institute of Agricultural Research
c/o Institute of Agricultural Research, Addis Ababa
Endale Bekele
Girma Tadesse

Awasa Research Centre
PO Box 6, Awasa
Tel. + 251-6-200224
Kelsa Kena
Asefa Zeleke

Bako Research Centre
PO Box 3, Bako
Tel. +251-7-611771
Tadesse Yohannes

Sirinka Research Centre
PO Box 74, Weldia
Getachew Alemu

Sinana Research Centre
PO Box 208, Robe, Bale
Tel. +251-6-610271
Mengistu Yadesa

Sheno Research Centre
PO Box 112, Debre Berhan
Getinet Desalegn

Universities and colleges

Alemaya University of Agriculture
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