Soil Fertility Management in Africa:

A Regional Perspective

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Academy Science Publishers (ASP)
in association with the
Tropical Soil Biology and Fertility of CIAT

Academy Science Publishers (ASP)
A Division of the African Academy of Sciences (AAS)
Academy Science Publishers (ASP)
African Academy of Sciences
P.O. Box 24916 Nairobi
Tel: 884401-5
Fax: 884406
E-mail: asp@africanonline.co.ke
Website: www.aasciences.org

A catalogue of this book is available from: African Academy of Sciences

First Published by the Academy Science Publishers, March 2003

ISBN: 9966-24-063-2

Typeset in Nairobi by: Hi-Tech Typesetters, P.O. Box 51709 Nairobi

Printed and bound in Kenya by: Red Arrow Graphics, P.O. Box 42268 Nairobi 00100

The Technical Centre for Agricultural and Rural Cooperation (CTA) was established in 1983 under the Lomé Convention between the ACP (African, Caribbean and Pacific) Group of States and the European Union Union Member States. Since 2000, it has operated within the framework of the ACP-EC Cotonou Agreement.

CTA's tasks are to develop and provide services that improve access to information for agricultural and rural development, and to strengthen the capacity of ACP countries to produce, acquire, exchange and and utilise information in this area. CTA's programmes are organised around four principle themes: developing information management and partnership strategies needed for policy formulation and implementation; promoting contact and exchange of experience; providing ACP partners with information on demand; and strengthening their information and communication capacities.

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The Tropical Soil Biology and Fertility (TSBF) Institute of CIAT is a research programme whose main aim is to contribute to human welfare and environmental conservation in the tropics by developing adoptable and suitable soil management practices that integrate the biological, chemical and socio-economic processes that regulate soil fertility and optimize the use of organic and inorganic resources available to the land users. TSBF research basically targets the empowerment of farmers so as to effectively (i) manage nutrient cycles; (ii) manage below ground biodiversity and (iii) manage ecosystem services, so as to achieve the necessarry sustainable Agro-ecosystem management.

The African Network for Soil Biology and Fertility (AfNet) is the single most important implementing agency of TSBF in Africa. Its main goal is to strengthen and sustain stakeholder capacity to generate, share and apply soil fertility and biology management knowledge and skills to contribute to the welfare of farming communities. It is a mechanism to facilitate and promote collaboration in research and development among scientists in Africa for the purpose of developing innovative and practical resources management interventions for sustainable food production. AfNet has membership from National Agricultural Research and Extension Services (NARES) and universities from various disciplines mainly soil science, social science, agronomy and technology exchange.

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Preface

In Sub-Saharan Africa (SSA) the economic growth and quality of life largely depends on the agricultural sector, which accounts for more than 25% of the Gross Domestic Product (GDP). Nonetheless, the region is characterised by declining per capita cereal production estimated at 150kg/person to 130 kg/person over the past 35 years. As a result recent estimates indicate that by year 2020, the SSA annual cereals imports will rise to more than 30 million metric tons.

Soil fertility degradation has been described as the single most important constraint to food security in SSA. A large proportion of soils in SSA have low inherent fertility but the major cause of soil fertility degradation is the imbalance caused by nutrients are not commonly replaced resulting to negative nutrient balances. Despite proposals for a diversity of solutions and the investment of time and resources by a wide range of institutions it continues to prove a substantially intransigent problem.

The effects of soil fertility degradation are not confined to the impact on agricultural production. The living system of the soil also provides a range of ecosystem services that are essential to the well being of farmers and society as a whole. Degradation of the soil resource also leads to:

- Reduced capacity to maintain vegetative cover;
- Decreased water quality;
- Lowered efficiency of use of water and management;
- Increased risk from pests and diseases because of lowered biological control capacity;
- Increased risk to human health for the same reason and because of lowered water quality;
- Increases in the emission of greenhouse gases with consequent effects on climate;
- Increased prevalence of catastrophic events such as landslides and floods.

In 1988, the Tropical Soil Biology and Fertility Programme (TSBF) established the African Network for Soil Biology and Fertility (AfNet) as the single most important implementing agent of TSBF programme. The network has the overall goal of strengthening and sustaining stakeholders capacity to generate, share and apply soil fertility management knowledge to contribute and to the welfare of farm communities. AfNet is a network of resource management scientists working in Africa whose objective is to promote research collaboration to develop sustainable soil management practices through the manipulation biological processes that control soil fertility. The network is unique in that research projects are developed primarily by scientists within national academic and research institutions so that research is conducted to meet national or regional priorities as well as personal and institutional goals. The purpose of this network research is to apply the principles of soil biology with emphasis on ways to increase food production in smallholder production systems. This book is a synthesis of results from AfNet and other sources and presents the views of African scientists on the critical issue of improving the fertility and productivity of the soils of the continent. The book incorporates both thematic and agroecological reviews. In the former case the main thrust lies in an integrated approach to soil fertility management - combining biological, physical and socio-economic scientific research with farmer's needs and opportunities. In the latter, the focus is to apply the lessons from the integrated analysis to the particular problems of different agroecological zones. This book represents the first step in disseminating AfNet results, concepts and recommendations to its clients. The writing of the book as a collaborative effort of scientists from several African countries has forced a synthesis of results and a sharing and distillation of ideas among network members from many countries and institutions. The book also attempts to compile the available information from the literature and from on-going work in soil biology. The target of such a book is the first level of clients - researchers and development personnel in Africa and influential international agencies. However, the authors have also attempted to address the issues of dissemination of results to the ultimate client - the farmer.

The presentation is divided into three main sections. The first section (Chapters 1 and 2) introduces the principles of soil biology and fertility. The second section (Chapters 3 to 8) focuses on the major production systems in each of the main agroecological zones in Africa. The ecological zones and the main soil fertility constraints are defined followed by selected case studies of important production systems. Each chapter has a synthesis of strategies for integrated resource management for that agroecological zone. The final section (Chapter 9) integrates the concepts in the framework of integrated soil fertility management

We anticipate that the book will serve as a source book for university students, alongside the two previous TSBF texts (Laboratory Methods of Soil and Plant Analysis: A Working Manual, edited by J.R. Okalebo, K.W. Gathua and P.L. Woomer and The Biological Management of Tropical Soil Fertility, edited by P.L Woomer and M.J. Swift). Teachers of courses on soil biology and fertility in the region currently have only limited examples from the tropical setting. Students sometimes have difficulties relating examples from textbooks devoted almost exclusively to temperate region agriculture to production systems in tropics. The format of this book is however, aimed to serve as a source text for courses in soil biology and fertility as a reference for agricultural scientists and development workers interested in sustainable agriculture in the tropics.

We are grateful to DANIDA who provided funds to support the workshop where the initial ideas to write the book were developed as well as subsequent meetings in Nairobi of the Editorial Committee (Mwenja Gichuru, André Bationo, Mike Swift). Dr. Mary Scholes, of the Department of Botany, University of the Witwatersrand, Johannesburg, Republic of South Africa, and a long time AfNet member, organised and provided the logistical support for the workshop. We are also grateful to the Technical Centre for Agricultural and Rural Cooperation (CTA) who provided the funds for the publication of this book. We also owe a debt of gratitude to the *African Academy of Sciences* who through their *Academy Science Publishers* kindly agreed to make our dream a reality by publishing this book. Special mention is made to the efforts of Professor Samuel O. Akatch of the *Academy Science Publishers* who worked tirelessly to co-edit the book and organise its final layout. Professor G.B.A. Okelo and Professor Thomas Odhiambo of the *African Academy of Sciences* on their part spared time to give valuable advise and direction for the book. All these efforts added value to the final output of the book. Last but not least we would also like to take this opportunity to thank all those who have been involved in one way or another to make this book a reality. Particular mention goes to the various donors who have funded the TSBF African Network research over the years and especially the Rockfeller Foundation.

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Introduction

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Soil fertility depletion has been described as the major biophysical root cause of declining per-capita food availability in smallholder farms in sub-Saharan Africa (SSA), with a decline from 150 to 130 kg per person over the past 35 years in production. Emerging evidence attributes this to insufficient nutrient inputs relative to exports, primarily through harvested products, leaching, gaseous losses and soil erosion. This results in yields that are about 2-4 times lower than the potential. Adequate and better solutions to combat nutrients depletion where known, are often limited in application because of the dynamics and heterogeneity of the African agro-ecosystems in terms of biophysical and socio-economic gradients. This calls for system-specific or flexible recommendations, rather than monolithic technical solutions such as blanket fertiliser recommendation.

In essence, overtime, this has necessitated changes in research approaches and context. There is more emphasis and shift in focus to the identification of productive and sustainable alternative land management techniques for the diverse farming circumstances of SSA. The need has been recognised for integration of socio-economic and policy research besides technical research geared to understanding farmers' perspectives and constraints. Soil fertility can no longer be regarded as a simple issue squared by the use of mineral fertilizer as the mainstream research approach. Moreover, reliance on the mere combination of organic and inorganic sources of nutrients alone may have its own limitations.

Emerging evidence indicate that there is considerable consensus on guiding principles for integrated soil fertility management (ISFM) as the more pragmatic and feasible approach to overcome the limitations of past research approaches. As a holistic approach to research on soil fertility, ISFM embraces responses to the full range of driving factors and consequences, namely biological, physical, chemical, social, economic and political aspects of soil fertility decline. The approach encompasses nutrient deficiencies, inappropriate germplasm and cropping system design, pest-disease interaction with soil fertility, linkage between land degradation and poverty and global policies, incentives as well as institutional failures. Such long-term soil fertility management strategy requires an evolutionary and knowledge intensive process and participatory research and development focus rather than a purely technical focus.

Translating knowledge gain and research outputs from processes into farm practices to increase productivity may require both mechanistic (e.g. defining recommendation domains with respect of biophysical and socio- economic conditions and extrapolation potential) and humanistic approaches (e.g. utilizing farmers experiences as a guide to the dissemination of technologies). Thus, farmers' practices and needs are linked with current scientific information and technology.

Despite prescription of a diversity of solutions and the investment of time and resources by a wide range of institutions and partners, soil fertility management in SSA has continued to be a substantially intransigent problem. Research efforts and results of the African Network for Soil Biology and Fertility (AfNet) of the Tropical Soil Biology and Fertility (TSBF) Institute of CIAT (formerly TSBF Programme of UNESCO) have however shown that the challenges faced in combating soil fertility decline while daunting, are nevertheless not insurmountable. This initiative has operated through networked experiments, information and documentation and training and capacity building with about 200 scientists from National Agricultural Research and Extension System (NARES) and universities in countries in Eastern, Southern, Central and Western Africa. AfNet ensures catalysis, facilitation and collaboration among partners in ecology, soil science, economics and social sciences underpinning the biological basis of soil fertility management.

Since its establishment in 1988, AfNet has been the single most important multidisciplinary implementing agency of the TSBF Programme. The senior authors of the chapters in this book are all members of AfNet. The results of the report however draws on a much wider source of literature of many institutions and individuals to give a broader perspective to the review. Since AfNet members are often members of other networks interactions focus on bringing together different but complementary approaches to ISFM and hence complement the agronomic and genetic expertise of other organizations with AfNet's biological and ecological approaches. Over a period of a decade, AfNet research efforts have been directed towards empowering farmers and land managers to combat soil nutrient depletion and land degradation, as major threats to food production in important agro-ecological zones (semi-arid, sub-humid, and humid zones) of East, Southern, Central and West Africa. These cover intensively managed irrigated lands, intensively managed high-quality rainfed lands, densely populated medium quality rainfed intensively managed lands and hill masses; extensively managed marginal lands and urban and peri-urban agricultural lands. This book is intended to summarize and highlight research findings accrued and their merit and/or limitations in confronting decline in soil fertility and agricultural productivity.

The book takes a regional perspective in order to confront the dynamics and heterogeneity of the African environment. The region-specific case studies are preceded by expositions on global perspectives of soil fertility and ISFM in SSA. The case studies finish with outlines of research gaps. This book approach and context is expected to appeal to a wide range of audience in readership.

1

Perspectives on Soil Fertility in Africa

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Introduction

Sub-Saharan Africa (SSA) is as the area south of the isoline of 75 days length of growing period, which runs from east to west through Southern Mauritania, Central Mali, Niger, Northern Chad and Sudan. It has a total land area of 1,510,600 ha. In SSA countries, like many other developing countries, the economic growth and quality of life largely depends on the agricultural sector, which accounts for more than 25% of the Gross Domestic Product (GDP), and is a source of income and employment for the rapidly expanding population (3% per annum). Recent estimates indicate that by the year 2020, the SSA annual cereal imports will rise to more than 30 million metric tons, because the *per capita* food production continues to decline against a background of rapidly growing population, as indicated by statistics given in Table 1.1. Pegged on an index of 100 for agricultural production and *per capita* food production in the year 1979/1980, there was a significant decrease of 12% in *per capita* food production in the period of 1975-80. However, the decline was more marginal. Apparently the level of production did not match population increase. Thus while production increased by 37% in the period 1980-95, the increase in population was more than 54%. This failure to match food supply to demand in SSA is being attributed to land degradation associated with the intensification of land use for agricultural production without adoption of proper land management practices and external inputs (Henao and Baanante, 1999).

Table 1.1. Agricultural production (total and *per capita*), population and fertilizer consumption in SSA in the period 1975 - 1995.

Year	Agricultural production index (1979 - 80 = 100)	Population (million)	*Per capita* food production index (1979 - 80 = 100)	Fertilizer consumption (1000 ton)
1975	97	318	112	693
1980	100	367	100	959
1985	114	425	98	1220
1990	132	498	98	1230
1995	137	564	96	1279

Source: FAO, 1995

According to Cleaver and Schreiber (1994), the problem of food insecurity is most acute in Africa compared to other developing countries. The authors argue that the attainment of food security in Africa, through increasing *per capita* agricultural production, is closely linked with reversing agricultural stagnation, safeguarding the natural resource base, notably, vegetation, water, biodiversity and soil fertility, and reducing population growth rate.

Soil fertility management is one of the most cherished natural resource that requires to be safeguarded at all costs. According to recent studies, the three root causes of declining *per capita* food production in Africa, are those of

(i) Lack of an enabling socio-economic environment such as limited or lack of access to credit facilities, inputs and impliments, markets and extension information, poor communication and infrastructure. Lack (inadequate) supportive socio-economic environment is linked to recent changes in agriculture-related policies, with negative consequences in agricultural intensification,

(ii) Limited agricultural intensification and diversification with high value crops and tree (forestry) products (Sanchez and Leakey, 1997; Sanchez *et al.*, 1996),

(iii) Land degradation manifested in form of soil fertility depletion, especially under smallholder farming sector (Stoorvogel and Smaling, 1990; Smaling *et al.*, 1997) and nutrient imbalance on large scale farms (Nandwa and Bekunda, 1998).

Soil fertility can be defined as the capacity of a soil to support plant growth and is determined by the physical, chemical and biological properties of the soil (Ingram, 1990). Soil fertility is closely linked to productivity and is a function of individual soil variables (inherent and influenced) such as climate, management and slope. According to the

Tropical Soil Biology and Fertility (TSBF) Programme, two perspectives of soil fertility are presently recognised (Seward and Woomer, 1992; Seward and Swift, 1993). The first recognition is that the capacity to manage soil fertility is dependent on the understanding of the biological processes regulating nutrient flux, organic matter dynamics and soil structure modification. The second recognition is that effective soil fertility management can be achieved by the integration of the contributory soil processes with other factors regulating ecosystem dynamics including those of resource availability and access, and the farmers' decision making processes. Therefore, in this context, soil productivity strictly relates to the inherent or intrinsic soil quality and refers to the productive potential of the soil (Tengberg and Stocking, 1997). Soil fertility decline and hence reduced productivity is a subject of major concern and debate in Africa.

Evidence and indicators of soil fertility decline in East and Southern Africa (Nandwa, 1999; Nandwa and Bekunda, 1998) and West Africa (Bationo *et al.*, 1999; Bationo *et al.*, 1998) includes:

(i) Appearance of widespread distribution of soils deficient in major macro-nutrients and micro-nutrients (ascertained from commensurate crop responses and soil analyses and local soil quality indicators);
(ii) Widespread appearance of plant species which thrive only under low soil fertility such as striga weed and poverty grass;
(iii) Changes in soil colour and texture associated with low fertility;
(iv) Widespread negative nutrient balances.

Causes of decline include: widespread disappearance of soil fertility restoration practices such as fallowing and inadequate and inappropriate nutrient adding practices and nutrient saving practices. The challenge of overcoming soil productivity decline is exercerbated by the fact that soil fertility status is not a static phenomenon (temporal variability), and that soil fertility can be fairly complex and heterogenous from the spatial point of view. Both issues are addressed in this chapter. The overall objectives of this chapter may be summarized as follows: to discuss the complexity of the variable African Environment followed by an examination of the changes that have taken place, or continue to take place in the African Farming Systems, which have contributed to the serious nutrient depletion in Africa. In spite of enormous research on soil fertility problems in Africa, the continent is still haunted with huge food deficits attributed to low crop yields due to low soil fertility, which is said to be at stake (Smaling *et al.*, 1997). Low return to investment in soil fertility research in the past, mitigates for change or shifts in soil fertility research approaches.

Heterogeneity of the African Environment

Africa is a continent covering an area of about 30.1 Million km^2, out of which about 2.3 Million km^2 represents natural water resources (FAO, 1978). The continent is diverse in endowment of agricultural resources. Approximately 27% of its total landmass is considered as potentially suitable for agricultural production (about 874 million ha). About 33% is too dry for rainfed agriculture. Most of the humid central region is agriculturally not used due to poor infrastructure, diseases (human, livestock and plant) and variable rainfall. Its diversity is also reflected in the wide range of climate (from arid to humid), altitude (from sea level to mountain peak) and geology (from young to old geological rocks).

Agro-ecological diversity

An Agro-Ecological Zone (AEZ) has been defined as a geographical area which represents approximately homogenous soil and climate conditions capable of producing approximately the same rainfed potential yield of crops, vegetation, livestock and their by-products depending on the relative state of soil quality and variability. Different criteria have been used to define AEZ. Climate and particularly rainfall, or a derivative thereof have usually been used as the primary determinant of AEZ. Besides rainfall, several other indices have been used to stratify SSA into AEZ as shown in Table 1.2. Thornwaite (1948) used the index of total monthly precipitation (P) divided by total monthly evaporation (E); each month's P/E being added together to obtain the indices for Arid zone (16) and Semi-Arid (16-31). Martonne (1962) used the aridity index said to be equal to:

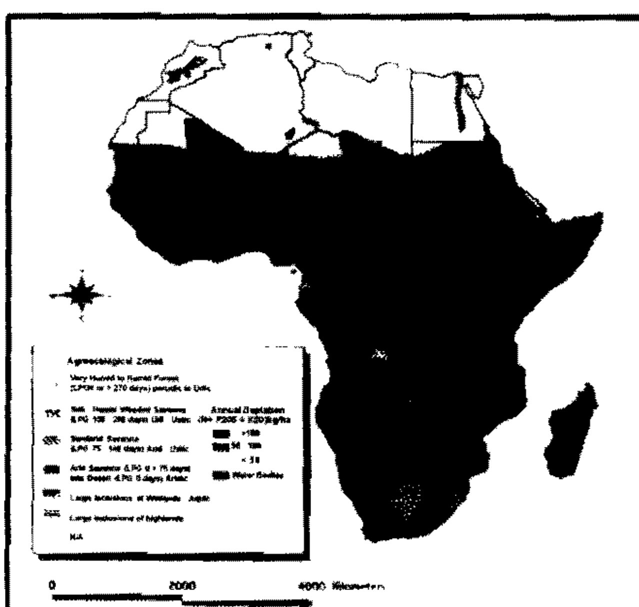
$$\frac{-np}{t+10}$$

Where
n = number of rain-days
p = mean precipitation per day (mm)
t = mean temperature for the period (°C)

Troll (1966) stratified climatic zones according to the number of humid months, defined as those months in which precipitation (P) is greater than evaporation (E). This scheme has also been used by FAO (1981) but defined in terms of months in which P is greater than 0.35E. FAO (1981) has also defined climatic zones on the basis of total rainfall and also length of days of growing period (FAO, 1978). In the latter case, length of growing period is defined as the accumulated number of days in which mean daily rainfall is greater than 50% E. Sombroek *et al.*, (1982) stratified zones, defined as ratio of average rainfall (r) over average annual potential evaporation (E_0) measured as a percentage.

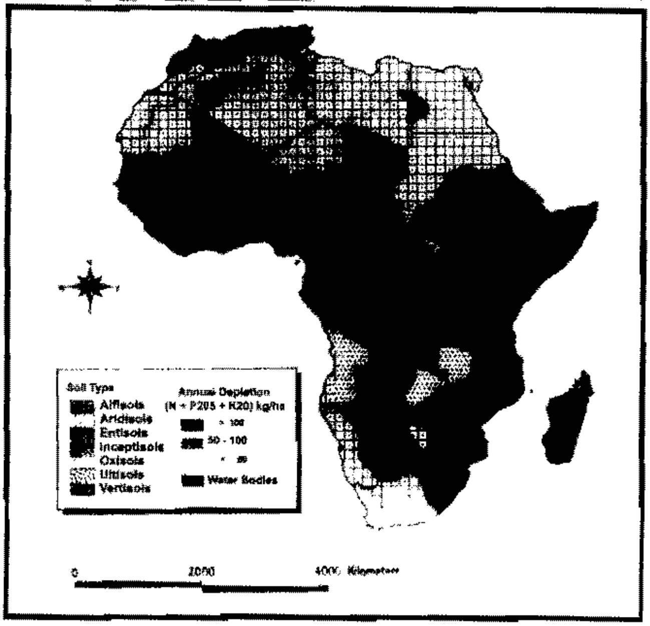
On the basis of rainfall and temperature regime, SSA can be divided into different Agro-Ecological Zones. Most classifications use the Length of Growing Period (LGP) which defines the potential moisture supply to the crop. Using this criteria, there are three major AEZs in SSA. These include the semi-arid zone (LGP 75 – 179 days, 34% of total SSA area), the sub-humid zone (LGP 180 – 269 days, 38% of the total SSA area) and the humid zone (LGP > 270 days, 28% of total SSA area), as shown in Fig. 1.1. There is a strong correlation between nutrient depletion, the AEZ (Fig. 1.1) and the dominant major soils of each AEZ as shown in Fig. 1.2 according to FAO classification system (Deckers, 1993). In the semi-arid zone, Lixisols, Arenosols and Vertisols cover 33%, 26% and 10% of the total surface area, respectively, while Ferralsols (32%), Lixisols (29%), Arenosols (10%), Acrisols (9%) and Nitisols (8%) are the most dominant soils in the sub-humid zone. In the humid zone, Ferralsols (32%), Acrisols (12%), Arenosols (9%) and Nitisols (5%) are equally important. From the crop production point of view, Ferralsols, Acrisols and Lixisols are of low chemical fertility while Arenosols are of poor physical fertility. These soils are most dominant in the humid and sub-humid zones. Because of these relationships, the logical way to assess soil fertility problems in SSA, in the light of sustainability, is to stratify SSA on the basis of AEZs (FAO, 1978 – 1981), focussed on the area of interest. While the zonation in West Africa is simplistically concentric (latitudinal) away from the coastline, zonation in the Central, East and Southern Africa is quite complex and varied within a short distance. The latter region is the main focus of this book.

Figure 1.1. Average Nutrient Depletion (NPK) in Agroecological Zones in Africa (Years 1993-95)



Source: Henao and Baanante (1999)

Figure 1.2 Average Annual Nutrient Depletion (NPK) in Soils in Africa (Years 1993-95)



Source: Henao and Baanante (1999)

Zones of focus and diversity of abiotic components or major soil units, constraints and potential land use

(a) Sub-humid Zone

The SSA sub-humid zone identified on the basis of LGP, includes three sub-regions:

- The sub-humid West Africa (LGP 180 – 269 days with 1,200–500mm rainfall and 8 humid months) consisting of parts of Nigeria, Ghana, Benin, Côte d'Ivoire and Guinea.
- The sub-humid and mountainous East Africa (LGP 180 – 269 days with 1,200–500mm rainfall, 8 humid months) consisting of Kenya, Ethiopia, Madagascar, Uganda, Eritrea, Rwanda and Burundi.
- The sub-humid and semi-arid Southern Africa (LGP 120 – 179 days with 1,200–600mm rainfall, 6 humid months) covering Tanzania, Zambia, Mozambique, Zimbabwe, Botswana, Namibia, Angola, Swaziland and Lesotho.

The characteristics of the major soil units in the sub-humid and mountainous East Africa and the sub-humid and semi-arid Southern Africa are given in Table 1.2 and 1.3. Table 1.3 also shows characteristics of major soil units in the Humid and Sub-humid West Africa. The major soils include Cambisols, Leptosols, Nitisols, Acrisols, Ferralsols and Vertisols. Of these soils, Cambisols tend to be found mainly in the mountainous steep highlands and upland areas, while Nitisols are often located in the uplands as well as lowlands, especially in Ethiopia and Kenya. The most dominant soils in the sub-humid Southern Africa are

Lixisols, Acrisols, Ferralsols, Luvisols, Planosols, Fluvisols, Histosols and Vertisols. Planosols are generally found in the sub-humid and most East African parts while Acrisols and Lixisols are found extensively in Tanzania, Zambia, Mozambique and Zimbabwe. Fluvisols and Luvisols tend to be found in river plains, depression lowlands, swampy areas and valley bottoms in the East and Southern Africa.

(b) Semi-arid zone

The semi-arid zones and arid drylands cover 4.8 and 6.1 Million km^2 of Africa, respectively (Ayensu, 1985). They are characterized by unpredictable and poorly distributed rainfall within and between seasonal rainfall variation from location to location. This is particularly true for the semi-arid areas in East and Southern Africa, whereby this feature has negative consequences on livestock and extensive crop production systems. Such effects have also much more serious implications in the semi-arid zones of Central and West Africa.

Defined on the basis of LGP, the semi-arid zones of Southern Africa have between 75 and 119 days annually for crop growth (FAO, 1978). In southern Africa, semi-arid areas stretch from the middle veld in Zimbabwe through the low veld which continues into parts of South Africa across Beitbridge and Messina in south east of Zimbabwe. Extensive parts of Botswana are in arid to semi-arid zones and are continuous to Namibia and South Africa, predominantly comprising the Kalahari and Namibian deserts.

Table 1.2. The characteristics of the major soil units in sub-humid East and Southern Africa

Sub-humid and mountain East Africa				
Major soil Units	Texture	Characteristics/ diagnoses	Major constraints	Potential land use
Cambisols	medium to fine	Cambic B horizon, slightly or moderately weathered	shallowness and stoniness	grazing and crop production
Nitisols	fine texture	Argic B horizon, high aggregates stability, good moisture holding		suitable for most crop production
Planosols	clay alluvial and alluvial deposit	Stagnating E: horizon slowly permeable subsoil layer-low structure stability	-waterlogging -low fertility -low buffering capacity	grazing and limited cropping

Table 1.2. *(Cont')*

Major soil Units	Texture	Characteristics/ diagnoses	Major Constraints	Potential land use
		Semi-arid and sub-humid Southern Africa		
Ferrasols	finer than SL.>8% clay	Ferralic B horizon CECs 16 cmol/kg	low fertility, low water holding capacity, high Fe^{2+}, Mg^{2+} and Al^{3+}	forest, crop production and agroforestry
Acrisols	finer than SL.>8% clay	Agric B horizon, CECs 24 cmol/kg, BS<than 50%	The same as above	The same as above
Lixisols	finer than SL,>8% clay	Agric B horizon CECs 24 cmol/kg	The same as above	The same as above
Luvisols	medium to fine	Agric B horizon, CECs 24 cmol/kg SB² 50%	Waterlogging	suitable wide range of crop production
Fluvisols	coarse sand to heavy clay	developed from alluvial deposits, fluvic properties	-low accessibility, water logging and acidity	wide range of crop production

Source: FAO, (1991, World Soil Resources No. 66.)

The most dominant soils include Lixisols (FAO/UNESCO, 1990) or Alfisols/Oxic Kandiudalfs (USDA, 1975); Arenosols (FAO/UNESCO, 1990) or Entisols/Psamments (USDA, 1975) and Vertisols (FAO/UNESCO, 1990). Lixisols are soils of importance in South and East Africa and in Madagascar. Although these soils have better physical fertility and storage of cations than Acrisols, they however have a clay accumulation horizon with a low capacity to store plant nutrients. Their pH is medium to high but with no occurrence of aluminium toxicity. An important area of occurrence of Arenosols is in South and Western Africa including parts of Botswana, Angola and Southwest parts of the Democratic Republic of Congo (DRC). Arenosols consist primarily of quartz with low water-holding capacity and nutrient content, a low nutrient retention capacity and deficiencies of micronutrients (zinc,

Table 1.3. Physical and chemical soil constraints to production (thousands of ha, and % of the sub-humid African zones)

		Physical constraints						Chemical constraints				
Zone	Total land area	Steep slopes	Sandy texture	Specific manage-ment problems	Low nutrient retention	Alumi-nium toxicity hazard	Phos-phorus fixation hazard	Low pota-ssium supply	Excess soluble salts	Excess sodium	Excess calcium carbonate	Sulphate acidity
Humid and sub-humid West Africa	206.6	15.3 (7.4)	57.5 (27.8)	63.0 (30.5)	111.9 (56.2)	67.1 (32.5)	38.1 (18.4)	86.3 (41.8)	3.0 (1.5)	3.9 (1.9)	0.6 (0.3)	1.8 (0.9)
Sub-humid and mountain East Africa	251.0	54.6 (21.8)	19.1 (7.6)	52.2 (20.8)	60.7 (24.2)	45.5 (18.1)	34.0 (13.6)	60.8 (24.2)	12.3 (4.9)	6.2 (2.5)	22.2 (8.8)	0.7 (0.3)
Sub-humid and semi-arid Southern Africa	559.2	49.1 (8.8)	271.4 (48.5)	51.1 (9.1)	387.8 (69.3)	169.1 (30.2)	99.2 (17.7)	171.9 (30.7)	14.4 (2.6)	7.0 (1.3)	31.8 (5.7)	0.2 (0.0)

Source: (FAO, 1986)

manganese, copper and iron) usually bonded to clay or organic matter. These soils suffer from severe leaching (nitrogen and potassium) and deficiencies of sulphur and potassium are common. They are highly prone to compaction of the subsoil and erosion of the topsoil due to their weak structure. The largest distribution of Vertisols occurs in the semi-arid and sub-humid zones especially in Ethiopia and East African shores of Lake Victoria. During the rainy season, Vertisols expand and surface flooding becomes a major problem to arable cropping (due to high content of swelling clays), while in the dry season the clay shrinks and large deep cracks develop. This implies that tillage is hampered by stickiness when wet and hardiness (stoniness) when dry. These soils have a very narrow range between moisture stress and water excess, with low permeability when moist (hence sensitive to erosion). Vertisols are generally chemically fertile (but phosphorus availability may be low). Losses of nitrogen under waterlogged conditions tend to be very high.

(c) Humid zone

The Humid zone of SSA consists of two sub-zones:

(i) The Humid Central Africa consisting of Cameroon, Central African Republic, Equatorial Guinea, Congo, Gabon and parts of DRC;

(ii) The Humid – Sub-humid West Africa consisting of parts of Nigeria, Benin, Togo, Ghana, Côte d'Ivoire, Liberia, Guinea, Sierra Leone and Guinea-Bissau.

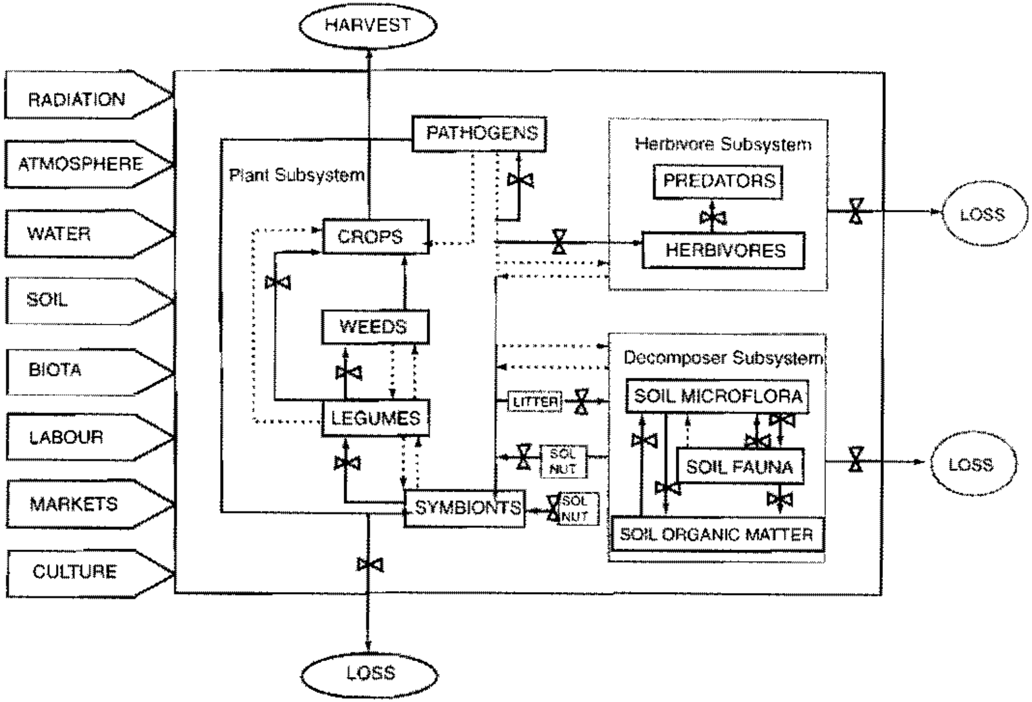
The most dominant soils are Ferralsols (FAO/UNESCO, 1990) or Oxisols (USDA, 1975) and Acrisols (FAO/UNESCO, 1990) or Ultisols (USDA, 1975). Ferralsols and Acrisols are characterized by low capacity to supply and retain nutrients (at acidic levels) which makes them prone to leaching of nitrogen. These soils also have a high capacity to fix phosphorus by free but toxic iron and aluminium oxides. Other common deficiencies include bases and molybdenum. They also suffer from the problem of moisture availability (both) and shallow rooting and high erodibility (for Acrisols). Correction of soil acidity through liming and/or organic matter management is one strategy to improve productivity of these soils.

Diversity and Complexity of Biotic Components of Agroecosystems

The diversity of SSA is in both natural and agricultural ecosystems. A major distinguishing feature between agricultural systems compared to natural systems is that of the internal regulation of the ecosystem function. Most Agroecologists agree that in a natural ecosystem, the internal regulation of function of the ecosystem is substantially a product of plant biodiversity through flows of energy, nutrients and information. On the other hand, this function is increasingly invested in the below-ground subsystems, regulated predominantly by agrochemicals, with the advent of agricultural intensification. The structure of agricultural system is perceived conveniently represented as a hierarchy, in whose products of interaction at the system function level are often not scale neutral. The biologists perceive a production unit as a convenient scale for study, characterized by the existence of fixed boundaries that facilitate ecosystem energy and/or nutrient budgeting. The boundaries are determined by social or economic factors as well as biological and/or physical factors, which may regulate or constrain ecosystem functioning. In considering the functional regulation of an agricultural system, Swift and Anderson (1993), sub-divide the biological production system into three subsystems: The plants, the herbivores and the decomposers as shown in Figure 1.3. They also do classify the biotic components of agricultural ecosystems in relation to the role they play in the productive function of the system, as well as in conventional ecosystem function term. The first class, termed the productive biotic consists of primary production or the crop plants and secondary production or the livestock; which account for the production of food, fibre or other products for consumption, use or sale, for medicinal or construction purposes. This is the component of biota that is deliberately chosen by the farmer and is the main determinant of the diversity and complexity of the system. Shifting cultivation farming system and the smallholder mixed farming system are examples in which internal ecosystem regulation is by biodiversity and agrochemicals, respectively. The second-class, termed beneficial resource biota consists of organisms which contribute positively to the productivity of the system but do not generate a product directly utilized by the farmer. This class might include plant species used as biomass transfer, improved fallows or cover crops for management of soil fertility. Some of the plant species may have both beneficial and deleterious effects such as leguminous weeds recycled back to the soil. A common dominant example of short-term fallows in the humid forest zone is *Chromolaena odorata*. Also fauna and flora of the decomposer system also fall in this class, and also predators of pests used directly as a biological control strategy or through inclusion of plants that encourage diversity in the herbivore subsystem. The third class, termed the destructive biota consists of weeds, animal pests and microbial pathogens, whose management is targeted at lowering their diversity.

The subsystem relationships discussed above indicate that ecological questions regarding ecosystem function and biodiversity in agroecosystems are pertinent to the concerns of practical agriculture. This is particularly significant in the issue of internal complexity such as nutrient cycling and efficiency of resource use. These findings are of

Figure 1.3. The functional regulation of an agricultural productive system



A generalized biological production system is represented within the *large box*. *Solid arrows* are flows of matter and/or energy; *broken arrows* represent information exchanges. The system is subdivided into three main functional sybsystems. The *boxes to the left* represent broad categories of factors influencing the function of the biological system; these factors may be categonzed as energetic and/or material and/or information of importance in soil fertility management. This mitigates for the need to change strategy to exploit biodiversity, as this leads to systems that are more sustainable, productive and more environmentally conservative. For example, recent studies indicate alley cropping and intercropping with 2 or 3 species systems yields comparative or even higher return than intensive monocrops. Similarly, judiciously managed smallholder mixed farming systems gives much more sustained yields than upland cereal-based farming system characterized by indiscriminate use of agrochemicals and mechanized operations. Therefore, coupling of activities between the plant and decomposer subsystem is a keystone process in ecosystem function in which plant biodiversity (rather than indiscriminate use of chemicals) plays an important role.

Changes in African Farming Systems

Although there is no commonly used and accepted comprehensive definition of a farming system (Simmonds, 1984), nevertheless, it is often defined as a unit consisting of a human group (usually a household) and the resources it manages (land, labour, capital) in its environment, involving the direct activities of producing plant and/or animal products (with or without contribution of off-farm activities) (Beets, 1990). The products may be in form of flows of outputs (in an ecosystem) such as food, raw material and cash. The system is always a part of a larger social, political, economic, cultural and political environment, that impacts on everything happening within the farming system. The type and complexity of a farming system is determined by both natural and socio-economic factors. Natural factors include both physical (climatic, topography, soil and physical structure) as well as biological factors (crop, livestock, weeds, pests and diseases). Among endogenous socio-economic factors determining a farming system include those of family composition, health and nutrition, education levels, food preferences, risk aversion, attitudes/goals and gender relations. Exogenous factors include; population, land tenure, off-farm opportunities, social infrastructure, credit, markets, prices, technology, input supply, extension and saving opportunities. The farming system can be pictured as series of linked sub-systems such as one or more socio-economic control units, food processing units and production units.

Farming systems in SSA are diverse and range from traditional farming systems, through a range of changing phases of true shifting cultivation to permanent and intensive arable cultivation with livestock and range production, at times with integration with wildlife enterprises. It is important to emphasize that in all areas, traditional farming system (including their pertinent soil management practices) were evolved and continue to evolve as coping strategies for the environment, and its changing biophysical and socio-economic circumstances. This in essence means that current farming systems are a mixture of aspects of traditional farming system, emergent and modern farming system or agriculture. In some areas of SSA, only one farming system can be found. For example we find shifting cultivation in large forest areas, while in other parts, several systems can be found in an intricate pattern or patchwork. The latter system may consist of a mixture of subsistence farms, for example a combination of smallholder tea/coffee farms and large-scale plantations as commonly observed in the highlands of Kenya.

Farming systems have severally been defined using different criteria. For example, Duckham and Masefield (1971) defined the farming systems of the world in terms of presence or absence of tree crops, tillage with grass, bush or forest, or systems of grassland or grazing of land consistently in indigenous or man-made pasture. The use of this criteria resulted in four farming systems: very extensive, extensive, intensive and semi-intensive. In defining farming systems at both farm enterprise level as well as regional/area level (the recommendation domain), Beets (1990) recognised seven crop-based farming systems:

(i) Shifting Cultivation,

(ii) Lowland Rice-Based System,

(iii) Upland Cereal-Based System,

(iv) Smallholder Mixed Farming,

(v) Irrigated Smallholder Farming,

(vi) Smallholder Farming with Plantation (Perennial) Crops, and

(vii) Agroforestry.

More recently, Scherr (1997b; 1999) defined farming systems in terms of seven land types and associated farming practices/systems namely: irrigated lands, high to medium quality rainfed lands practicing either high-external input (market-oriented) agriculture or high-internal input (subsistence-oriented) agriculture; densely populated, intensively managed marginal lands; extensively managed marginal lands; and urban and peri-urban agricultural lands.

A combination of the three classification criteria gives six farming systems (See Table 1.5); namely, irrigated lands; high quality rainfed lands; high-medium quality rainfed lands with poor soil fertility; densely populated marginal lands; extensively managed marginal lands and urban and peri-urban agriculture.

Table 1.5. Major pathways of change in agricultural land use and farming systems in developing countries and associated degradation problems

Land type	Farming Systems	Main Changes	On-site Soil Degradation
1. Irrigated Lands	a) Commercial enterprise type of technology e.g. drier areas of Kenya, Sudan Egypt, Chad etc. b) Traditional techniques of dryland or upland system of irrigation e.g. Upland Rice-Based Systems (wetlands with soil flooded to 5 - 10 cm through rainwater throughout the growing season) c) Phreatic upland or ground water system depends on both rain and ground water e.g. lowland rice-based systems (swamp land and lower parts of catena)	With the exception of a few countries e.g. Egypt where 40% of all arable land was under irrigation (1994) only 4% of Africa's arable land is under irrigation thus making the system to be unimportant in many of the continent's countries (World Bank, 1997). Recently there are increasing number of plans for lowland rice-based development of hitherto unused lowlands in Africa especially in West Africa (WARDA, 1990). This implies intensification and diversification of the system towards the Asia type of green revolution (e.g. use of HYVS, agrochemicals, and mechanization, etc)	a) Salinization- there is need for integration of technical solutions that work under prevailing biophysical and socio-economic conditions to counteract salinity-related problems. b) Water logging c) Nutrient constraints under multiple cropping associated with imperfect marketing infrastructure and supply of production inputs. d) Biological degradation due to blanket excessive use of agro-chemicals.

2. High-quality rainfed lands: in areas with naturally deep fertile and less weathered soils e.g. the East African Highlands, Tropical areas with vertisols and alfisols e.g. West African Savannahs.	a) Upland Cereal-based systems of the East African Rift Valley with soils of high to medium potential, whereby cereals e.g. maize, wheat, barley, Triticale are commercially and predominantly produced as cash crops (in cereal mono-cropping farms but sometimes mixed with livestock) b) Plantation Crop-Based systems found in Eastern and Western African Highlands with farms dominated with one or more cash or industrial tree or shrub crops (e.g. coffee, tea, cocoa, oil palm, rubber e.t.c.) or non-woody perennials (sugarcane and bananas)	• Transition from predominantly crop-livestock based systems to upland cereal based. • Transition from short fallow to continuous cropping with mechanization. • Evolution of present system comes naturally via shifting cultivation (e.g. coffee in Ethiopia) or via arable-cultivation fallow farming towards a sequence of arable cropping-perennial crops feeding to stationary system. • Exploitation by middlemen leads to a vicious cycle of low income, little plantation maintenance, low productivity and low income. • Less commercial-oriented farms may revert to multi-story cropping to improve productivity • Future sustenance will depend on less reliance on world market prices which require policy on the establishment of critical hectarage	a) Nutrient imbalance due to non-balanced fertilization. b) Nutrient mining due to depletion c) Increased use of low quality planting materials, fertilizers and pest control contributes to low productivity and low income

3. High-medium quality rainfed intensively managed lands in the Eastern and Southern African Highlands. These are areas which are well watered but with considerable poor soil fertility areas e.g. in Zambia	a) Small-holder mixed farming systems (e.g. in the highlands of Kenya, Uganda, Rwanda, Cameroon, Ethiopia) with complete crop-livestock integration. Tends to be largely subsistence (finger-millet, maize, potatoes, vegetables, rice, wheat, teff, fruit trees, enset and bananas) sometimes with cash crops (coffee, tea, enset, bananas, chat etc.) b) Small-holder farming with plantation crops. c) Integration of agro-forestry practices ("bush fallow", home gardens, taungya afforestation, agro-silviculture, traditional agriculture etc)	• Transition from shifting cultivation to continuous cultivation with rotation/ mixed cropping/ multistoreys which tends to make the system sound and sustainable. • Transition from traditional practices to HYVS agro-technical sophistication and fine tuning the system with crop intensification and diversification	a) Nutrient and SOC mining though depletion b) Nutrient imbalance due to non-balanced fertilization. c) Acidification d) Soil erosion e) Biological degradation with agro-chemicals f) Loss in biodiversity resulting in environmental deterioration
4. Densely populated, semi-intensively managed marginal lands e.g. hill masses of Machakos District, Kenya	Small-holder crop livestock system of the arid and semi-aridd lands in the Eastern, Southern and Western Africa. The system is common in the seasonally semi-arid tropics with high-	• Transition from long to short fallows or continuos cropping • Transition from extensive grazing and cropping only in traditional landscapes to cropping in new landscape niches e.g. valley bottoms,	a) Soil erosion b) Soil fertility depletion c) Removal of natural vegetation perennials from landscape. d) Soil compaction, physical degradation

	textured easily erodible soils and the seasonally humid parts of Eastern and Southern African and the marginal zones of the Sahel and Guinea Savanna parts; with pockets found on the deep vertisols e.g. Kenya, Zimbabwe and Nigeria. The system is based on a self sufficient semi-sedentary form of agriculture primarily founded on grain crops (millet and sorghum etc. in drier areas, maize etc in wetter areas) and cash crops such as cassava, sunflower, forage crops, cotton, groundnuts and sesame.	high fertility niche crops, inclusion of various low fertility adapted crops.	from over cultivation. e) Acidification.
5. Extensively managed marginal lands	The farming systems of the Savanna Margins and Pioneer Forests	• Immigration and land clearing for low-external input agriculture.	a) Soil erosion from land clearing. b) Soil erosion from crop/ livestock production c) Soil nutrient depletion d) Weed infestation e) Biological degradation from top soil removal.
6. Urban and peri-urban agricultural lands (intensive and semi-intensive system)	(a) Subsistence-oriented, compost-based urban agriculture (b) Urban sewage farming (c) Urban ornamental farming (d) Commercial-oriented peri-urban agriculture	• Rapid urbanization • Diversification of urban food market. • Rise in urban poverty	a) Soil erosion from poor agricultural practices. b) Soil contamination from urban pollutants. c) Overgrazing and compaction.

The growth of urban, peri-urban and rural agriculture is now recognized to be important in the alleviation of food security and poverty to meet the needs of fast growing population and urbanization. Presently, nutrient mining, pesticide pollution, water degradation and loss of biodiversity; besides spread of human disease vectors and air/water pollution; attributed to agricultural intensification/extensification, threatens the attainment of this goal. There is need for interaction between the three spatially differentiated types of agriculture with particular regard to food, nutrients and financial exchanges. Future research should aim at the enhancement in the improvement of these flows and stocks in order to increase food security and stabilize and increase the profitability of the three agricultural sectors. The next section looks at the strategies for combating nutrient and soil organic carbon depletion.

Nutrient and Soil Organic Carbon Depletion

The concept of nutrient depletion is derived from quantification of nutrient flows resulting in negative nutrient balances and/or stocks. The concept is not new, because more than 150 years ago Justus von Liebig stated "that nutrients taken away from the soil should be replenished." This culminated in the recognition of the importance of plant nutrient balance sheets in soil fertility by Cooke (1967). More recently, the attention has shifted from nutrient stocks to nutrient flows, with the main focus shifting from soil fertility *per se*, towards imbalances between nutrient inputs and outputs, and their agronomic, economic and environmental consequences. This implies that both organic matter and soil fertility must be recognized as important regulators of plant nutrients and therefore critical components of production in cropping and forestry systems (Doran and Smith, 1987). Although SOM is not a requirement for plant growth *per se*, it is however of fundamental importance in chemical, physical and biological aspects of soil fertility (Follet *et al.*, 1987). The recognition of the importance of SOM in nutrient cycling has prompted extensive studies on SOM and its transformations (Schimel *et al.*, 1985; Janssen, 1987; Parton *et al.*, 1988), which have provided evidence that SOM is not uniform but has components that turn over or decompose at different rates. Therefore, SOM like other plant nutrients, is a depletable natural resource capital (since primary production combines carbon sequestration by photosynthesis) like with nutrient balances. Soil Organic Carbon (SOC) has been widely used as an index or indicator of soil quality and sustainable land management in East and Southern Africa (Woomer *et al.*, 1994). Yet when it comes to calculating balances, little attention has been directed to SOC depletion. Results from long-term soil fertility trials indicate that losses of upto 0.69 t carbon ha^{-1} yr^{-1} in the soil surface layers is common in SSA even with high levels of organic inputs (Nandwa, 2000).

The political significance of the concept is increasingly being recognized in developed as well as developing countries. The importance of "nutrient mining" in tropical environments is gaining momentum, partly as a result of Agenda 21, the legacy of 1992 UNCED conference. Not too long ago, European member states around the North Sea agreed on implementing "balanced fertilization" in agriculture by the year 2002, despite the fact that an accepted definition of balanced fertilization was still lacking (Vagstad, 1994). Nevertheless, until recently, the concept of nutrient depletion was hardly given recognition in SSA. This is because of several reasons, namely

(i) Although nutrient balance studies are supposed to serve the reflection and desires of the information users (farmers, extension staff, researchers, policy makers etc), so far, most studies have tended to serve research purposes of quantitative understanding of nutrient pathways and cycling in agro-ecosystem (Sconnes and Toulmin, 1998),
(ii) Not much data was available to convince policy makers and economists about the extent of the problem. Thus despite the long-term recognition of the problem, the hard data has been very slow to accumulate,
(iii) The issue has been perceived differently at various spatial scales. For example, it is difficult to convince farmers and policy makers to react proactively to agro-ecosystems with negative nutrient balances (depletion class), which are continuously cultivated till organic matter contents can no longer buffer nutrient depletion, by making plant available Nitrogen and Phosporus to be more than what is required.

Nutrient stocks, flows and balances are currently and increasingly being used as powerful tools for estimating nutrient depletion/ accumulation. There are several, simple and complex approaches and methods for calculating nutrient balances, which strongly depend on the purpose of the exercise and the end-user of the results obtained. Black-box models are mostly used at higher spatial scales and have "awareness raising" as their main goal, and policy makers as the principal audience. In this approach, nutrient depletion or enrichment of the system simply follows from the difference between total nutrient inputs (mineral fertilizers, organic inputs, deposition, biological nitrogen fixation, sedimentation, subsoil nutrient exploitation) and outputs (harvested products, crop residues, leaching, gaseous losses, erosion, faeces and urine), without paying attention to processes within the box..

More complex approaches used include process models, process and compartment models; budgeted flows and compartment models; and simulation models. The compartment approach considers nutrient pools compartments, connected by nutrient pathways and transfer rates and allows calculation of output/input ratios for the whole agro-ecosystem as well as for each compartment. These dynamic, compartment models are used at plot and farm level to assist farmers and policy makers in evaluating the agronomic and environmental impact of their farm management practices, by providing the nutrient output/input ratios for each compartment of the farm.

In assessing nutrient depletion through use of nutrient balances, agro-ecosystems of spatial scale (S), at any given time (t), may be characterized by a nutrient balance, made up of a number of nutrient inputs that may exceed nutrient outputs ($\Sigma IN - \Sigma OUT >> 0_{i}$ termed surplus nutrient accumulation class); or where nutrient outputs exceed inputs ($\Sigma IN - \Sigma OUT << 0_{i}$, termed nutrient depletion class); or where $\Sigma IN - \Sigma OUT = 0_{+}$, which is termed balanced or equilibrium class.

Status of Depletion at Different Spatial and Temporal Scales

Nutrients flow at every spatial agro-ecosystem level (country, region, district, catchment area, farm, plot and soil solution), but the basic unit of study in agriculture is commonly the farm, which is fundamentally, a socio-economically defined system of production. The nutrient budget concept also includes different temporal scales, ranging from a few minutes to geological time scales. For example, long-fallow-based agro-ecosystems do not need to be balanced annually, since a negative balance in one or few years may be compensated with soil fertility restoration during subsequent years. According to Fresco and Kroonenberg (1992) in ecological and geological time-scales, equilibrium situations as to nutrient budgets hardly exist as climate change, volcanism and biodiversity development all have their more or less gradual impact on agro-ecosystems. Irrespective of the temporal scale at each spatial level, different processes and flows determine actual value of the nutrient budget. To calculate the nutrient budget of a spatial scale, one must visualize the box walls that encompass the system. Table 1.6 and Figure 1.4 indicates the six key nutrient inputs (IN 1-6), outputs (OUT 1-6) and internal flows (INT FL 1-6), and what it takes to quantitatively analyse nutrient stocks and flows at higher and at lower spatial scales, and whether to use black box or compartment approaches and models.

Table 1.6. Nutrient flows considered in Farm-NUTMON and their sources and destination

Flows into the farm		**Destination (unit – sub-unit)**
IN 1	Mineral fertilizers	ppu-soil
IN 2	Organic inputs	
IN 2a	organic feeds	ppu-ff, spu-fe
IN 2b	organic fertilizers	ppu-ff
IN 2c	input by browsing	spu-an, spu-dh
IN 2d	purchased food	hs-fs
IN 3	Atmospheric deposition	
IN 3a	dry deposition	ppu-soil
IN 3b	wet deposition	ppu-soil
IN 4	Biological nitrogen fixation	
IN4a	symbiotic fixation	ppu-crop
IN 4b	non-symbiotic fixation	ppu-crop
IN 5	Sedimentation, as a result of:	
IN 5a	irrigation	ppu-soil
IN 5b	natural flooding	ppu-soil
IN 6	Subsoil exploitation	ppu-soil
Nutrient flows out of the farm		**Source (unit – sub-unit)**
OUT 1	Farm products leaving the farm	
OUT 1a	crop product	ppu-crop
OUT 1b	animal products (meat and milk)	spu-an
OUT 2	Other organic products leaving the farm	
OUT 2a	crop residues	ppu-crop
OUT 2b	Manure	ppu-dh
OUT 3	Leaching	
OUT 3a*	soil nutrients	ppu-soil
OUT 3b	nutrients from dunghills	spu-dh
OUT 4	Gaseous losses	
OUT 4a	soil nutrients	ppu-soil
OUT 4b	nutrients from dunghills	spu-dh
OUT 4c	burning of crop residues	spu-crop
OUT 5	Runoff and erosion	ppu-soil
OUT 6	Human faeces	hs-ff

Key:
ppu - primary production unit (crops)
spu - secondary production unit (livestock)
hs - household
dh - dunghill

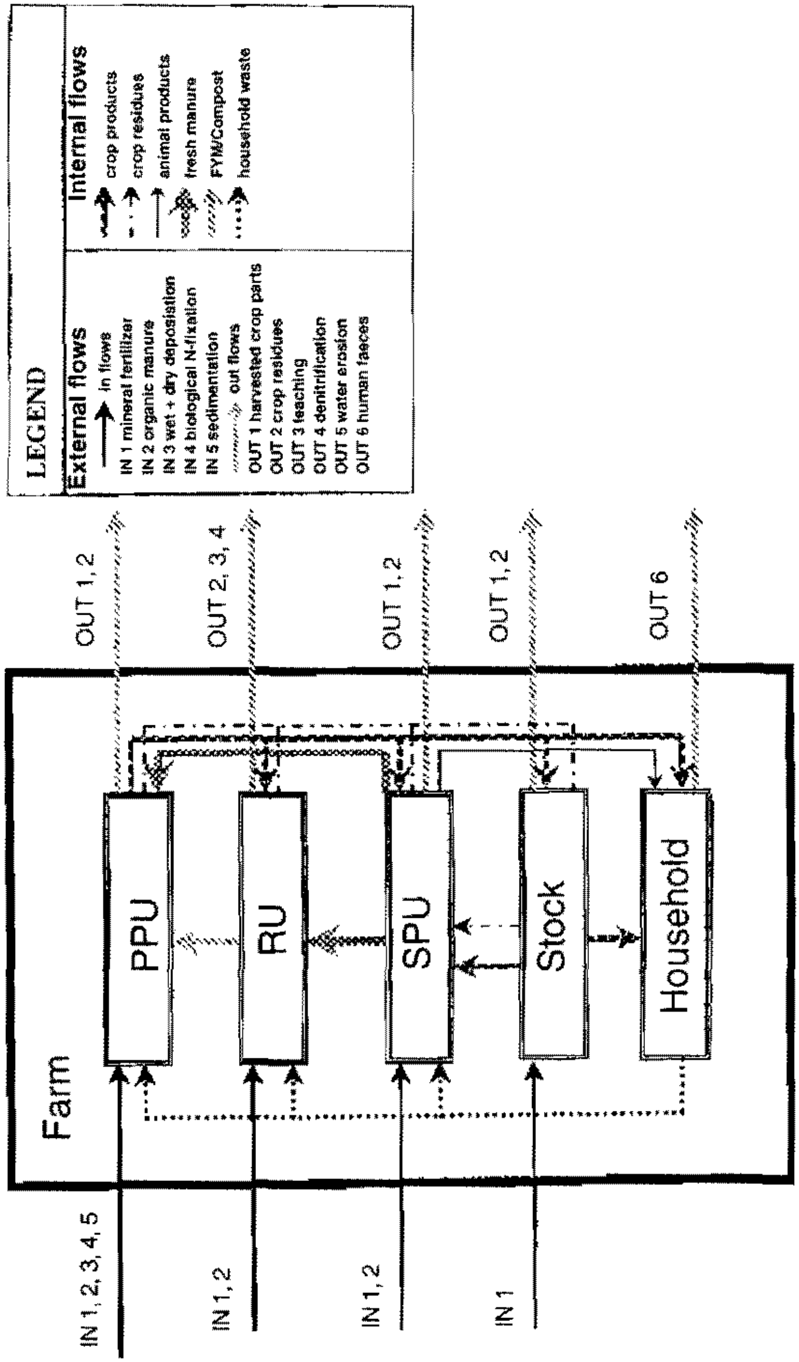
Table 1.6. Nutrient flows considered in Farm-NUTMON and their source and destination *(continued)*

Internal flows		**Source (unit – subunit)**	**Destination (unit –) subunit)**
FL 1	External feeds		
FL 1a	consumption of external feeds	ppu-ff	spu-an
		spu-fe	spu-an
FL 1b	decay of external feeds	ppu-ff	ppu-soil
		spu-fe	left-overs
FL 2	Household waste		
FL 2a	redistribution of household waste	ppu-crop	ppu-ff
		ppu-crop	spu-fe
FL 2b	consumption of household waste	ppu-ff	spu-an
		spu-fe	spu-an
FL 2c	decay of household waste	ppu-ff	ppu-soil
		spu-fe	left-overs
FL 3	crop residues		
FL 3a	redistribution of crop residues	ppu-crop	ppu-ff
		ppu-crop	spu-fe
FL 3b	consumption of crop residues	ppu-ff	spu-an
		spu-fe	spu-an
FL 3c	decay of crop residues	ppu-ff	ppu-soil
		spu-fe	left-overs
FL 4	grazing of vegetation	ppu-ff	spu-an
FL 5	animal manure		
FL 5a	excretion of manure by the animals	spu-an	spu-dh
FL 5b	redistribution of farmyard manure	spu-dh	ppu-soil
FL 6	farm products to the house keeping		
FL 6a	crop products to the food stock	ppu-crop	hs-fs
FL 6b	animal products to the food stock	spu-an	hs-fs
FL 6c	consumption of food items	hs-fs	hs-fs
		hs-ff	hs-gh

Key:

ppu	= primary production unit
soil	= subunit soil
ff	= subunit feeds and fertilizers
crop	= subunit crop
spu	= secondary production unit
an	= subunit animals
fe	= subunit feed stock
dh	= subunit dunghill
hs	= unit homestead
fs	= subunit food stock
ff	= subunit farm family
gh	= subunit garbage heap

Figure 1.4. NUTMON Farm Concept with its compartments, sub-compartments and nutrient flows into and out of the farm and internal flows



A majority of the nutrient budget studies in SSA have been conducted primarily at the Plot/Farm level (Elias *et al.*, 1998; Baijukya and De Steenh, 1998; Wooman and Kaizzi, 1998; Harris, 1998; Bosch *et al.*, 1998; Shepherd and Soule, 1998; Brouwer and Powel, 1998), with only a few studies also covering the village/community level (Defoer *et al.*, 1998; Brand and Pfund, 1998) and district/country level (Folmer *et al.*, 1998). Similarly, a majority of the above-cited studies have used full balances (IN 1-5 minus OUT 1-5) except that of Brouwer and Powel (1998), Harris (1998) and Defoer *et al.*, (1998) who reported partial balance results (IN 1-2 minus OUT 1-2). In this context the farm is conceptualized as a set of dynamic units which, depending on the management, form the source and/or destination of nutrient flows and economic flows. The external of the farm is defined in terms of nutrient pools consisting of markets, other families and neighbours, being a source and a destination at the same time which is itself not monitored. Internal to the farm are found the household (groups of persons who usually live in the same house or group of houses and who share food regularly) and stock (other amount of staple crops such as cereals and pulses, crop residues for cattle feeding, and chemical fertilizers temporarily stored for later use). Within the farm are found four units examplified by Farm Section Units (FSU) which is farm land with rather homogenous properties of soil, slope and tenure characteristics; Primary Production Units (PPU) namely, crop activities for example one or more annual or perennial crops, or pasture; a fallow or a farmyard located in one or more FSU; Secondary Production Unit (SPU) namely, livestock activities for example a group of animals within the farm that are treated by the farm household as a single group in terms of feeding, herding and confinement, usually consisting of a single species; and Redistribution Unit (RU) namely, location within the farm where nutrients gather and from which they are redistributed for example, manure heaps and compost pits.

(a) Higher Spatial Scales: From Continent to District to Land Use System

The nutrient balance study for 38 SSA countries (Stoorvogel and Smaling, 1990; Stoorvogel *et al.*, 1993) involved the partitioning of the continent into rainfed cultivated, irrigated and fallow land, for which FAO provided hectarages and yields. Rainfed land was further divided on the basis of the length of growing period, and the FAO Soil Map of Africa, at a scale of 1:5000 000. The basic spatial unit was the land use system, for which 5 nutrient inputs (IN1-5) and 5 nutrient outputs (OUT 1-5) were calculated. For this task, country statistics, maps, reports and literature were scrutinised.

The amount of data available to calculate IN 1-5 and OUT 1-5 varied largely between and within countries. As a consequence, much available detail had to be dropped and discrete ratings had to be developed for variables that normally represent a continuum. Soil fertility classes, for example, were merely rated low (1), moderate (2), high (3), on the basis of soil classification (sub) orders. Mollisols, for example, were ranked 3, whereas Psamments were ranked 1. Also, average values were used for properties that showed wide ranges, such as crop nutrient contents. Other methodological setbacks at this spatial scale are discussed in detail by Stoorvogel and Smaling (1997).

Results obtained (Table 1.7) can be portrayed per land use system, per agro-ecological zone, per country and also per nutrient for the entire continent. The average N, P and K balances for SSA were -22, -2.5 and -15 kg ha^{-1} yr^{-1}, respectively. It is particularly nutrients exported in harvested products (OUT 1) and in runoff and eroding sediments (OUT 5) which are high and which cause the balance to be negative. The implication of the N value, for example, is that on the average, soils in SSA have to supply 22 kg N ha^{-1} each year to balance the ledger, leading to a decline of the N stocks. Table 1.7 shows that the mountainous and densely populated countries in East and Southern Africa (Malawi, Rwanda, Kenya and Ethiopia), have higher nutrient depletion rates than those of the drier countries (Mali, Benin and Botswana). This is caused by the high values of nutrients in harvested products and erosion, and also by the higher inherent fertility of the soils in East and Southern Africa. In Sahelian soils, there are relatively little nutrients left to be lost.

Table 1.7. Average of 1982–1984 nutrient balances of N, P and K (kg ha^{-1} yr^{-1}) for the arable land for some sub-Saharan African countries

Country	N	P	K
Botswana	0	1	0
Mali	-8	-1	-7
Senegal	-12	-2	-10
Benin	-14	-1	-9
Cameroon	-20	-2	-12
Tanzania	-27	-4	-18
Zimbabwe	-31	-2	-22
Nigeria	-34	-4	-24
Ethiopia	-41	-6	-26
Kenya	-42	-3	-29
Rwanda	-54	-9	-47
Malawi	-68	-10	-44

Source: (Stoorvogel *et al.*, 1993).

The study identified three nutrient depletion classes, calculated for countries shown in Table 1.8.

(i) Moderate/Low rate – less than negative 30 kg NPK ha^{-1} yr^{-1}

(ii) Medium – between negative 30 and 60 kg NPK ha^{-1} yr^{-1}

(iii) High – greater than negative 60 kg NPK ha^{-1} yr^{-1}

The highest nutrient depletions in Eastern Africa (Ethiopia, Kenya, Rwanda and Malawi) were primarily attributed to high outputs of nutrients in harvested products in the relatively high inherent fertility of the soils (AHI, 1997). Least nutrient depletion in the Sahelian Belt and Central Africa was attributed to low inherent fertility of the soils, low rainfall and low nutrient exports.

Table 1.8. Countries grouped by average level of NPK balances (kg NPK/ha/year) in 1993-95

High Worse than –60kg	Medium Between –30 and –60 kg	Moderate/Low Better than –30kg
Burkina Faso	Benin	Angola
Burundi	Cape Verde	Botswana
Cameroon	Central Republic of Africa	North African Countries
Côte d'voire	Chad	South Africa
Democratic Republic of Congo	Congo	Zambia
Ethiopia	Equatorial Guinea	
Gambia	Gabon	
Ghana	Lesotho	
Guinea	Mauritania	
Guinea-Bissau	Niger	
Kenya	Sierra Leone	
Liberia	Sudan	
Madagascar	Togo	
Malawi	Zimbabwe	
Mali		
Mozambique		
Nigeria		
Rwanda		
Senegal		
Somalia		
Swaziland		
Tanzania		
Uganda		

In country studies, the focus is often on districts or regions which constitute the country. For monitoring purposes, the largest spatial scale in a district may be the Land Use Systems (LUS). The sub-continental scale-inherent limitations (data paucity) triggered studies in the south-western Kenya district of Kisii consisting of two temperature zones, 16.2°C - 18°C (with three land use types) and 18.0°C - 20.5°C (with four LUTS) (Smaling *et al.*, 1993). The aggregated nutrient balance of the seven LUTS for the Kisii District were –112 kg N, - 3 kg P and –70 kg K ha^{-1} yr^{-1}. The study shows that pyrethrum LUT III had one of the lowest K depletion and the strongest N depletion being accounted for by harvested products and erosion (Table 1.9). Another subsequent nutrient balance study was carried out for 26 farms in three different districts in Kenya, namely, Kisii, Kakamega and Embu (Bosch *et al.*, 1998). The farm nutrient balances for Kisii District were close to those of the earlier study (-102 kg N, -2 kg P and -34kg K ha^{-1} yr^{-1}). In Kakamega and Embu Districts potassium (+18) and phosphorous (+9) were found to accumulate, respectively. The nutrient balance for Kakamega was –72 kg N, -4 kg P and +18 kg K ha^{-1} yr^{-1} while that for Embu was –55 kg N,+9 kg P and –15 kg K ha^{-1} yr^{-1}. The mean balance of the 26 farms was –71 kg N, +3 kg P and –9 kg K ha^{-1} yr^{-1} with little variations between districts but large variations between farms.

Land Use Type (LUT) balances are obtained from aggregated balances of major farm types in such LUT. In the assessment of soil fertility depletion in Mozambique, determined by combining land units (soil fertility, precipitation and erosion) and land use types (crops, scale and occupation percentage of the land) into land use types, nutrient depletion was calculated for cultivated fields, nutrient depletion was averaged over land use systems (cultivated and non-cultivated land) and nutrient balances compared with nutrient resources to assess buffering capacity. While maize/cassava plots had the highest nutrient depletion at field level, on the other hand cultivated fields with more than 1000 mm precipitation per annum and annual erosion of 25 t ha^{-1} had the highest nutrient depletion at land use system level.

The country balance was: -32.9 N, -6.4 P and -25.0 kg K ha^{-1} yr^{-1} compared to
Irrigated farms balance which was: -34.4 N, -4.1 P and 20.0 kg K ha^{-1} yr^{-1} and
Large scale rainfall balance which was -49.9 N, -8.6 P and -37.2 kg K ha^{-1} yr^{-1} and
Small scale rainfall balance which was -32.6 N, -6.4 P and -24.9 kg K ha^{-1} yr^{-1}

In the district studies in Kisii, six LUT were identified (Table 1.9). As one moves from tea/dairy LUT towards coffee/banana LUT both N and K depletion become accelerated, while more P accumulates. The agro-ecological zone related nutrient balances showed no consistent correlation with return to land and net farm income.

Table 1.9. Nutrient balances and economic performance of six LUT farms in Kisii district

No.	Land Use Type	Nutrient balance			Net farm Income Ksh	Return to Land (Ksh/ha)
		N	P	K		
I	Tea/Dairy	-49	4	14	74,841	-11,922
II	Tea/Pasture/Dairy	-67	5	-2	205,948	16,242
III	Pyrethrum	-88	2	10	17,168	-72,918
IV	Tea/Coffee/Pyrethrum	-82	7	-31	28,021	-8,469
V	Coffee/Banana	-94	21	-21	59,543	6,801
VI	Coffee/Extensive grazing	-46	11	-6	57,341	3,500
		60 Ksh = 1 US Dollar (1998 rate)				

Source Van den Bosch *et al.*, 1998; de Jager *et al.*, 1998

(b) Lower Spatial Scales: From Farm to Plot to Niches

Farm and subsequent farm typology balances are obtained from aggregated balances of farm plots. In studies carried out in the three districts in Kenya (Kakamega, Kisii and Embu), a strong correlation between nutrient balances and production goal notably market orientation (Table 1.10) and crop activities (Table 1.11) was obtained, such that the higher the market orientation the higher the nutrient depletion of the farm typologies and farm plots (Table 1.10) (de Jager *et al.*, 1998). However, correlation between nutrient balance and net farm income was observed between less than 33% farms and 33-66% farms, but net farm income declined with more than 66% farms. At activity level, the Kisii District pyrethrum LUT shows a strong negative correlation between market orientation and N balance as shown in Table 1.9.

Table 1.10. Relationship between nutrient balances and market orientation of different farms

Nutrients	Market orientation		
	< 33% farms	33 - 66% farms	> 66% farms
N (Kg ha^{-1} yr^{-1})	-26	-89	-106
P	-2	5	6
K	32	-12	-68
Net farm income (US$ $farm^{-1}$)	1380	1620	1455

Source: de Jager *et al*; 1998

Plot level nutrient balances are shown in Table 1.11. Depletion of N, P and K was accelerated on moving from coffee, tea, maize/beans to napier. High return to milk of $645 (derived from napier feed) compared to maize ($85) and maize and beans ($205) did not guarantee adequate replenishment of N, P and K. This also applies to coffee and tea which gave the highest returns.

Table 1.11. Relationship between nutrient balances (Kg ha^{-1}) and plots of crop types (index of market orientation)

	Farm activity plots					
Nutrients	Coffee	Tea	Maize	Maize-Beans	Pyrethrum	Napier grass
N	-36	-46	-68	-74	-88	-154
P	6	17	-1	-2	+2	-10
K	-4	-26	-44	-37	+10	-153
Return (US$ ha-1)	1355	620	85	205	-12,153	645

Source: de Jager *et al.* 1998

Soil fertility at lower scales for example, of individual niches and plots in farms and village settings can also differ considerably. Reasons range from differences in soil texture, land use/fallow history to microclimatic differences. Smallholder farmers exploit microvariability, as for each weather condition, there are always pieces of land where crops perform well (Brouwer, 1993). Hence, farm and field heterogeneity is often regarded as an asset by those who are after adequate subsistence levels rather than bumper harvest. A striking example of farm-level variation is in the ring management systems in semi-arid West Africa, where inner circles near the farms and village are much more intensively used and managed (Table 1.5), and the 'homestead fields' represent the plots just around the homestead, and receive substantial amounts of nutrients from animal manure and household wastes. As a consequence, soil productivity in this part of the farm remains at a relatively high level. One way of solving the use of microscale data is to extrapolate to macroscale may be through use of appropriate data upscaling tools such as GIS and modelling.

(c) Implication of Nutrient Depletion Results on Agroecosystem Productivity and Sustainability

The foregoing studies indicate that high SSA population growth rates and subsequent intensification of agriculture without proper land management and addition of nutrients is the primary cause of its high nutrient depletion, thereby predisposing soil fertility at stake (Smaling *et al.*, 1997). This is exacerbated by the widespread soils with inherent low mineral stocks and the climatic conditions characteristic of the vast interior plains and plateaus which aggravate the consequences of nutrient depletion, which is not matched by gains through mineral fertilization, deposition and nitrogen fixation. Moreover, most phosphorus is depleted through erosion, which also depletes nitrogen, besides leaching (together with potassium). All these contribute to reduction in agricultural productivity, as a result of declining soil fertility. Strategies are required that help bring back the depleted soils to their original sustainable agriculture production potential.

Soil Fertility Management Strategies, Approaches and Options to Combat Nutrient and Soil Organic Carbon Depletion

The fundamental biophysical cause for declining *per capita* food production in SSA (17% in 1980 – 1995) is soil fertility depletion in smallholder farms. During the last 30 years, this depletion has been estimated at an average of 660 kg N ha^{-1}, 75 kg P ha^{-1} and 450 kg K ha^{-1} from about 200 million ha of cultivated land in 37 African countries (Sanchez *et al.*, 1997). To produce enough food for a growing population, requires an increase from 1 billion tonnes per year at present to 2.5 billion tonnes by 2030 (Walker *et al.*, 1999). These authors believe that in SSA such increases are possible with judicious implementation of agricultural intensification to contribute 53% of the increase, with other increases coming from extensification (30%) and diversification and cash cropping (17%).

(a) Intensification

The strategy entails increasing agricultural production primarily through increased yield per unit area of land and/or of individual crops, through two approaches

(i) Increased use of production inputs, notably plant nutrients, and
(ii) Improving nutrient use efficiency.

(i) Options for increasing farm inputs

Mineral fertilizer (IN1) use in SSA is variable for example from 234 kg NPK ha^{-1} yr^{-1} in Egypt to 99 kg in Swaziland, 46 kg in Kenya but is less than 10 kg ha^{-1} yr^{-1} for most countries in SSA (Henao and Baanante, 1999). Even where fertilizers are used, they are mostly applied to cash crops and plantation crops (coffee, tea, cocoa, cotton, tobacco, sugarcane and oil palm), because of the high profitability. For most food crops, unfavourable crop/fertilizer price ratios and financial constraints are the two key factors responsible for current low level of fertilizer use in many countries in SSA. Therefore, most food crops are continuously grown with little or no replenishment of nutrients removed through crop harvests or other losses, thus resulting in the depletion of natural capital stocks below critical levels. To maintain current average levels of crop production without soil nutrient depletion, Africa will require to use approximately 11.68 million metric tonnes of NPK in fertilizers annually. A number of strategies and options are being recommended and their implementation explored, on how to meet such targets.

Soils with below critical nutrient levels, require *"Recapitalization fertilization."* (IN 1b) an application that views depletion as a loss of national resource capital (Buresh *et al.*, 1997). Such soil replenishment seeks to recapitalize soils after several years or decades of losses as a means of restoring agricultural productivity and prosperity of smallholder farming communities faced with the problem of nutrient-depleted soils. This is an approach of "jump-starting" rehabilitation of their degraded soils. This approach has attracted attention of the donors who argue that those who benefit should share the costs in equitable manner (World Bank, 1996). It suffices to say that SSA is operating under rules such as credit, subsidy and infrastructure which do not apply in North America and Europe. This disparity could affect the desired impact of the approach, unless accommondative caveats or exceptions are integrated into the approach.

(ii) Replacement fertilization

This approach regards mineral fertilizer inputs as the sole external input hence is intended for routine application at recommended rates which may be blanket (uniform) fertilizer recommendation because the limiting nutrients have not been adequately diagnosed and delineated (lack of soil tests or representative field trials). When these limitations are overcome, then specific climate, soil and crop fertilizer recommendations are adopted to combat nutrient depletion. The latter, "replacement fertilization recommendations" are well developed in SSA. Usually, zone-specific fertilizer recommendations have to be replaced with *"balanced fertilization"* as nutrients not limiting production initially, emerge in form of deficiencies. Besides "Replacement" and "Recapitalization" and "Balanced" fertilization, there is further need for *"Complementary Soil Fertility Management Practices"* that help farmers to increase production inputs in their cropping systems so as to ameliorate nutrient depletion. This is particularly important when considering the sources of nitrogen and phosphorus (and potassium to some extent). Most phosphorus replenishment strategies tend to be mainly mineral fertilizer-based with biological supplementation. This is in contrast to nitrogen replenishment strategies which are mainly biologically-based (manures, residues and leaf litter, agro-industrial by products and wastes, biomass transfer and improved fallows) with mineral fertilizer supplementation. Complementary approaches are required to overcome the problem of prohibitive high cost of imported fertilizers, (especially non-nitrogeneous types) and consequences on subsequent draining of scarce foreign exchange, against a background of currency devaluation in SSA. One such approach underpins the need to strengthen research on use of regionally and locally available inorganic sources of plant nutrients and amendments. These include rock phosphate, since there is ample phosphate rock deposits in the region (McClellan and Notholt, 1986) that can be used directly or processed as superphosphates to reverse P depletion (Woomer and Muchena, 1996; Okalebo and Nandwa, 1997; Kathuli and Nguluu, 1996). Other locally available resources include limestones (Grant, 1981), gypsum (Weil and Mughogho, 1993), sulphur and magmax, besides use of ashes, termitaria soil and the strategy of subsoil nutrient exploitation by help of deep-rooted plants.

Options for nitrogen replenishment in SSA are receiving a lot of attention and include use of leguminous tree fallows, improved fallows, agroforestry trees and herbaceous leguminous cover crops grown *in situ* (Mureithi, 1999; Gachene *et al.*, 1999). Other options include green manure which plays a major role in both N capture and internal nutrient cycling in ways that are compatible with most farmers constraints. An example of such complementary approach is on-going work in Western Kenya, in South Western Uganda and Eastern Zambia (Rao *et al.*, 1998). In Western Kenya options used include integrated use of inorganic P (rock phosphate or triple super phosphate) and organic nutrient sources either through short duration fallows of *Crotalaria* or *Tephrosia* or biomass transfer from *Tithonia* green manure. In South-Western Uganda, the options include stabilization of terrace risers with napier grass/ *Calliandra* contour hedge rows, integrated with use of inorganic P and organic matter on terraces and tree fallows with shrub or cover crops on terraces. This compares favourably with the use of a 2-years *Sesbania* fallows with mixed intercropping with *Gliricidia* and relay planted *Sesbania* in Malawi; or 1-2 years *Sesbania* and *Tephrosia* fallows in Tanzania; or use of a 2-years tree fallows and 1-year *Calliandra* or pigeon pea shrub fallows in Cameroon.

These results demonstrate how agricultural research and extension can have an impact in combating nutrient depletion and increasing agricultural production by adapting promising solutions to actual conditions faced by different countries and smallholders of different cultural and resource endowments (Waddington and Snapp, 1999). In Malawi, low resource endowed farmers tend to have access to small, infertile fields, characterized by predominance of sandy soils with low nitrate levels and limited growth of *Sesbania*, which implies reduced benefits from organic matter technologies systems (Kanyama-Phiri *et al.*, 1998). Such farmers may be candidates for more intensive use of grain legume intercrops and rotations, as benefits from the grain are essential for such food-insecure households; and will complement soil fertility restoration as a means of combating nutrient depletion.

(iii) Options for increasing nutrient use efficiency

Although increasing production inputs may be the centre piece approach for successful agricultural intensification while combating nutrient depletion, however, environmental and socio-economic circumstances dictate the need for enhanced nutrient use efficiency. Several options are available and offer promise for combating nutrient depletion while at the same time enhancing returns to inputs. One such embracing approach is that of Integrated Nutrient Management (INM), loosely defined as combined use of organic and inorganic sources of plant nutrients (Janssen, 1993). Many studies conducted in SSA under the framework of the Tropical Soil Biology and Fertility Programme's (TSBF) Synchrony theme have demonstrated high nutrient recoveries when organics are combined with inorganics (TSBF 1985, 1987). In the first Nutrient Use Efficiency (NUE) hypothesis, states that in the long-term, the system nutrient retention remains highest when the nutrients are applied in the least available forms such as low available nutrient index (ANI) materials which have a high Organic Stability Index (OSI) (Parr *et al.*, 1986). The second N trap hypothesis states that in environments where significant leaching or denitrification occurs, plant uptake of nitrogen can be increased by simultaneous application of a low N organic material which temporarily immobilizes N early in the crop cycle, allowing it to remineralize when the crop is ready for uptake. Split application of nitrogen fertilization underpins the philosopy behind this hypothesis. The third, organic optimization hypothesis states that, in the short-term (current crop) the maximum yield achievable by the use of mineral fertilizer inputs can be approached or exceeded by optimizing the time of application, placement, quantity and quality of organic nutrient sources. The fourth hypothesis, the P trap states that immobilization of P by microbe following addition of low quality organic material, can prevent P-fixation, thereby improving medium term availability of P. This is an effective strategy for fertility management in soils with low organic matter and high Fe, but prone to P-fixation. Many experiments whose results are reported in this book, have tried to confirm or repudiate the validity of these hypotheses.

Integrated nutrient management is recently perceived much more broadly as the judicious manipulation of all nutrient inputs (IN 1-6) and all nutrient outputs (OUT 1-6) and internal flows (INTFL 1-6) (Table 1.5) (Smaling *et al.*, 1996). This approach provides windows of opportunities for combining practices in High Yielding Variety Technologies (HYVTS) and Low Yielding Variety Technologies (LYVTS), also called Low-External Input Agriculture (LEIA). This definition and approach of INM recognizes the fact that nutrients enter and leave managed ecosystems in different capacities and hence the need for better understanding of the nutrient balances. In continental nutrient balance studies reported elsewhere in this section by Stoorvogel and Smaling (1990), the highest nutrient depletion rates calculated for the sub-humid and mountainous East African Region were mostly attributed to erosion (OUT 5) and harvestable products (OUT 1). This suggests that for efficient return to increased agricultural production inputs will have first to depend on the extent to which farmers minimize or eliminate non-useful outflows like OUT2 (residue burning), OUT 3 (leaching), OUT 4 (gaseous losses, for example, undesirable volatilization and denitrification escape of nutrients), OUT5 (erosion) and OUT 6 (human waste and sludge). In recognition of this strategy and approach of combating nutrient depletion, FAO and World Bank have jointly launched the Soil Fertility Initiative in SSA aimed at recapitalizing Africa's soils through INM approaches (Smaling *et al.*, 1999).

In most soil fertility replenishment initiatives, promotion of high nutrient use efficiency is achieved through many cropping options. For example agroforestry intercrops and crop rotation systems are adopted to help not only increase nutrient pools but also help to reduce loss of SOM, sediments and run-off. Tillage practices are also adopted which help reduce erosion and hence water infiltration, while use of soil amendments such as liming, manuring of acid soils has been found to correct acidity, especially in the Ultisols and Oxisols from sub-humid and humid areas and thereby increase nutrient use efficiency.

Another option entails refraining from application of higher doses of fertilizers to less responsive indigenous crop varieties or cropping systems (liable to be leached or volatilized). The key to successful implementation of these options, requires that the approaches rely primarily on locally-available resources and to improve upon them with fertilizers such as fortification of composts with rock phosphate or lime; improve manure quality with livestock mineral supplement and use of improved legume seed inoculant among others. In conclusion, it can be said that INM practices that optimize nutrient inputs while concurrently minimizing nutrient losses are most likely to contribute towards increased efficiency of the applied nutrient material, manifested in high crop response.

(b) Extensification

Extensification system of expanding cultivated land in total or in sequence is common where land and labour are available, and low yields are being experienced in presently cultivated fields (often attributed to nutrient depletion plus or minus high "pest" status). These circumstances usually force farmers to expand cultivated land, often at the expense of forested areas or marginal soils subject to erosion or desertification. In SSA, there is some uncertainty in the scope to contribute the projected 30% increase in food production (1998-2010) through extensification. It must be emphasized that such scope for area expansion in new areas (semi-humid and semi-arid) is limited because these are the areas with low inherent soil fertility, hence requiring very long fallow periods (sometimes upto 20 years). The potential success of this strategy lies primarily on two options: that is focus on newly opened lands that ensures establishment of balanced nutrient systems put in place, and reclamation of wastelands through biological management of the system that ensure recapitalization. Slash and burn extensification where land expansion is plausible still offers hope. Among the deleterious effects of agricultural extensification through slash-and-burn include disadvantages of above-ground biomass volatilization losses of nitrogen, sulphur, phosphorous and potassium, often estimated to amount to 96%, 76%, 47% and 48%, respectively. These deleterious effects can however be overcome through replacement of the natural fallow with short duration cover crops (Luna-Orea and Wagger, 1996) or with alley cropping (Wade and Sanchez, 1983; Palm, 1988) or mulching or incorporation of slashed vegetation (Braakhekke *et al.*, 1993). However the reduction of the systems productivity following shorter fallowing in traditional slash and burn such as rice yields reduced by 47% and 80% after 4 and 10 years fallowing, respectively, makes such innovation unacceptable to the farmers (Kato *et al.*, 1999). But this constraint may be overcome when judicious fertilizer use is part of the intensification approach. Kato *et al.* (1999) reports that application of fertilizer was able to raise yields of rice from around 0.7 t ha^{-1} to over 2 t ha^{-1} and that of cowpea from less than 0.2 t ha^{-1} to around 1.5 t ha^{-1}, in spite of the reduced fallowing. These results thus show that the risk of soil degradation (declined productivity) due to intensified cropping by shortened fallow or prolonged cropping periods is considered low, so long as adequate plant material and nutrients are supplied to the soil by fire-free land preparation and fertilization. It has been recently reported that the extensification systems that maintain sustainable productivity of crops and forest products are those in which the length of the arable phase is adjusted to fit nutrient stock replenishment (Nandwa and Bekunda, 1998).

(c) Diversification and Cash Cropping

The third most important method of increasing agricultural production is by intensifying the production system by increasing the number of crops (including cash crops) or cropping cycles sown on a particular area of land. In cases where economic activities allow, farmers may devote their land to cash crops, and use income from them for purchasing food from elsewhere and also to invest in measures for combating nutrient depletion. Sustainable production of food fibre and fuel for rapidly increasing population in developing countries to some extent imply changes in types of crops grown to satisfy food as well as cash earnings. In Kenya success has been achieved in the Western Kenya Soil Fertility Replenishment Project whereby farmers after successful intensification, start to partially substitute land devoted to the staple crops with high value crops (Niang *et al.*, 1999).

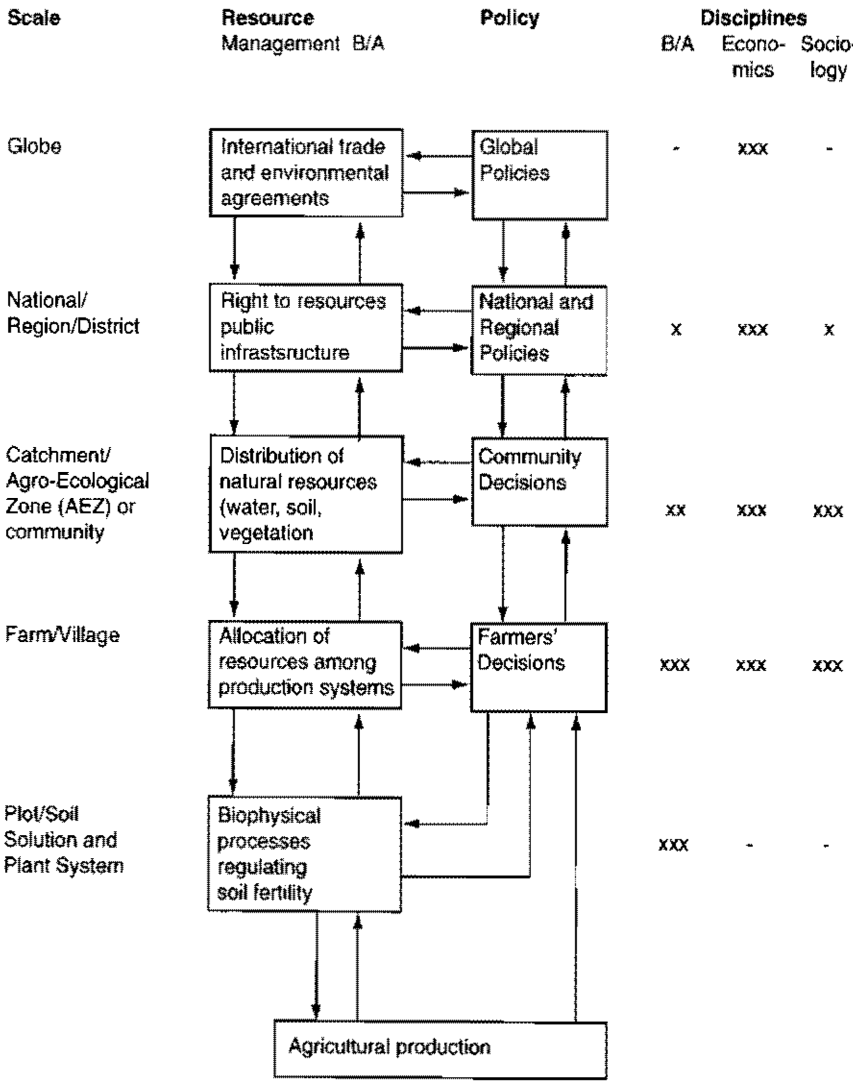
Increasing number of cropping cycles (another option) if done successfully, should optimise use of non-renewable inputs and technologies such as shifting from single annual cropping to double or triple cropping, whereby the agro-economic benefits of the latter outweigh the former. This option may be exploited through increased number of crops for example in kitchen garden or double-dug beds (Hamilton, 1997); or through a shift from pure-stand or mono-cropping to crop mixtures (intercrops and relays) (FURP, 1987, 1994). This may also be achieved through introduction of crop varieties that are tolerant or resistant to abiotic and/or biotic factors limiting production of commonly grown crops. This calls for land evaluation to establish its suitability for growing of different types of crops (Da Costa, 1999). One of the factors driving a system to a high level of diversification is the goal to attain complete self-sufficiency at farm level by growing staple crop such as maize, banana, cassava, potatoes, sorghum or millet, a protein (leguminous crop), an oil crop (sesame, coconuts, sunflower and soya-beans), a fibre for clothing (cotton) and various minor products (herbs, medicines and dyes). In most cases, most farming systems become less diversified as traditional crop and soil fertility management practices are lost and families get less diversity in farm products and diets. Commercialization is often the reason for loss in farmers' skills and for present-day systems becoming less diversified. This may be in form of sale of surplus production of subsistence crops or through cultivation of specialized cash and/or export crops which cannot be used directly on the farm, but have a high market value.

Emerging Approaches in Soil Fertility Management Research and Development

The foregoing sections show that low agricultural productivity attributed to degraded arable lands, is the major cause of food-insecurity in SSA. Technical solutions to the problems of land degradation are being researched and tested, and many show potential for redressing the problem in some places. How widely applicable these technologies may be somewhat uncertain. This suggests that technical research approach should shift focus to identification of productive and sustainable alternative land management techniques for diverse farming circumstances in SSA. Besides, technical research, there is also need for integration of socio-economic and policy research to identify factors that may inhibit or favour adoption of more sustainable land management practices. In soil fertility management research, these factors have received less focus and have been less well researched than biophysical factors affecting land management practices (Fig. 1.5). The need to better understand farmers' perspectives, constraints and facilitation of a favourable policy environment are both critical determinants of the success of effort to promote sustainable development. Part of the failure for widespread adoption of technical options is because of the oversight of these determinants.

This therefore means that the maintenance of the complexity of the landscape, for example agro-ecosystems in SSA creates implications for the relationship between technological change in resource-management practice and the policy environment necessary for its success. Inevitably, the spatial scale at which this link is made is once again of critical importance (Swift, 1998). This is increasingly being demonstrated in studies to monitor and evaluate flows of nutrients and stocks in agro-ecosystems, with implication for on-site and off-site effects (de Jager *et al.*, 1998a; 1998b). In the nutrient flow studies, agriculture is described as a hierarchy of nested agro-ecosystems, that one may trace to a greater complexity and longer temporal scales, from the crop and animal communities upwards, through the farm system (with plot and soil solution as the lowest spatial scales) with potential to upscale and extrapolate solutions at catchment, regional (district), national and even global levels. These are the scales which are perceived as being appropriate for society to assess the by-products of soil management practices (Figure 1.4). The figure clearly shows that as we move across the scales, significant variation occurs, not only in the nature of the resource management determinants, but also in the type and origin of policies necessary to govern them.

Figure 1.5. The relationships between resource management and decision-making (policy) across a range of spatial scales; and required disciplinary research



Source: (Adapted from Swift, 1998)

Key

The arrows represent flows of information; solid arrows are strong influences, broken arrows are weak influences. The determinants of sustainable resource management differ from scale to scale, as do the origins and types of policy decisions.

B/A - Biophysics/Agronomy,
xxx - Major focus,
x - Least focus.

Framework for research and development

Wider adoption of strategies, approaches and soil fertility management options requires that their profitability for smallholder farmers be carefully evaluated, infrastructural and institutional arrangements for enhancing their access to inputs and output markets be developed, and appropriate policies be established to support an economic environment for the farmers to adopt recommended technologies and options. Policy research and advocacy is inevitably required to create an enabling policy environment. At the research and development (R&D) level, there is also need for priority setting and targeting of potential "best bet" technology for smallholder farmers in terms of agronomic superiority, economic viability and culturally acceptable options (Waddington and Snapp, 1999). To meet both goals requires a shift in research focus, approach and partnerships. Thus, there is need for creation of a holistic framework for closer interaction between soil fertility subject matter specialists (SMS), economists, extensionists and policy makers (multi-disciplinary approach) in strategies for combating nutrient depletion in a manner that involves increased farmer participation and all stakeholders. The degree of farmers' participation in research is expected to vary with shift from contract type of research (researcher-designed and managed) to collaborative, consultative, collegial (researcher and farmer-designed and farmer-managed). It is only in collegial type of research where the farmers' role is less passive.

A handful of examples of the collegiate type of research approach reported in Africa, has been attributed to limited training in participatory research skills, tools and methodologies such as Participatory Rural Appraisal (PRA) (Chambers, 1993), Participatory Learning and Action Research (PLAR) (Defoer *et al.*, 1998) and Participatory Agro-Ecosystem Management (PAM). Secondly, it is difficult to sustain intensive farmer participation in the research cycle such as that adopted in the Farming System Approach to Research Extension and Training (FSA-RET) with the cycle activities ranging from diagnosis through to planning; experimentation; end of research project evaluation and re-planning (if necessary); recommendation and dissemination of technologies; and adoption and impact assessment. A third reason is that of researchers' hesitance to pre-maturily expose their work to clients for fear or inability to publish in journals and also fear of interference by farmers or losing dominance and control over the research agenda, especially in contract type of research. A recent improvement in FSA-RET approach has been the integration of gender and multi-disciplinary teams. As this shift is intensified and internalized by the players, it is interesting to speculate on how this new dimension in approach is likely to progress through different farming systems and how far they present real innovation on the other systems, as the farmer becomes the central personage of the research system. What will be exactly the partnership between the researcher and different stakeholders in this context? How will Indigenous Technological Knowledge (ITK) and modern scientific knowledge marry each other in these approaches? These questions are already major challenges in many case studies of participatory research in Africa.

The major intriguing issue with the proposed framework is that of the dilemma of participatory research, namely meeting farmer needs when every farmer is unique. Limitations of studies at higher spatial scales are many, as discussed by Stoorvogel and Smaling (1997) and Scones and Toulmin (1998). Results at sub-national level, for example, may conceal the wide variation around the mean when individual farms are taken into account. The 'positive outliers' may, for example, in fact, provide valuable information on preconditions and driving forces for sound resource management. For example, in Kisii District in Kenya (Sub-humid), with reliable rainfall and deep, relatively fertile soils, more options are available to safeguard soil fertility than in Machakos District in Kenya (Semi-Arid) with less and erratic rainfall and sandy soils. At farm household level, however, microclimate and soil fertility of individual plots and niches can be considerably modified by the farmer (Table 1.5). Individual households can be strikingly active and innovative, increasingly making use of indigenous knowledge to adjust their farming practices to changing agro-ecological conditions.

Linking productivity to sustainability

The two primary challenges in soil fertility management research are to improve and maintain or sustain crop productivity to meet demands for food, fibre, fuel and materials for agro-based industries and to enhance the quality of land, water and other natural resources. The major forms of soil fertility research in Africa is therefore to replenish mined nutrients on one hand as reported in Chapter 1.4 and identifying ways to solve the problem of imbalanced plant nutrition, currently regarded to be a serious degradation problem in high input agroecosystems. Judicious management and balanced application of plant nutrients is a strategy that should overcome the hazards of nutrient depletion through mining as well as environment pollution for example deterioration in biodiversity and ecosystem function (Swift and Anderson, 1993).

Agricultural research approaches, like agricultural systems in Africa, have evolved with time (historical perspective) as well as in the context (methodological perspective) as well as integrative approaches. This shift in research now to focus to INM system equally implies a broader mandate and greater responsibility for soil and plant analytical laboratories in Africa (Smaling and Braun, 1996). Long ago, low soil fertility was regarded as an issue that was straightforwardly squared by the use of mineral fertilizer as the mainstream research approach, in a linear way namely, more fertilizer gives higher plant production and hence more food or more income. But in the course of time, the benefits of mineral fertilizers (agronomic, economic and environmental) started to be questioned on several grounds such as

(i) The high energy consuming process for production of fertilizers,
(ii) Limited up-scaling of results from limited representativeness of earlier trials examplified by the FAO Programme,
(iii) Even if scaling up was possible as in FURP (FURP, 1994), low resource-endowed farmers do not have sufficient means to purchase fertilizers, or backed off because of low benefit/cost ratios or climatic vagaries,
(iv) Moreover, Structural Adjustment Programme (SAP) put a cruel end to fertilizer subsidies making the option non-sustainable for many SSA countries. This was followed shortly by advocacy for low-external input agriculture (LEIA) as the only strategy for sustainable agriculture (Reijntjes *et al.*, 1992), which has been found to be elusive (Nandwa *et al.*, 1999).

In early 1990's the debate of LEIA versus High External Input Agriculture (HEIA) changed to INM, already described above, as an "open-ended" cure. In the narrow definition of INM (combination of organic and inorganic nutrient inputs). Kabete's long-term soil fertility trial results indicate that only a combined annual application of high inputs of manure (10 t ha^{-1}) and mineral fertilizers (120 kg N ha^{-1} and 52 kg P ha^{-1}) maintains maize yields above the original yield potential of 3.5 t ha^{-1} grain, after 20 years of continuous maize-beans rotation cropping (Figure 1.6). However, none of the treatments (including INM) is able to improve and sustain most soil chemical properties (except phosphorus) as shown in Table 1.12. In the new INM-based research, INM is defined as the "judicious" manipulation of nutrient stocks and flows in order to arrive at a "satisfactory" and "sustainable" level of agricultural production. In the biophysical approach of new INM, an attempt is made to quantify or estimate what is meant by "judicious", "satisfactory" and "sustainable." In the new participatory or actor approach of INM, room is created for farmer "perceptions", "views" and "opinions" that do not necessarily correspond with "best technical means". Thus, while the conventional or former approach uses and generates fundamental, scientific knowledge on nutrient flows and INM technologies, the latter approach (actor) uses a combination of scientific, experiental and religious-cultural knowledge and the approach tends to be tailored to a particular agro-ecological and socio-economic context.

Table 1.12. Changes in macro soil nutrients (1976/77 to 1987) from continuous cropping at NARL Kabete long-term soil fertility trial

Treatment	Change in soil nutrients					
	Δ N%	Δ C%	Δ P ppm	Δ K	Δ Ca	Δ Mg
			m.e%			
1. Nil	-0.02	-0.55	-2.9	-0.97	-1.1	-0.48
2. FYM	+0.03	-0.32	-5.8	-0.82	-0.2	-0.41
3. NP	+0.01	-0.32	+0.8	-0.98	-1.3	-0.96
4. FYM + NP	-0.02	-0.66	-4.5	-0.90	-0.6	-0.03

Key:
FYM – Farmyard Manure
NP – Nitrogen – Phosphorus

Dichotomy of Large Numbers of Monolithic Soil Fertility Management Projects Against a Background of Worsening Nutrient Depletion in SSA

From the foregoing sections, it is evident that many agricultural research and development projects have been directed towards the problem of soil fertility decline (net decrease of available nutrients and organic matter in the soil) caused by nutrient depletion namely a negative balance between output (harvesting, burning, leaching, erosion etc) and input of nutrients and organic matter (manures/fertilizers, crop residue restitution, irrigation etc). This is often associated with biological degradation (decline in carbon biomass, organic matter content, and decrease in flora and fauna populations or species resident in the soil, such as earthworms, termites and micro-organisms) as a result of intensive cropping, mechanical soil disturbance, accelerated soil erosion, excessive pesticide application or industrial waste contamination causing pollution and watershed degradation and lowering of water quality and loss of biodiversity. If these issues are addressed by the many past and on-going projects then what keeps Sub-Saharan Africa from becoming fertile and productive? This is because the nutrient balance approach at different spatial scales consistently shows that soil fertility in Africa is at stake! The current perception is that most past projects have not regarded soil as an environmental asset, part of the natural capital in which soil nutrient stocks are capital stocks and nutrient fluxes are equivalent to service flows from economic principles point of view. This view is clearly defined in special symposium at the annual America Society of Agronomy and Soil Science Society of America meeting in 1996 as part of the World Bank's Soil Fertility Initiative for Africa. The review postulated on strategies for building up phosphorus and nitrogen capital, a more vulnerable capital than phosphorus through integrated soil fertility management.

Conclusion

The author believes that examples and information presented and discussed above and in subsequent chapters helps to underpin and will be incorporate in integrated soil fertility management research the currently widespread perception that agricultural development should no longer be concerned solely with maximizing biological or economic yield, but also with the issue of sustainability, including enhancement of biodiversity and ecosystem function in agroecosystem. Secondly, the author believes that soil fertility building up should be regarded as a capital investment, a perspective which needs to be accepted by both public and private donors of agricultural research and development, rather than increased number of projects.

References

AHI. (1997) African Highland Initiative, Phase I Report. ICRAF, Nairobi, Kenya.

Allan, W. (1965) The African Husbandman. Oliver and Boyd, Edinburgh and London, Uk.

Badiane, O. and Delgado, C. L. (1995) A 2020 Vision for Food, Agriculture and the Environment in Sub-Saharan Africa. *Food, Agric. and Environ. Dis.* Pap. 4 Int. Food Policy Res. Inst., Washington, D. C.

Baijukya, F. P. and de Steenhuijsen Piters, B. (1998) Nutrient Balances and Their Consequences in the Banana-Based Land Use Systems of Bukoba district. *Agric. Ecosyst. Environ.* **71**: 147-158.

Bationo, A., Lompo, F. and Koala, S. (1998). Research on Nutrient Flows and Balances in West Africa: State-of-the-Art. *Agric. Ecosyst. Environ.* **71**: 21-38.

Bojo, J. (1994) "The cost of Land Degradation arom a National Perspective: An Assessment of Africa Evidence." A Paper Presented at the 8th International Soil Conservation Conference, December 4th - 8th, New Delhi, India.

Boserup, E. (1965) The Conditions of Agricultural Growth. The Economics of Agrarian Change Under Population Pressure. George Allen and Unwin, London, Uk.

Brouwers, J. H. A. M. (1993) Rural Peoples' Response to Soil Fertility Decline: The Adja Case, Benin. Ph. D. Thesis No. 93-94. Wageningen Agricultural University, Netherlands.

Buresh, R. J., Smithson, P. C. and Hellums, D. T. (1997) Building Soil Phosphorus Capital in Africa. In: R. J. Buresh *et al.* ed. Replenishing Soil Fertility in Africa. SSSA Spec. Publ. 51. SSSA, Madison, WI. This Publication.

Buresh. R. J., Sanchez, P. A. and Calhoun, F. (Eds). (1997) Replenishing Soil Fertility in Africa. SSSA Special Publication No. 51. Madison, U.S.A. 251pp.

CABI. (1994) Soil Fertility Research in East Africa. CAB International, Wallingford, Uk.

Cardish, G. and Giller, K. E. (Eds). (1997) Driven By Nature: Plant Residue Quality and Decomposition. CAB International, Wallingford. .

Chambers, R. (1993) Rural Appraisal: Rapid Relaxed and Participatory. Institute of Development Studies, University of Sussex, UK.

Cleaver, K. M. and Schreiber, G. A. (1994) Reversing the Spiral, The Population, Agriculture and Environment Nexus in Sub-Saharan Africa. World Bank, Washington, D. C.

Deckers, J. (1993) Soil Fertility and Environmental Problems in Different Ecological Zones of the Developing Countries in Sub-Saharan Africa. In: Van Reuler, H. and Prins, W. H. Ed. The Role of Plant Nutrients and Sustainable Food Production in Sub-Saharan Africa. Vereniging van Kunstmest Producenten, Leidschendam, The Netherlands.

Defoer, T., Budelman, A., Toulmin, C., Carter, S. and J. Ticheler. (1998) Soil Fertility Management in Africa. Resource Guide for Participatory Learning and Action Research. Tools for the Field, Part 3. IIED. UK.

De Jager, A., Kariuki, I., Matiri, F. M. Odendo, M. and Wanyama, J. M. (1998) Monitoring Nutrient Flows and Economic Performance in African Farming Systems. NUTMON. IV. Linking Farm Economic Performance and Nutrient Balances in Three Districts in Kenya. *Agric. Ecosyst. Environ.* **71:** 83-94.

Deugd, M., Rolling, N. and Smaling, E. M. A. (1998) A New Praxeology For Integrated Nutrient Management Facilitating Innovation with and by Farmers. *Agric. Ecosyst. Environ.* **71:** 271-285.

Donovan, G. and Casery, F. (1998) Soil Fertility Management in Sub-Saharan Africa. World Bank Discussion Papers No. 408, Washington, DC, USA.

Doran, J. W. and Smith, M. S. (1987) Organic Matter Management and Utilization of Soil and Fertilizer Nutrients. *Soil Sci. Soc. Amer. J.* – Special Publication No. 19.

Duckham, A. N. and Masefield, G. B. (1971) Farming Systems of the World. Chatlo and Windus, London.

Elias, E., Morse, S. and Belshaw, D. G. R. (1998) Nitrogen and Phosphorus Balances of Kindo Koisha Farms in Southern Ethiopia. *Agric. Ecosyst. Environ.* **71:** 93-113.

FAO. (1976) Guidelines for Land Evaluation. Soils Bulletin No. 32, FAO, Rome.

FAO. (1976) Soil Map of the World. Vol. 6: Africa FAO/UNESCO, Paris.

FAO. (1978) Report on the Agro-Ecological Zones Project. Vol. 1. Methodology and Results for Africa. World Soil Resources Report No. 48, FAO, Rome.

FAO. (1978-1981) Report on the Agro-Ecological Zones Project Vols. 1-4. FAO World Soil Resources Report. 48. 1-4 , Rome, Italy: FAO.

FAO. (1981) An Ecosystem Classification of Inter-Tropical Africa. Plant Production and Protection Paper No. 31, FAO, Rome.

FAO. (1995) The State of Food and Agriculture, Rome, Italy.

FAO/UNESCO. (1990) Soil Map of the World. Revised Legend World Soil Resources Report 60. Rome, Italy.

Follet, R. H. Gupta, S. C. and Hunt, P. G. (1987) Conservation Practices: Relation to the Management of Plant Nutrients for Crop Production. *Soil Sci. Soc. Amer. J.* Special Issue No. 19.

Folmer, E. C. R., Genrts, P. M. H. and Francisco, J. R. (1998) Assessment of Soil Fertility Depletion in Mozambique. Maputo. *Agric. Ecosyst. Environ.* **71:** 159-167.

Freeman, H. A.; Owiti, J. M. and P. O. Andi. (1998) Characterizing Farmers for Research on Soil Fertility Maintenance in Semi-Arid Areas of Eastern Kenya. In: G. E. Okwach and Siambi, M. M. Eds. Agricultural Resource Management for Sustainable Cropping in Semi-Arid Eastern Kenya. CARMASAK Proceeding No. 1. KARI, Machakos, Kenya.

Fresco, L. O. and Kroonenberg, S. B. (1992). Time and Spatial Scales in Ecological Sustainability. *Land Use Policy.* 9.

FURP. (1987) Fertilizer Use Recommendation Project. Description of First Priority Trial Sites in the Various Districts, Volume 1-32. National Agricultural Research Laboratories. Narl , Nairobi, Kenya.

FURP. (1994) Fertilizer Use Recommendations, Vol. 1-23. KARI, FURP, Nairobi, Kenya.

Gachene, C. K. K., Palm, C. A. and Mureithi, J. G. (1999) Legume Cover Crops for Soil Fertility Improvement in the East African Region. Report of an AHI Workshop Held at TSBF, Nairobi, Kenya, 18th – 19th February, 1999.

Gebremeskel, T. and De Vries, C. A. (1985) Report on the Agro-Socio-Economic Survey of Two Sites in Central Nigeria WURP, Phase II. Pre-Implementation Stage. ILRI, Wageningen, The Netherlands.

Geurts, P. M. H. and Van Den Berg, M. (1998) A Simple Agro-Ecological Zonation for Fertilizer Recommendations in Mozambique. *Soil Use and Management.* **14:** 136-141.

Grant, P. M. (1981) The Fertilization on Sandy Soils in Peasant Agriculture. *Zimbabwe Agric. J.* **78:** 169-175.

Hamilton, P. (1997) Goodbye to Hunger: The Adoption, Diffusion and Impact of Conservation Farming Practices in Rural Kenya. *Association for Better Land Husbandry.* Report No. 12, Nairobi, Kenya.

Handayanto, E., Cardish, G. and Giller, K. E. (1997a) Regulating N Mineralization from Plant Residues by Manipulation of Quality. In: Cardish, G. and Giller, K. E. Eds. 1997. Driven by Nature: Plant Residue Quality and Decomposition. CAB International, Wallingford.

Handayanto, E., Giller, K. E. and Cardish. G. (1997b) Nitrogen Mineralization from Mixtures of Legume Tree Prunings of Different Quality and Recovery of Nitrogen by Maize. *Soil Biol. Biochem.* **29:** 1417-1426.

Harris, P. J. C., Lloyd, H. D., Hofny-Collins, A. H., Barret, H. R. and Browne, A. W. (1997) Organic Agriculture in Sub-Saharan Africa: Farmer Demand and Potential for Development, a Study to Inform Policy. ODA Project R632a Final Report. International Research Dept., Henry Double-Day Research Association, Ryton-on-Dunsmore, Coventry and Africa Studies Centre, Coventry University, Uk.

Hassan, R. M., Onyango, R. and Rutto, J. K. (1998) Relevance of Maize Research in Kenya to Maize Production Problems Perceived by Farmers. In: Hassan, R. M. (ed). Maize Technology Development and Transfer: A Gis Application For Research Planning In Kenya. A CIMMYT – KARI – CABI International. Oxon, Wallingford, UK.

Henao, J. and Baanante, C. (1999) Estimating Rates of Nutrient Depletion in Soils of Agricultural Lands in Africa. International Fertilizer Development Centre, Muscle Shoals, Alabama, USA.

IIED. (1999) A Study Tour Report of the Concerted Action INCO-DC Programme-Enhancing Soil Fertility in Africa: From Field to Policy Maker: A Visit by African Researchers to Scotland, The Netherlands and Belgium.

Izac, Annie Marie. (1997) Ecological Economics of Investing in Natural Resource Capital in Africa. In: Buresh, R. J. *et al.* (ed). Replenishing Soil Fertility in Africa. SSA Spec. Publi. 51. SSSA, Madison, WI.

Janssen, B. H. (1993) Integrated Nutrient Management: The Use of Organic and Mineral Fertilizers. In: Van H. Reuler and Prins, W. H. (eds). The Role of Plant Nutrients for Sustainable Food-Crop Production in Sub-Saharan Africa.

Janzen, H. H. (1987) Soil Organic Matter Characteristics After Long-Term Cropping to Various Spring Wheat Rotations. *Canadian Journal of Soil Science*. **67:** 845-856.

Jones, R. B. and Wendt, J. N. (1995) Contributions of Soil Fertility Research to Improved Maize Production by Smallholders in Southern Africa. In: Jewell, D , Waddington, S. R.

Kanyama-Phiri, G., Snapp, S. and Minae, S. (1998) Partnership With Malawian Farmers to Develop Organic Matter Technologies. Outlook on Agriculture 27. **3:** 167-175.

Kathuli, P. and Nguluu, S. N. (1996) Evaluation of Agronomic Effectiveness of Minjingu Rock Phosphate Mimeograph Pamphlet, KARI, Nairobi, Kenya.

Kato, M. S. A., Kato, O. R., Denich, M. and Vlek, P. L. G. (1999) Fire-Free Alternatives to Slash-and-Burn for Shifting Cultivation in the Eastern Amazon Region: The Role of Fertilizers. *Field Crops Research*. **62:** 225-237.

Kumwenda, J. D. T., Waddington, S. R., Snapp, S. S., Jones, R. B. and Blackie, M. J. (1995) Soil Fertility Management Research for the Smallholder Maize-Based Cropping Systems of Southern Africa: A Review Network Research Working Paper No. 1 of the Soil Fertility Network for Maize-Based Cropping Systems in Countries of Southern Africa. CIMMYT Maize Programme, Harare, Zimbabwe.

Kuyvenhoven, A., Bouma, J. and Van Keulen, H. Eds. (1998) Policy Analysis For Sustainable Land Use and Food Security. *Agricultural Systems*. **58:** 281-481.

Lee, B. 1993. Escaping From Hunger: Research to Help Farmers in Semi-Arid Kenya to Grow Enough Food. ACIAR Monograph No. 23.

Lekasi, J. K., Tanner, J. C., Kimani, S. K. and Harris, P. J. C. (1998) Manure Management in the Kenya Highlands: Practices and Potential for High Potential Production System Portfolio of the Natural Resources Programme-Renewable. Natural Resources Knowledge Strategy Department for International Development. HDRA Publications.

Mafongoya, P. L., Giller, K. E. and Palm, C. A. (1998) Decomposition and Nitrogen Release Patterns of Tree Prunings and Litter. *Agro-For. Syst.* **38:** 77-97.

Martonne, E. De. (1962) Une Nouvelle Function Climatoloque: L'indice D'aridite. La Me'te'rologie Nouvelle 2 P 449-458.

McClellan, G. H. and Notholt, A. J. H. (1986) Phosphate Deposits of Tropical Sub-Saharan Africa: In: Mokwunye, A.V. and Vlek, P.L.G. Eds. Management of Nitrogen and Phosphorus Fertilizers in Sub-Saharan Africa. Martinus Nijhoff Publishers, Dordrecht.

Mureithi, J. (1999) Legume Research Network Project Annual Report. 1998 , Kari/Rockefeller Foundation, Nairobi, Kenya.

Nandwa, S. M. and M. A. Bekunda. (1998) Research On Nutrient Flows And

Balances In East And Southern Africa: State-of-the-Art. *Agric. Ecosyst. Environ.* **71:** 5-18.

Nandwa, S. M., De Jager, A., Onduru, D. and Ogulu, B. (1999) Farmers and Researchers join forces in Nutrient Monitoring (NUTMON): The Development of Integrated Nutrient Management. (INM) in Sub-Humid Parts of Kenya and Semi-Arid Areas of Uganda. In Press.

Ndiritu, C. G., Kiome, R. M. and Nandwa, S. M. (1999) Strategies for Sustainable Productivity of Cropping and Forestry Systems Under Global Change with Particular Reference to Sub-Saharan Africa. Paper Presented at the Food and Forestry Global Change and Global Challenges, GCTE, Focus 3 Conference, 20th - 23rd Sept. 1999, University of Reading, UK.

Ojiem, J., Odendo, M. and Nandwa, S. M. (1995) Biological Management of Soil Fertility in Small-Scale Farming Systems in Kakamega District. Annual Report. KARI, Kakamega, Kenya.

Okalebo, J. R. and Nandwa, S. M. (1997) Effect of Organic Resources With and Without Inorganic Fertilizers on Maize Yields, Mainly on P Deficient Soils in Kenya. National Soil Fertility Plant Nutrition Research Programme Technical Report Series No. 12 KARI, Nairobi, Kenya.

Okigbo, B. N. (1979) Cropping Systems in The Humid Tropics of West Africa and Their Improvement. Paper Presented at the IITA Review 1979. IITA. Ibadan, Nigeria.

Okigbo, B. N. (1981) Alternatives to Shifting Cultivation. *Ceres*. **14:** 41-45.

Osunlaja, J. O. (1990) Effect of Organic Soil Amendments on the Incidence of Stalk Rot of Mâize. *Plant and Soil.* **2:** 237-241.

Palm, C. A., Myers, R. J. K. and Nandwa, S. M. (1997) Combined Use of Organic and Inorganic Nutrient Sources for Soil Fertility Maintenance and Nutrient Replenishment. In: Buresh, R. J., Sanchez, P. A. and Calhoun, T. (Eds) Replenishing Soil Fertility in Africa. Sssa Special Publication No. 51. Madison, USA. Pp 193-217.

Palm, C. A., Giller, K. E., Mafongoya, P. L. and Swift, M. J. (1999) Management of Organic Matter in the Tropics: Translating Theory into Practice. *In Press.*

Parr, J. F., Papendick, R. I. and Colacicco, D. (1986) Recycling of Organic Wastes for Sustainable Agriculture. *Biological Agriculture and Horticulture.* **3:** 115-130.

Parton, W. J., Stewart, J. W. B. and Cole, C. V. (1988) Dynamics of C, N, P and S in Grassland Soils: A Model. *Biogeochemistry.* **5:** 109-131.

Pratt, D. J., Greenvay, P. J. and Gwynne, M. D. (1966) A Classification of East African Rangeland with an Appendix on Terminology. *J. Appl. Ecol.* **3:** 369-382.

Rao, M. R., Niang, A., Kwesiga, F., Duguma, B., Franzel, S., Jama, B. and Buresh, R. J. (1998) Soil Fertility Replenishment in Sub-Saharan Africa; New Techniques and the Spread of their Use on Farms. *Agroforestry Today.* **10(2):** 3-8.

Reijntjes, C., Haverkort, B. and Waters-Bayer, A. (1992) Farming for the Future: An Introduction to Low External Input and Sustainable Agriculture. Leia, Leusden, Netherlands.

Ruthenberg, H. (1976) Farming Systems in the Tropics. Oxford, Oxford University Press.

Sanchez, P. A., Izac, A. M. N., Valencia, I. and Pieri, C. (1996) Soil Fertility Replenishment in Africa: A Concept Note. P. 200-207. In: Breth, S. A. (Ed).

Achieving Greater Impact from Research Investments in Africa. Sasakawa Africa Assoc., Mexico City.

Sanchez, P. A. and Leakey, R. R. B. (1997) Land-Use Transformation in Africa: Three Determinants for Balancing Food Security with Natural Resource Utilization. *Eur. J. Agron.* **7:** 1-9.

Scherr, S. J. (1997b) People and Environment: What is the Relationship Between Exploitation of Natural Resources and Population Growth in the South? *Forum for Development Studies.* **1:** 33-58.

Scherr, S. J. (1999) Past and Present Effects of Soil Degradation. In: Scherr, S. J. (Ed). Soil Degradation – A Threat to Developing-Country Food Security by 2020. International Food Policy Research Institute 2020 Discussion Paper 27, Washington DC. Pg 13-30.

Schimel, D., Stillwell, M. A. and Woodmansee, R. G. (1985) Biogeochemistry of C, N and P in a Soil Catena of the Shortages Steppe. *Ecology.* 66: 276-282.

Schnier, H. F., Recke, H., Muchena, F. N. and Muriuki, A. N. (1997) Towards a Practical Approach to a Fertilizer Recommendations for Food Production in Smallholder Farms in Kenya. *Nutrient Cycling in Agroecosystems.* **47:** 213-226.

Scoones, I. and Toulmin, C. (1998) Soil Nutrient Balances: What Use for Policy? *Agric. Ecosystems Environ.* **71:** 255-267.

Scoones, I. and Toulmin, C. (1999) Policies for Soil Fertility Management in Africa. A Report Prepared for the Department for International Development, IDS/IIED.

Seward, P. D. and Woomer, P. L. (1992) The Biology and Fertility of Tropical Soils: Report of the Tropical Soil Biology and Fertility Programme. (TSBF). 1992.

Seward, P. D. and Woomer, P. L. (1992) Tropical Soil Biology and Fertility Programme Report of the Fourth TSBF African Network Workshop. Harare, 20-26 July, 1993 , Report No. 8.

Shepherd, K. D. and Soule, M. J. (1998) Soil Fertility Management in West Kenya: Dynamic Simulation of Productivity, Profitability and Sustainability at Different Resource Endowment Levels. *Agric. Ecosyst. Environ.* **71:** 133-147.

Smaling, E. M. A., Nandwa, S. M., Presteele, H., Roetter, R. and Muchena, F. N. (1992) Yield Response of Maize to Fertilizers and Manure Under Different Agro-Ecological Conditions in Kenya.

Smaling, E. M. A., Stoorvogel, J. J. and Windmeijer, P. N. (1993) Calculating Soil Nutrient Balances in Africa at Different Scales. II. *District Scale. Fert. Res.* **35:** 237-350.

Smaling, E. M. A. and Fresco, L. O. (1993) A Decision-Support Model for Monitoring Nutrient Balances Under Agricultural Land Use. (NUTMON). *Geoderma.* **60:** 235-256.

Smaling, E. M. A., Fresco, L. O. and De Jager, A. (1996) Classifying, Monitoring and Improving Soil Nutrient Stocks and Flows in African Agriculture. *Ambio.* **25:** 492-496.

Smaling, E. M. A. and Braun, A. R. 1996. Soil Fertility Research In Sub-Saharan Africa: New Dimensions, New Challenges, Commun. *Soil Sci. Plant Analysis.* **27:** 365-386.

Smaling, E. M. A., Fresco, L. O. and De Jager, A. (1996) Classifying, Monitoring and Improving Soil Nutrient Stocks and Flows in African Agriculture. *Ambio.* **25:** 492-496.

Smaling, E. M. A., Nandwa, S. M. and Janseen, B. H. (1997) Soil Fertility in Africa is at Stake. In: Buresh, R. J., Sanchez, P. A., Calhoun, F. (Eds). Replenishing Soil Fertility in Africa. SSSA Special Publ. SI. SSSA, Madison, WI.

Smaling, E. M. A., Van Keulen, H. and Nandwa, S. M. (1999) Soil Fertility Management in Africa. *In Press.*

Sombroek, W. G., Braun, H. M. H. and Van Der Pouw, B. J. A. (1982) The Exploratory Soil Map and Agroclimatic Zone Map Kenya. Scale 1:1,000,000. Exploratory Soil Survey Report No. El. Kenya Soil Survey.

Stoorvogel, J. J. and Smaling, E. M. A. (1990) Assessment of Soil Nutrient Depletion in Sub-Saharan Africa, 1983-2000. Report 28. DLO Winand Starring Centre For Integrated Land, Soil and Water Research, SC-DLO , Wageningen, Netherlands.

Stoorvogel, J. J., Smaling, E. M. A. and Janssen, B. H. (1993) Calculating Soil Nutrient Balances in Africa at Different Scales. I. Supra-National Scale. *Fertilizer Research.* **35:** 227-235.

TSBF. (1985) Tropical Soil Biology and Fertility. TSBF: Planning for Research. *Biology International Special Issue* No. 9. International Union of Biological Sciences, Paris.

TSBF. (1987) Tropical Soil Biology and Fertility. TSBF: Inter-Regional Research Planning Workshop. *Biology International Special Issue* No. 13. International Union of Biological Sciences, Paris.

Vagstad, N. (1994) The Complexity of Balanced Fertilization. Report of Expert Meeting on Balanced Fertilization, Oslo.

Van Den Bosch, H., De Jager, A. and Vlaming, J. (1998) Monitoring Nutrient Flows And Economic Performance In African Farming Systems. (NUTMON) II. Tool Development. *Agric. Ecosyst. Environ.* **71:** 51-64.

Van Der Pol, F. (1992) Soil Mining, An Unseen Contributor Income in Southern Mali. Bulletin 325. Royal Tropical Institute Kit, Amsterdam.

Wadding, S. R. and Snapp, S. (1999) Workshop on "Best Bet" Soil Fertility Technologies Revisited for Malawi and Zimbabwe. In: Waddington, S. R. (Ed) Target, the Newsletter of the Soil Fertility Research Network for Maize-Based Cropping Systems in Malawi and Zimbabwe.

Walker, B., Steffen, W., Canadell, J. and Ingram, J. (1999). The Terrestrial Biosphere and Global Change: Implications for Natural and Managed Ecosystems, Chapters 1 and 9 Reproduced with Permission for GCTE Focus 3 Conference, Cambridge University Press.

Woomer, P. L., Martin, A., Albrecht, A., Resck , D. V. S. and Scharpenseel, H. W. (1994) The Importance of Soil Organic Matter in the Tropics. In: Woomer, P. L. and Swift, M. J. (Eds). The Biological Management of Tropical Soil Fertility. Wiley-Sayce, Chichester, Uk, Pp 47-80.

Woomer, P. L. and Muchena, F. N. (1996) Overcoming Soil Constraints in Crop Production in Tropical Africa.

World Bank. (1996) Natural Resource Degradation in Sub-Saharan Africa: Restoration of Soil Fertility. African Region. World Bank, Washington DC.

World Bank. (1997) Soil Fertility Initiative for Africa. Washington D. C. The World Bank.

Wortman, C. S., Lunze, L., Ochwon, V. and Lynch, J. (1995) Bean Improvement for Low Fertility Soils in Africa. *Africa Crop Science Journal.* **3(4):** 469-477.

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2

Principles of Integrated Soil Fertility Management

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Introduction

Africa's agriculture, requires transformation if it has to contribute towards alleviation of poverty, food insecurity and environmental conservation. Many countries in the continent are unable to match agricultural production to fast growing population to overcome food deficits. Cereal grain yield increase is about 1% against a population growth rate of about 3% and soil fertility management is at a crisis point (Smaling *et al.*, 1997). Approximately 65% (121 million hectares) of Africa's total land (187 million hectares) is degraded. Rates of nutrient depletion are particularly high in areas with favourable climates for crop production and high population densities. High External Input Agricultural Systems (HEIA), most of which are characterized by intensified production, are increasingly becoming non-attainable. Moreover, in extensification systems which tend to be low external input agriculture (LEIA), production takes place at the expense of soil as a natural capital, the common property resource base.

Despite diversity of approaches and solutions and the investment of time and resources by a wide range of institutions, soil fertility degradation continues to prove to be a substantially intransigent problem, and as the single most important constraint to food security in the continent (Sanchez *et al.*, 1997). For example, soil loss through erosion is estimated to be 10 times greater than the rate of natural formation. Return to investment in soil fertility has not been commensurate to research outputs (AHI, 1997). Farmers are only likely to adopt sound soil management if they are assured of return on their investment. Integrated soil fertility management (ISFM) is now regarded as a strategy that helps low resource endowed farmers. mitigate many problems and the characteristics of poverty and food insecurity by improving the quantity and quality of food, income and resilience of soil productive capacity. The next section defines ISFM, lists multiple purpose ISFM options/components/ technologies and guiding principles for sustainable ISFM.

What is Integrated Soil Fertility Management (ISFM)?

Essentially, ISFM is the adoption of a systematic conscious participatory and broad knowledge intensive holistic approach to research on soil fertility that embraces the full range of driving factors and consequences such as biological, physical, chemical, social, economic and political aspects of soil fertility degradation. The approach advocates for careful management of soil fertility aspects that optimize production potential through incorporation of a wide range of adoptable soil management principles, practices and options for productive and sustainable agro-ecosystems. It entails the development of soil nutrient management technologies for adequate supply and feasible share of organic and in-organic inputs that meet the farmers' production goals and circumstances. The approach includes other important aspects of the soil complex; soil life, structure and organic matter content. The approach integrates the roles of soil and water conservation; land preparation and tillage; organic and inorganic nutrient sources; nutrient adding and saving practices; pests and diseases; livestock; rotation and intercropping; multipurpose role of legumes and integrating the different research methods and knowledge systems. The approach also includes a social and economic dimension.

Range of ISFM components/technologies

The major emphasis in the ISFM paradigm is on understanding and seeking to manage processes that contribute to change. Literature review indicates that there is a wide range of ISFM components and technologies in the continent. The increasing adoption of ISFM as a long-term perspective and holistic approach derives its success on the emergence of a consensus on its guiding principles. This paradigm is closely related to the wider concepts of Integrated Natural Resources Management (INRM), thereby representing a significant step beyond the earlier, narrower concept and approach of nutrient replenishment/recapitilization for soil fertility enhancement (Sanchez *et al.*, 1997). ISFM thereafter embraces the full range of multiple purpose options (MPOs) and driving factors and consequences (namely, biological, physical, chemical, social, economic and political), of soil degradation in different farming systems and land types, reviewed in Chapter 1. The ISFM MPOs may include:

(i) Integrated Nutrient Management (INM), which is the technical backbone of ISFM approach. It entails integrated use of organics as well as in-organic sources of plant nutrients; as well as the entirety of possible combinations of nutrient-adding practices and nutrient saving techniques. The latter INM is perceived as the judicious manipulation of nutrient inputs, outputs and internal flows to achieve productive and sustainable agricultural systems (Smaling *et al.*, 1996).

(ii) Integrating the beneficial and deleterious effects of the relationship between abiotic factors (including tillage, soil and water management) and biotic stresses (including integrated pest and disease management; integrated crop management).

(iii) Integration of crop and livestock production.

(iv) Integration and greater productive use of local and indigenous knowledge, innovations, practices and resources and science knowledge based-management system.

(v) Integration of policy and institutional framework, as well as on-site and off-site (landscape) effects.

Amongst success stories in the adoption of MPOs in parts of SSA include the practices of intercropping and integration of multiple purpose legumes (green manure, cover crops and herbaceous, tree, forage or fodder and grain or food legumes); manure use by low resource endowed farmers; and the emerging spread of improved fallows and biomass transfer, especially of high quality organic inputs; use of regionally and locally available inorganic sources of plant nutrients and amendments (for example rock phosphates, limestones, sulphur and magmax, termitaria soil, ashes etc.). Another option entails the use of high-efficiency micro-dose fertilizers on high value crops as opposed to their application to less responsive indigenous crop varieties or cropping systems. Besides these technical research options, there is also need for integration of socio-economic and policy research to identify factors that may inhibit or favour adoption of more sustainable land management practices (for example MPOs), a neglected area of soil fertility research. Other new dimension in the ISFM approach is the focus on farm scale recommendations within farm variability instead of plot scale-base recommendations, upscaling of strategies beyond village boundaries and focus on ISFM instead of INM. This was embraced recently in the TSBFI, CIAT and ICRAF strategic alliance to "improve rural livelihoods" in SSA through sustainable ISFM (TSBF, 2002b).

Principles of ISFM

Diversification of nutrient sources

In Africa, high fertilizer use efficiency is not achieved (N recovery < 30%) and access to inorganic fertilizer by smallscale farmers is increasingly becoming elusive, and it is now apparently clear that there is need for rapid reintroduction of organic sourcing of plant nutrients in smallholder agriculture. This may be achieved through improved fallows, rotations, green manuring, farmyard or compost and animal manures, mixed cropping with legumes, crop residues restitution, agroforestry and biomass transfer. For example, there are areas where agricultural practices are predominantly based on organic sources of plant nutrients and has been termed "organic" or "conservation" or "eco-intensification" farming, at its extremity. By definition, such smallholder agriculture is "regenerative" to some extent. This is because their farms are characterized by multiple cropping, for example, maize-based systems including legumes, roots and tubers, fibre and horticultural crops grown in complex mixtures. As low-external input soil management systems, soil fertility buffering in such farming systems is mainly from organic nutrient sources. The potential benefits of adding organic nutrient sources include: source of nutrients (multiple nutrients); regulation of mineralization or immobilization (synchrony or asynchrony); energy source for microbes (enhanced nutrient cycling); precursors to SOM (residual effects). But the amount available and quality of organics is often the main limitation to the widespread adoption of this option.

To satisfy crop demands and ligands for reducing P-fixation and Al toxicity requirements, there is need to understand the merits and trade-offs of the organics (Prasad and Power, 1991) and non-conventional inorganic sources (Nandwa and Bekunda, 1998) especially factors which regulate the decomposition and mineralization and nutrient release patterns (Whitemore and Hadayanto, 1997). The technologies so formulated must take into account the access and availability (quantity or rates) of the materials, their quality (that is the rate of nutrient release in relation to uptake demand by maize) placement and time of application with respect to crop sequence and time of planting. Presently, many studies and field experiments are conducted in the region aimed at gaining insights of the processes which regulate the release of nutrients from materials of contrasting qualities (Kimetu, 2002). Many of them are conducted within the framework of the Tropical Soil Biology and Fertility (TSBF) programme, especially the African Network (AfNet) of the programme (TSBF, 1995, 1997a, 1997b; Woomer *et al.*, 1995). The adoption of minimum site characterization, data sharing and use of standard methodology are among the requirements of the AfNet partnerships (Anderson and Ingram, 1993). Results obtained from such studies indicate that a wide range of organic materials can be considered as alternative source of plant essential nutrients, soil amendment and supplants (substitute) for chemical fertilizers (Kayuki and Wortman, 2001). The TSBF research on managing nutrient cycles seeks to optimize the use of organic inputs for ISFM through manipulation of decomposition and other soil biological processes. The manipulation helps in the enhancement of the soil organic carbon pool as an integrator of various soil-based functions related to production and ecosystem services (demonstrating the environmental benefits and trade-offs that accrue from diverse, healthy and active soil biological community). Research on characterization of organic materials has helped develop an organic resource database and translate the information into soil management practices relevant for and targeted at conditions experienced by farmers. A decision tree (Decision Support System) on the use of organic resources for INM is a useful tool (Figure 2.1) emerging from this approach (Palm *et al.*, 1997, 2001; Singh *et al.*, 2001). A farmer user-friendly decision tree provides indicators farmers can use to predict the nutrient release potential of organic inputs (Figure 2.2) (Palm *et al.*, 2001; IIRR, 2000).

In the two decision tools (DTs), the quality of organics depends on the amount of nitrogen, lignin polyphenol and whether the leaves are waxy or not. Physically dark green and yellowish leaves contain high and low nitrogen, respectively; and make good and poor organic fertilizer, respectively. Secondly, leaves with low and high lignin contents will flow easily and with difficulties, as indicators of good and poor organic fertilizer, respectively. Thirdly, testing organic materials will reveal that those with high polyphenol (substances that inhibit rotting) will have astringent taste as an indicator of a poor organic fertilizer while good organic fertilizer will have no or limited astringent taste. Fourthly, waxy leaves inhibit rotting as an indicator of poor quality organic fertilizer çompared to good organic fertilizer.

The quantity of nutrients sourced from organics vary greatly as shown in Table 1. However, many of the materials when applied in modest amounts i.e. < 5 t dry matter ha^{-1}, contain sufficient N to match that of a 2 t crop of maize but they cannot meet P requirements and must be supplemented by inorganic P in areas where P is deficient.

Figure 2.1. A preliminary quantification of the Decision Support System for organic N management

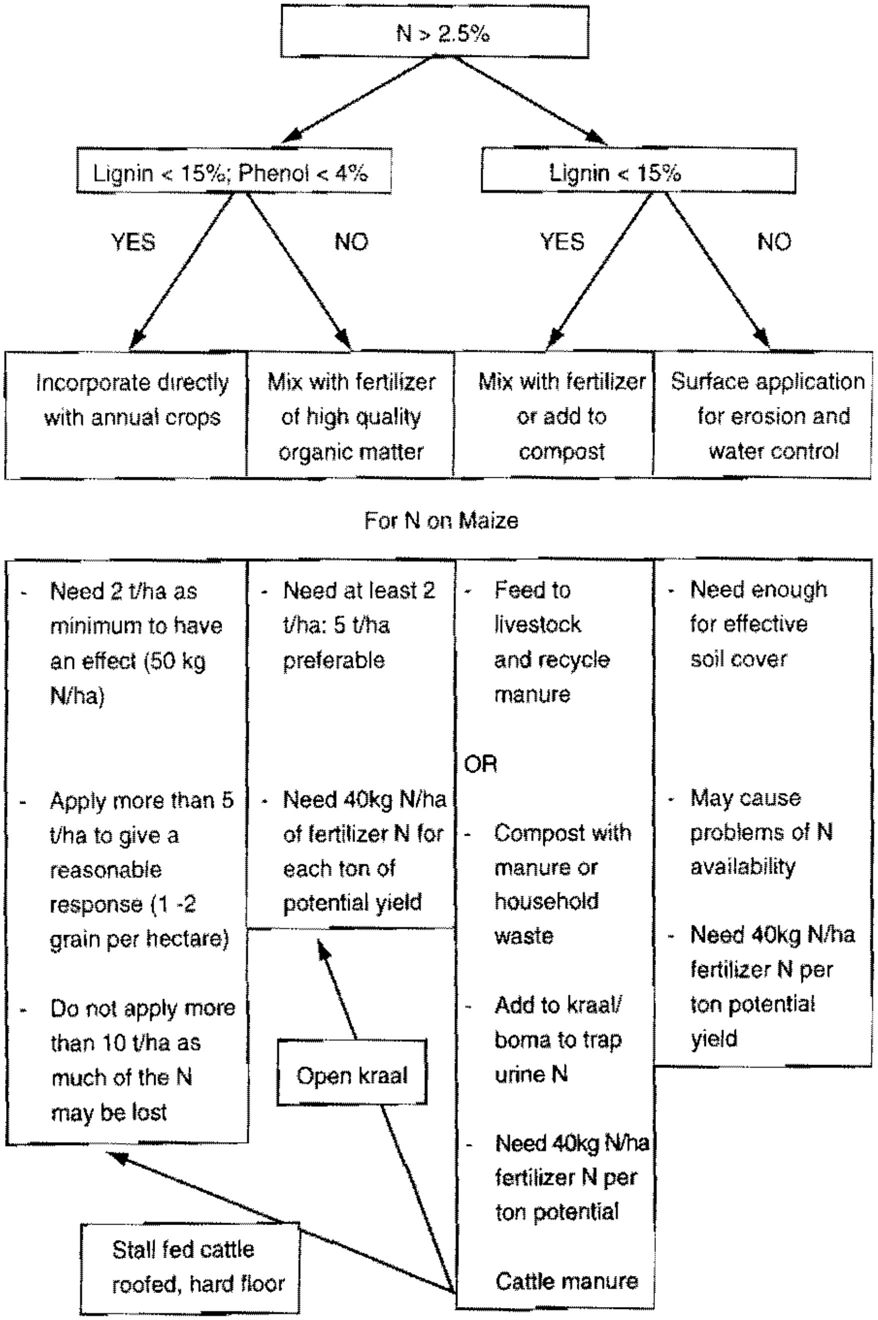
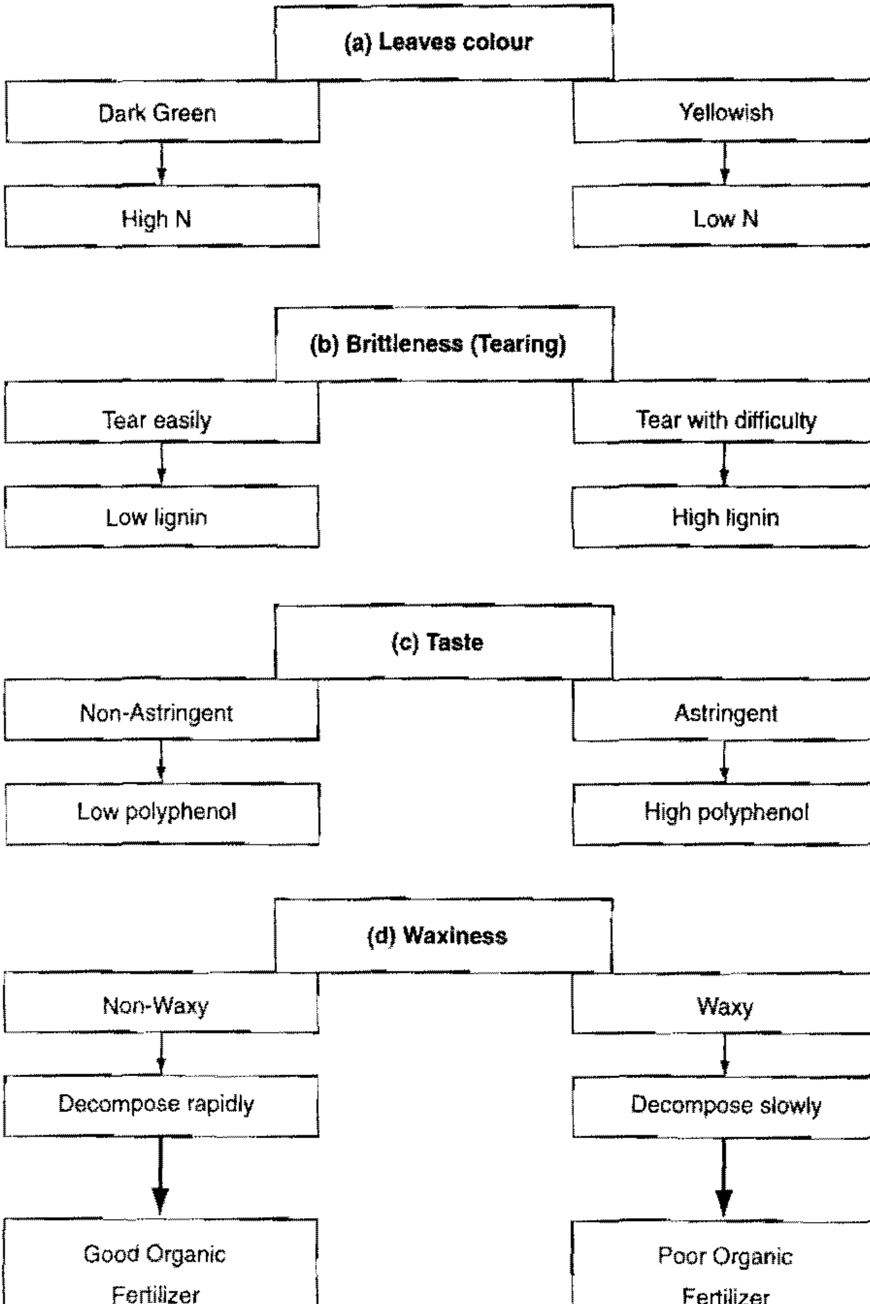


Figure 2.2. The use of leaves colour, waxiness, brittleness and astringent taste to distinguish between good and poor organic fertilizer



Source: Nandwa, S. M. adopted from IIRR, 1998

Table 2.1. Average nutrient contents on a dry matter basis of selected plant materials and manures collected in Eastern and Southern Africa (Palm *et al.*, 1997)

Material	(kg t^{-1}) N	P	K
1. Crop residues restitution			
Sorghum stover	10	<1	15
Maize stover	6	<1	7
Millet stover	13	4	18
Bean trash	7	<1	14
Green maize stover	20	2	6
Tea leaves waste/litter	21	3	2
Pigeon pea green leaves	23	2	13
Mango tree leaves	18	<1	19
Banana leaves	19	2	22
Acacia mearnzii	23	4	20
Sweet potato leaves			
2. Biomass transfer material			
Tithonia diversifolia	36	3	43
Lantana camara	27	3	21
Grevilia robusta	14	<1	6
Chromolaena ordonata	38	3	15
Pasture grass	29	4	46
3. Compost manures			
Urban garbage (low quality)	11	8	15
Urban garbage (medium quality)	20	7	20
Water hyacinth	19	29	4
Earthworm (Vermiculture)	11	7	8
4. Agro-processing waste-products			
Sugarcane trash (baggase)	8	<1	10
Filter mud	14	8	4
Coffee husks	16	4	12
Cofuna organic fertilizer	20	8	65
5. Animal manures			
Cattle			
High quality	23	11	6
Medium quality	15	4	7
Low quality	7	1	8
Chicken			
High quality	48	18	18
Low quality	24	7	14
Goat (low quality)	19	8	24
Mixture of low quality Cattle/Goat/Chicken	18	8	20

Table 2.1 *(Cont')*

6. Leguminous cover crops (Herbaceous impound fallows species)			
Crotalaria ochroleuca	42	2	9
Dolichos lablab	41	2	2
Mucuna pruriens	35	2	7
Canvalia ensiformis	37	1.3	11
7. Leguminous trees (Woody tree fallows)			
Calliandra calothyrsus	34	2	11
Gliricidia sepium	33	2	21
Leucaena leucocephala	34	2	21
Sesbania sesban	34	2	11
Tephrosia vogelli	21	2	8
Senna spectabilis (Non-BNF)	33	2	16
Crotalana grahamiana	21	1.6	12

Maximization of input use efficiencies and return to investments

One of the basic principle for adoption of ISFM especially INM is underpinned in the value of combining of organic and inorganic materials to maximize nutrient use efficiency. Fertilizer N losses of 20-40% through gaseous and leaching losses are commonly reported (Palm *et al.*, 1997) while yield reductions due to low quality organics may also occur, suggesting the need for appropriate combination. INM trials in the continent have been used to establish the fertilizer equivalencies of locally available organic resources. Higher N content results in higher fertilizer equivalent values. For example *Tephrosia* (4% N), Tithonia (3.5% N), *Sesbania* (3.5% N) and Pigeon Pea (2.8% N) have been reported to have 93, 87, 36 and 33% fertilizer equivalencies, respectively (Palm *et al.*, 2001). In a recent study in Kenya, *Tithonia diversifolia, Calliandra calothyrsus* and *Senna spectabilis* had fertilizer equivalencies of 130, 72 and 68, respectively (or yield increases over control of 71.4, 48 and 43%, respectively) (Kimetu, 2001). Many studies including long-term ones have shown that, INM results in more yield and nutrient use efficiency than that expected from mere additive effects of sole applications (Bekunda *et al.*, 1997; Kang and Baleshbramanian, 1990). The higher utilization efficiency (agronomic and/or nutrient recovery efficiency) obtained from INM (as compared to sole application) may be attributed to the principles of synergistic effects involving different mechanisms for example synchrony, which underscores the importance and need for mechanistic understanding of the soil biological processes.

The higher values of fertilizer equivalency of the tested organic materials suggest that organic amendment have beneficial roles besides the addition of plant nutrients such as improvement of water holding capacity. Therefore, the release of nutrient with mineralization over time can synchronize with plant demand resulting in higher nutrient use efficiency from the organic amendments. The amendments have also been reported to reduce the capacity of the soil to fix P thereby increasing P availability for uptake and hence higher P use efficiency (Buresh *et al.*, 1997). In long-term soil management trials, application of crop residues, N, ridging and rotation of pearl millet with cowpea were evaluated to determine their effect on phosphorus use efficiency (PUE). and results obtained showed that PUE increased from 46% with P application alone to 133% when P is combined with N and crop residue applications and the crop sown on ridges in a rotation (Table 2).

Table 2.2. Effect of mineral fertilizers, crop residues, nitrogen (N) and crop rotation (R) on pearl millet yield (kg ha^{-1}) and phosphorus use efficiency (PUE, kg grain kg P^{-1}) at Sedore, Niger, rainy season 1998. The results were compared when P was applied (13kg ha^{-1}) and ridging (RG) was practiced or not

Treatment	Yield RONO (PUE)		RONI (PUE)		RINO (PUE)		RINI (PUE)	
Control	33		58		61		98	
P alone	633	46	1030	75	726	51	1212	86
P + RG	448	32	946	68	785	56	1146	81
P + R	1255	94	1441	106	1475	109	1675	121
P + R + RG	1391	104	1581	117	1703	126	1829	133

SE + (407 for grain in all cases)

Source: A. Bationo, unpublished data

Recent studies in improved fallows have identified short/medium-term legumes that yield 6 - 11 t ha^{-1} of dry matter, 150-300 kg ha^{-1} of N and 20-30 kg ha^{-1} of P in 6-12 months. A 4-year experiment in India (Goyal *et al.*, 1992) compared the N substitutive effects of wheat straw, FYM and Sesbania green manure on pearl millet *(Pennisetum glaucum [L] R. Br.)* yields, N uptake and SOM. The results (Table 3) showed that crop yields, N uptake and N recovery were greater with the combination of FYM and/or green manure and urea compared with application of urea alone but less recovery was obtained when wheat straw was combined with urea. The highest N use efficiency (% recovery) of 38 and 33% was obtained with urea + sesbania and urea + FYM, respectively compared to 29% (urea alone) and 17% (urea + straw).

Table 2.3. Pearl millet yield, N uptake, N recovery, and soil properties following 4 yr of application of fertilizer (urea) compared with the combination with organic materials of differing qualities

Treatment†	Grain yield t ha^{-1}	N uptake kg ha^{-1}	N recovery %	SOM-C† g kg^{-1}	Microbial C mg C kg^{-1}
N0 P0	1.51	31	—	4.0	180
N120 P40	2.76	66	29	4.3	290
N60 P20 + N60 (FYM)	2.81	71	33	5.0	330
N60 P20 + N60 (wheat straw)	2.33	51	17	4.5	
355					
N60 P20 + N60 (sesbania)	3.15	76	38	4.8	315
LSD ($P = 0.05$)	0.27	5.7		0.6	19

† N = kg of N added as fertilizer or organic material, P = kg of P added as inorganic fertilizer.

Adapted from Goyal *et al.*, 1992

Emerging knowledge has also revealed that in environments with high leaching and denitrification potential, immobilization of N initially may after all help increase nutrient use efficiency eventually, thus mimicking the concept and principle of split application of N fertilizer. In conclusion, it may be stated that INM practices that optimize nutrient inputs while concurrently minimizing nutrient losses are most likely to contribute towards increased efficiency of the applied nutrient material manifested on high crop response. This has been clearly demonstrated by long-term INM trials in West Africa (Kang and Balasubramanian, 1990) and Africa (Bekunda *et al.*, 1997).

Research on the determination of optimum combination of inorganic and organic N sources (Tithonia and Sesbania) in Eastern and Southern Africa have shown 50% organic and 50% mineral N source (e.g. urea) as the optimum combination ratio (Palm *et al.*, 1997). NUTMON studies and results (see Chapter 1) have demonstrated that for efficient return to increased agricultural production, inputs will have first to depend on the extent to which farmers minimize or eliminate non-useful outflows like OUT 2 (residue burning), 3 (leaching), 4 (gaseous losses such as volatilization and denitrification escape of nutrients), 5 (erosion) and 6 (human waste and sludge). A case study of two farm types on eastern slopes of Mount Kenya (Gitari *et al.*, 1999), showed higher net farm income (Kshs 94,300) in medium resource endowed farm compared to low resource endowed farm (Kshs 39,000), which was associated with positive (105 kg NPK ha^{-1} yr^{-1}) and negative (-15 kg NPK ha^{-1} yr^{-1}) balances, respectively (Table 2.4). Thus, the predominantly low or no cost nutrient supplies in the first farm was responsible for high return to investment.

Table 2.4. Economic performances and nutrient balance of two farm types in land use zone IV and V in Embu District, Kenya

Characteristics	Tobacco and Food Crops Farm Type in Land Use Zone IV (Nitisol/Cambisols) Zone V (Arenosols)	Extensive Livestock Grazing and Shifting Cultivation Farm Type Land Use
Resource endowment	Low	Medium
Nutrient Balance N	-26	43
P	15	2
K	-4	60
NPK	-15	105
Net Farm Income (Kshs/farm/year) *(1 US$ = Kshs 80)*	39,000	94,300
Sources and cost of nutrient supplies	High level of inorganic fertilizers is provided on credit basis and used in the production of tobacco (approximately 30 kg NPK ha^{-1} $year^{-1}$ compared to zero mineral fertilizers but 70 kg NPK ha^{-1} $year^{-1}$ manures in LUZ V)	Browsing of livestock from communal grazing land and accumulation of manure in kraals is responsible for positive balance in spite of no external mineral fertilizers brought in the farm
Crop and livestock contribution to farm income (%)	78 and 22 respectively	53 and 47, respectively

Source: Gitari *et al.*, 1999

ISFM as a knowledge intensive holistic approach and long-term perspective

Agricultural productivity is as much a function of human capacity and ingenuity as it is of biological and physical process (Pretty *et al.*, 1996). Integration of the two helps to show the potential synergy and complementarily of the processes (Onduru *et al.*, 2001). One of the TSBF research foci is empowering farmers, which aims to strengthen farmers status by facilitating access to knowledge and decision-making through; evaluation of management options for ISFM; facilitating pathways of knowledge interchange and; improving policies for sustainable soil management. On-farm ISFM research involves the need to understand the basis for decision making by farmers and the extent to which the decisions are based on principles of scientific processes and how these are modified by the socio-economic constraints.

Participatory learning and action research (PLAR)

Recent trend to make ISFM a knowledge intensive approach is by integrating local and scientific knowledge through the development of Participatory Learning and Action Research (PLAR) for ISFM, as a process to help farmers to improve their soil fertility management strategies (Baltissen *et al.*, 2000). This can be achieved through:

(i) Self-diagnosing and analyzing of current soil fertility management (SFM) strategies and practices;

(ii) Planning, experimenting and evaluating alternative SFM practices that are practical, appropriate to their particular situation and better able to exploit available resources and diversity, and

(iii) PLAR for ISFM aims to build effective and efficient farmer organizations that will ensure that successful and continued development of ISFM practices (Defoer and Budelman, 2000).

PLAR enables farmers to discover and experiment with new SFM practices on a step-by-step basis, promotes joint learning between farmers and facilitates demand-driven extension. The potential for institutionalization of PLAR for ISFM should be determined by capacity building in PLAR skills and involvement of policy makers in the process and training in related participatory research approaches. A good example is the development of a guide for identifying, classifying and integrating local indicators of soil quality (LISQ) and technical indicators of soil quality (TISQ) to guide the development of sustainable management principles and strategies for ISFM (Barrios *et al.*, 2000). Integration of LISQ and TISQ helps in the capture of farmers knowledge about soils which is the result of hundreds of years of trial and error and accumulated experiences. Such valuable knowledge tends to fade away with time. Moreover, it is the farmers who know and experiment with their soils, and hence such knowledge integration facilitates actors (farmer, extension and research technicians) to have a shared understanding of the soils. The approach helps to overcome some of the past conventional research methods and assumptions such as fields are uniform resulting in general and irrelevant recommendations for dealing with fertility problems of heterogeneity gradients and niches. A good example is from a case study of Kabras Division in Kenya, where seven niches were identified under a smallholder farm which tended to vary tremendously in fertility (Table 2.5) (Ojiem *et al.*, 2000). From a case study on experiences in participatory diagnosis of soil management in Kenya, Onduru *et al.* (1998) found close correlation between LISQ and TISQ in Machakos District, thus emphasizing the importance and feasibility of the integration. These farmers' participatory research approaches tailor research focus on recommendation domains e.g. based on farmers wealth classes. In conclusion, these approaches emphasize empowering farmers to do their own analysis, learn, adapt and do better and not transfer of known technology; not a package of practices to be adopted but a basket of choices and options from which to select, not precepts but principles; not strict messages but methods. This integration of farmers' indigenous knowledge with science knowledge gives allowance for farmer "perceptions," "views" and "opinions" that do not necessarily correspond to the "best technical means" to ISFM (Defoer *et al.*, 1998; Garforth and Gregory, 1997). This approach contrasts with science approaches that use and generate fundamental scientific knowledge that may not be readily translated into farming systems practices because of socio-economic constraints (de Villiers, 1996).

NUTMON: Nutrient stocks and balances as indicators of productivity and sustainability

Nutrient Monitoring (NUTMON) is another Participatory Farmer Research Approach (like PLAR) that uses INM as the judicious manipulation of nutrient stocks and flows, in order to arrive at a "satisfactory" and "sustainable" level of agricultural production, at minimum environmental cost. Nutrient budget is often simplified as the summation difference between nutrient inflows and outflows which results in a net flow figure (termed the balance). In the 1830s, experiments of Boussingault set up to draw up balance sheets to show how far manure and other sources of nutrient supply (air, rain and soil) had satisfied the crop. In the 1950s, approaches to inputs and output analysis formed a major focus of systems ecology. Therefore, the importance of the concept of nutrient balance sheets or budget in soil fertility is not new (Cookes, 1967). More than 150 years ago Justus Von Leibig stated that "nutrients taken away from the soil should be replenished." But more recently, the nutrient balance focus has shifted from soil fertility *per se* towards imbalances between nutrient inputs and outputs, and their agronomic and environmental consequences. The nutrient budget concept consists of spatial and temporal scales. The spatio-agroecosystem levels include country, region, district, catchment area, farm, plot and soil solution. The concept includes different temporal scales ranging from a few minutes to geological time scales. Irrespective of the temporal scale, at each spatial level, different processes and flows determine actual value of the nutrient budget.

Table 2.5. Niches identified by smallholder farmers in Western Kenya, farmers exploitation and management strategies

Niche Type	Valley Bottom Pen	Old Cattle	Old Homestead	Light Soil	Red/Brown Soil	Black/ Dark Soil	Shallow/ Eroded Soil
Probability of niche existing on a farm	0.4	0.7	0.7	0.95	0.75	0.65	0.9
Relative size	Small	Small	Large	Large	Medium	Medium	Medium
Common use	Fruit Vegetables	Fruit Vegetables	Cassava Sweet potatoes	Maize Beans Sugarcane	Maize Beans Vegetables	Grazing	Maize Beans Arrow-roots
Fertility rating	High	Medium	Low	Medium	High	Low	High
Fertility management	No amendment	No amendment	Farmyard manure (FYM)	FYM/Inorganic fertilizers	FYM/Inorganic fertilizers	Manure (*in-situ* grazing)	Mainly crop residues (*in-situ*)

Nutrient stocks, flows and balance are currently and increasingly being used as powerful tools and indicators for estimating nutrient depletion or accumulation. There are several, simple and complex approaches and methods for calculating nutrient balances, which strongly depend on the purpose of the exercise and the end-user of the results obtained. Black-box models are mostly used at higher spatial scales and have "awareness raising" as their main goal and policy makers as the principal audience. In this approach, nutrient depletion or enrichment of the system simply follows from the difference between total nutrient inputs (mineral fertilizers-IN 1, organic inputs-IN 2, deposition-IN 3, biological nitrogen fixation-IN 4, sedimentation-IN 5, subsoil nutrient exploitation-IN 6) and outputs (harvested products-OUT 1, crop residues-OUT 2, leaching-OUT 3, gaseous losses-OUT 4, erosion-OUT 5, faeces and urine-OUT 6), without paying attention to processes within the box. Soil fertility (including nutrient stocks) is not a static feature but changes constantly and its direction (accumulation or depletion) is determined by the interplay between physical, chemical, biological, and anthropogenic processes and principles (Smaling *et al.*, 1997).

Nutrient budget is therefore, "best first approximation estimate" of agro-ecosystems productivity and sustainability. Since most work in Africa reveals that most SSA agro-ecosystems can be labelled as non-sustainable due to negative nutrient budgets and low nutrient stocks (from few studies), it is meritable to adopt ISFM approaches to generate technologies that are agronomically superior, economically viable and socially acceptable. There is great need however to intensify ISFM research agenda based on nutrient budget results and knowledge gaps in the context of prevailing socio-economic factors at each spatial scale.

The success of the application of nutrient budget results has been at the higher spatial scale level (country/district), where they have been used to influence policy to help in initiating projects to combat nutrient depletion. There is urgent need for nutrient budget research at farm/watershed level to help influence farm household decision making and perception regarding increased investment in nutrient recapitalization, replenishment and balanced fertilization, taking into account the trade-off between the economic, sustainability and environmental issues. Integration of participatory and multidisciplinary approaches is a major precondition to success. Presently most nutrient budgeting studies overlook the conventional soil productivity indicators such as soil chemical analytical parameters, crop growth and yield, fertility indicator plant species etc.

There is need for research to provide a better insight on the dynamic aspects of nutrient flows, nutrient balances and stocks and their relation to crop yields and related to soil productivity indicators. The imperative is to present reliable sustainability indicators and more accurate economic impact assessments. Research needs to determine future yield developments under specific nutrient balances and nutrient stock levels. This will mitigate for the development of tools that enable integration of large amount of available information collected in nutrient monitoring and also to enable "what-if" type of calculations to explore various options and assumptions. This approach should help provide essential inputs in scenario studies and play a major role in placing integrated soil fertility management (ISFM) and sustainability issues on the agenda of policy makers (Scoones and Toulmin, 1998). A major breakthrough in farmer participatory research (FPR) include integration of gender and multidisciplinary expertise; training in skills, tools and FPR methodologies. As the marriage between ITK and MSK becomes a reality the farmer becomes the central personage in the FPR cycle. This makes the approach a keystone of agricultural improvement in which all programmes aimed at sustainably raising agricultural productivity must be constructed.

Interaction between abiotic and biotic factors (stresses)

In most agroecosystems in Africa, potential yields of improved crop cultivars are not achieved because of the interaction between the germplasm, environment and crop husbandry (Y = G x E x H). For example, in a case study on the very poor Sahelian soils, research demonstrated that there was high potential to increase the staple pearl millet yields by integrating rotation and crop residue restitution, which resulted in 21.6 and 52.8% yield increases, respectively (besides yield increase of 23.9% from N fertilization) (TSBF, 2002). However, replacing land cultivation and planting on flat beds with animal traction and planting on ridges, resulted in a yield decline of 18.4%. The lowest yield of 146 kg ha^{-1} was obtained in traditional planting without fertilization, rotation and crop residue restitution (compared to a yield of 1866 kg ha^{-1} under opposite conditions). Integration of green manure cover crops (GMCCS), another important aspect of ISFM, provides the potential to improve soil productivity through increased SOM content, improved soil microbial and physical properties, suppression of weeds and pests, erosion control and contribution of nitrogen through N fixation. But often this may cause trade-offs such as competing with the food crops of inter - or relay-cropped or for land if rotated. These deleterious effects need to be investigated as a precondition for successful introduction and integration of GMCCS in the agricultural systems as part of the ISFM. For example, work in Eastern and Southern Africa has shown variable results with *Crotalaria grahamania* and *C. ensiformis* to repel mole rat, while *Tephrosia vogelii* has been reported to be prone to root knot nematodes. The studies have shown that short-term legume fallows reduce weed infestation and are also effective in striga weed control. Potential niches for such legumes include:- cereal-legume intercrops, relay cropping, rotational systems, short-term improved fallows, cover crops in steep slopes or under tree crops, fodder systems or bench terraces, under bananas, etc.

Major research breakthroughs have been made in integrating ISFM and IPM, especially through Farmers' Field Schools. The success include management of bean roots diseases through soil fertility improvement, cultural control and use of resistant varieties and integrated disease management (AHI, 1997). Crop tolerance to roots was improved through application of green manure's of *Tithonia diversifolia* (Otsyula *et al.*, 1998). Similarly, bean stem maggots are now effectively managed through optimum time of sowing, earthing up, planting density/soil fertility improvement, use of resistant varieties and use of pesticides (conventional insecticides as well as botanical insecticides such as neem). Integrated potato disease management for Potato Bacterial Wilt (PBW) studies showed that PBW could effectively be managed through use of clean seed, spacing, full roguing, cereal-potato inter-copping/rotation and minimum cultivation after crop emergence (AHI, 1997). But in related studies the development of an IPM programme for the banana weevil, based on sound soil fertility management practices has been constrained by lack of thorough understanding of the interactions among the pest, mulching and organic fertilizers (AHI, 1996). This is an area that requires more ISFM-oriented research.

Crop-livestock Interactions

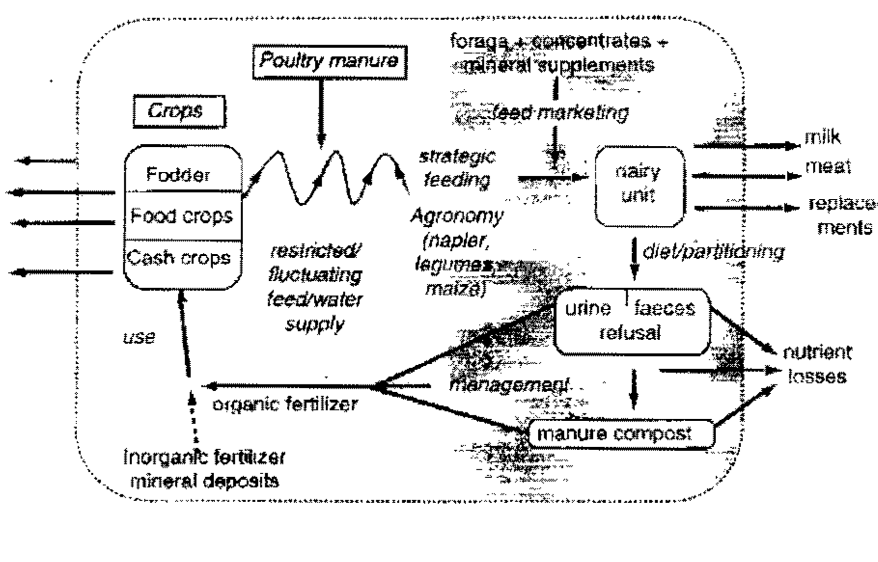
Mixed farming (crop-livestock) is and has been commonly practiced in the intensively managed high quality rainfed lands; densely populated, high/medium quality rainfed intensively managed lands; and the sparse to densely populated, semi-intensively managed marginal land (discussed in Table 1.5, Chapter 1). Recent studies indicate transition from predominantly crop-livestock based system to upland cereal-based system n the high quality rainfed lands. On the other hand in the marginal lands, the transition is from extensive grazing and cropping in new landscape niches resulting in several forms of degradation: Soil erosion, soil fertility depletion, removal of natural vegetation perennials from the landscape, soil compaction and acidification. Degradation in the high quality land include nutrient mining due to depletion or imbalance (due to non-balanced fertilization), and increased use of low quality planting materials, fertilizers and pest control. Purposive integration of crop and livestock farming is perceived to be one strategy to overcome these types of degradation.

A survey conducted in West Africa agricultural intensification system showed that:

(a) Ecology, population density and market access and their interactions are important drivers, manifested both in terms of higher levels and/or intensity of use of various production inputs and interactions and integration between crop and livestock in the various socio-economic domains that represent their interaction.

(b) Intensification increases as one moves from low to high population densities through increased intensity of use of farm resources, commercial inputs (like fertilizers) and sale of outputs. The study confirmed manure as the hub of crop-livestock interaction. One way to improve quality of manure is through evolution of pastoral to mixed farming or crop farming to mixed farming, which may involve an initial decline in the share of livestock or crop income in gross revenue of farms. In the East African Highlands introduction of full or potential livestock confinement (zero-grazing dairy unit) has resulted in higher quality manure and crop yields and involves complex inter-relationships (figure 2.3).

Figure 2.3. Crop-livestock interactions in East African highlands



(Modified from Jon Tanner, DFID, UK)

Policy and institutional framework

Institutional, socio-economic and biophysical factors governing agro-ecoystems in Africa are highly diverse. This calls for the need for combined approaches, with special attention for strengthening farmers' capacity to adopt their systems over time. In this context, ISFM approach should aim to contribute more broadly to sustainable livelihoods of the target farmers. This calls for direct interventions to improve soil status, support to micro-finance and formal credit systems, improving market access, strengthening farmer knowledge and skills, and improving organizational linkages which promote better learning and sharing of ideas (Hilhorst and Toulmin, 2000).

A macro-policy focus may be ideal in circumstances where farmers are sufficiently well integrated into economic and policy circuits for changes at national level to feed rapidly down to the farm. For ISFM to be successful there is need to: influence input and output prices; improve market arrangements; facilitate credit provision; strengthen networks of input suppliers; invest in rural infrastructure, communication and training; change research and extension approaches; accomodate changes in land tenure; and promote diversification of the rural economy. This calls for participatory policy design. Reflection on policies for ISFM clearly needs to link into what is being done in other fields of agricultural policy.

Conclusion

The ISFM, as a new research approach, seeks to overcome the shortcomings of past conventional approaches. This is based on agro-ecological principles, farmers' participation and interdisciplinary perspective and therefore, emphasizes context-specific and adaptive responses, tailored to local conditions, as well as opportunities and constraints faced by farmers. It links the development of resource conserving technologies, support to institutions and farmer groups and provision of enabling policy environment for agricultural investment. The approach advocates for participatory farmers research; a holistic approach to address many and complex farming systems problems so as to achieve wide validity and adoption of agro-ecosystems that operate with dynamic natural and economic environment. Research based on new approaches indicate that ISFM is a rational research approach and is based on sound soil management principles. These include:

- Maximization of input use efficiencies and return to investments through integrated use (supplantation or supplementation) of mineral fertilizers with organic resources of animal or plant origin,
- Integration of legumes with multi-purpose roles in agro-ecosystems,
- Crop-livestock integration to improve the sustainability of nutrient cycles,

- Integration of abiotic factors such as water harvesting and soil conservation methods to control soil loss and improve water capture and use efficiency,
- Integration and judicious application of knowledge on the relationship and interaction between soil fertility management and biotic stresses of crop diseases, pests and weeds,
- Integration and application of knowledge gained from studies aimed at enhancing of the soil organic carbon pool as an integrator of many abiotic-based functions related to ecosystems services,
- Integration of farmers and scientist knowledge.

The ISFM also requires that the notion of dynamics and diversity be integrated in policy interventions. Policies which positively influence the profitability and security of farming are likely to have important impact in the investment in ISFM.

References

AHI (1996) Relationships of the Banana Weevil with its Host Plant and Soil Fertility. *The African Highlands Initiative Technical Report* Series No. 2. 22 pages.

AHI (1997a) *The African Highlands Initiative, A Conceptual Framework*, 24 pages, ICRAF, Nairobi, Kenya.

AHI (1997b) Integrated Pest Management for Beans. *African Highlands Initiative*, Nairobi, Kenya. 12pp.

AHI (1997c) Phase II Workshop and Budget (1998-2000). *African Highlands Initiative* 61 pages, Nairobi, Kenya.

Baltissen, G., Wabwile, E. and Defoer, T. (2000) Up-scaling and Institutionalizing Participatory Learning and Action Research (PLAR) for Integrated Soil Fertility Management (ISFM) in Western Kenya. *Managing Africa's Soils* No. 20. IIED, UK.

Barrios, E., Bekunda, M., Delve, R., Esilaba, A. and Mowo, J. (2000) Identifying and Classifying Local Indicators of Soil Quality: Participatory Methodologies for Decision Making in Natural Resource Management. Eastern Africa Version, Cali, Columbia.

Buresh, R. J., Smithson, P. C. and Hellums, D. T. (1997) Building Soil Phosphorus Capital in Africa. SSSA Special Publication No. 51, *Replenishing Soil Fertility in Africa*. p 111-150.

Defoer, T., H. de Groot, Hilhorst, T., Kante, S. and Budelman, A. (1998) Participatory Action Research and Quantitative Analysis for Nutrient Management in Southern Mali: a fruitful marriage? *Agric. Ecosyst. Environ.* **71**: 217-230.

Defoer, T., Kante, S., Hilhorst, T. and de Groote, H. (eds) (2000) Managing soil fertility. *A Resource Guide for Participatory Learning and Action Research*. Royal Tropical Institute, Amsterdam.

de Villiers, A. K. (1996) *Quantifying indigenous knowledge: a rapid method for assessing crop performance without field trials*. Agricultural Research and Extension Network, AgREN Paper No. 66.

Garforth, C. J. and Gregory, P. J. (1997) Maintaining Soil Fertility: Farmers' and Scientists' Perceptions. In: Gregory, P. J., Pilbeen, C. J. and Walker, S. H. (eds) *Integrated nutrient management in farmers' fields: Approaches that work.* Pp 17-26, Department of Soil Science, University of Reading. Occasional Paper No. 1. UK.

Gitari, J. N., Matiri, F. M., Kariuki, I. W., Muriithi, C. W. and Gachanja, S. P. (1999) Nutrient and Cash Flow Monitoring in Farming Systems on the Eastern Slopes of Mount Kenya. In: Smaling, E. M. A. Oenema, O. and Fresco, L. O. (eds). *Nutrient Disequilibria in Agroecosystems: concepts and case studies*, CABI Publishing pp 211-228.

Hilhorst, T. and Toulmin, C. (2000) *Integrated Soil Fertility Management. Policy and Best Practice.* Document No. 7. Ministry of Foreign Affairs, The Hague, Netherlands.

IIRR (1998) *Sustainable Agriculture Extension Manual for Eastern and Southern Africa.* International Institute of Rural Reconstruction, Nairobi, Kenya. p125-126.

Kayuki, C. and Wartman, C. S. (2001) Plant Materials for Soil Fertility Management in Sub-Humid Tropical Areas. *Agronomy Journal.* **93(4):** 929 - 935.

Kimetu, J. M. (2001) Determination of Nitrogen Fertilizer Equivalent for Organic Materials Based on Quality and Maize Performance at Kabete, Kenya. A Thesis submitted to Kenyatta University in Partial Fulfillment of the Requirements for the Degree of Master of Environmental Studies in Agroforestry and Rural Development. 64 pages.

Onduru, D., Gachini, G. N. and Nandwa, S. M. (1998) Experiences in Participatory Diagnosis of Soil Nutrient Management in Kenya. Managing Africa's Soils No. 3. IIED, UK.

Otsyula, R. M., Ajanga, S. I., Burnchara, R. A. and Wortman, C. S. (1998) Development of an integrated bean root rot control strategy for Western Kenya. *African Crop Science Journal.* **6(1):** 61-67.

Palm, C. A., Gachengo, C. N., Delve, R. J., Cardish, R. J. and Giller, K. E. (2001) Organic Inputs for Soil Fertility Management in Tropical Agroecosystems: Application of an Organic Resource Database. *Agric. Ecosyst. Environ.* **83:** 27-42.

Scoones, I. and Toulmin, C. (1998) Soil Nutrient Balances: What Use for Policy. In: E. M. A. Smaling (ed) Nutrient Balances as Indicators of Productivity and Sustainability in Sub-Saharan African Agriculture. *Agric. Ecosyst. Environ.* Special Issue. **71:** 255-267.

Singh, V., Giller, K. E., Palm, C. A., Ladha, J. K. and Breman, H. (2001) Synchronizing N Release from Organic Residues: Opportunities for Integrated Management of N. *The Scientific World.* **1(52):** 880 - 886.

TSBF (2002a) *Tropical Soil Biology and Fertility Institute of CIAT.* The African Network for Soil Biology and Fertility (AfNet): Network Research Progress Report, 2002 p 9-10.

TSBF (2002b) Soil Fertility Degradation in Sub-Saharan Africa: Leveraging Lasting Solutions to a Long-term Problem. Conclusions from a workshop held at Rockefeller Foundation Bellagio Study and Conference Centre, March 4-8th, 2002. TSBFI, Nairobi, Kenya.

3

Maize Based Cropping Systems in the Subhumid Zone of East and Southern Africa

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Introduction

The subhumid zone accounts for 38% of the total land area of Sub-Saharan Africa (SSA) (Deckers, 1993). The subhumid zones of Southern Africa, Central, East and West Africa have a variable growing season length of 180 to 270 days. The rainfall pattern in the Southern Africa region is unimodal with a range of 800 to 1200 mm per annum. The rainfall pattern in East and Central Africa is bimodal characterized by short and long rainy seasons. In the unimodal subhumid areas, rainfall pattern is highly variable in terms of start of the season and amount of total rainfall received in the season. This high variability in the amount of rainfall received is associated with mid-season droughts and variable crop yields especially for maize. The zone is commonly referred to as 'the bread basket of Africa' and it is characterized by high variability in soil types, rainfall, altitude and climate. High population densities are found in this zone resulting in various degrees of agricultural intensification.

The major soil types in the subhumid zone of East, Central and Southern Africa are a result of parent material, age and past and current climatic conditions. The main soil types found in this zone are shown in (Table 3.1).

Table 3.1. Distribution of major soil types in the subhumid zone of Sub-Saharan Africa

FAO classification	USDA Taxonomy	Area in km^2	% coverage of total area	Areas of major occurrences
Ferralsols	Oxisols	1847898	32	Zaire, Angola, Zambia, Rwanda, Burundi, Uganda, Southern Sudan
Acrisols	Ultisols	530603	9	Subhumid West Africa, Southern Guinea, Togo, Benin, Nigeria, Central, Cameroon, Côte d'Ivoire
Lixisols	Alfisols	1666151	29	South-East Africa, Madagascar
Nitisols	Paleustults Paleulistalfs	435931	8	Ethiopia, Kenya, Tanzania, East Zaire
Arerosols	Psamments	580433	10	N. Senegal, N. Mali, Southern Niger, E. Sudan, S-E Zaire, Botswana, Angola
Vertisols	Vertisols	158785	3	Sudan, Tanzania, Ethiopia
Others	Various	301258	9	Limited occurrences
Total	-	5753564	100	

Source: Decker, (1993) and Sanchez and Logan, (1992)

With the exception of Uganda, Burundi and Rwanda where bananas are the main staple food, maize is the main staple food crop in East and Southern Africa, with an estimated land area of about 15.5 million ha (Pingali, 2001). Rosegrant *et al.* (1996), estimated that the demand for maize in this region of Sub-Saharan Africa would rise from 21.3 million tonnes per year in 1990 to over 52 million tonnes in 2020. Compared to the minor cereals such as millet and sorghum, maize is a main staple food due to its:

- Higher grain yields compared to millet
- Requires less processing
- Not susceptible to bird damage when compared to sorghum
- Maize crop has wide plasticity; it is grown in a wide range of environments
- Maize is also a cash crop with ready markets within the region
- High input responsiveness
- Easy to grow agronomically using hand labour and tools
- High suitability for many agro-industrial processes

This chapter will discuss the soil fertility management in the subhumid zone in relation to soil biology, then discuss the main maize cropping systems such as intercropping and maize monocropping systems and soil fertility management issues in these systems. Maize-livestock interaction will be discussed since manure is a predominant source of nutrients for most maize cropping systems in the subhumid zone. Issues on integrated resource management including organics combined with inorganics are also discussed. A synthesis is presented including some highlights of what works and some indication of innovations for future research.

Soil Fertility Constraints

Soil constraints in the subhumid tropical Africa can be divided into two major types: soil chemical and physical constraints. The chemical constraints include low nutrients reserves, low cation exchange capacity (CEC), aluminium toxicity, soil pH and phosphorus fixation as suggested by Sanchez and Logan (1992). The physical constraints to increased soil productivity are limited rooting depth, low water holding capacity and susceptibility to soil erosion, soil crusting and compaction.

Low nutrient reserves and cation exchange capacity

About 55% of the soils in the subhumid zones of SSA have inherent low nutrient reserves (Sanchez and Logan, 1992). For instance, net annual losses of more than 30 kg N/ha have been estimated for some Eastern and Southern African countries (Smaling, 1993; Stoorvogel *et al.*, 1993). This constraint is especially found in highly weathered soils such as Oxisols and Ultisols. These and other soils such as the sandy Psamments have limited capacity to retain and to supply cations and other major nutrients such as Nitrogen (N), Phosporus (P) and Sulphur (S) required by plants, with the exception of Vertisols and Alfisols. Most of these soils are extremely nutrient-depleted and crop production can only be sustained by regular addition of external nutrients and by proper soil organic matter management.

Nitrogen deficiency

Nitrogen is the key nutrient for crop production. This element is the most mobile and also the most easily exhausted nutrient in the soil. Smallholder farmers rely on natural fallow periods and use of leguminous crops to restore soil nitrogen status (Nye and Greenland, 1960; Kwesiga and Coe 1994; Hartermink *et al.*, 1996). However due to high population density and land pressure in subhumid tropics, long fallow periods are no longer sustainable. To sustain high crop yields in intensive and continuous crop production system, nitrogen fertilizer input is required. This is particularly so in commercial farms in Kenya and Zimbabwe. As nitrogen is the most costly nutrient and its availability can also be a problem to smallholder farmers, efforts should be made to increase efficiency of nitrogen fertilizer use (that is reported to be very low in most smallholder farms (Palm *et al.*, 1997)) and develop an integrated nitrogen management system that can fully exploit biological nitrogen fixation and other organic sources of N in various production systems.

The potential N contribution from biological nitrogen fixation (BNF) and other organic inputs can be very significant in maize production systems. The beneficial effects come mostly from nitrogen in the crop residues and tree prunings. Nitrogen contribution by grain legumes, however, may be small due to N removal in grain at harvest compared to contribution from prunings of tree legumes and it is also usually higher from sole than intercropped legumes. Sole grain legumes in rotation with maize can contribute between 40-70 kg N/ha to the subsequent crops. Inclusion of legumes as green manure, cover crops and improved fallows in maize based cropping systems offers additional benefits such as weed suppression, soil erosion control and soil structure amelioration. The organic input can also provide carbon sources to microbial biomass and increase microbial activity (unlike inorganic N fertilizer) and assist in maintaining or increasing soil organic matter status of the soil.

Phosphorus deficiency, fixation and soil acidity

Apart from nitrogen, phosphorus is a major element limiting crop production in the tropics (Buresh *et al.*, 1997) especially in East Africa. Phosphorus problem is exacerbated by fixation by aluminum (and iron) in the vast majority of soils in the zone especially Ferralsols, Acrisols and Nitisols (Buresh *et al.*, 1997). This problem may be overcome by application of small amounts of P and other P strategies reviewed by Buresh *et al.* (1997).

Another related problem of Ferralsols, Acrisols, Lixisols and Nitisols is the pH dependency of the nutrient storage capacity. Regular application of lime and organic inputs into the soil would raise soil pH and reduce phosphate fixation and aluminium toxicity. The action of organics is attributed to production of organic acids during decomposition that block or react with P fixing sites (bind aluminum reducing its saturation and thereby reducing soil acidity) (Wong *et al.*, 1995; Nziguheba *et al.*, 1998). In addition, application of organic inputs especially those of high quality may lead to increase in soil microbial biomass and thus may increase nutrient availability.

Poor structural stability and induced hard pan formation

The structural stability of many soils in subhumid zones, particularly the Alfisols, is very low and the aggregates are easily destroyed on watering by rainfall or irrigation water. The break down of main aggregates is due to entrapped air and differential swelling called sling, which results in formation of micro aggregates. Such crusting reduces aeration and infiltration of rainwater. Cultivation of such soils when wet leads to formation of hard pans in the plough layer. Low organic matter content and low clay content (3 to 12%) are some of the conditions that lead to crusting and compaction.

The consequences of hard crusting and compaction lead to:

- Increased runoff and erosion rates
- Restricted root growth
- Seed germination impairment
- Decreased crop yields

Application of organic inputs to the soil may lead to higher soil organic matter (SOM) content and increased microbial population leading to more aggregate stability which will increase infiltration rate and reduce erosion losses of soil and nutrients. Despite the belief that soil organic matter contents cannot be replenished in tropical soils under cultivation due to the 'fast rate of oxidation', there are examples where SOM has been increased depending on the amount of organic residues returned to the soil. For example Bache and Heathcote (1969), demonstrated that addition of cattle manure at 2 t/ha for 15 years led to small increases in soil carbon (from 0.24 to 0.43%) and N (from 0.021 to 0.034% N content at Samaru, Nigeria. At Kabete, Kenya however, addition of 10 t/ha of cattle manure combined with return of all crop residues failed to prevent a decline in the SOM contents in an Alfisol cropped annually to maize and beans (Kapkiyai *et al.*, 1997).

Soil moisture is a major constraint to increased crop productivity especially in subhumid zones. Soils such as Oxisols, Ultisols and Psamments have limited ability to hold water due to their low clay content. Associated with this property is the occurrence of soil erosion especially on Psamments and some Alfisols. Application of organic inputs may lead to high SOM and increase the water holding capacity of these soils.

Maize Cropping Systems

Due to high variability in climatic conditions, diverse soil types, population density and socio-economic factors, maize cropping systems are very diverse in this zone. They range from intercropping systems for risk management and efficient use of land and labour resources to solecropping systems. Solecropped maize can be produced from high fertilizer inputs (commercial maize production especially in Kenya and Zimbabwe) to solecropped maize rotated with legumes or maize produced with integration of organic and inorganic inputs.

Maize sole cropping

As mentioned earlier, maize is the main staple food in the subhumid tropics of Africa. During the colonial era, farmers were encouraged to solecrop maize instead of the traditional practice of intercropping. A case in point was in Zimbabwe where the *master farmer scheme* by colonial extension system encouraged sole cropping and rotation of maize with legumes for farmers to get a master farmer certificate. The advantages of sole cropped maize were ease of mechanization, weed control and use of fertilizers.

This extension practice of sole cropping led to the use of the mouldboard plough. The continuous use of the plough for the same ploughing depth led to the formation of hard pans with its associated problems. The soil fertility maintenance practice under solecropping was rotation of maize with grain legumes or green manures. Manure from livestock was also applied to maize as a source of nutrients. Where subsidies to farm inputs were available, inorganic fertilizers were used to maintain high maize yields. The use of inorganic fertilizers on maize has been largely uneconomic in some countries since the removal of government subsidies (Benson, 1997). This led to continuous cropping without inorganic inputs resulting in negative nutrient balance for N, P and K in most countries (Smaling, 1993). This led to the search for more sustainable technologies such as crop rotations, improved fallows, biomass transfer, hedgerow intercropping and integrated nutrient management techniques which combine inorganic and organic sources of nutrients.

Commercial monocropping maize system

Commercial agriculture based on high level mechanization, huge amounts of inorganic fertilizer inputs and agrochemicals were introduced in subhumid Africa since the advent of the green revolution. This was particularly important for maize with the introduction of high yielding hybrid varieties. Commercial farmers especially in Zimbabwe and Kenya have adopted the green revolution in maize production. It is estimated that 50% of the annual global food supply will come from the application of inorganic fertilizers alone (Dyson 1995). Maize yields up to 10 t/ha have been obtained with inorganic fertilizer inputs of 600-1000 kg of nutrients per ha. This has been responsible for meeting half of the national maize requirements and also for export markets. While productivity of this type is very high, its sustainability in terms of soil biology and productivity and economic viability is starting to be questioned.

Literature review by Bekunda *et al.* (1997) showed that continuous application of inorganic fertilizers over the long term led to decrease in maize yields. Similar results have been observed in the long term experiments at the National Agricultural Research Laboratories, Kenya (Kapkiyai *et al.*, 1999). The reasons for this decline could be due to the following:

- Soil acidification by fertilizers, especially ammonium-based fertilizers
- Mining of nutrients via harvest (more nutrients in grain and stover than added through fertilizer application)
- Leaching of N fertilizer
- Declining of soil organic matter

Mineral fertilizers should be part of the overall strategy to restore soil fertility and increase crop productivity in subhumid Africa. However exclusive use of inorganic fertilizers will not solve the soil mining problems considering the fact that the use of such a nutrient source does not replenish the declining SOM that is crucial to the sustainability of agriculture especially for the smallholder farmers. As such an integrated approach of using inorganic fertilizers with organic inputs should be promoted to ensure sustainability of the cropping systems.

Maize intercropping systems

Maize intercropping systems are very common in large areas of East and Southern Africa. Maize and beans (*Phaseolus vulgaris*) are predominant in East Africa. In Southern Africa, maize is intercropped with cowpeas, groundnuts and bambara nuts to a less extent. The importance of intercrops is widely recognized by farmers. This arises from the stabilizing effect of crops on food security, enhanced use efficiency of land, water and labour and risk aversion in case of crop failure. The role of intercrops in soil fertility maintenance is also documented. The low plant densities of legumes found in most intercrops means that they can input modest amounts of N and organic matter each year to maintain soil fertility. However, because they do not take away land from cereals, farmers may be willing to use them every year so that the aggregate effect may be enhanced land productivity.

Grain legume intercropping systems

Intercropping of grain legumes generally results in the legume deriving a greater proportion of its N from N_2 fixation than when grown alone, but legume dry-matter production and N accumulation are usually reduced because of competition from the companion crop (Table 3.2) so that the overall amount of N_2 fixed is less than that of sole crop of a legume. Cowpea intercropping was advantageous with maize or millet in seasons with adequate rainfall, but the cowpea competed strongly with the cereal crop for soil water when rainfall was limiting (Shumba *et al.*, 1990). One notable exception again is traditional pigeonpea, which has a phenology complementary to that of most cereal crops. Its initial aboveground growth and development is very slow, hence there is little direct competition between the two crops (Natarajan and Mafongoya, 1992). The long duration and its ability to root deeply allows the pigeonpea to grow on after the companion cereal crop has been harvested, utilizing residual moisture in the soil. However, although sole pigeonpea produced clear residual effects in the growth of subsequent maize, the residual effects of maize – pigeonpea intercrops were not substantial (Kumar-Rao *et al.*, 1983, Kumar-Rao and Dart, 1987), presumably because of reduced inputs of N. Despite claims for substantial *transfer* of N from grain legumes to companion cereal crops, the evidence indicates that benefits are limited and largely due to *sparing* effects (Giller *et al.*, 1991). Benefits are more likely to accrue to subsequent crops as the main transfer pathway is due to root and nodule senescence and fallen leaves (Ledgard & Giller, 1995).

Table 3.2. Biomass and nitrogen accumulation of green manure crops in Malawi

Legume crop	Cropping system	Age in weeks	Dry matter t/ha	N accumulation kg/ha
Crotalaria	Sole	16-24	2.6	50-190
ochroleuca	Intercrop	16-24	1.5	38
Mucuna pruriens	Sole	13-18	2.9	60-290
	Intercrop	13-18	3.6	105
Cajanus cajan	Sole	35-52	4.8	75-200
	Intercrop	35-52	2.5	105
Mucuna	Sole	52	3.3	131
	Intercrop	52	0.4	16
Sun hemp	Sole	52	15.0	ND
	Intercrop	52	5.0	ND

Source: Kumwenda *et al* (1996)
ND = not determined

Relay intercropping maize systems

Intercropping and relay cropping of legume green manures or trees have the advantage that crops are still produced while organic material is produced for soil amendment. The obvious disadvantages are that the green manures or trees may compete with the crops, and that the amounts of organic material produced are generally less as compared to when they are produced alone. Thus, whether intercropping with green manures and trees is advantageous depends on this balance and the costs and benefits involved. The net benefits may however, vary significantly between sites and seasons, depending on the availability of water and nutrients, and the unpredictable nature of the interactions between the green manure and the crop adds a risky complication. Relay planting can reduce the likelihood of competition with the crop where rainfall is limited, with the production of the green manure restricted by its ability to use residual water after the main cropping season.

Hedgerow intercropping maize system

Hedgerow intercropping (also referred to as alley cropping), developed by scientists at the International Institute for Tropical Agriculture (IITA) in the early 1980s, has been very useful in developing a better understanding of tree-crop interactions (Vanlauwe *et al.*, 1996). It consists of growing food crops in the alleys formed by hedgerows of multipurpose trees and shrubs (MPTs) that are usually N_2 fixing. The hedgerows are cut back (lopped) and periodically pruned during the cropping season to prevent shading of the companion crops. The prunings provide nutrients when incorporated into the soil as green manure or spread on the soil surface as mulch (Kang *et al.*, 1990). By retaining woody perennials in crop production fields on a continuing basis, alley cropping simulates the role of fallow in soil fertility regeneration in shifting cultivation (Nair, 1993).

Though alley cropping technology has generated a lot of data to date, it seems that the system performance is location-specific and greatly influenced by the choice of tree species and the type of management adopted (Mugendi *et al.*, 1999a;b). Generalizations and extrapolation of results to seemingly similar environments is, therefore, difficult and as well misleading (Nair *et al.*, 1999). In order to assess the long-term performance of alley cropping, Rao *et al.* (1997), reviewed the results of 29 trials, mostly with small plots, conducted for four or more years over a wide range of soils and climates across the tropics. The results showed both positive and negative effects of alley cropping on crop yields. In the semiarid sites, only two of ten studies gave substantial yield increases. In subhumid environments, significant positive yield responses were observed in seven out of eleven studies while in the humid tropics, maize and taro did not benefit from hedgerow intercropping in four out of eight trials, though bean and cowpea yields invariably increased.

Low biomass production of the hedgerow tree species (2 to 3 Mg/ ha/yr) and competition of hedgerows for water with crops are the major drawbacks limiting the potential of prunings to improve fertility and productivity of soils in the water-limited areas (Ong *et al.*, 1991; Rao *et al.*, 1991; Mugendi *et al.*, 1997; Mathuva *et al.*, 1998). Inadequate water limited the response of crops even though alley cropping improved soil fertility in certain sites of the semiarid tropics. In such cases, a biomass transfer (cut-and-carry) system has been proposed as a more beneficial system than alley cropping (Jama *et al.*, 1995). In certain other sites, especially in the subhumid zone, where hedgerow intercropping has been demonstrated to be a viable technology, issues revolving around labour required in the intensive management of the tree hedges have continued to be a disincentive to the adoption of the technology (Kang *et al.*, 1990; Mugendi *et al.*, 1999a;b). An exception may be on steeply sloping lands, where hedgerows can be planted on contours to help prevent soil erosion (Young, 1997).

Another form of hedgerow intercropping is the one that has recently been developed by scientists at the Makoka Research Station (ICRAF, 1997) in southern Malawi known as mixed intercropping system. The system allows continuous cultivation without fallowing. The soils in southern Malawi are mainly deficient in nitrogen, but fallowing is precluded because of small land holding due to high population density. High population density and extremely small farm size also preclude cattle production, thereby eliminating the potential use of manure as nutrient input. Mixed intercropping system that integrates *Gliricidia sepium* trees grown in furrows with maize occupying the ridges has been developed to address this problem of nitrogen deficiency. The system ensures that maize population is the same as in the sole cropping system. The trees are coppiced and the prunings applied as green manure to the maize ridges. The results so far indicate that use of *Gliricidia* green manure can greatly increase maize yields over those obtained through continuous sole cropping. The beneficial effect of the mulch was significant in four of the five cropping seasons, when maize yields from intercropped treatments were substantially higher than those from control plots (both with and without the addition of mineral fertilizer) as exemplified by the results of the maize grain yields in both 1996 and 1997 (Table 3.3). Lower yields in 1997 were attributed to excessive rainfall and waterlogging. Topsoil ammonium, nitrate and total inorganic nitrogen (ammonium + nitrate) were significantly correlated with maize grain yields in both 1996 and 1997. For both seasons combined, pre-season inorganic nitrogen was correlated with maize grain yield.

Table 3.3. Maize grain yield with and without *gliricidia* intercropping and fertilizer nitrogen in 1996 and 1997 at Makoka, Malawi

	<u>1996</u>	<u>1997</u>		
Fertilizer added (kg N/ha)	No. tree	Tree	No. tree	Tree
	Maize grain yield (t/ha)			
0	1.0	4.8	0.4	3.5
24	3.5	6.1	2.0	3.6
48	4.2	6.7	2.1	4.3

LSD (0.05): N rate = 0.45, tree biomass = 0.36 for 1996

LSd (0.05): N rate = 0.50, tree biomass = 0.41 for 1997

Source: ICRAF (1997)

Intercropping and relay cropping of legume green manures or trees have the advantage that crops are still produced while organic material is produced for soil amendment. The obvious disadvantages are that the trees may compete with the crops and that the amounts of organic material produced are generally less than when the land is devoted to soil improvement. Whether intercropping with green manures and trees is advantageous depends on the balance between the benefits and the costs. The net benefits may vary significantly between sites and seasons, depending on the availability of water and nutrients and the unpredictable nature of the interactions between the green manure and the crop adds a risky complication. Relay planting can reduce the likelihood of competition with the crop where rainfall is limited, with the production of the green manure restricted by its ability to use residual water after the main cropping season.

Green manure and cover crops

Many leguminous species are now grown as green manure and cover crops for erosion control, weed suppression and for soil fertility restoration. The advantages associated with the use of cover crops include:

(1) enriching the soil with biologically fixed N,
(2) conserving and recycling soil mineral nutrients,
(3) providing ground cover which helps minimize soil erosion, and
(4) requiring little or no cash input (Franzluebbers *et al.*, 1998).

Biological N contribution is probably the main reason why farmers include legume cover crops in cropping systems (Jeranyama *et al.*, 1998).

A legume cover crop may contribute N to a subsequent non-leguminous crop, reducing N fertilizer needs by 100 kg N/ha and more in some cases (Hesterman *et al.*, 1992). It is however, also worth noting that cover crops can also deplete the soil moisture necessary for grain production in semi-arid areas (Badaruddin and Meyer 1989) and can compete for light and nutrients with the revenue crop (Badaruddin and Meyer 1989). Farmers can therefore take advantage of the beneficial effects of green manure and cover crop species to maintain and improve their farm productivity.

Many fast growing leguminous species such as mucuna (*Mucuna pruriens*), soya beans (*Glycine max*) and various species of the *Phaseolus* family can be especially useful as green manures and cover crops. Gitari *et al.* (2000) studied the performance of *Mucuna pruriens* and *Crotolaria ochroleuca* green manure legumes under different combinations with crops in Mount Kenya region. In the long rain season, maize grain yield was 6.5 and 3.1 t/ha, where only legume residue was used as a source of N at Karurina and Gachoka sites, respectively. This is compared with farmer practice (use of different combinations of inorganic fertilizers) grain yield of 3.5 and 2.7 t/ha for the same sites. In general, maize grain yields at both sites were highest in plots where legume green manure was used alone or in combination with either animal manure or mineral fertilizers. In a similar study carried out by Kamidi *et al.* (2000) at Matunda in Western Kenya, legume green manures tended to boost maize and bean grain yields. The green manures planted were velvet bean (*Mucuna pruriens*), soybeans (*Glycine max*), dolichos (*Lablab purpureus*), sunnhemp (*Crotalaria ochroleuca*) and cowpeas (*Vigna unguiculata*). The yields from plots under legume cover and half the recommended rates of inorganic fertilizers recorded significantly higher grain yields (velvet bean- 7.2 tha^{-1}, soybeans- 6.9 tha^{-1}, sunnhemp- 7.4 tha^{-1}, cowpeas- 7.1 tha^{-1} and dolichos- 6.6 tha^{-1}) than that obtained from farmer practice (4.8 tha^{-1}). In this same study Mucuna had the highest ground cover (72%) followed by *Crotalaria* (63%) and *Lablab* (54%). Soybeans and cowpeas gave the lowest ground cover (32% and 38%, respectively). The groundcover offered by these green manures greatly reduced soil erosion especially during the long rain season as noted by Gachene *et al.* (2000).

Increasingly the traditional nutrient sources for soil fertility management are produced in insufficient quantities and quality to meet maize crop demands (Palm *et al.*, 1997). Alternative higher quality sources must be found but there must also be niches on farms, or the vicinity, where they can be produced. Leguminous plant materials provide higher quality organic inputs to meet N demands, if not P, but incorporating non-food legumes in the farming systems require a sacrifice of space or time that is normally devoted to crop production. Additional labour requirements for planting, transporting and incorporating these materials is also high (Jama *et al.*, 1997). As such legumes for soil fertility improvement have not been widely adopted by farmers (Jama *et al.*, 1998). The economic and social trade-offs of improved soil fertility using legumes and other high quality organic materials must be properly assessed in comparison to that of the management of crop residues and animal manures. Moreover access to seed, incidences of pests and diseases as well as competition for water, light and nutrients between the crop and the green manure/ cover crops need to be properly understood inorder to make this technology sustainable.

Grain legumes in crop rotations

The role of leguminous crops in maintaining soil fertility is well recognized but has too frequently been overestimated. Mixed intercropping of cereals with herbaceous legumes such as groundnuts (*Arachi hypogaea*), soybeans [*Glycine max* (L) Merr] and *Phaseolus* beans or tree legumes such as pigeonpeas (*Cajanus cajan*) has been advocated (MacColl, 1989). Tropical grain legumes can certainly fix substantial amounts of N given favourable conditions, but the majority of this N is often harvested in the grain. Legumes such as soybean that have been subject to intense breeding efforts are very efficient at translocating their N into the grain, and even when the residues are returned to the soil there is generally a net removal of N from the field (Giller *et al.*, 1994). Some promiscuous soybean varieties that are leafier, have a greater potential to add N to the soil, and are potentially more appropriate for cultivation by smallholder farmers than the recommended varieties grown on commercial farms in Southern Africa (Mpepereki *et al.*, 1996). Soybean residues at harvest are lignified (10% lignin) with C/N ratios around 45:1 and these tend to immobilize N when they are added to the soil (Toomsan *et al.*, 1995). By contrast, groundnut (*Arachis hypogaea* L.) residues can contain >160 kg Nha^{-1}, are less lignified (5% lignin), and are rich in N, as the crop is harvested while still green.

If returned to the soil, groundnut residues can easily lead to doubling of maize yields (Snapp *et al.*, 1998). For many years rotation of maize with groundnut has been the most common legume and cereal crop sequence on smallholder farms in sub-humid parts of Zimbabwe (Shumba, 1983; Metelerkamp, 1987). Under favourable management and when groundnut residues are incorporated on sandy soils, groundnut in rotation can double the yield of the following maize, particularly when the maize is grown with little or no N fertilizer (Mukurumbira, 1985). There is growing realization that on most smallholder fields where the grain and biomass yields from grain legumes are very poor and where both the grain and most of the legume stover are removed from the field, there may be little or no net N contribution by the legume to the soil and so little improvement in yield of the subsequent maize (MacColl, 1989).

The exceptions to this rule of large losses of nutrients in grain harvests are the longer duration grain legumes such as pigeonpea [*Cajanus cajan* (L) Millsp.] and varieties of cowpea [*Vigna unguiculata* (L.) Walp. ssp unguiculata], which may lose a substantial amount of biomass in the form of roots and leaves that fall before harvest (Giller & Cadisch, 1995). A sole pigeonpea crop drops up to 40 kg N/ha in fallen leaves during its growth (Kumar-Rao *et al.*, 1983), and its small harvest index means that a relatively large proportion of the fixed N remains in the field which can give a substantial benefit to subsequent crops. In addition, the rooting habit of pigeon pea has an added advantage of mining nutrients from deeper soil horizons thereby enriching the upper surface of the soil through leaf fall and litter decomposition (Van Noordwijk, 1989; Mekonnen *et al.*, 1997).

But virtually all the information that is available on legume N contributions is from research conducted on experimental stations where the crops have been adequately fertilized with P and other nutrients, and often irrigated. As biomass and yields of sole-cropped grain legumes under smallholder conditions in Africa are often small (<500 kg/ha of grain), the amounts of N_2 fixed are barely significant. For example, in the Usambara Mountains in northern Tanzania, where bean (*Phaseolus vulgaris* L.) is the staple grain legume, most farmers' crops lacked nodules because of severe P deficiency, and amounts of N_2 fixed were estimated to be 2 to 8 kg N ha^{-1} (Amijee and Giller, 1998). Amounts of N_2 fixation by grain legumes also can however be severely constrained by drought.

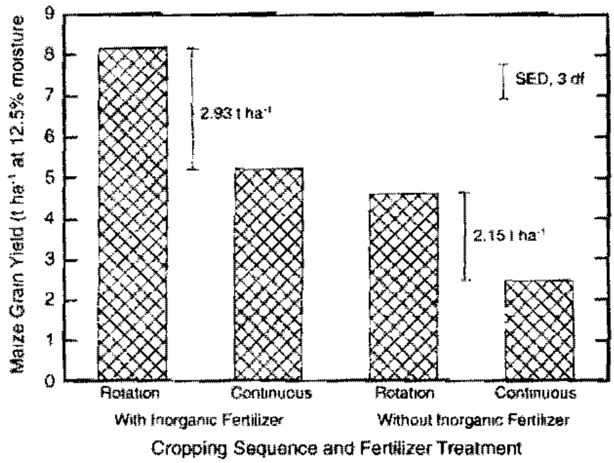
Improved fallows

Traditional shifting cultivation such as chitemene and fundikila (in Zambia) and other forms of shifting cultivation with intermittent long natural fallow periods were adequate to maintain soil fertility and crop production. However, the increasing demand for land as a result of population increase has reduced the fallow periods from about 5 to 2 years making the system unsustainable. Planted tree fallows with leguminous trees or shrubs that accumulate N in the biomass through biological nitrogen fixation (BNF) and capture of subsoil nitrogen (otherwise unutilized by crops) have been found to be an excellent option to replace natural fallows and increase maize yields on N deficient sites (Kwesiga and Coe, 1994).

Short-term fallows of leguminous trees and herbaceous cover crops can provide a practical means of nutrient cycling when grown in rotation with cereal crops. Two-year tree fallows of sesbania [*Sesbania sesban*) (L) Merr.] or tephrosia (*Tephrosia vogelii* Hook. F.) have replenished soil

N to levels sufficient enough to grow three subsequent high-yielding maize crops in N-depleted, but P-sufficient soils in Southern Africa (Kwesiga and Coe, 1994; Kwesiga *et al.*, 1998; Figure 3.1). In general, woody fallows accumulate larger N stocks than herbaceous ones because of their larger and continuing biomass accumulation than those of herbaceous fallows do. The residual effects of tree fallows are therefore longer than herbaceous fallows.

Figure 3.1. The grain yield of maize with and without fertilizer in the fourth year of a long-term trial involving rotations with groundnuts, Domboshava, 1995/96



Rotation = Maize after groundnuts in a maize/maize/gnuts/maize rotation
Continuous = Fourth year of continuous maize
With inorganic fertilizer = 92 kgN, 17 kg K ha^{-1} each year on maize, no fertilizer on groundnuts
Without inorganic Fertilizer = No fertilizer on maize for four years, no fertilizer on groundnuts

Source: Snapp *et al* (1998)

There is evidence that non-N-fixing trees and shrubs of the genus *Senna* and *Tithonia* accumulate as much N in their leaves as N-fixing legumes presumably because of their greater root volume and ability to scavenge nutrients from the soil (Szott *et al.*, 1991; Garrity and Mercado, 1994, Gachengo, 1996). But it is important to note that these non-fixing trees are only cycling the N present in the soil, not adding inputs to the system, as happens via BNF in woody and herbaceous leguminous fallows. Non-fixing trees and shrubs can only be considered to be N inputs when biomass is transferred from one field to another.

Tree roots are often able to capture nutrients at depths beyond the reach of most crop roots. This can be considered an additional nutrient input in agroforestry systems when such nutrients are transferred to the topsoil via the incorporation and subsequent decomposition of tree litter. Hartemink *et al.* (1996), and Buresh and Tian (1997), detected subsoil nitrate levels in the order of 70 to 315 kg N ha^{-1} at 0.5- to 2 m depth in maize- based systems in Oxisols and Alfisols of Western Kenya.

They also found that sesbania fallows depleted this pool, thus capturing a resource that was unavailable to maize crops (Mekonnen *et al.*, 1997). The source of this nitrate pool is believed to be the result of the mineralization of organic N in the topsoil, which is relatively high in these soils, followed by nitrate leaching into subsoil layers. The nitrate anions are then held in the subsoil by positively charged clay surfaces.

Subsoil nitrate accumulation and its depletion was detected in East Africa decades ago but such findings were not given practical attention at that time. It is probable that trees also capture K at same depths in similar soils and thus help prevent K deficiencies. In order for nitrate anions to move, they must be accompanied by a cation; K is the main leachable cation in such soils. Nitrate accumulation in the subsoil is well documented in soils rich in Fe oxides that provide anion-exchange sites to hold nitrate ions (Cahn *et al.*, 1992). Many such subsoils, however, are highly Al-toxic, preventing significant plant root development, but subsoil acidity is not a widespread constraint in African soils cultivated by smallholder farmers.

The rotation of annual crops with short-duration fallows containing deep-rooted perennials holds promise as a way to use subsoil nitrate that would otherwise be unavailable to crops. This resource may not be replenished when cropping systems become more intense, as nitrate leaching from the topsoil may be diminished by more extensive crop root systems. The magnitude of the captured subsoil nitrate needs to be assessed in other soils, but soil chemistry indicates that subsoil nitrate accumulation will not be as significant in many other types of soils found in Africa. Nevertheless there are 260 million ha of soils in Africa that have anion-exchange capacity in the subsoil. The use of this hitherto unrecognized N source via its capture by deep-rooted trees is an exciting area of research in the region. Improved fallows with leguminous species are a promising technology for improving maize yields in nutrient depleted soils of East and Southern Africa. Studies report estimated 5000 farmers in Eastern Zambia and 10000 in Western Kenya (Jama and Mafongoya, 1999) now adopting and adapting improved fallows for maize production. Whereas the improved fallows can meet the nitrogen needs for a maize grain yield of 3 to 4 t/ha, phosphorus needs must be met by application of inorganic P sources such as TSP or high quality rock phosphates (PR) like Minjingu PR.

In general planted fallows have potential in areas where:

- Land is not limiting
- Opportunity cost of labour is low
- Trees provide by-products such as fuelwood and fodder
- Soils of high pH and clay content
- Fallow species produce high quality biomass. On P deficient soils P fertilization may be necessary to sustain the fallow effect on subsequent crops

Economic analysis of improved fallows was done using data from twelve farms in eastern Zambia (Table 3.4). Over a five year period, a hectare of improved fallows required 11% less labour than a hectare of unfertilized maize and 32% less labour than fertilized maize (Franzel *et al.*, 1999). The returns to the land Net Present Values (NPV) per hectare for fertilized maize were over 30% higher than for improved fallows. Assessing returns to labour, which is more relevant to most small holder farmers than returns to land because labour tends to be more scarce than land, improved fallows performed better than unfertilized and fertilized maize (Table 3.4). In this example, an increase in maize yields of only 1.1 t/ha was needed in the third year to cover the costs of establishing and maintaining the fallow relative to unfertilized maize in terms of returns to land and labour. The performance of improved fallows relative to continuous fertilized maize was too sensitive to changes in key economic factors. An increase in maize prices for example, raised the returns to fertilized maize at a much faster rate than the rise in the returns to improved fallows. Similarly, the relative profitability of the two practices was highly sensitive to price of fertilizer; where reductions in fertilizer price greatly increased the profitability of fertilized maize relative to improved fallows. Changes in the discount rate and in the labour and seedlings had little effect on the performance of improved fallows relative to fertilized maize.

Financial returns

Table 3.4. Comparison of two-year *Sesbania sesban* improved fallows and continuously cropped maize over a 5- year period, Eastern Zambia

Option	Returns to land: net present value (USD/ha)	Returns to labour: Net returns (USD) per workday
Continuous unfertilized maize	5	0.42
Improved 2 year-sesbania fallow	160	1.02
Continuous fertilized maize	203	0.93

Source: Franzel *et al* (1999)

There are, however, several concerns that need to be addressed. First, improved fallows may not be an option for a large number of farmers with very small land holdings. The biomass produced (and N recycled) by fallows could be constrained by low soil fertility and by pests. There are also uncertainties about Biological Nitrogen Fixation (BNF) – for instance, how much N is fixed relative to the needs of the crop and what should be the management practices of the fallow species that would enhance it (e.g., appropriate rhizobium for each species and the need for P application). Other issues of concern are N and water dynamics in fallow systems effect of improved fallows on soil physical properties and biological processes, effect of mixed fallow species on subsequent crops, how to prolong residual fallow effects on crops and P cycling in improved fallows. Unless these issues are addressed, short-duration improved fallows with leguminous species may not produce sufficient N for high maize yields especially when P is added and hybrid seed is used. This means the shortfall of N should be met through inorganic N fertilizers.

There is need to evaluate a wider range of improved fallow management options and understand their socio-economic limitations. Specifically, the following are areas of high priority:

a) economics of alternative improved fallow species (sesbania vs tephrosia),
b) coppicing fallows (gliricidia vs sesbania) and,
c) economics of pure (sole) fallows vs established intercropped with maize and other crops. There is need to assess impact achieved so far. This should include the following aspects: identifying the number and type of farmers adopting the technologies, the impact of adoption on food vs. cash crops and, the environmental effects on farm, household and village scales.

Finally there is need to understand the institutional support required to sustain a wide-scale adoption. Some of the key issues are the need to develop:

a) Community-based germplasm (seed) supply,
b) Individual nurseries and community nurseries,
c) Farmer researcher linkage groups,
d) Community fire control and grazing systems and,
e) Marketing and credit facilities.

Biomass transfer system

This technology may be practiced by any of the following ways:

a) Transfer of leaf biomass produced from one field to another on the farm

b) Transfer of biomass produced outside the farm

c) Recycling of nutrients through livestock manure

d) Movement of manure from pastoral areas to cropping fields

In Zimbabwe farmers traditionally collect leaf litter from miombo secondary forest as a source of nutrients to maize (Nyathi and Campbell, 1993). In the long term this practice is not sustainable for it mines nutrients from the forest ecosystems in order to build soil fertility in the croplands. Miombo litter collected is also of low quality and it may immobilize N instead of supplying N immediately to the maize crop (Mafongoya and Nair, 1997). An alternative means of producing high quality biomass is through establishment of on-farm biomass banks from which the biomass is cut and transferred to crop fields in different parts of the farm. In Western Kenya for example the use of *Tithonia diversifolia*, *Senna spectabilis*, *Sesbania sesban* and *Calliandra calothyrsus* planted as farm boundaries, woodlots and fodder banks or found along the roads as a source of nutrients has proven beneficial in improving maize production (Maroko *et al.*, 1998; Nziguheba *et al.*, 1998; Palm, 1995; Palm *et al.*, 2001). In a study by Gachengo (1996), tithonia green biomass grown outside a field and transferred into a field was found to be as effective in supplying N, P and K to maize as an equivalent amount of commercial NPK fertilizer, and in some cases maize yields were higher with tithonia biomass than commercial inorganic fertilizer. Recent work in Malawi (Ganunga *et al.*, 1998) and Zimbabwe (Jiri and Waddington, 1998) have similarly reported tithonia biomass to be an effective nutrient source for maize.

Biomass transfer using leguminous species is a far much sustainable means of maintaining nutrient balances in maize-based systems as these trees are able to fix atmospheric N_2. Tithonia is not a legume, and it does not biologically fix atmospheric N_2. The transfer of tithonia biomass to fields, therefore, constitutes the cycling of nutrients within the farm and landscape rather than a net input of nutrients to the system. The continual transfer of nutrients from tithonia hedges to crop fields constitutes nutrient mining and might not be sustainable for long periods. Whereas the application of fertilizers to tithonia could ensure sustained production of tithonia, this is unlikely to be an option for resource-poor farmers. The integration of tithonia with N_2-fixing legumes may merit investigation.

The issue of synchrony between nutrient release from tree litter and crop uptake can potentially be achieved in a biomass transfer system. The management factors that can be manipulated to achieve this are litter quality, rate of litter application, method and time of litter application (Mafongoya *et al.*, 1998; 1999). However variability in climatic factors such rainfall and temperature makes the concept of synchrony an elusive goal to achieve in practical terms (Myers *et al.*, 1994).

Although prunings from MPTs increased maize yield, cutting transporting and managing prunings on crop fields required high labour inputs (Jama *et al.* 1997; Jama *et al.* 1998; Mutuo *et al.*, 2000). Where family labour is available at no additional cost, the technology can be profitable even where land is scarce (Jama *et al.*, 1997; Mutuo *et al.*, 2000). However, considering that farm labour is one of the most constraining input in smallholder agriculture, the associated cost makes this technology unattractive and may serve as a disincentive for its adoption by farmers. In monetary terms, the higher maize yield does not compensate for the high labour cost. In promoting this technology farmers may require to be provided with a source of additional resources to invest in labour and land. Most economic analyses have shown that it is unprofitable to invest in biomass transfer system when labour and land are scarce. However, in areas where land is abundant and the prunings are applied to high value crops like vegetables, the technology is profitable (ICRAF, 1997).

In summary, the biomass transfer system has greatest potential when biomass is of high quality and rapidly releases nutrients, the opportunity cost of labour is low, the value of the crop is high and if the biomass does not have other valued uses other than as source of nutrients

The effectiveness of biomass transfer as nutrient sources using organic inputs from MPT species depends on their chemical composition (Mafongoya and Nair, 1997). These systems can meet the N requirement of most crops in smallholder farming systems. However, they cannot meet the requirement of P. There is need to apply inorganic sources of P in addition to organic sources. When biomass is also valued as fodder there is need to assess the trade off of applying it directly to the soil or feeding it to livestock and then applying the resultant manure. There is evidence to indicate that depending on the quality of the biomass there may be no advantage in feeding it to livestock and then applying the manure as source of N to crops (Mafongoya *et al.* 1999). However, in other instances, it has been shown that it is more advantageous to first feed the biomass to livestock and then apply the resulting manure to crops (Jama *et al.*, 1997). Among the areas that call for more research in the use of biomass transfer are the residual effects of low and high quality biomass, combinations of organic and inorganic nutrient sources, effect of biomass banks on nutrient mining and the economic analysis of the system.

Maize-Livestock Interaction and Zero Grazing Systems

Mixed crop-livestock farming systems are characteristics of large areas of Africa. There are ecological and socio-economic interaction between livestock and maize cropping systems whereby livestock provide manure, which is a source of nutrients to maize in many countries in subhumid Africa while the stover from maize is the source of feed to livestock during the dry season when there is shortage of high quality fodder. In addition, livestock serves as a form of capital to buy inorganic inputs for maize production and also as a means of transport to carry inputs and outputs from and to the markets.

Manure has traditionally been used as a source of nutrients before and after the advent of inorganic fertilizers. The use of manure can improve crop yields considerably. This has been shown in several studies and reviews (Ikombo, 1984; Probert *et al.*, 1995; Haque, 1993; Murwira *et al.*, 1995). The demonstrated benefits of manure include increase in soil pH, water holding capacity, hydraulic conductivity and infiltration rate and decreased bulk density. Manure can be an important source of nutrients, especially N, P and K. In Zimbabwe, for instance, estimates from the Mutoko communal area suggest that over 80% of the N applied to field and garden crops is derived from kraal manure and about 10% from leaf litter (Scoones and Toulmin, 1985). Details of manure management are presented in Chapter 7.

This section will concentrate on stall fed/ 'cut and carry' based dairy schemes which are important in the central highlands of Kenya, Chagga gardens of Kilimanjaro (Tanzania) and smallholder dairy schemes in Zimbabwe. In these systems farmers keep from one to five dairy cows or more depending on whether the farmer is practicing zero or limited grazing system. Generally, fodder is cut and carried to the animals confined in stalls. The main source of forage is napier grass (*Pennisetum purpureum*) which is normally grown in fodder banks and around the edges of the cultivated fields. Recently tree legumes like *Acacia angustissima*, *Calliandra calothyrsus* and herbaceous legumes like siratro have also been included in the fodder banks as cheap sources of protein. Additionally, crop residues are important source of supplementary feeds. This system offers potential to control quality of manure and losses of nutrients by:

- Type of feed used
- Management of manure
- Housing facilities of the animals
- Minimum volatilization losses of urine

In the longer term the recalcitrant component of the manure forms a reserve pool of mineralizable nutrients that will be available for plant uptake in future seasons. Manure has also the long-term effect of raising soil organic matter levels with all the concomitant benefits associated with improved soil organic matter status of a soil. The quantities of manure available are, however, often inadequate to maintain soil fertility and crop yields. The quality is also often poor. This can, however, be improved through management practices (See Chapter 7).

Quantity and quality of manure available

Manure is generally a scarce commodity on most farms. The amount of manure available to a farmer is dependent on several factors such as herd size and management system (free grazing or zero-grazing 'stall fed', etc). For farmers with no livestock, the existence of manuring contracts whereby farmers can gain access to manure in exchange of crop residues is common in many places. Manure production is also dependent on seasonal differences and rainfall conditions, which determine availability of fodder. Manure production especially from unimproved livestock breeds in free-grazing, open systems is generally low and highly variable. Probert *et al.* (1995), estimated production levels of 1 ton/livestock unit/year for unimproved local production levels of local breed in maize-livestock system in the semi-arid parts of Eastern Kenya

In spite of the low levels of manure production, recommended manure application levels are often as high as 10 to 15 t ha^{-1} yr^{-1} (Grant, 1981), though the actual application rates by farmers are far much lower. The manure used in trials often emanates from feedlots and ranches with higher feed quality and supply than communal areas. The quality of kraal manure from livestock in communal areas is highly variable, with N levels as percentage of dry matter (DM) ranging from 0.46 to 1.98% (Tanner and Mugwira, 1984; Ikombo, 1984; Mugwira and Mukurumbira, 1985; Mureithi *et al.*, 1994). Such levels are far lower than N contents found in manures derived from feedlot cattle. The P concentration can vary greatly depending on the source, the diet of the animal, storage and management (Guar *et al.*, 1985). Additionally, communal area cattle manure contains high fractions of sand due to the mixing of manure with soil during trampling by the livestock (Mugwira, 1984). Nitrogen levels also vary between seasons with changes in the quality and availability of fodder resources.

One way to improve manure quality (i.e., nutrient content) is to supplement livestock with nutrient rich concentrates and fodder. Many trees and shrubs used in agroforestry systems provide fodder that can improve the quality of manure produced. Jama *et al.* (1997), showed that high P content manure (0.49% P) can be obtained if the grass fed to zero-grazed improved breed dairy cows is supplemented with the fresh leaves of *Calliandra calothrysus*, a leguminous shrub with fodder value. The effects of the resultant high quality manure, either broadcast-applied and soil-incorporated or spot-placed in the planting hole at the rate of 2

tha^{-1} (equivalent to 10 kg Pha^{-1}) compared to inorganic P fertilizer (triple superphosphate, TSP) applied at the same rate on maize yield at two P deficient sites in Western Kenya was that maize yield increased by 3 to 4 times over continuous maize cropping in the first season after application as well as during the second season when residual effects were monitored. Net economic benefits were, however, higher for manure (no difference between broadcast-applied and spot-placed) compared to TSP, (Jama, 1999). Thus, the relatively high net benefits for manure application whether placed with the seed or broadcast, highlights the need for high quality manure as a source of nutrients on P deficient soils.

While better management of the available manures may improve their quality, the amounts available may still pose constraints in smallholder farms. On these farms, it is important to examine ways to increase the use efficiency of the little available manure. One such strategy is placement of the manure in the planting hole instead of broadcasting it. This is a common practice among farmers as a measure to maximize the use of a limited resource, reducing leaching and volatilization effects and maximizing yield. Spot placement requires farmer knowledge, skills and labor inputs. To aid this or any other strategy that aims at efficient use of manure, information on the rates of decomposition and mineralization of the manure is required.

Nutrient losses from manure

Given the importance of manure in maintaining productivity of the soil, Ransom *et al.* (1995), concluded that sustained production of fodder and developing improved manure handling techniques that minimize nutrient losses are essential elements in sustaining maize productivity in maize-livestock-based systems. Data on losses of nutrients during manure management in smallholder farming is generally lacking. Some recent estimates, however, suggest that up to 60% N and 10% of P can be lost through poor manure management (Shepherd *et al.*, 1996). Although there are uncertainties in these estimates, they do suggest the need for accurate measurement particularly in the context of intensive dairy schemes with high manure fluxes and the need to device appropriate management practices that minimize losses.

Since 40 to 60% of the N excreted by livestock (ruminants) is in the form of urine, the potential for nutrient loss can be greater under stall-feeding than range grazing extensive systems where only excreta is captured and applied to crop fields (Powell and Williams, 1995). More intensive stall-feeding systems of livestock could, therefore, increase nutrient losses and jeopardize long-term soil productivity if technologies are not available that capture and recycle the nutrient voided by stationary animals.

In systems involving livestock, nutrients can be lost via several avenues. An important one in traditional livestock enclosures ("bomas") is the leaching and loss of nutrients from the surface soil, for example, Probert *et al.* (1995) from their studies in Western Kenya observed that the enrichment of N and K extended to the full sampling depth of 2.1m, but for P the effect was restricted to the surface layers as expected from its low mobility. This leaching of nutrients from 'poor' storage shows an accumulation of nutrients beneath the 'bomas', which act as sinks for nutrients that have been removed from farm soils or crop lands and are no longer being put to use. Current studies in Zimbabwe have been designed to reduce nutrient losses from manure through construction of better kraals (Nzuma and Murwira, 1998).

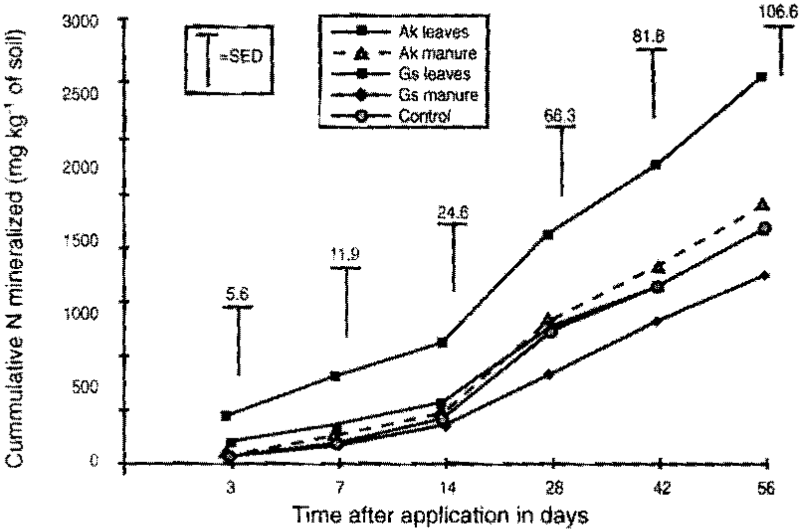
The rate of mineralization of N is faster, and losses from volatilization are greater from animal excreta than from plant litter. This makes ammonia volatilization a major loss pathway of N from manure. For instance, Vertregt and Rutgers (1988), estimated that ammonia losses accounted for four times as much of the N excreted from animals compared with N losses from decaying herbage from pasture. Hence, although animal excreta provide nutrients for plants in a more usable form, the loss of N from the system could be much higher. The loss can however be reduced by incorporating manure into soil at time of planting, controlling losses in the kraals by use of residue as bedding as well as proper citation of the kraals (Murwira, 1995).

Decomposition and N release patterns of leaves and manure

Decomposition and nutrient release rates (especially N) are determined by the quality of leaves or manures, the environment and decomposer organism present (Swift, 1987). The quality of organic inputs also determines the type of SOM fractions formed after application of organic inputs. Quality here refers to the constituents (chemical composition) and the nutrient contents of the organic input (Palm, 1995; Mafongoya *et al.*, 1997; Cadisch and Giller, 1997). Organics of high quality are high in N but low in both lignin and polyphenol content. Such high quality organic resources decompose and release N rapidly. On the other hand, low quality organics are low in N but high in polyphenol and lignin contents. Low quality organic materials decompose slowly and may immobilize N and other nutrients.

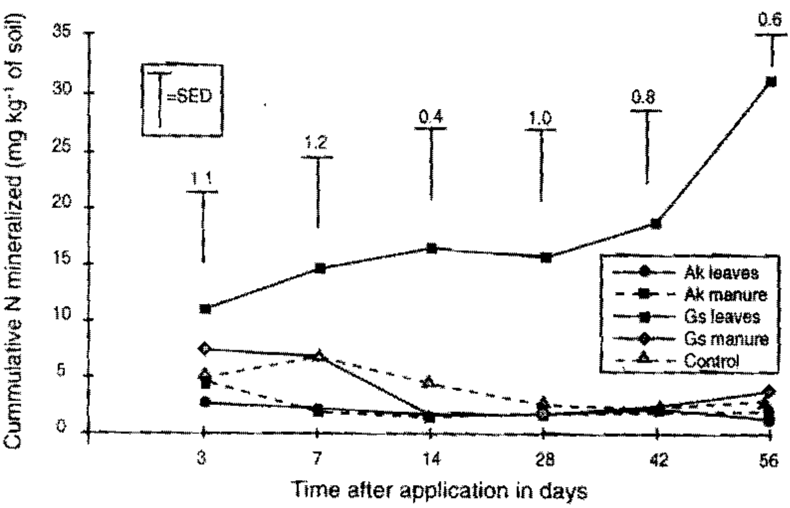
Numerous examples in literature indicate that quality of an organic input is an important aspect in determining the rate of decomposition and mineralization of that particular organic once incorporated into the soil. For example, Figure 3.2 gives the results of a study conducted in Zimbabwe to compare the rates of decomposition of acacia and gliricidia leaves compared to the manures that resulted from feeding livestock (goats) with those respective leaves. *Gliricidia* leaves decomposed and significantly evolved more carbon dioxide than the rest of the organic amendment. There were no significant differences in decomposition patterns of *Acacia karoo* leaves, *Acacia karoo* manure and *Gliricidia sepium* manure. Cummulative N release also followed the same pattern (Figure 3.3) (Mafongoya *et al.*, 1999).

Figure 3.2. Cummulative amount of CO_2 evolved as affected by tree leaves, manure and incubation period (AK = Acacia kroo; GS = Gliricidia sepium)



Source: Mafogoya *et al* (1999)

Figure 3.3. Cummulative amount of net N mineralized as affected by tree leaves, manure and incubation period (AK = Acacia kroo; GS = Gliricidia sepium)



Source: Mafogoya *et al* (1999)

Nutrient cycling in a mixed farming system can be manipulated through the chemical composition of the diet and manure quality. Whether to feed leaves to livestock and then apply the resulting manure to crops or to apply the prunings directly to crops depends on crop response to mulching, animal response to feed suppliments and the prices of the crop and animal products. For example, recent work by Jama *et al.* (1997) from Eestern Kenya has indicated that leguminous tree species such as *calliandra* are best profitable when utilized as fodder supplements for livestock as compared to direct application to crops as green manure. The economics of these options needs further evaluation on farmer's fields.

Improving quality of manure through composting with rock phosphate materials

Rock phosphate materials are quite an abundant resource in East and Southern Africa (Buresh *et al.*, 1997). These could be low cost fertilizer materials. Their chemical composition and reactivity limit the use of these rock phosphate materials. Dorowa Phosphate Rock (DPR) which is the main mineral source of P in Zimbabwe provides an opportunity to develop low cost P fertilizer. The direct use of DPR as a P fertilizer has been reported to be agronomically ineffective both in greenhouse and field studies (Dhliwayo and Mukurumbira, 1996).

Benefication (removal of impurities) of DPR is needed to enhance its agronomic effectiveness. Studies in Zimbabwe on composting DPR with cattle manure have shown higher residual effect of composted DPR compared to inorganic P fertilizers alone (Dhliwayo, 1998). The percentage of groundnut yield over control was 74% and 99% for manure and manure and DPR composted in the kraal (Table 3.5). These studies have shown that residual agronomic effectiveness of DPR and cattle manure can be greatly enhanced by composting DPR with cattle manure in kraals. This technology is feasible to farmers who stay near DPR deposits with minimum transport costs.

Table 3.5. Effect of landuse on maize grain yields kg/ha

	Season					
Land use systems	Long rains 96		Short rains 96		Long rains 97	
Fallow system	No P	P	No P	P	No P	P
Natural fallow	1452	2180	1286	1501	1863	2813
Continuous maize	595	774	810	849	1432	1517
Sesbania fallow	2112	2630	1393	1246	2336	2183
Sesbania fallow (seedlings)	2289	2865	1512	1706	2365	2395
SED	256		166		313	

Source: ICRAF (1997)

In East Africa the most promising PR sources are Minjingu in northern Tanzania and Busumbu in Eastern Uganda. Minjingu PR has been reported to be a very suitable source of P to crops in P-deficient soils because of its high solubility and its high relative agronomic effectiveness (Bromfield *et al.*, 1981; Woomer *et al.*, 1997). On the other hand, Busumbu PR is of generally low solubility and lesser reactivity compared to Minjingu PR. However, an option of blending Busumbu PR with small quantities of triple superphosphate (TSP) and/or manures to improve its reactivity is currently being tested in Western Kenya (Jama *et al*, 1999).

Strategies for Integrated Nutrient Management

The primary goal of integrated nutrient management (INM) is to combine old and new methods of nutrient management into ecologically sound and economically viable farming systems that utilize available organic and inorganic sources of nutrients in a judicious and efficient way (Franzluebbers *et al.*, 1998). INM attempts to achieve tight nutrient cycling with synchrony between nutrient demand by crop and release in the soil while minimizing losses through leaching, runoff, volatilization and immobilization. Organic nutrient sources include plant residue, leguminous cover crops, mulches, green manure, and household wastes. Judicious combination of these organic resources with inorganic fertilizers can help ensure immediate nutrient release for present crop as well as the long-term build up of soils nutrient reserves.

In the recent past a number of strategies for soil organic matter management have been studied. These include:

(a) Returning of organic materials to the soil to replenish soil organic carbon lost through decomposition (recycling of plant and animal residues, farmyard and green manuring, composting, cover crop rotation);
(b) Ensuring minimum disturbance of the soil surface (residue mulch, conservation tillage) to reduce rate of decomposition;
(c) Reducing soil temperature and water evaporation by mulching the soil surface with plant residues; and
(d) Integration of multipurpose trees and perennials into cropping systems to increase production of organic materials (Franzluebbers *et al.*, 1998). Most of these strategies have been discussed in the earlier sections of this chapter and point to the realization that judicious use of both organic and inorganic nutrient management strategies could be a solution to the declining soil fertility problem in the maize-based systems of East and Southern Africa.

Many farmers in Africa use organic or inorganic inputs or a combination of organic and inorganic sources of nutrients to try to meet crop demands. This is necessitated by inadequate amounts of each input.

Crop yields obtained may be low because of inadequate amounts added, low quality organic materials and inappropriate and inefficient combinations. Given the problems of inorganic fertilizer procurement in Africa, the objective should be to provide much of the nutrients through organic inputs especially N and making up the shortfall for P and N through inorganic fertilizers.

Results of Itimu *et al.* (personal communication) showed that the interaction between mineral N and organic residues indicated that there was no bonus to be gained in terms of increasing fertilizer use efficiency by mixing mineral and organic inputs at moderate levels. Significant effects on soil structure, nutrient retention and root penetration is likely to be increased only when sufficient organic inputs have been added compared to use of mineral fertilizers (Palm *et al.*, 1997). However, there are exciting results of increasing phosphorus availability by mixing inorganic P sources with high quality residues such as tithonia. This area deserves further research.

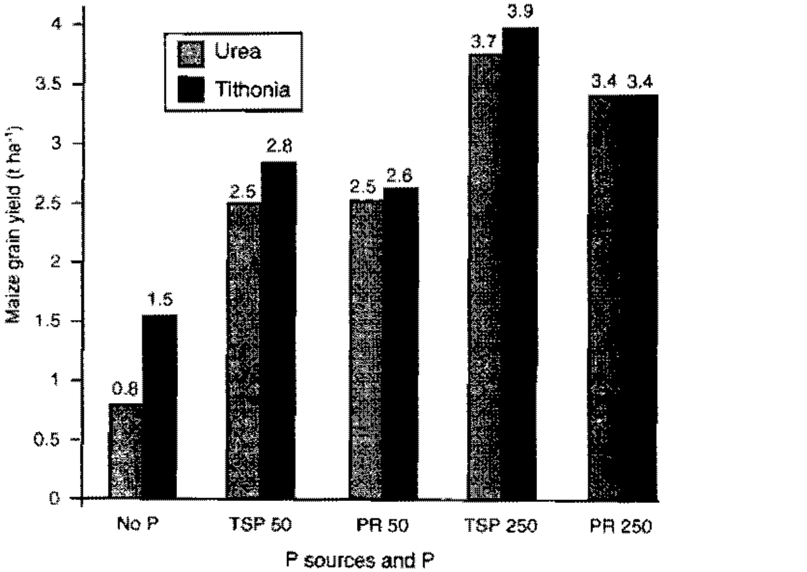
To make recommendations for combined nutrient use, information on the fertilizer equivalency of organics is needed. Lacking is the understanding of how much of the different quality organics to apply to get yields equivalent to those obtained from inorganic fertilizers and how much of the applied nutrients remain to be used by the subsequent crops. Recent research has shown that low quality organic inputs have longer residual effects than high quality organic inputs (Snapp *et al.*, 1998). However, the long-term effects of low quality organic inputs on soil physical and chemical properties need further research. Guidelines are therefore needed which link the use of mixtures and organic inputs of different quality and their short-term fertilizer equivalency value and also their longer-term residual effects on SOM pools. These guidelines can only be obtained from well-designed long-term experiments conducted in soils with appropriate limiting nutrients. Farmer's circumstances, perceptions including available resources allocation, soil types and socio-economic circumstances need to be included in such experiments.

The following section highlights a few examples on integrated nutrient management and especially on the need for phosphorus provision that can not be supplied in sufficient quantities by organic sources to meet crop demands.

Use of tithonia and inorganic phosphorus fertilizer

Most soils of Western Kenya and some parts of Southern Africa are deficient in phosphorus, nitrogen or both nutrients. Work on soil fertility recapitalization (ICRAF, 1996) has shown interesting results with the use of organic and inorganic nutrient sources. The work compared leafy biomass of tithonia (*Tithonia diversifolia*) and urea as sources of N and two sources of P fertilizer (Phosphate rock- PR and triple superphosphate-TSP). Application of P either as PR or TSP significantly increased maize yields with tithonia and urea application (Figure 3.4). There was a significant yield increase when tithonia was added to the P fertilizer in comparison with commercial N fertilizer. Maize grain yields were higher after application of tithonia than they were after urea in the absence of added P and with each P source (Figure 3.4). Further observations of the same data revealed that both tithonia and TSP at equal P application rates rapidly increased plant available P in the soil as determined by resin P extraction. The increase was however, more with tithonia than with TSP indicating that tithonia was more effective than TSP in reducing P sorption (fixation) by iron and aluminium oxides in the soil (Jama, 1999; unpublished). It has been suggested that, unlike inorganic TSP, tithonia reduces P sorption by producing organic acids during decomposition that compete with P for soil sorption sites (Nziguheba *et al.*, 1998). The integrated use of tithonia with commercial inorganic P fertilizer also resulted in greater soil biological activity as determined by higher microbial biomass P than either sole tithonia or sole TSP treatments (Jama, 1999; unpublished). The effectiveness of fresh tithonia leafy biomass for soil fertility improvement can be partially attributed to the fact that tithonia is a high quality biomass that rapidly decomposes releasing plant available nutrients like P, N and K.

Figure 3.4. Maize responses to phosphorus and tithonia applications in Western Kenya representing annual maize yield from the two maize cropping seasons averaged over three sites. The green foliar biomass of *Tithonia diversifolia* was incorporated into the soil at the beginning of the long-rains at the rate of 1.8 t dry matter ha to provide 60 kg N/ha, 6 kg P/ha and 60 kg K/ha. Triple superphosphate (TSP) and Minjingu phosphate rock (PR) were added at a recapitalization rate of 250 kg P/ha (250) or annually at 50 kg P/ha (50). Blanket potassium application of 60 kg K/ha was added to the first of the two crops.



Source: Bashir Jama (unpublished)

Use of sesbania fallows and phosphorus fertilizer

Improved fallows with leguminous trees such as *Sesbania sesban* have been shown to overcome N deficiency in maize through biological nitrogen fixation and the deep capture of subsoil nitrate. Many studies have shown that trees cannot supply enough P through their biomass or increase the availability of P pools in the soils.

Once N deficiency has been overcome through use of improved fallows, there is need to ensure adequate supply of P to crops in order to avoid P negative balances. Work of ICRAF (1997), in Western Kenya has shown promising results with sesbania fallows and the use of inorganic P fertilizers such as TSP. Sesbania fallow plots were split into two plots; one half received 22 kg of Pha^{-1} as TSP and other half received no fertilizer. The application of P increased the yield of maize in all systems but most in the plots that were under sesbania fallows (Table 3.6). Economic analysis showed that higher returns to labour and land were obtained from sesbania fallow system with P compared to the other land uses. The conclusions from these studies have shown that in order to take full benefits of the fallows, inorganic P has to be applied at a moderate rate of 20-kg P/ha. Recurrent P application at this rate are necessary if economic benefits are to be sustained. The results of this study are from one location only. There is need therefore to test these results in more sites in East and Southern Africa to determine the need for inorganic P in improved fallows.

Table 3.6. Residual effect of composted rock phosphate, manure and inorganic fertilizers on groundnut grain yield and stover yield (kg/ha)

Fertilizer treatment	Kernel yield	Stover yield
Control (no fertilizer added)	915	2626
Manure + DPR composted in kraal	1823	5671
Single superphosphate fertilizer	1271	3476
Compound D fertilizer	1253	3517
LSD ($P<0.05$)	317	792

Source: Dhliwayo, 1998

Integration of manure with inorganic fertilizers

In systems where manure is a major avenue for recycling nutrients, an important consideration is whether manure alone can meet and sustain the nutrient needs for a reasonable crop yield. There is sufficient evidence to indicate that the nitrogen demand (and to some extent K) to produce a reasonable maize yield crop can be met by manure. Phosphorus, however, cannot be provided in sufficient quantities by manure (Palm *et al.*, 1997) therefore an important issue in this regard is improving both the P content and P cycling potential of manure.

Probert *et al.* (1995) in a review of the African literature reported a range of P concentration of manures from 0.06 to 0.57%. The P concentration can vary greatly depending on the source, the diet of the animal, storage and management (Guar *et al.*, 1984). In nutrient-flux studies conducted in the maize-livestock-coffee system studies, Ransom *et al.* (1995), observed that with the exception of phosphorus, inputs of nutrients through manure far exceeded their removal by stover. Application of inorganic P supplied more than 50% of the phosphorus needs. Therefore, in order to meet the P requirements for a reasonable crop of maize, inorganic P must be integrated with manures.

Besides P, manure alone is also unlikely to meet the N requirements of high yielding maize crops because of its inability to supply continuously large amounts of readily available N (Mugwira, 1985). Integration of manure and inorganic fertilizers may result in greater residual effects of the organic than the inorganic sources and also the added advantages of manure (in addition to supplying nutrients), such as improved soil physical properties (Murwira *et al.*, 1995).

Case Studies

Hedgerow Intercropping in the Central Highlands of Kenya

A hedgerow intercropping experiment was initiated in 1992 in the subhumid tropical highlands of Central Kenya to address the constraint of declining soil fertility caused by continuous cropping without addition of adequate fertilizers and/or manure inputs (Mugendi *et al.*, 1999a, b). The overall objective of the trial was to evaluate the influence of soil-incorporated leafy biomass of *Calliandra calothyrsus* and *Leucaena leucocephala* on soil fertility improvement and crop sustainability.

Results from this study showed that maize alley-cropped with *leucaena* and with prunings incorporated into the soil produced higher grain yield than non alley-cropped, no fertilizer control (absolute control). The yields were also higher compared to those obtained from the treatment that received the recommended level of N fertilizer (50 kg Nha^{-1}). On the other hand, calliandra alley-cropped treatments produced yields equal to or less than those that absolute control did (Mugendi *et al.*, 1999a; b).

The choice of the multipurpose tree or shrub selected for hedgerow intercropping purpose, is very crucial for some tree species tend to be more competitive than others, drastically reducing the benefits of alley cropping due to competition between the hedgerow tree species and the companion crop for growth resources. For example, results from the above-mentioned study showed that *Calliandra* hedges were more competitive than *leucaena* hedges. The yields of *Calliandra* alley-cropped maize were, on average, 50% lower than those of non alley-cropped treatments that received *Calliandra* prunings from *ex situ* grown trees (biomass transfer), whereas the decrease was, only 8% when the similar *Leucaena* treatments were compared. It was, however, noted that, both *Calliandra* and *Leucaena* treatments that received *ex situ* prunings produced yields that were not significantly different from each other in all the seasons (Mugendi *et al.*, 1999a;b). The competitiveness of *Calliandra* over *leucaena* hedges was further affirmed by analyzing the yield data through the approach (equation) developed by Ong (1996) where the effects of including or excluding hedges or prunings were assessed in relation to the performance of the absolute control. A simplified version of the equation expresses the overall tree-crop interaction (I) as a function of soil fertility (F) and tree crop competition (C), ie,

$$I = F + C$$

Where

I is the overall tree-crop interaction (measured by the difference between crop yields of the alley cropped, prunings applied treatments (Hm) and the absolute control where no prunings were applied (Co)),

F is the benefit of tree prunings on soil fertility (estimated by the yield difference between *ex situ* applied prunings treatments (Cm) and the control Co)), and

C is the crop yield reduction due to interspecific competition between tree and crop (measured from the yield difference between Cm and Hm).

Table 3.7. Interaction, fertility, and competition effects of Calliandra and Leucaena hedges on maize yield (Mg/ha) in the subhumid tropical highlands of Kenya.

Season	Treatment	I (Hm-Co)	F (Cm-Co)	C (Cm-Hm)
SR 94	*Calliandra c.*	0.15	0.53*	-0.39
	Leucaena l.	0.78**	0.31	0.47*
LR 95	*Calliandra c.*	-0.62*	0.01	-0.63*
	Leucaena l.	0.46*	0.56*	-0.1
SR 95	*Calliandra c.*	-1.03**	1.46***	-2.50***
	Leucaena l.	0.44*	1.24**	-0.80**
LR 96	*Calliandra c.*	0.18	1.98***	-1.80***
	Leucaena l.	1.80***	2.06***	-0.26

Level of significance: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Seasons; LR = long rain; SR = short rain
I = interaction, F = fertility, and C = competition;
Hm = alley crop, prunings applied, Co = monocrop, no fertilizer (absolute control), and Cm = monocrop, prunings applied.

It is evident from this table that there was a significant negative interaction (I) between calliandra hedges and maize yield in two of the seasons (LR and SR 1995) whereas the interaction was positive (but not significant) in the remaining two seasons. On the other hand, leucaena hedges had a positive significant interaction with maize yield in all the seasons. It is further observed that fertility factor (F) for both species was almost identical across the seasons, but competition (C) for calliandra was much higher than leucaena's resulting in the observed negative interactions for calliandra hedges with maize yield.

The competitiveness of calliandra tree hedges over leucaena's could be explained by the root morphology of the two species. Calliandra trees develop strong superficial root system in addition to the tap root whereas leucaena is reported to have a strong tap root system that develops few lateral roots which also grow downward following emergence with later root development tending to be confined in the lower levels of the soil (van Noordwijk *et al.*, 1996). Results on the total root length (unpublished data) indicated that 60% of all the calliandra roots were located in the top 90 cm (soil) while only 25% of leucaena roots were found in the same soil depth. Thus, calliandra roots that occupied 60% of the top 90 cm depth competed more intensely with maize crop compared to leucaena whose greater percentage of roots were located below the effective rooting zone of the maize crop. Indeed, Jama *et al.* (1998) demonstrated that calliandra had the greatest root density in the top 15 cm of soil when compared to four other multipurpose tree species (*Eucalyptus grandis, Sesbania sesban, Markhamia lutea,* and *Grevillea robusta*) evaluated in the Western highlands of Kenya.

The importance of choosing appropriate tree species for alley cropping under different environmental conditions was further emphasized by Jama *et al.* (1995), who observed that, in the semiarid or subhumid conditions of Kenya, maize grain yield was better when alley-cropped with *Senna (Cassia) siamea* than with leucaena.

Results from moisture-stressed conditions suggest that alley cropping technology may not be effective in these conditions (Rao *et al.*, 1990; Jama *et al.*, 1995). Low biomass production of the hedgerow tree species and severe competition (that exceeds the fertility factor) for water are the major drawbacks limiting the potential of prunings to improve fertility and productivity of soils in these regions (Sanchez, 1995). In such cases, a biomass transfer system (cut-and-carry system or *ex situ* grown biomass) might be more beneficial than alley cropping system (Jama *et al.* 1995).

Despite the promising results shown by the alley cropping technology in the humid and subhumid regions of the tropics, the question of labor availability needs to be addressed properly before a wide adoption by farmers can be envisaged. The technology is labor-intensive with much of the demand for labor occurring during the rainy season, which happens to be the busiest time of the year (Nair, 1993). Additional labor for persons already fully occupied at peak labor seasons is considered more costly than when additional demands come during slack periods. The cost of production will therefore be increased considerably if additional labor must be hired (Hoekstra, 1987). Although these additional labor costs will be offset by increased yields, the immediate need for additional labor could sometimes be a disincentive to the adoption of the technology (Kang *et al.*, 1990).

Rebuilding the Productive Capital of African Soils by use of Phosphate Rock (P Recapitalization)

Soil fertility depletion in smallholder farms is the major biophysical root cause for the declining per-capita food production in most of sub-Saharan Africa (Sanchez *et al.*, 1997). This is attributed to input of nutrients not exceeding losses, especially with harvested products. One such area is Western Kenya where phosphorus losses of 3-13 kg $ha^{-1}yr.$ over several decades have led to maize yields of less than 1 tha^{-1} (Sanchez *et al.*, 1997). Meanwhile, population growth coupled with reduction in farm sizes has resulted in less land available for food production. These pose a serious threat to food security throughout the Eastern and Southern Africa.

Although P deficiency is widespread in East Africa, it is most severe in the densely populated highlands of Western Kenya. Responses of maize to P are significant even at rates as low as 10 kg Pha^{-1} (Jama *et al.*, 1997) indicating the importance of adding P to crops in this area. A survey in three districts of this region, for example, indicated that about 80% of the smallholder land used for maize production is deficient in available soil P.

Options for P inputs are organic materials, mineral P fertilizers or phosphate rocks (PR). Phosphorus content of organic materials (e.g., leaves of trees and shrubs, farmyard manure) are generally low to provide enough P for annual crops (Palm *et al.*, 1997). Manure is the most common soil amendment in Western Kenya, but the majority of the farmers in the area own no livestock and therefore have no source of manure (Shepherd and Soule, 1998). Thus low P content, low availability and competing uses and labor will generally preclude exclusive use of organics for P fertilization requirements, although they are certainly important as supplements.

There are PR deposits in East Africa, which have a proven capacity to alleviate phosphorus deficiency. The prevailing soil conditions are also attractive to the use of PR. The direct use of PR generally requires acidic soils with pH less than 5.5 (Sanchez, 1976; Rajan *et al.*, 1996). This is the case for most soils in Western Kenya.

Phosphate rock use

The use of indigenous PR has recently received tremendous interest as an alternative to mineral P fertilizers that are nearly all imported, high priced and often unavailable when needed. There are a number of PR deposits of variable reactivity in East Africa that differ greatly in their P composition and suitability as sources of P for P-deficient soils such as those in Western Kenya (Van Straaten, 1997). According to a recent report by Van Straaten (1997), the most promising PR sources are Minjingu in Northern Tanzania and Busumbu in Eastern Uganda.

A number of studies have highlighted the suitability of Minjingu PR as P source for crops in P-deficient soils. For instance, Bromfield *et al.* (1981) reported a relative agronomic effectiveness (RAE) of 75% for Minjingu PR in the five seasons following application to maize in Western Kenya. Based on results of 559 comparisons of rock and fertilizer at equal levels of added P, Woomer *et al.* (1997) also observed higher maize yield increases with Minjingu than with some other PR found in Africa. They concluded that strong potentials exist to further develop the Minjingu PR.

With the exception of Minjingu (biogenic sedimentary), most of the other PR deposits of Eastern and Southern Africa are weathered carbonatite deposits of igneous origin and of generally low solubility, and often with substantial Fe and Al oxide content. Typical of such deposits is Busumbu PR in Eastern Uganda. Busumbu PR is of lesser reactivity than Minjingu but close proximity to Western Kenya (less than 10 km away) compared with Minjingu that (greater than 820 km away) makes it attractive. There are known natural PR deposits in Kenya (e.g., Rangwe valley and Mrima hills) but they are not as reactive as either Minjingu or Busumbu PR.

The choice between soluble P fertilizers and PR as a source of P for crops depends on relative agronomic effectiveness (RAE) and cost. Relative agronomic effectiveness is defined as yield increase with PR relative to that with TSP expressed as a percentage. For correct determination of RAE, P should be the only nutrient limiting crop yield.

Phosphate rocks with low reactivity can be processed in different ways to improve RAE. One method is the compaction of PR with water-soluble P fertilizer, such as TSP. This is, however, likely to be costly on large-scale operation. The impurities, particularly magnetite, can also be removed through magnetic separation using inexpensive small-scale operations. These produce a concentrate of 13% P which can then be blended with mineral fertilizers (e.g., TSP) to increase its reactivity. Through the hydrolysis of TSP, the blend provides an initial quick dose of P and a sustained slow release of P as the acid produced by the hydrolysis process slowly reacts with the PR. Busumbu PR concentrate and a blend made from it (70% Busumbu: 30% TSP) are currently being tested in researcher-managed field trials in Western Kenya.

Studies with phosphate rock in Western Kenya

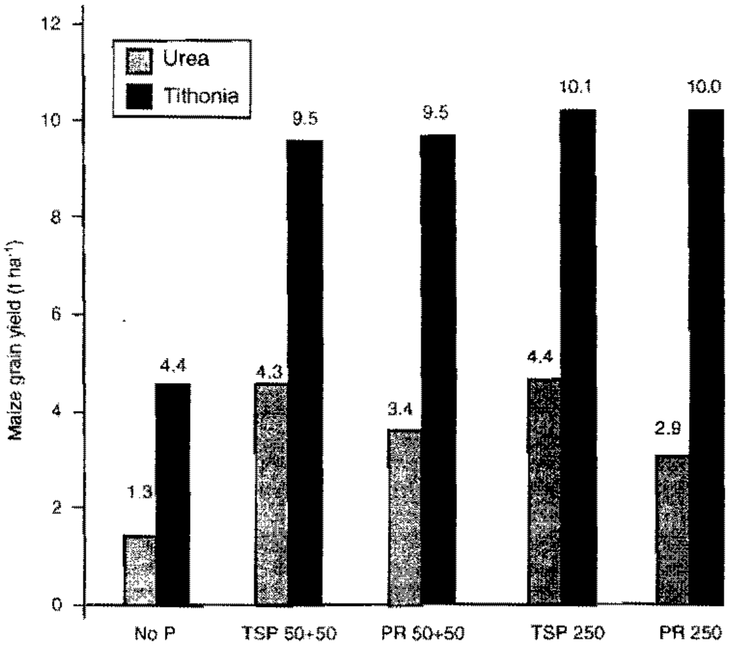
The International Centre for Research in Agroforestry (ICRAF), in collaboration with Kenya Agricultural Research Institute (KARI), Kenya Forestry Research Institute (KEFRI) and Tropical Soil Biology and Fertility (TSBF) Programme, began work with Minjingu PR in Western Kenya in 1996. The first study compared Minjingu PR with TSP at annual applications of 50 kg P/ha and a large one-time application of 250 kg P/ha, both broadcast-applied and soil-incorporated. Potassium was blanket applied to all treatments at 60 kg/ha. Nitrogen was applied annually at the rate of 60 kg/ha through either urea or foliar biomass of *Tithonia diversifolia*, a shrub common in hedges and roadsides in Western Kenya. The N rate of 60 kg ha is the recommended rate for maize in area. Maize yield responses to N application beyond this rate are usually small, probably because of the inherently high organic matter (3.0 to 3.3%) of the soils in many areas. Rapid mineralization of soil organic matter under the humid and hot conditions of the area can often supply N sufficient for at least 1.0 t dry matter ha maize grain yield.

Tithonia foliage has high concentrations of N, P and K and decomposes very rapidly in the soil (Jama *et al.*, 2000). The study was conducted at three sites where the soils are classified as Kandiudalfic Eutrudox (Soil Taxonomy) or Ferralsol (FAO-UNESCO 1979), pH 5.1 with clay content of 30 to 35%. These sites are fairly representative of the soils and rainfall conditions of the Western Kenya highlands neighboring Lake Victoria.

The annual maize yield from the two maize cropping seasons in the first year, averaged over three sites, indicated comparable response for the two P sources. Maize yield increased dramatically with the application of P at either 50 or 250 kg/ha (Fig. 3.5). Without P but urea as N source, maize grain yield averaged 0.8 t/ha. Maize grain yields less than 1.0 t/ha is typical in this area, which has highly P deficient soils (Sanchez *et al.*, 1997). Such low yields are not sufficient to feed the large number of people in the area. As a consequence, there has been considerable migration of people to cities and farms elsewhere to seek off- farm employment that can supplement their food and other needs.

It is interesting to note from Fig. 3.5 that with no P added, maize yield was higher with tithonia alone (1.5 tha^{-1}) than urea alone (0.8 tha^{-1}). This was probably due to the P (6 kgha^{-1}) supplied by tithonia applied at the rate sufficient to provide 60 kgha^{-1}. Responses of maize to P are known to be significant in this area even at rates as low as 10 kg P/ha (Jama *et al.*, 1997). The addition of P at 50 kgha^{-1} (either as TSP or PR) increased maize grain yields by at least three times (2.5 tha^{-1}) compared to yields from urea alone (no P applied) and by about two times with tithonia alone. As expected, the yields were higher with application of P at the rate of 250 kgha^{-1}, with the increases being about four to five times those with urea alone.

Figure 3.5. P Sources and P Rates



Source: Bashir Jama (unpublished)

The RAE of Minjingu PR from this study averaged 83% with tithonia and 93% with urea as N source. In another multi-location study, RAE of Minjingu PR averaged only 70% in the first year in 26 P responsive sites in Western Kenya (Lijzenga, 1998). Bromfield *et al.* (1981) also reported a RAE of 75% for Minjingu PR in the five seasons following application to maize in Western Kenya. In an on-going, long-term trial with maize on an acid, P-deficient soil in Western Kenya, the RAE in the first season after P application averaged 74% at 50 kg P/ha and 80% at 250 kg P/ha (ICRAF, 1997). These high RAE would suggest that Minjingu PR could be used as a substitute for TSP.

Besides the supply of nutrients, organic inputs may also enhance PR solubility. Direct enhancement of Minjingu PR solubility was demonstrated by Ikerra *et al.* (1994), with compost- and manure-amended soil in Tanzania. Such an effect would, indeed, be desirable for low soluble Busumbu PR. No data are available yet on the RAE of Busumbu concentrate (BP) and BP-TSP blend in Western Kenya. Observations from ongoing field trials, however, suggest that a blend of 70% BP and 30% TSP might be comparable to Minjingu PR in RAE, whereas BP alone is less effective.

Economics of phosphate rock use

Minjingu PR is the only deposit in Eastern Africa with sufficient quantity and reactivity hence potential for direct application. Although far from Western Kenya (820 km away), the use of Minjingu PR is likely to be more economical than TSP in Western Kenya. The estimated retail price at Maseno in Western Kenya in December 1996 ranged from US$ 1.3 to 1.8 kg/P compared with about US$2.36 kg P^{-1} of TSP (Buresh *et al.*, 1997). Minjingu PR on a unit P basis was, therefore, 55 to 76% of the cost of TSP. This estimate should, however, be interpreted with caution as it was based on limited amount of PR acquired for on-farm research by farmers in a pilot project. It could become even cheaper if the PR was mined and delivered to Western Kenya on a large scale.

The economics works out favorably for Minjingu PR with its estimated 55 to 76% relative cost compared with TSP and approximately 70 to 75% RAE on acid soils in Western Kenya. The one-time large application of 250 kg/ha is perceived as a corrective measure for severely P-deficient soils as opposed to a gradual build-up of phosphorus capital through annual applications of small amounts. However, logistic costs, credit schemes and soil properties will be the main factors involved in the choice of P rates to use.

Benefits of integrating inorganic P sources with organic fertilizers

Based on the encouraging agronomic results and costs of Minjingu PR in Western Kenya, a pilot project was initiated in 1997 with the objective of disseminating to farmers the integrated technology of Minjingu PR application and organic sources of nutrient. This combination was effective in sites with multiple nutrient deficiencies as the organics primarily overcame N and K deficiencies while the PR met the P needs. Because of their low tissue P concentration, the organics cannot meet the P requirements of the crops unless applied at high rates, which is unfeasible and uneconomical.

The major organic sources of nutrients available to farmers were:

(1) tithonia leaf biomass from hedges on farms and
(2) short-duration improved fallows with fast-growing species such as *Sesbania sesban*, *Crotolaria grahamiana* and *Tephrosia vogelii*.

Tithonia is targeted mainly for biomass transfer while the other woody perennials are for improved fallows. These species are relay-cropped with maize 4 to 5 weeks after maize is sown. Relay cropping minimizes negative effects of the woody perennials on crops while allowing the woody perennials to benefit from fertilizer and weeding provided to the crops. The practice also permits the growth of the woody perennials to be extended to two instead of one season. When the crop is harvested at the end of the first season (July-August), the woody perennials are left to grow during the second season until they are cut in February-March and the cropping cycle repeated.

Once the woody perennials are cut, wood is removed and the leaf and small twigs are left on the field and incorporated into the soil during land preparation. Such a fallow can provide 90 to 120 kg N/ha depending on rainfall during the fallow period. The source of this N could be N found accumulating in the subsoil of the soils of the study area (Hartemink *et al.*, 1996), N_2 biologically fixed from the atmosphere and N mineralized from the soil organic matter. The levels of nutrients provided through the foliage of the woody perennials in improved fallow systems is usually sufficient to produce 3 to 4 tonnes of maize per hectare. Inorganic nutrient inputs would, however, be required for higher yields and/or if the fallow biomass is used as livestock feed.

Inorganic fertilizers will also be required to supplement any short falls in what the organics (such as improved fallows and biomass transfer) provide. This may become necessary to sustain tithonia biomass production since it is not a legume that can biologically fix atmospheric N_2. To determine the sustainability of nutrient supply through tithonia biomass transfer, one has to consider the possibility that tithonia planted on the boundaries of the farms and contour bands could act as a trap for nutrients moving down the slope with water and soil. This would minimize the need for external inputs to sustain biomass production of tithonia which would also cycle back to the farm nutrients that would otherwise have been lost. What is required, therefore, is an understanding of nutrient acquisition mechanism by tithonia and redistribution of nutrients within the landscape through transfer of tithonia biomass. Long-term studies or farm nutrient budgets may also help determine the sustainability of tithonia-use systems.

Another important component of the package extended to farmers in the pilot project is soil conservation without which most of the P applied could be lost through soil erosion on sloping lands. Fortunately, there are well-proven biological erosion control options, such as contour hedgerows with leguminous species and grass strips (Kiepe and Rao, 1994) which also provide useful products in the form of fodder or organic inputs for green manuring of adjacent fields. The increased plant cover from P input alone can also reduce loss of soil nutrients. For example, in an experiment in Western Kenya on slopes of 3–4%, application of 500 kg P/ha reduced soil erosion and the loss of total P was not higher than that under unfertilized maize (Jama, 1999). While the high P rate used in this study may not be recommendable for resource-poor farmers now, it reflects one of the approaches to replenish the P depleted soils (one time application of a large amount). It could, however, become an option for farmers if and when fertilizers become affordable through either a subsidy program or improved structure and marketing conditions.

About 4000 farmers are currently testing and adapting improved fallows many with integration of Minjingu PR. Another 1400 or so farmers are also testing tithonia biomass transfer, many also in combination with Minjingu PR. Farmers are extremely pleased with the results, as their crop yields have increased many folds. The farmers are also testing these technologies on many crops – maize, maize and bean intercrops and on vegetables such as 'sukuma wiki' (Kale: *Brassica oleraceae*) and tomato. Tithonia biomass transfer can be labor intensive but its use on such crops as kale that are higher-valued than maize make its use attractive to farmers (ICRAF, 1997).

Conclusion

Soils in the tropics are renowned for low soil fertility particularly low nitrogen. Consequently low soil fertility ranks as the second most important abiotic constraint to maize production in the subhumid zones after drought. Intensified land uses, and the rapid declines in fallow periods, coupled with extension agriculture into marginal lands, have contributed to rapid decline in soil fertility particularly in the high potential subhumid zone.

Nitrogen and phosphorus deficiencies are severe and widespread biophysical constraints to smallholder maize productivity, and in turn to long term food security of the resource poor in Southern and Eastern Africa. Crop rotations, intercropping, improved fallows, green manures, inorganic fertilizers and integrated nutrient management practices (organic and inorganic nutrient source) have been developed as a means of replenishing soil fertility and increasing maize productivity. In our conclusion a critique of which technologies will be widely adopted is given.

Inorganic fertilizers have been recommended as a quick means for increasing maize productivity. Where smallholder farmers apply fertilizers, the quantities applied are too low that they contribute little on long term fertility management. It has been calculated that farmers apply an average of 10 kg/ha for fertilizer nutrients. The high grain to nutrient price ratios and high levels of production risk are two of the underlying factors of the low fertilizer use. Even when fertilizer is used in farmer's fields the nutrient use efficiency is very low and this also reduces overall productivity. Progress has been made in developing maize cultivars which efficiently utilize soil available nutrients especially nitrogen and covert it to grain. It is estimated that N-use efficient cultivars could increase maize yield gains by 25%. Further increase of farm yields must come from enhanced and more efficient use of chemical fertilizers and organic manures and adoption of agronomic practices that increase fertilizer responsiveness such as early planting and appropriate land management practices.

A central aspect of sustaining soil fertility on smallholder farms is the maintenance and management of soil organic mater (SOM). Inorganic fertilizers do not add organic carbon in the soils unless the crop residues are ploughed back in the soil. Organic inputs from crop rotations and other techniques will contribute to some maintenance of SOM.

Crop rotation with annual grain legumes offer much higher opportunity for widespread adoption. These annual legumes offer a good compromise for meeting both food security and soil fertility needs for farm household. Grain legumes can provide seed and sometimes leaves for home consumption, income while adding organic matter and nitrogen to the soil. The most promising species combine high grain yield, high root and short biomass and low nitrogen harvest index. Such legumes include self-nodulating promiscuous types of soyabean, pigeon pea, groundnut, cowpea and bambara nuts. Under favourable conditions green manure crops can generate large amounts of organic matter (up to 200 kg N/ha) in 100-150 days of growth of which 30-50 kg are available to crop growth. Although there is a long history of experimentation with green manures for improving soil fertility in Southern and Eastern Africa, the adoption rate by smallholder farmers is very low or none. However, promising research results from the Soil Fertility Network (SOILFERTNET) of Southern Africa on green manures have started to emerge. The on-going research is focussed on the potential of undersowing maize with green manures for improving soil fertility. Undersowing *Tephrosia vogelli* appears to be one of the most promising as it grows through the dry season and produces a large amount of organic matter. Velvet beans have also shown good potential for use as a green manure in rehabilitation of exhausted soils and are able to produce large amounts of biomass under acidic soils.

Improved fallows are the most promising agroforestry basal soil fertility replenishment systems in both Southern and Eastern Africa. This practice has been adopted in extensive farming system such as Eastern Zambia and intensive land use systems in Western Kenya. About 30 000 farmers are experimenting with improved fallows in these two regions. In addition to supplying nitrogen and improving maize productivity, tree fallows provide other benefits. Fuelwood production is on the order of 15 t/ha^{-1} after 2 year sesbania fallows. *Sesbania sesban* and other tree fallows have decreased the seed pool of parasitic weed *Striga hermonthica* by 50% in Western Kenya and Eastern Zambia. Tree fallows can also relay other nutrients such as potassium from depth and improve soil physical properties such infiltration rate aggregate stability and water storage. A lot of NGOs are disseminating improved fallow for soil fertility replenishment in the region. However there are several concerns which need to be addressed. Improved fallows may not be an option for a larger number of farmers with small land holdings. Low soil fertility and pests can reduce the biomass produced by fallows.

There are also no clear answers on how much N is fixed by trees on different soil types and unless this is addressed improved fallows may produce inadequate N for high maize yields. There is need to continue evaluating different fallow species, management and adoption across biophysical and socio-ecomic gradients. The institutional support required for wide adoption of fallows needs to be understood.

There are no silver bullet solutions for soil fertility replenishment. Various options suit farmers depending on their biophysical and socio-economic circumstances. The promotion of integrated soil fertility management practices seems to offer much potential than promoting one or two options. For these technologies to make an impact on-farm income and livelihood there several issues which need to be addressed. These include seed production, pest species diversity and microsymbionts of legumes. The strategy for scaling up different options should involve farmers, extensions, researchers, NGOs and policy makers. Without this concerted effort, researchers will continue to produce technological bullets in the institutional vacuum!

References

Amijee, F. and Giller, K. E. (1998) Environmental constraints to nodulation and nitrogen fixation of *Phaseolus vulgaris* L. In Tanzania: 1 A survey of soil fertility and root nodulation. *Afr. J crop. Sci.* In press.

Bache, B.W. and Heathcote, R.G. (1969) Long-term effects of fertilizers and manure on soil and leaves of cotton in Nigeria. *Experimental Agriculture* **5**:241-247.

Bekunda, M.A., Bationo, A. and Ssali, H. (1997) Soil Fertility Management in Africa: A Review of Selected Research Trials. American Society of Agronomy and Soil Science Society of America, Madison, WI 53711, USA. *Replenishing Soil Fertility in Africa.* SSSA Special Publication.

Benson, T. (1997) The 1995/96 fertilizer verification trial- Malawi: economic analysis of results for policy discussion. Ministry of Agriculture and Livestock Development, Lilongwe.

Badaruddin, M. and Meyer, D.W. (1989) Water use by legumes and its effects on soil water stress. *Crop Science.* **29**:1212-1216.

Bromfield, AR, Hancock, IR, and Debenham, DF (1981) Effects of ground PR and elemental S on yield and P uptake of maize in Western Kenya. *Experimental Agriculture* **17**:383-387

Buresh, R.J. and Tian, G. (1997) Soil improvement by trees in sub-Saharan Africa. *Agrofor. System.* **38**: 51-76

Buresh, R.J., Smithson, P.C. and Hellums, D.T. (1997) Building soil phosphorus capital in Africa. p. 111-149. In: Buresh, R.J., Sanchez, P.A. and Calhoun, F. (eds). *Replenishing soil fertility in Africa.* SSSA Special Publication No. 51, Soil Science Society of America, Madison, Wisconsin, USA.

Cadisch, G. and Giller, K.E. (1997), (eds.) *Driven by nature: Plant litter quality and decomposition.* CAB International: Wallingford, UK.

Cahn, M.D., Bouldin, D.R., and Cravo, M.S. (1992) Nitrate sorption in the profile of an acid soil. *Plant Soil.* **143:**179-183.

Deckers, J. (1993) Soil fertility and environment problems in different ecological in sub- Saharan Africa In: *Role of Plant Nutrients for Sustainable Food Production in sub- Saharan Africa.*

Dhliwayo, D.K.C. and Mukurumbira, L.M. (1996) Enhancing the Agronomic effectiveness of low-cost fertilizer materials in Zimbabwe. In: *Research Results and Network Outputs.* Proceedings of the Second Meeting of the Soil Fertility Network Working Group held at Kadoma Ranch Motel, Kadoma, Zimbabwe 18-21 July 1995. CIMMYT, Harare, Zimbabwe. pp 16-18.

Dhliwayo, D.K.C. (1998) Beneficiation of Dorowa phosphate rock through composting with cattle manure: Residual effects on groundnut. In: *Soil Fertility Research for maize-based farming systems in Malawi and Zimbabwe.* pp 173-178.

Dyson, T. (1995) World food demand and supply prospects. *In The Fertilizer Society Proc.* 367, Cambridge, 6-8 Dec. (1995). Greenhill House, Peterborough, England.

Franzel, S., Phiri, D. and Kwesiga, F. (1999) ICRAF working paper No. 124.

Franzluebbers, K., Hossner, R.L. and Juo, A.S.R. (1998) Integrated nutrient management for sustained crop production in sub- Saharan Africa (A review). *Soil management CRSP: TropSoils/ TAMU Technical Bulletin.* 98-03.

Gachene, C.K.K., Karanja, N.K. and Mureithi, J.G. (2000) Effect of soil erosion on soil productivity and subsequent restoration of productivity using green manure cover crops: data summary of a long-term field experiment. *Legume Research Network Project Newsletter*, Issue No. 4:8-10.

Gachengo, C.N. (1996) *Phosphorus release and availability on addition of organic materials to phosphorus fixing soils.* MPhil Thesis, Moi University.

Ganunga, R., Yerokun, O. and Kumwenda, J.D.T. (1998) *Tithonia diversifolia:* An organic source of nitrogen and phosphorus for maize in Malawi. In: Waddington, S.R. *et al.* (eds). *Soil fertility research for maize-based farming systems in Malawi and Zimbabwe*, pp191-194. Soil Fert Net and CIMMYT-Zimbabwe, Harare, Zimbabwe.

Garrity, D.B. and Mercado, A.R. Jr. (1994) Nitrogen fixation capacity in the component species of contour hedgerows: How important? *Agrofor. System.* **27:** 241-258.

Giller, K.E., Ormesher, J. and Awar, F.M. (1991) Nitrogen transfer from *Phaseolus* bean to intercropped maize measured using 15N- enrichment and 15N-isotope dilution methods. *Soil Biol. Biochem.*, **23:** 339-346.

Giller, K.E., McDonagh, J.F. and Cadisch, G. (1994) Can biological nitrogen fixation sustain agriculture in the tropics? P. 173-191. In: Syers, J. K. and Rimmar, D. L. (eds.). *Soil science and sustainable land management in the tropics.* CAB Int., Wallingford, England.

Giller, K.E. and Cadisch, G. (1995) Future benefits from biological nitrogen fixation: An ecological approach to agriculture. *Plant Soil.* **174:** 255-277.

Gitari, J.N., Karumba, S.K. and Mwaniki, K. (2000) Performance of green manure legumes in two contrasting sites in Embu and Mbeere districts of Mount Kenya region. *Legume Research Network Project Newsletter*, Issue No. **4:** 8-10.

Grant, P.M. (1981) The fertility of sandy soil in peasant agriculture. *Zimbabwe Agricultural Journal.* **78:** 169-175.

Guar, A.C., Neelakanan, S. and Dargan, K.S. (1984) *Organic Manure*. Indian Council of Agriculture Research. New Delhi, India.

Haque, I. (1993) Nutrient management and feed improvement in crop livestock systems of Saharan Africa: present status and future outlook. *ILCA Environmental Sciences Division Working Document No. 28*. ILCA (International Livestock Centre for Africa), Addis Ababa, Ethiopia.

Hartemink, A.E., Buresh, R.J., Jama, B.A. and Janssen, B.H. (1996) Soil nitrate and water dynamics in sesbania fallows, weed fallows and maize. *Soil Sci. Soc. Am. J.* **60:** 568-574.

Hesterman, O.B., Griffin, T.S., Williams, P.T., Harris, G.H. and Christenson, D.R. (1992) Forage legume-small grain intercrops: Nitrogen production and response of subsequent corn. *Journal of Production Agriculture*. **5:** 340-348.

Hoekstra, D. (1987) Economics of agroforestry. *Agroforestry Systems*. **5:** 293-300.

ICRAF. (1996) *Annual report 1995*. International Centre for Research in Agroforestry, Nairobi, Kenya.

ICRAF. (1997) *Annual report 1996*. International Centre for Research in Agroforestry, Nairobi, Kenya.

Ikerra, T.W.D., Mnekeni, P.N.S. and Singh, B.R. (1994) Effects of added compost and farmyard manure on P release from Minjingu PR and its uptake by maize. *Norwegian Journal of Agricultural Science*. **8:** 13-23.

Ikombo, B.M. (1984) Effects of farmyard manure and fertilizers on maize in semi-arid areas of eastern Kenya. *East Afr. Agric. J.* **44:** 266-274.

Jama, B.A., Nair, P.K.R. and Rao, M.R. (1995) Productivity of hedgerow shrubs and maize under alley cropping and block planting systems in semiarid Kenya. *Agroforestry Systems* **31:** 257-274.

Jama, B.A., Swinkels, R.A., Buresh, R.J. (1997) Agronomic and economic evaluation of organic and inorganic sources of phosphorus in Western Kenya. *Agronomy Journal*. **89:** 597-604.

Jama, B., Buresh, R.J., Ndufa, J.K. and Sherpherd, K.D. (1998) Vertical distribution of roots and soil nitrate: Tree species and phosphorus effects. *Soil Sci. Soc. Am. J.* **62:** 280-286.

Jama, B., Buresh, R.J. and Place, F.M. (1998). Sesbania tree fallow on phosphorus-deficient sites: maize yield and financial benefits. *Agron. J.* **90:** 717-726.

Jama, B. (1999) Phosphate rock application for rebuilding the productive capital of African soils: Experience from East Africa. Paper submitted for the Second Issue of *Africa Soil Fertility Management Newsletter*. IFDC, Togo.

Jama, B.A., Palm, C.A., Buresh, R.J., Niang, A., Gachengo, C., Nziguheba, G. and Amadalo, B. (1999) *Tithonia diversifolia* green manure for improvement of soil fertility: A review from Western Kenya. *Agroforestry Systems*. **49:** 201-221.

Jama, B. and Mafongoya, P.L. (1999) Strategies for soil fertility recapitalization in Africa: Experiences from Western Kenya and Eastern Zambia. In *FAO Proceedings on Soil Fertility Initiative*. Sub-Saharan Africa.

Jeranyama, P., Hesterman, B.O. and Waddington, S.R. (1998) The impact of legumes relay-intercropped into maize at Domboshava, Zimbabwe. In: Waddington, S.R., Murwira, H.K., Kumwenda, J.D.T., Hikwa, D. and Tagwira, F. (eds.) *Soil fertility research for maize-based farming systems in Malawi and Zimbabwe*. Proceedings of the Soil Fert Net Results and Planning

Workshop held from 7 to 11 July 1997 at Africa University, Mutare, Zimbabwe. Soil Fert Net and CIMMYT-Zimbabwe, Harare.

Jiri, O. and Waddington, S.R. (1998) Leaf prunings from two species of tithonia raise maize grain yield in Zimbabwe, but take a lot of labour! *Newsletter of Soil Fert Net*, Harare, Zimbabwe. *Target*. **16:** 4-5.

Kamidi, M., Gitari, F., Osore, P. and Cheruiyot, D. (2000) Effect of green manure legume on the yield of maize and beans in Matunda Farm, Trans Nzoia district. Legume Research Network Project Newsletter, Issue No. 4:8-10.

Kang, B.T., Reynolds, L., and Atta-Krah, A.N. (1990) Alley farming. *Advances in Agronomy*. **43:** 315-359.

Kapkiyai JJ, Woomer PL, Qureshi J, Smithson P and Karanja KN (1997) Effects of fertilizer and organic inputs on soil organic matter and nutrient dynamics in a Kenyan Nitisol. In: Bergstrom, L. and Kirchmann, H. (eds.) *Carbon and nitrogen dynamics in natural and agricultural tropical ecosystems*. CAB International, Wallingford, UK.

Kapkiyai, J.J., Karanja, K.N., Quresh, J.N., Smithson, C.P. and Woomer, P.L. (1999) Soil organic matter and nutrient dynamics in a Kenyan Nitisol under long-term fertilizer and organic input management. *Soil Biology and Biochemistry*. **31:** 1773-1782.

Kiepe, P. and Rao, M.R. (1994) Management of agroforestry for the conservation and utilization of land and water resources. *Outlook in Agriculture*. **23(1):** 17-25.

Kumar, Rao, J.V.D.K., Dart, P.J. and Sastry, P.V.S.S. (1983) Residual effect of pigeonpea (*Cajanus cajan*) on yield and nitrogen response of maize. *Exp. Agric.* **19:** 131-141.

Kumar, Rao, J.V.D.K. and Dart, P.J. (1987) Nodulation, nitrogen fixation and nitrogen uptake in pigeonpea (*Cajanus cajan* (L) Millsp.) of different maturity groups. *Plant Soil*. **99:** 255-266.

Kumwenda, J.T., Waddington, S.R., Snapp, S.S., Jones, R.B. and Blackie, M.J. (1996) Soil fertility management research for the maize cropping systems of smallholders in Southern Africa: A review. *Nat. Resour. Group Pap.* 96-2. CIMMYT, Mexico, D.F.

Kwesiga, F., Franzel, S., Place, F., Phiri, D. and Simwanza, C.P. (1998) *Sesbania sesban* improved fallows in eastern Zambia: The inception, development and farmer enthusiasm. In: Buresh, R.J. and Cooper, P.J. (eds.). *The science and practice of short-term improved fallows*. Kluwer Academic Publication, Dordrecht, the Netherlands.

Kwesiga, F. and Coe, R. (1994) The effect of short rotation *Sesbania sesban* planted fallows on maize yield. *For. Ecol. Manage.* **64:** 199-208.

Ledgard, S.J. and Giller, K.E. (1995) Atmospheric N2- fixation as an alternative nitrogen source. P. 443-486. In: Bacon, P. (ed.) *Nitrogen fertilization and the environment*. Mercel Dekker, New York.

Lijzenga, M. (1998) *Maize response to NPK in relation to fertility indices in Western Kenya*. MSc thesis. Wageningen Agricultural University, The Netherlands.

MacColl D (1989) Studies on maize (Zea mays L.) at Bunda, Malawi. II. Yield in short rotation with legumes. *Expt. Agric.* **25:** 367-374.

Mafongoya, P.L., Barak, P. and Reed, J.D. (1999) Carbon, nitrogen and phosphorus mineralization from multipurpose tree leaves and manure from goats fed these leaves. *Biology and Fertility of Soils*. (In press).

Mafongoya, P.L. and Nair, P.K.R. (1997) Multipurpose tree prunings as a source of nitrogen to maize under semiarid conditions in Zimbabwe. Nitrogen recovery rates in relation to pruning quality and method of application. *Agroforestry Syst.* **35:** 47.

Mafongoya, P.L., Giller, K.E. and Palm, C.A. (1997) Decomposition and nutrient release patterns of prunings and litter of agroforestry trees. *Agroforestry Systems* **38:** 77-97.

Mafongoya, P.L., Giller, K.E. and Palm, C.A. (1998) Decomposition and nitrogen release patterns of tree prunings and litter. *Agroforestry Systems.* **38:** 77-97.

Maroko, J.B., Buresh, R.J. and Smithson, P.C. (1998) Soil nitrogen availability as affected by fallow-maize systems in two soils in Kenya. *Biol. Fertil. Soils.* **26:** 229-234.

Mathuva, M.N., Rao, M.R., Smithson, P.C. and Coe, R. (1998) Improving maize (Zea mays) yields in semiarid highlands of Kenya: agroforestry or inorganic fertilizers? *Field Crops Res.* **55:** 57.

Mekonnen, K., Buresh, R.J. and Jama, B. (1997) Root and inorganic distribution of sesbania fallows, natural fallow and maize. *Plant Soil.* **188:** 319-327.

Metelerkamp, H.R.R. (1987) Review of crop research relevant to the semiarid areas of Zimbabwe. In: *Cropping in the semiarid areas of Zimbabwe.* Proceedings of a workshop held in Harare, 24 to 28 August 1987, pp.190-315.

Mpepereki, S.F., Makonese, F. and Giller, K.E. (1996) *Soybeans in smallholder farming systems in Zimbabwe.* CIMMYT, Harare, Zimbabwe.

Mugendi, D.N., Mochoge, B.O., Coulson, C.L. and Sang, F.K. (1997). Effect of intercroppnig cassia siamea prunings on maize yield in semiarid Kenya. *Afr. Crop Sc. J.* **5:** 27.

Mugendi, D.N., Nair, P.K.R., Mugwe, J.N., O'Neill, M.K., and Woomer, P.L. (1999a) Calliandra and leucaena alley cropped with maize. Part 1: Soil fertility changes and maize production in the subhumid highlands of Kenya. *Agrof. Syst.* **46:** 39-50.

Mugendi, D.N., Nair, P.K.R., Mugwe, J.N., O'Neill, M.K.O., Swift, M.J. and Woomer, P.L. (1999b) Alley cropping of maize with calliandra and leucaena in the sub humid highlands of Kenya. Part 2. Biomass decomposition, N mineralization and N uptake by maize. *Agroforestry Systems* **46:** 51-64.

Mugwira, L.M. (1985) Effects of supplementing communal area manure with lime and fertilizer on plant growth and nutrient uptake. *Zimbabwe Agricultural Journal.* **82:** 153-159

Mugwira, L. and Mukurumbira, L. (1985) Nutrient supplying power of different groups of manure from communal areas and their effect on plant growth and maize grain yields. *Zimbabwe Agricultural Journal.* **83:** 25-2.

Mureithi, J.G., Taylor, R.S. and Thorpe, W. (1994) The effects of alley cropping with *Leucaena leucocephala* and of different management practices on the productivity of maize and soil chemical properties in lowland coastal Kenya. Agroforestry Systems **27:** 31-51.

Murwira HK (1995) Ammonia losses from Zimbabwean cattle manure before and after incorporation into soil. *Trop. Agric. Trin.* **72:** 269-276.

Murwira, H.K., Swift, M.J. and Frost, P.G.H. (1995) Manure as a key resource in sustainable agriculture. p. 131-148. *In* Powell LM, Fernandez-Rivera S. Williams OT and Renard C (ed) *Livestock and sustainable nutrient cycling in mixed farming systems of sub-Saharan Africa.* Volume II. Technical papers.

Proceeding of an International Conference held in Addis Ababa, Ethiopia, 22-26 Nov. 1993. International Livestock Centre for Africa, Addis Ababa, Ethiopia.

Mukurumbira, L.M. (1985) Effects of rate of fertilizer nitrogen and previous grain legume crop on maize yields. *Zimbabwe Agric. J.* **82:** 177-179.

Mutuo, P.K., Mukalama, J.P., Agunda, J., Kobare, S., Palm, C.A., Jama, B., Kinyangi, J., Amadola, S. and Niang, A. (2000). On- farm testing of organic and inorganic phosphorous source on maize in Western Kenya. In: *The Biology and Fertility of Tropical Soils*: TSBF Report, pp 22.

Myers, R.J.K., Palm, C.A., Cuevas, E., Gunatilleke, I.U.N. and Brossard, M. (1994) The synchronization of nutrient mineralization and plant nutrient demand. In: Woomer PL and Swift MJ (eds.) *The Biological Management of Soil Fertility*, pp81-116. John Willey and Sons, Chichester, UK.

Nair, P.K.R. (1993) *An Introduction to Agroforestry*. Kluwer, Dordrecht, the Netherlands.

Nair, P.K.R., Mugendi, D.N. and Latt, C.R. (1999) Nutrient cycling in Tropical Agroforestry Systems, Myths and Science. In: *Agroforestry in Sustainable Agricultural Systems*, CRC Press/ Lewis Publishers.

Natarajan, M. and Mafongoya, P.L. (1992) A study on intercropping of pigeonpea (*Cajanus cajan* L Millsp.) with maize, sunflower and groundnut in Zimbabwe. *Zimbabwe J. Agric. Res.* **30:** 163-171.

Nyathi, P. and Campbell, B.M. (1993) The acquisition and use of miombo litter by small-scale farmers in Masvingo, Zimbabwe. *Agroforestry Systems*. **22:** 43-48.

Nye, P.H. and Greenland, D.J. (1960) The soil under shifting cultivation. *Technical Committee no. 51*. Commonwealth Bureau of Soils. Harpenden.

Nziguheba, G., Palm, C.A., Buresh, R.J. and Smithson, P.C. (1998) Soil phosphorus fractions and adsorption as affected by organic and inorganic sources. *Plant and Soil*. **198:** 159-168.

Nzuma, J.K. and Murwira, H.K. (1998). Effect of management on changes in manure nitrogen during storage. In: *The Biology and Fertility of Tropical Soils*: TSBF Report.

Ong, C.K., Corlet, J.E., Singh, R.P. and Black, C.R. (1991) Above and below ground interactions in agroforestry systems. *For. Ecol. Mgt.* **45:** 45.

Ong CK (1996) A framework for quantifying the various effects of tree-crop interactions. In: Ong, C.K. and Huxley, P. (eds.). *Tree crop interactions. A physiological approach*. CAB International, Wallingford, UK.

Palm, C.A. (1995) Contribution of agroforestry trees to nutrient requirements of intercropped plants. *Agroforestry Syst.* **30:** 105-124.

Palm, C.A., Gachengo, C.N., Delve, R.J., Cadisch, G. and Giller, K.E. (2001) Organic inputs for soil fertility management: some rules and tools. *Agriculture, Ecosystems and Environment*. **83:** 27-42.

Palm, C.A., Myers, R.J.K. and Nandwa, S.M. (1997) Combined use of inorganic and organic nutrient sources for soil fertility maintenance and replenishment. In: Buresh, R.J., Sanchez, P.A. and Calhoun, F. (eds.). *Replenishing soil fertility in Africa*. SSSA Special Publication No. 51. Soil Science Society America, Madison, Wisconsin, USA, pp. 193-217.

Pingali, P.L. (ed.) (2001) CIMMYT 1999-2000 world maize facts and trends. *Meeting world maize needs: Technological opportunities and priorities for the public sector*. Mexico, DF: CIMMYT.

Probert, M.E., Okalebo, J.R. and Jones, R.K. (1995) The use of manure on smallholders' farm in semi-arid Eastern Kenya. *Expl. Agr.* **31:** 371-381.

Powell, J.M. and Williams, T.O. (1995) An overview of mixed farming systems in sub-Saharan Africa. pp. 21-36. In: Powell, L.M., Fernandez-Rivera, S., Williams, O.T. and Renard, C. (ed) *Livestock and sustainable nutrient cycling in mixed farming systems of sub-Saharan Africa.* Volume 11. Technical papers. Proceeding of an International Conference held in Addis Ababa, Ethiopia, 22-26 Nov. 1993. International Livestock Centre for Africa, Addis Ababa, Ethiopia.

Rajan, S.S.S., Watkinson, J.H. and Sinclair, A.G. (1996) Phosphate rocks for direct application to soils. *Advances in Agronomy.* **57:** 77-159.

Ransom, J.K., Ojiem, J. and Kanampiu, F.K. (1995) Nutrient flux between maize and livestock in a maize-coffee-livestock system in Central Kenya. p. 411-419. In: Powell, L.M., Fernandez-Rivera, S., Williams, O.T. and Renard, C. (eds.) *Livestock and sustainable nutrient cycling in mixed farming systems of sub-Saharan Africa.* Volume II. Technical papers. Proceeding of an International Conference held in Addis Ababa, Ethiopia, 22-26 Nov. 1993. International Livestock Centre for Africa, Addis Ababa, Ethiopia.

Rao, M.R., Sharma, M.M., and Ong, C.K. (1990) A study of the potential of hedgerow intercropping in semiarid India using a two-way systematic design. *Agroforestry Systems.* **11:** 243-258.

Rao, M.R., Sharma, M.M. and Ong, C.K. (1991) A tree/crop interface design and its use for evaluating the potential of hedgerow intercropping. *Agrofor. Syst.* **13:** 143.

Rao, M.R., Nair, P.K.R. and Ong, C.K. (1997) Biophysical interactions in tropical agroforestry systems. *Agrof. Syst.* **38:** 3-49.

Rosegrant, M.W., Agaoili-Sombailla, M. and Perez, N.D. (1996) Global food Projections to 2020: Implications for investment, food, agriculture, and the Environment. Discussion Paper 5. Washington, D.C. IFPRI.

Sanchez, P.A. (1976) *Properties and management of soils in the tropics.* John and Wiley and Sons, New York, NY, USA.

Sanchez, P.A. and Logan, T.L. (1992). Myths and Science about the Chemistry and Fertility of Soils in the tropics In: *Myths and Science of Soils of the Tropics* Lal, R. and Sanchez, P.A. (eds.) SSSA Special Publication No. 29 SSSA and ASA, Madison Wisconsin.

Sanchez PA (1995) Science in agroforestry. *Agroforestry Systems.* **30:** 5-55.

Sanchez, P.A., Shepherd, K.D., Soule, M.J., Place, F.M., Buresh, R.J., Izac, A-M.N., Mokwunye, A.U., Kwesiga, F.R., Ndiritu, C.G. and Woomer, P.L. (1997) Soil fertility replenishment in Africa: An investment in natural resource capital. p. 1-46 in: Buresh RJ, Sanchez PA and Calhoun F (eds.) *Replenishing soil fertility in Africa.* SSSA Special Publication No. 51, Soil Science Society of America, Madison, Wisconsin, USA.

Scoones, I. and Toulmin, C. (1985) Socio-economic dimensions in nutrient cycling in agropastoral systems in dryland Africa. In: Powell, J.M., Fernandez-Rivera, S., Williams, T.O. and Renard, C. *Livestock and sustainable nutrient cycling in mixed farming systems of sub-Saharan Africa.* Vol. 2: technical papers. Proc. of an International Conference held in Addis Ababa, Ethiopia, 22-26 Nov. 1993. ILCA (International Livestock Centre for Africa). Addis Ababa, Ethiopia. 568 pp.

Shepherd, K.D. and Soule, M.J. (1998) Assessment of the economic and ecological impacts of agroforestry and other soil management options on Western Kenya farms using a dynamic simulation model. *Agric Ecosys Environ.* **71:** 131-145.

Shumba, E.M. (1983) Factors contributing to a decline in groundnut production in the Mangwende-Murewa District, and the need for a technical research input. *Zimbabwe Agricultural Journal* **80:** 251-254.

Shumba, E.M., Dhliwayo, H.A. and Mukok, O.Z. (1990) The potential of maize-cowpea intercropping in low rainfall areas of Zimbabwe. *Zimbabwe Journal of Agricultural Research.* **29:** 81-85.

Smaling, E.M.A. (1993) Soil nutrient depletion in sub- Saharan Africa. In: Van Reuler, H. and Prins, W. (eds.), *The role of plant nutrients for sustainable food crop production in sub- Saharan Africa.* VKP, Leidschendam, The Netherlands.

Snapp, S.S., Mafongoya, P.L. and Waddington, S.R. (1998) Organic matter technologies for integrated nutrient management in smallholder cropping systems of Southern Africa. *Agriculture Ecosystems and Environment.* **71:** 185-200.

Stoorvogel, J.J., Smaling, E.M.A. and Janssenm, B.H. (1993) Calculating soil nutrient balances in Africa at different scales. I. Supranational scale. *Fertilizer Research.* **35:** 227-235.

Swift, M.J. (1987) Tropical soil biology and fertility: Interrogational research planning workshop, special issue 13. In: *Biology International.* IUBS: Paris.

Szott, L.T., Palm, C.A. and Sanchez, P.A. (1991) Agroforestry in acid soils of the humid tropics. *Advances in Agronomy.* **45:** 275-301.

Tanner, P.D. and Mugwira, L. (1984) Effectiveness of communal area manures as sources of nutrients for young maize. *Zimbabwe Agric. J.* **81:** 31-35.

Toomsan, B., McDonagh, J.F., Limpinuntana, V. and Giller, K.E. (1995) Nitrogen fixation by groundnut and soyabean and residual nitrogen benefits to rice in farmers' fields in Northeast Thailand. *Plant Soil,* **175:** 45-56.

Vertregt, N. and Rutgers, B. (1988) *Ammonia volatilization from grazed pasture. Centre for Agrobiological Research Report 84.* Centre for Agrobiological Research, Wageningen, The Netherlands. 37 pp.

Vanlauwe, B., Swift, M.J. and Merckx, R. (1996) Soil litter dynamics and N use in a leucaena (Leucaena leucocephala lam. (de Wit) alley cropping system in southwestern Nigeria. *Soil Biol. Biochem.,* **28:** 739-749.

Van Noordwijk, M. (1989) Rooting depth in cropping systems in the humid tropics in relation to nutrient use efficiency. In: Van der Heide J (ed.) *Nutrient Management for Food Crop Production in Tropical Farming Systems.* Institute of Soil Fertility, Haren, The Netherlands, pp 129-169.

Van Noordwijk, M., Lawson, G., Soumare, A. and Groot, J.J.R. (1996) Root distribution of trees and crops: Competition and/ complementarity. In: Ong CK and Huxley P (eds.) *Tree crop interactions, a physiological approach.* CAB International: Wallingford, UK., Ch. 9.

Van Straaten, P. (1997) Geological phosphate resources in central East Africa. *Trip report, 23 June to 21 July* 1997. Department of Land Resource Science, University of Guelph, Ontario, Canada.

Wong, M.T.F., Akyeampong, A., Nortcliff, S., Rao, M.R. and Swift, R.S. (1995) Initial responses of maize and beans to decreased concentrations of monomeric inorganic aluminium with application of manure or tree prunings to an Oxisol in Burundi. *Plant Soil.* **171:** 275.

Woomer, P.L., Okalebo, J.R. and Sanchez, P.A. (1997) Phosphorus replenishment in Western Kenya: from field experiments to an operational strategy. *African Crop Science Journal.* **3:** 559-570.

Young, A. (1997) *Agroforestry for soil management.* CAB International, Wallingford, UK.

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Potentials and Challenges of Soil Fertility Management in the Banana-Based Cropping Systems of Eastern Africa

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Introduction

Banana (*Musa* spp.) is an important crop in East and Southern Africa with production estimates of 15 million tonnes of fruit annually, and representing 21% of world output (Vuylsteke, 1996). It is a main staple for about 50% of peoples in the humid mid-altitude zones of the Great Lakes countries comprising Uganda, Rwanda, Burundi, Eastern Congo, Western and Central Kenya, and the Kagera and Kilimanjaro areas of Tanzania. The most cultivated and endemic *Musa* in Eastern Africa are triploids of the AAA genomic constitution (Vuylsteke, 1996) with varietal introductions (AA, AB and ABB types) apparently increasing as a result of the decline in yields of the AAA cooking types. Fruits for cooking bananas are harvested when mature but still green, peeled, steamed and mashed before eating. For beer bananas, mature fruit are ripened and squeezed to extract juice that is fermented with sorghum to produce banana wine. Desert bananas are eaten when ripe while fruit for roasting bananas are preferably ripened and roasted before eating. Banana is also an important source of income for the small scale farmers who produce the bulk of the crop.

The bananas originated from South East Asia (Simmonds, 1962). The earliest records of the crop in East Africa is from Mombasa in 1300 A.D., believed to have come from Java via Madagascar. The bananas in the region are now commonly referred to as the East African Highland bananas and, because they exhibit great diversity from somatic mutation and human selection, the region is considered a secondary centre of diversity for the *Musa* AAA group (Ortiz and Vuylsteke, 1996).

Bananas grow on diverse soils. Yost and Eswaran (1990) characterised 5 different soils (Oxisols, Alfisols, Inceptisols, Mollisols and Ultisols) within a distance of 20 km in the banana growing central region of Uganda. Ideally, bananas require a deep, well-drained loam soil with high humus content (Zake *et al*, 2000). The dominant soils in the East African region to which banana is grown are Oxisols and Ultisols with physical conditions that are good for root growth but whose nutrient status declines rapidly after land clearing (Delvaux, 1995). Yet bananas take up considerable amounts of nutrients, especially potassium (Table 4.1); those removed in harvested fruit must be replaced if continuous production of the plantation has to be maintained. Coffee takes up much less nutrients than banana but receives more fertiliser inputs because it is a "cash" crop (Bekunda and Woomer, 1996). Research should demonstrate that using fertiliser on stable food crops, like the banana, is also profitable so as to enable adoption of skills and technologies for better fertiliser use.

Table 4.1. Average amount of nutrients (kg ha^{-1}) in banana plantations[1]

Nutrient	Amount removed in fresh fruit	Amount in remaining plants	Total	Coffee[2]
Nitrogen	189	199	388	227
Phosphorus	29	23	52	16
Potassium	778	660	1438	234
Calcium	101	126	227	129
Magnesium	49	76	125	33

[1]Based on 2400 mother plants per hectare (roots not included) and yields of 50t ha^{-1} (Lahav and Turner, 1983). The banana cultivars were of the Cavendish type; we have not established data for the East African highland bananas for which mineral uptake may be different. [2]Based on 1350 coffee trees per hectare (Wilson, 1985)

Banana cultivation in Eastern Africa has been described in Bekunda (1999), based on the Ugandan growing systems. Bananas are commonly grown on smallholdings around homesteads. Cultivation is through clonal propagation, using healthy suckers of about 1.5 m high and 45 cm girth, and spaced at 3 by 3 m. When being established, crops like beans, maize and sweet potatoes are intercropped with the young banana plants and phased out at canopy closure. Some fruit trees, like the jack fruit (*Artocarpus heterophyllus*) and pawpaw (*Carica papaya*) are established with the plantation as sources of fruit and to serve as windbreaks. Sometimes the intercrops are cash crops like coffee and vanilla which benefit from the shade provided by the banana plant. Of recent, human pressure upon land has increased and intercropping is widely practised in old plantations.

Mulching of banana fields is a traditional agronomic practice favoured for its suppression of weeds, conservation of moisture and maintenance of soil fertility. Traditionally, pruned banana leaves and plant parts remaining after harvest are spread on the plantation floor and supplemented with materials from crop fields, fallow fields, swamps and livestock manure. Household wastes are typically distributed near the homestead resulting in a soil fertility gradient which causes higher yields near the homestead and lower yields as the distance from the house increases.

Per capita consumption of bananas in the Great Lakes Region is between 220-460 kg annually, the highest in the world (Tushemereirwe *et al*, 1993). Demand for banana is increasing resulting in more intensive use of soils that are often inherently low in fertility (Sanchez *et al.*, 1989). Soil degradation occurs as little fertilizer is used and farm-level nutrient balances are negative (Bekunda, 1992; Wortmann and Kaizzi, 1998). A major shift in banana production in Uganda has occurred with decreased production in the central region and increased production in the south-west (Gold *et al*, 1999). The decline in Central Uganda, where banana remains a highly preferred food, was attributed to reduced soil fertility, increased incidence of pests, and less labour invested resulting in sub-standard management of plantations. At the national scale, average banana fruit yields have continued to decline, from 8.4 in the 70s to 5.4 t ha^{-1} yr^{-1} in the 90s (Zake *et al*, 1994), and the life span of the plantations from over 50 to between 7-10 years (Bekunda, 1999).

In this chapter, we examine the response to the challenge of declining banana yields by the farmers and highlight research advances by researchers in East Africa, with emphasis on identifying nutrient management practices that could meet nutrient demands by bananas to maintain or restore soil fertility. Because of the high cost and uncertain accessibility of mineral fertilisers in the region, the goal should be to identify fertility management strategies based on available organic resources that provide much of the nutrients. The shortfall could then be made up through the use of mineral fertilisers. We shall review research results that show the effects of using organic and inorganic nutrients on banana fruit yields and soil fertility which are necessary for formulating guidelines for their utilisation. Research needed to fill gaps in the development of effective fertility management strategies shall be identified.

Soil Fertility Status in Banana Fields

Soil fertility embraces the physical, chemical and biological properties of the soil, and is associated with the management practices within a cropping system. As stated above, the soils to which bananas are grown in East Africa generally have good physical conditions, further favoured by the traditional mulching practices. Thus soil fertility management studies have focussed more on diagnosing plant nutrition and monitoring fertilisation effects.

In a nation-wide survey of banana production areas in Uganda, nutrient levels in foliar tissue indicated potassium to be marginal or deficient in 7 out of 10 sites and N deficient in two sites (Zake *et al.*, 1994). As part of the same survey, soil analytical data for 24 sites indicated that K, N and P were deficient in 23, 14 and 9 sites, respectively. In central Uganda, results of foliar analyses indicated that in addition to N and K, Mg deficiency may be important, (Gold *et al.*, 1999). Research in Rwanda indicated that soil texture had little influence on banana production, while chemical factors had a major effect. Potassium and phosphorus were identified as the most limiting nutrients (Godefrey *et al*, 1991a).

Magnesium deficiency symptoms in banana were reported to be common in Bukoba, Tanzania (Janssen, 1993). Janssen also noted signs of Zn deficiency, possibly induced by high P levels resulting from many years of manure application. Symptoms of Mg deficiency are also common in parts of Arusha and Kilimanjaro Regions of Tanzania in banana, as well as in maize, beans and appear to be related to the unusually high soil exchangeable K:Mg ratios, often ranging between 1 – 5 (Giller *et al.*, 1992). On an equivalent weight basis, this ratio should ideally not be greater than 1.5 (Tisdale *et al.* 1990).

For the region, these diagnostic results are variable, perhaps reflecting the heterogeneity of the soils to which bananas are grown. Based on surveys in the Kagera Region of Tanzania in which leaf analyses were done, it was observed that achieving a good diagnosis of nutritional constraints in banana may be difficult (Wortmann *et al*, 1993; Bosch *et al*, 1995). Banana fields exhibit spatial heterogeneity because they are usually not ploughed to allow uniform dispersion of nutrients through the soil, and neither do farmers evenly apply inputs onto the ground. Alternative interpretation of data based on the critical nutrient level concept (Lahav and Turner, 1983) indicated that K and Zn deficiencies were most frequently constraining banana production, while S, B and Cu deficiencies were of secondary importance. Mg level in the leaf tissue was significantly correlated to banana yield, however, while the levels for other apparently deficient nutrients were not related to yield. Total soil N, available P and exchangeable K were not related to estimates of banana productivity.

Data from the Kagera research were used to estimate critical nutrient levels, cation ratios and DRIS (Diagnosis and Recommendation Integrated Systems) norms for East African Highland Banana (Wortmann *et al*, 1994a). DRIS evaluates nutrient relationships and the adequacy of each nutrient in relation to other nutrients using ratios between all possible pairs of nutrients (Sumner, 1977). A nutrient ratio from a tissue sample is compared to a corresponding ratio called the "norm", a standard value used to evaluate nutrient relationships potentially applicable to the specific crop regardless of where it is grown. The critical nutrient levels proposed for foliar tissue were 3.1% N, 1.13% Ca, 0.48% Mg, 18.4 ppm Zn and 10.0 ppm B. DRIS norms were estimated for 55 different nutrient ratios. These values have not been validated but optimal levels and ratios for some nutrients appear to differ for cooking and brewing types (Bosch *et al*, 1995).

Soil nutrient levels in banana fields are generally higher than in other parts of the farm, probably due to several factors: more fertile fields were selected for banana production initially, rates of nutrient loss from banana fields may be less, and nutrients are transferred from other parts of the farm to banana fields, especially in form of mulch. Newly established banana plantations in Rwanda had lower soil organic matter, lower soil pH, and lower levels of available cations and P than plantations that had been established for 5 or more years (Godefrey *et al*, 1991b). In Kagera Region, soils from banana fields were found to have much higher levels of P and exchangeable cations than soils of the surrounding grasslands, probably due to nutrient transfer over many years to the banana crop (Janssen, 1993). In Uganda and Democratic Republic of Congo, soils in banana fields had higher nutrient, pH and organic carbon levels than in adjacent fields cultivated for other crops (Elukessu *et al*, 1996; Wortmann and Kaizzi, 1998). Banana fields typically show a fertility gradient from the household to outer field boundaries due to the application of household waste (Friedrich, 1968; Elukessu, 1996). Wortmann *et al.* (1993) found that banana yield and banana leaf N and Bo content increased with proximity to the house. But the special attention to the soils resulting in the relatively higher fertility status of the soils has not stemmed the decline in banana production. Then, either the fertility status is not enough to support expected banana productivity or it is secondary to some other factor(s) that reduce banana productivity.

The soil fertility status indicators, namely soil and foliar analytical data, show that the banana plantations of eastern Africa are poorly nourished but from different nutrients, perhaps reflecting the heterogeneity of the soils. This makes diagnosis of nutritional constraints in banana using these methods of limited value. The development of new approaches, such as the use of DRIS, to improve utility of these tests in identifying the limiting nutritional condition is a necessary strategy. This could be supplemented by research leading to the establishment of response curve functions for soils of different status.

Soil Fertility Management in Banana-Based Cropping Systems

Soil fertility is often managed to favour banana over other crops through the application of manure, crop residues and other organic materials. In a survey of 510 farm families practicing banana-based cultivation along the Lake Victoria Basin of Southern-Central Uganda (Bekunda and Woomer, 1996), 97% of the farmers interviewed left banana stalks and leaves in the banana fields upon pruning and harvest. Farmers also reported various external inputs and organic resource transfers Eighty one percent of the farmers applied field crop residues to banana fields and 31%, animal manure. Only 4% applied inorganic fertilisers to their plantations.

At four locations in Central and Eastern Uganda, Wortmann and Kaizzi (1998) found that all farmers left banana residue in banana fields. Plant residues of annual crops were commonly applied to banana with location means for the proportion of the total quantity available ranging from 9-52, 13-62, 0-37 and 35-86 percent for maize, bean soybean and groundnut, respectively. At the Pallisa location, there were more livestock, more fallow land and less banana production than at the other locations studied. Only about 10% of the manure were applied to banana in Pallisa with very little application to other crops. In comparison, 90% of the available manure was applied at the other three locations although nutrients contained in available manure averaged only 13.6, 5.5 and 16.5 kg farm^{-1} of N, P and K. In the three locations, soil fertility levels were generally similar to levels at the Pallisa location, but their land use was more intensive and manure was recognised as a valuable resource.

The supply of organic manures is generally inadequate to replace the significant amounts of nutrients removed from banana fields through fruit harvests, erosion and other losses. Farmyard manure is often scarce as the number of livestock in intensively cultivated areas is usually small. In Rwanda, 78% of farmers interviewed said they lacked manure for more than half their fields, and only 6% reported adequate manure for their needs (Voss and Graf, 1991). In Kagera Region of Tanzania, only 15% of farmers had access to manure (Bosch *et al.*, 1989). Bazira *et al* (1997) estimated that farmers with comparatively well-tended plantations were adding about two t ha^{-1}yr^{-1} of organic materials which did not supply sufficient nutrients to compensate for the losses.

In Bukoba District of Tanzania, nutrients are transferred from the *rweya* grasslands in forms of manure obtained from grazing animals and grass mulch. However, the ratio of grassland to banana area varies from 1.2 to 20 (Janssen, 1993), and is often insufficient to provide enough nutrients to the banana stands for the maintenance of soil productivity (van de Kop, 1995). Negative nutrient balances were observed for the banana - bean intercropping system in Tanzania, with significant leaching losses (Table 4.2). The estimates are based on the assumption that grass harvested from 0.1 ha of *rweya* grassland is applied as mulch annually to each hectare of banana, a practice that is not likely to be sustainable (van der Eijk, 1995). The export of nutrients through banana harvest was mainly due to the consumption of the fruit as other parts of the banana plant are returned to the soil.

Table 4.2. Nutrient balances of a banana-bean intercropping system in Bukoba District, Tanzania

	N	P	K	Mg
		kg ha^{-1}yr^{-1}		
Inputs				
Mulch	4	0.6	4	0.6
Deposition	30	3.7	60	17.0
N-fixation	23	0.0	0	0.0
Sedimentation	0	0.0	0	0.0
Exports				
Banana	42	4.0	50	2.4
Beans	30	1.5	12	1.5
Leaching	26	0.3	38	26.0
Gaseous	5	0.0	0	0.0
Erosion	0	0.0	0	0.0
Net Change	-46	1.5	-62	-12.9

Source: Janssen, 1993; van de Kop, 1995; and van der Eijk, 1995
Note: Bukoba District receives 2000 mm yr^{-1} of rainfall and has sandy loam soils

Nutrient balances for the banana-based land use type estimated at the four locations in Eastern and Central Uganda (Wortmann and Kaizzi, 1998) varied from -9.0, 5.7, -56.0 to 27.2, 22.1 and 13.1 kg ha^{-1} N, P, and K, respectively (Table 4.3). The balance for K tended to be worse than for other nutrients. Estimated nutrient balances at the four locations were generally negative but the deficits were less than estimated for Bukoba, perhaps due to the different inputs and management systems.

Table 4.3. Nutrient balances in banana fields at four locations in Uganda (kg $ha^{-1}yr^{-1}$).

Nutrient	Location			
	Pallisa	Iganga	Mpigi	Kamuli
Nitrogen	13.2	27.2	-9.0	7.1
Phosphorus	1.2	22.1	5.7	6.3
Potassium	-35.7	13.1	-56.0	-50.3

Source: Wortmann and Kaizzi, 1998

Banana-based systems provide good erosion control with less soil loss than with annual crops. The crop management factor (C) value of the Universal Soil Loss Equation (USLE), calculated as the ratio of soil loss from the crop of interest over soil loss from tilled fallow, for the banana-bean association was determined to be 0.10 in Rwanda (Clay and Lewis, 1990). Other crops had C values ranging from 0.15 for peas to 0.45 for tobacco. Brunner (1991) reported an average soil loss of 4.5 t $ha^{-1}yr^{-1}$ for banana - bean fields compared to a mean of 7 t $ha^{-1}yr^{-1}$ for all crops on a 10% slope. The low erosion associated with the banana - bean system may be due to several factors including a good canopy cover throughout the year and additional manuring and mulching. These factors contribute to less intensive raindrop impact, increased soil organic matter, increased water infiltration and improved soil aggregate stability.

Organic Matter Management in Banana-Based Cropping Systems

The manure and mulch materials commonly applied to banana fields differ widely in their chemical characteristics, even within species (Table 4.4). Most of the materials are low in N, P and K at the time of their application. These qualities point to prohibitive quantities of materials required to provide nutrients in amounts necessary for optimal growth of bananas.

Decomposition and mineralisation rate characteristics of some of the residues obtained in recent studies (Bwamiki, 1995; Bazira, 1998; Lekasi, 1998 and Murekezi, 1998) confirm those summarised by Myers *et al* (1994) showing that the processes are regulated by C:N ratios and further modified by lignin:N ratios. Non structural cations, as exemplified by K, are released at faster rates than structural elements (Table 4.5), which may result in a supply of nutrients, especially if the C:N ratio is high, that may be out of balance with the plant requirements. The significance of this imbalanced supply of nutrients has not been assessed; it may not be very important for a quasi-perennial crop such as banana which can luxury feed, essentially store nutrients in the plant, and remobilise for further growth when supply is low. Of greater concern may be cation imbalances as K and Mg compete for uptake; Mg deficiency might be induced if much plant material having a high K:Mg ratio are applied.

Table 4.4. Selected nutrient contents of crop residue materials commonly used in mulching banana plantations

Material	%N	%P	%K	%Ca	Reference
Coffee husks	0.48	0.12	1.0	0.25	Ochwoh, 1977
Coffee husks	1.27	0.12	2.0	1.20	Matovu, 1979
Coffee husks	2.20	0.17	4.0	2.10	Bwamiki, 1996
Coffee husks	1.60	0.20	2.9	0.54	Murekezi, 1998
Maize stover	1.00	0.10	1.3	ND	Zake *et al*, 1996
Swamp grass	0.80	0.09	1.0	ND	Zake *et al*, 1996
Soybean residue	1.20	0.11	0.7	ND	Zake *et al*, 1996
Mucuna residue	3.60	0.80	1.2	ND	Zake *et al*, 1996
Bean residue	0.80	0.12	0.8	ND	Wortmann and Kaizzi, 1998
Napier grass	2.60	0.20	3.2	0.50	Bekunda *et al*, 1998
Napier grass	1.72	0.14	2.9	0.40	Bazira *et al*, 1998
Spear grass	0.94	0.10	1.2	0.30	Bazira *et al*, 1998
Banana residue	2.90	0.15	3.5	0.40	Bazira *et al*, 1998
Banana leaves	2.75	0.10	4.9	1.34	Lekasi *et al*, 1998
Banana pseudostem	1.01	0.07	7.7	0.75	Lekasi *et al*, 1998
Banana pseudostem base	0.47	0.06	3.2	0.39	Wortmann *et al*,1994
Cattle manure	0.79	0.47	2.7	0.10	Bekunda *et al*, 1998

Key:
ND = not determined

Table 4.5. Comparison of nutrient mineralisation patterns from materials used as mulch in banana plantations, based on the time (t_{50}, days) when 50% of the nutrient has been mineralised.

Material	Half-life (t_{50})			
	Dry Matter	N	P	K
Banana pseudostem	33	35	22	16
Maize stover	37	23	10	6
Beans trash	21	8	5	3
Coffee husks	158	231	115	19
Napier grass (*Pennisetum purpureum*)	41	89	122	9
Spear grass (*Imperata cylindrica*)	45	106	118	11

Source: Lekasi, 1998; Bazira, 1998.

Another concern is nutrient loss from mulch expected due to denitrification, leaching and P fixation, which would affect recycling of available nutrients. For banana residues, it has been postulated that recycling of nutrients is more efficient when harvested pseudostems are left standing for sometime to allow their nutrients translocate to the growing pseudostems (Turner and Barkus, 1973). Wortmann *et al* (1994b) estimated that 46%, 37% and 23% of the N, P and K, respectively in the lower 1.5m of pseudostem was translocated to growing pseudostems within six weeks after harvest. The rate of nutrient release was similar for translocation from the harvested pseudostems as for decomposition of a mulch of shredded pseudostems. The rate of recycling of nutrients is therefore higher, and loss of nutrients probably less, with translocation of nutrients from the harvested pseudostems to the growing parts of the mat than from decomposition due to the expected losses.

Response of Bananas to Soil Fertility Management

We have shown in the previous section that there are different strategies farmers use to replenish nutrients in banana fields. The strategies differ in terms of scale and degree of reliance upon the amount and quality of inputs that are available, but may also be influenced by the returns to the strategy. Yield response is one indicative measure of the appropriateness of the strategy.

Responses to organic residues

Recycling banana residue alone will not provide sufficient mulch for both moisture conservation and nutrient replenishment. Nutrient amounts removed in fruit are more than those immobilised in other above ground parts (Table 4.1). Consequently, about 86% of banana farmers in the Lake Victoria Basin of Uganda supplement the banana residues with one or more additional inputs (Bekunda and Woomer, 1996). When reported bunch weights (representing yield) were plotted against the number of types of organic resources utilised (representing soil fertility management), it was observed that those farmers applying supplementary field crop residues and cattle manure obtained the highest bunch weights, averaging 20.3 kg bunch^{-1} and representing a 55% increase over banana residues alone. Supplementary field crop residues alone increased yield by 25%, and field crop residues plus small livestock manure by 9%.

The bunch weights recorded above are not optimal, a result of the addition of inputs that did not supply adequate amounts of nutrients. Woomer *et al* (1999) obtained much less bunch weights from the annual application of 10t ha^{-1} of either Napier grass or cattle manure to a highly nutrient deficient soil (Table 4.6). Banana residues transferred from some of the treatments and also applied at a rate of 10 t ha^{-1} were observed to be effective sources of nutrient inputs in cabbage production (Lekasi, 1998).

The use of organic residues, especially of field crops origin, is a matter of nutrient relocation between commodities, for example depletion of crop fields of nutrients and transferring them to banana fields. Over the long term, this system is not sustainable. For the residues obtained away from the farm, their economic potential could rapidly diminish as transportation costs and distances between the source and the farm increase. Supplementary use of mineral fertilisers becomes a plausible alternative.

Table 4.6. Effects of organic resource management on banana bunch mass and dimensions after three years of cultivation at Mukono District farm Institute, Uganda.

Resource management	Banana bunch		
	Mass (kg)	Length (cm)	Circumference (cm)
No inputs, banana residues retained	6.54	28.9	83.6
No inputs, banana residues removed	4.11	20.7	70.1
+ manure, banana residues retained	7.34	30.8	91.1
+ manure, banana residues removed	8.10	31.4	92.6
+ Napier grass, banana residues retained	6.23	29.1	86.0
+ Napier grass, banana residues removed	8.28	31.2	92.5
$LSD_{0.05}$	2.59	7.9	16.2

Source: Woomer *et al*, 1999.

Responses to mineral fertilizers

Very little work has been conducted on the use of mineral fertilisers in the banana farming systems in East Africa. Based on soil analytical data that showed potassium as the likely limiting nutrient to banana production in Uganda, an experiment was set up at Kabanyolo to determine the yield response curve of banana to K (Zake *et al.*, 1996), but only with the basal application of adequate amounts of N and P. While there were significant increases of more than 5 t ha^{-1} resulting from the K treatments, the differences between the different levels of K additions (ranging from 25 to 200 kg ha^{-1}) were not significant. The average fruit yield of 24 t ha^{-1} from the K treatments is not the maximum yield attainable. These results suggest that although K may have been limiting, some other factor(s) became limiting on addition of small amounts of K. The concern about the imbalance of cations expressed for structural elements being released fast during decomposition may also apply to the results of this study. In an earlier report of a research to determine requisite soil and foliar nutrient levels for optimum banana production, significant improvement in growth was obtained with the addition of N and K, and not with P (Parish, 1970).

Soil amendments for banana production need to be applied with the knowledge on how best they can be placed for efficient nutrient uptake by the roots. Awullo-Okullo (1970) reported that the banana crop is mainly a surface feeder, but subsequent studies have shown that the whole banana root system responds appreciably to soil management. Ssali (1973) also reported highest root activity near the soil surface, but it increased deeper in the dry season suggesting that soil moisture management had a role to play, as observed by Nkedi-Kizza (1973). Bwamiki (1995) observed that incorporating coffee husks to a depth of 30 cm increased depth of rooting to 140cm compared to 40 cm when the coffee husks were surface applied. In addition, incorporation resulted in a root biomass accumulation that was 1.3 times more than surface application; fruit yield was 1.6 times higher. The high root biomass development also acts as a temporal safety-net especially in high rainfall areas that suffer from nutrient leaching. Farmers using organic sources for soil fertility improvement may therefore opt to increase nutrient use efficiency by manipulating their application methods, the costs of manipulation and the physical characteristics of the residues notwithstanding.

Intercropping

The intercropping of bananas and other crops is common in many parts of East Africa, and soil fertility improvement, when it occurs, is sometimes a secondary benefit to the primary purpose of the practice. Perennial cash crops, like coffee, are intercropped with bananas for the provision of shed especially at establishment. *Ficus natalensis* is a source of fibre (Baganda traditional bark cloth), fuel wood, animal feed and curvings. However, these crops may benefit the bananas by recycling nutrients from deep capture, because of their rooting systems, via litterfall.

Bean is the annual crop most commonly associated with banana in the mid-altitude areas of Eastern and Central Africa (Bekunda and Woomer, 1996; Youngquist and Wortmann, 1998). The two crops are compatible in a multi-story system as bean does not compete with banana above ground and is more shade tolerant than most other food crops. Smallhold farmers have about 360,000 ha of banana-bean intercrop per year in Eastern Africa (Wortmann *et al*, 1998). Farmers intercrop bean with banana to use land and labour more efficiently, but the reason most frequently cited by farmers was to diversify production (Table 4.7).

Table 4.7. Reasons given by farmers for intercropping beans with banana in two districts in Uganda

Reason	District	
	Mpigi	Rakai
	% of farmers interviewed	
Improved land use	59	80
Improved labor use	30	56
Reduces soil erosion	0	20
Increased income	0	40
Diversified production	93	72

Source: Nakachwa and Nabawanuka, 1988

In a study conducted in Uganda (Wortmann *et al.*, 1992), the land equivalent ratio for the banana - bean system ranged from 1.00 to 2.28 over three seasons with an average of 1.6, or a 60% increase in productivity. Banana was more competitive than bean as indicated by competitive ratios for banana of 0.76 - 2.57, and 0.39 - 1.31 for bean. Bean yields intercropped with banana were 52% of sole crop yield in the Uganda study (Table 4.8), while banana yield was similar for intercrop and sole crop. Competition for water to 90 cm depth was not found to influence productivity of the banana-bean intercrop system in Uganda. Gravimetrically measured soil moisture levels in the intercrop system were not different from those of the sole crops (Wortmann *et al*, 1992). Bean and banana compete for nutrients, especially K. Bean foliar concentrations of K and Zn were lower and of Mn and Fe higher, while other nutrient levels were not affected in bean intercropped with banana as compared to sole cropped bean (Table 4.9). Reduced photosynthetically active radiation appeared to be the main constraint to productivity of bean intercropped with banana. Direct sunlight was reduced by approximately 50% by the banana canopy, while a 25% reduction due to artificial shading caused a 13% reduction in bean yield.

Table 4.8. Mean yields of beans grown in sole crop and inter-cropped with bananas (Mg ha^{-1}) at Kawanda and Mufungu Research Stations in Uganda and DR Congo, respectively.

Cropping system	Non-climbing bean in Uganda, 3 seasons	Three bean types in DR Congo, 2 seasons		
		Type I	Type III	Type IV
Sole crop	1.19	0.63	0.92	2.56
Intercrop	0.63	0.20	0.20	1.19
Significance	***	*	*	*

Sources: Wortmann, *et al*, 1992; Elukessu, 1996
Key: astericks indicate levels of significance, P= 0.001 or 0.05.

Table 4.9. Mean nutrient concentrations in foliar tissue of beans grown in sole crop and intercropped with bananas for three seasons at Kawanda Research Station in Uganda.

Cropping system	Nutrient			
	K (%)	Fe (ppm)	Mn (ppm)	Zn (ppm)
Sole crop	1.86	363	177	34.9
Intercrop	1.45	547	349	27.8
Se_x	0.05	45	32	1.9

Source: Wortmann *et al*, 1992

Key:
Se_x = standard error of the mean

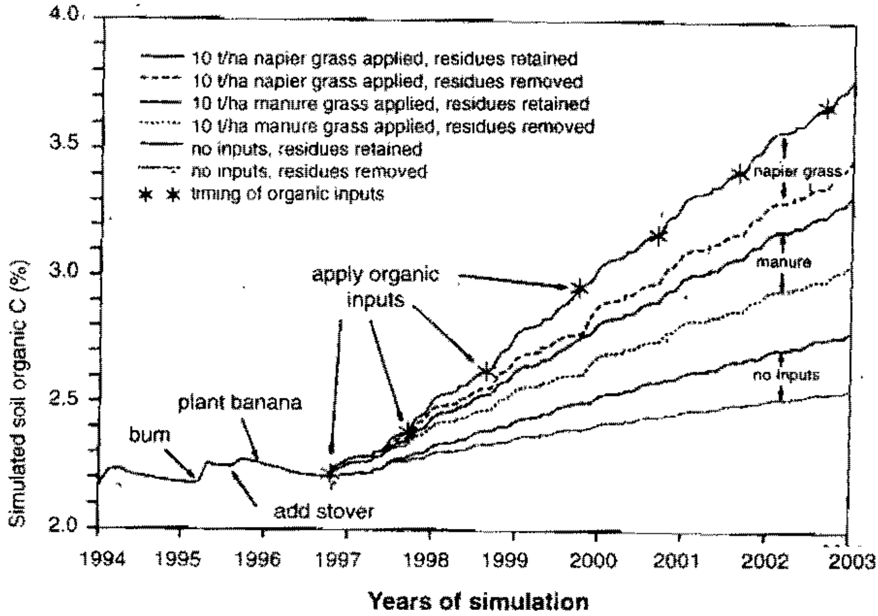
The higher soil fertility levels under banana, as compared to other cultivated land, favours the climbing bean. Elukessu *et al.* (1996) found that yield of climbing bean was proportionally less reduced by intercropping with banana than yield of bush bean; both types had about 47% fewer pods per plant with intercropping but bush bean had a greater reduction in seeds per pod. A concern is that the greater productivity associated with the climbers results in more nutrient removal. In the highlands of Southwest Uganda, for example, nutrient removal was more with climbing bean than with bush bean, even with removal of only the pods of climbing bean and even though the climbing beans fixed approximately 10 more kg ha^{-1} N than bush beans. If the nutrients are not replaced, the system may not be sustainable.

Intercropping as a deliberate soil management practice in banana fields was tested over a five year period at Kabanyolo, Uganda, using Mucuna (*Mucuna pruriens*) as a live mulch (Zake *et al*, 1996). Unlike food crops, no part of the live mulch was harvested from the field. The effects of the live mulch on banana fruit yield were negative and could be attributed to competition with banana for moisture and nutrients. We consider that for live mulch to be effective, it should be sown at low density and should be pruned regularly to minimise competition. This was not the case in the above study.

Effects of Fertility Management on Soil Characteristics

In many of the studies on soil fertility management in bananas, the direct effects of the management practices on soil characteristics have not been measured. We have noted earlier that soils from banana fields are significantly higher in fertility than soils from other crop fields because they receive more input. This practice tends to mask differences between soil characteristics and fruit yields of bananas growing on different soil types (Bazira, 1998; Wortmann *et al*, 1993). We can infer from models and from studies using inputs similar to those applied to bananas or on other test crops, to gain insight in how soil characteristics change in response to applied management practices. Using the Century Model, for example, Woomer *et al* (1998) predicted that organic matter in soils of Mukono District, Uganda, would steadily increase with the annual addition of 10t ha^{-1} of either Napier grass or cattle manure (Figure 4.1) signalling potential chemical, physical and biological benefits to the soil resulting from these treatments. The simulated changes in soil organic carbon suggested that retention of harvest residues has a greater effect on the maintenance of soil organic matter than above ground productivity. In the same soils, a mulch of 10t ha^{-1} of banana residue was observed to perform better than mineral fertilisers in increasing earthworm population, soil N mineralisation and soil moisture holding capacity after two rain seasons (Table 4.10). Weed control enhanced these responses. Better understanding of the usefulness of the different soil inputs is necessary in order to offset nutrient depletion in banana fields.

Figure 4.1. Simulated dynamics of organic matter matter in soils of a banana experiment at Mukono, Uganda, using the Century Model.



Source: Woomer *et al*, 1998

Table 4.10. Earthworm population size, macrofaunal biomass, *in situ* nitrogen mineralisation and soil moisture content of soils cultivated in cabbage under different management.

Management practice	Earthworms (no. m^{-2})	Macrofauna (g m^{-2})	N minerlization (ppm wk^{-1})	Soil moisture (%)
weeded	33	1.0	31.4	29.8
unweeded	183	10.7	21.4	28.9
plastic mulched	117	2.8	32.9	35.2
fertilized & weeded	150	5.8	-13.0	30.9
banana mulched	433	29.0	31.9	29.5
banana mulched & weeded	917	15.3	62.6	32.1
$LSD_{0.05}$	397	ns	33.0	1.5

Source: Lekasi, 1998

Soil Fertility Interaction with Soil-Borne Banana Pests

Pests and diseases are considered the third major determinant of banana yield after agronomic traits of cultivars and soil fertility (Stover, 2000). The banana weevil (*Cosmopolites sordidus)* and the Nematode (*Radopholus similis)* root rot appear to be the most important soil-borne pest and disease, respectively, in the East African bananas.

Weevil infestation has been implicated as one of the factors leading to yield decline of highland cooking bananas in central Uganda and western Tanzania (Gold *et al*, 1999) through prevention of crop establishment and shortened plantation life. Damage to the plant is done by the larvae which tunnel in the rhizome (Ssengooba, 1986), and yield loss increases with crop cycle, up to 44% in the fourth cycle (Rukazambuga *et al*, 1998). There is evidence that the destructive acts of the weevil occur simultaneously with the decline in soil fertility (Oketch and Gold, 1996), but data to support the hypothesis that the weevil is only important in poor soils is scanty. Early research in East Africa (Harris, 1947, Ingram, 1970 and McNutt, 1974) indicated that vigorous plants withstand weevil attack better than weak plants, and recommended management for growing vigorous plants, including use of manure and mulch, soil conservation, weeding and desuckering. Such practices may affect the weevil directly or indirectly. For example, the weevil can live for months in moist soils without feeding but dies less than 72 hours in a dry environment (Okech and Gold, 1996). Indirectly, the weevil could be affected by the soil conditions through nutritional changes in the banana plant which hosts the eggs and larvae.

Farmers have practiced removal of harvested corms and pseudostems as a means of denying the pest major breeding sites (Treverrow *et al*, 1991), but there is no quantitative data to show the effectiveness of the practice. Besides, this practice may be detrimental to young suckers that are attached to the mother plant and from whose post-harvest stumps they derive part of their nutrients (Wortmann *et al*, 1994b). It is also possible that the residues draw ovi-positing weevils away from the young suckers, thereby reducing potential crop losses. There is no record of research trials on these soil management practices that have been conducted to conclusively explain the underlying mechanisms and relationships between them and the weevil.

Nematode root rot causes uprooting and lower bunch weight. Surveys in East Africa identified that the damage is dominantly caused by uprooting than reduced bunch weight (Kashaija *et al*, 1994), ranging from a minimum of 3% in Uganda (Speijer *et al*, 1994) to a maximum of 30% in Kagera, Tanzania (Sikora *et al*, 1990). In a trial at Sendusu in the central banana growing region of Uganda, Speijer and Kajumba (2000) obtained bunches that were significantly higher in weight and more in numbers from plots planted with disinfected propagules than in those plots planted with nematode infested material. The overall production was 51% higher. Until the beginning of the 1990's, however, little research had been done on nematodes and weevils as constraints to the productivity of bananas grown as food crops by small-scale and subsistence farmers (Sarah, 1989). For these farmers, therefore, no control measures that are effective and applicable to their situations have been scientifically identified.

Bridge (2000) has listed a wide range of management practices that can theoretically be used for nematode damage, including a soil fertility management action of mulching with organic wastes. It is hypothesised that mulching could compensate for or suppress nematode damage by stimulating and improving root growth, increasing populations and activities of beneficial soil organisms antagonistic to the nematodes, or producing nematicidal compounds. The actual interactions of organic amendments and nematode populations needs further research.

It appears certain that greater biological understanding of the nematode and weevil management problems in relation to soil fertility constraints is still required in order to develop management methods which farmers can adapt to their different farming systems and circumstances.

Strategies for Integrated Resource Management

The decline in banana productivity occurring for most of the Great Lakes region is partly linked to decline in soil fertility. Pest and disease infestations also result in reduced productivity. The research done in this region and the practices of the farmers reveal that better production can be obtained with improved soil management. Organic amendments could help recycle nutrients within the cropping systems and also improve the soil physical and biological conditions, but inorganic additions may be necessary to offset nutrient losses through harvests and erosion and to correct nutrient imbalances. Research is still needed in several areas:

- The interaction of the banana pest-disease complex with soil fertility and intensification of production needs to be understood. Especially interesting may be the role of *Fusarium solani*, which is hosted by highland bananas supposedly with resistance.
- The diagnosis of nutritional disorders needs to be improved as results of soil and tissue analyses have not been very predictive of response to applied nutrient inputs.
- Soil cation balances are important to banana performance as K competes with Mg and Ca for uptake. The effects of the K:Mg ratios often observed in Arusha might be investigated. Cultivars may react differently to cation imbalances or have different optimal balances.
- Potassium deficiency is the most widely occurring deficiency of banana. Application of inorganic K is likely to be increasingly essential for high levels of productivity. However, the resource poor farmers need high returns to their investments and farmer-oriented decision guides are needed to enable them consider soil differences for response to applied nutrients. Weed flora, for example, may be a useful indicator of soil nutrient supply. Digitaria and euphorbia occupied a greater proportion of the total weed flora when soil exchangeable K was low, while bidens, galinsoga, wild sorghum and eleusine occupied greater proportions of the weed populations when K levels were relatively high (Unpubl.).
- Fertilizer N and P might be most efficiently used by application to nearby annual crops with eventual transfer of nutrients to banana in the plant residues.
- Banana may benefit from short and medium term fallows, which precede establishment of banana, and well managed live mulches. In addition to soil improvement, effects on nematodes may be considered. *Mucuna pruriens* and *Crotalaria grahamiana* suppress root knot nematodes but may host lesion nematodes as well as other species.

References

Awullo-Okullo, G.J. (1970) Root Distribution of Bananas (Nakyetengu). M.Sc. Thesis, Makerere University, Kampala, Uganda.

Bazira, M.H., Bekunda, M.A. and Tenywa, J.S. (1997) Decomposition Characteristics of Mixed Grass and Banana Residues and their Effects on Banana Plant Performance. *African Crop Science Proceedings.* **3:** 421-428.

Bazira, M.H. (1998) Characterisation of Plant Materials Utilised in the Restoration of Low Fertility Soils Under Bananas. Msc Thesis. Makerere University, Kampala, Uganda.

Bekunda, M.A. (1992) Research on Phosphorus Fertility in Soils of Uganda: An Overview. In: H. Tiessen and Frossard, E. (Eds), Phosphorus Cycles in Terrestrial and Aquatic Ecosystems (Africa). Saskatchewan Institute of Pedology, Saskatoon, Canada.

Bekunda, M.A. (1999) Farmer Responses to Soil Fertility Decline in Banana-Based Croping Systems of Uganda. Managing Africa's Soils: Working Paper No. 4. IIED, London, UK.

Bekunda. M.A. And Woomer, P.L. (1996) Organic Resource Management in Banana-Based Croping Systems of the Lake Victoria Basin, Uganda. *Agriculture, Ecosystems and Environment.* **59:** 171-180.

Bosch, C., Mukandala, L. and Ngaiza, P. (1989) Bean Hubandry in Bukoba District. Tanzania/Netherlands Farming Systems Research Project, Lake Zone, Field Note 6. Ari Maruku, Bukoba and Royal Tropical Institute, Amsterdam.

Bosch, C., Lorkeers, A., Ndile, M.R. and Sentozi, E. (1995) Diagnostic Survey: Constraints to Banana Productivity in Bukoba and Muleba Districts, Kagera Region, Tanzania. Tanzania/ Netherlands Farming Systems Research Project - Lake Zone, Working Paper No. 8. ARI Maruku, Bukoba and Royal Tropical Institute, Amsterdam.

Bridge, J. (2000) Nematodes of Bananas and Plantains in Africa: Research Trends and Management Strategies Relating to the Small-Scale Farmer. *Acta Horticulturae.* **540:** 391-408.

Brunner, J. (1991) Etude sur la perte des nutriments par l'erosion dans les communes de Ruhsya, Rusatiar, au Rwanda. Raport Annual.

Bwamiki, D.P. (1995) Effect of Coffee Husks Aplication Methods on Soil Fertility and Banana Production. Msc Thesis, Makerere University, Kampala, Uganda

Clay, D.C. And Lewis, L.A. (1990) Land Use, Soil Loss, and Sustainable Agriculture in Rwanda. *Human Ecology.* **18:** 147-161.

Delvaux, B. (1995) Soils. In Gowen, S. (Ed.), Bananas And Plantains. Chapman & Hall, London.

Elukessu, K.L., Lunze, L., Ngongo M. and Malia, K. (1996) Haricot volubile sous bananeraie: I. Evaluation de la fertilite des sols de bananeraies pour le haricot. Unpubl. manusc.

Elukessu, K.L. (1996) Haricot volubile sous bananeraie: II. Etude de comportement des types de croissance du haricot common. Unpubl. manusc.

Giller, K.E., Aimjee, F., Brodrick, S.J., Mcgrath, S.P., Mushi, C., Edje, O.T. and Smithson, J.B. (1992) Toxic Concentrations of Iron and Manganese in Leaves of Phaseolus V*ulgaris* l. Growing on Freely Drained Soils of pH 6.5 in Northern Tanzania. *Communications in Soil Science and Plant Analysys.* **23:**1663-1669.

Godefrey, J., Perrier, X., Rutunga, V. and Sebahutu, A. (1991(a)) Relations entre les carateristiques physico-chimiques des sols de la region de Kibungo au Rwanda et le potentiel de production des bananiers. Aplication a la gestion de la fertilite des sols. *Fruits.* **46**:625-630.

Godefrey, J., Rutunga, V. and Sebahutu, A. (1991(b)) Les terres de bananeraies dans la region de kibungo au Rwanda: Resultantes du milieu physique et des systemes de culture. *Fruits.* **46**:109-124.

Gold, C.S., Karamura, E.B., Kiggundu, A., Abera, A.M.K., Bagamba, F., Wejuli, M., Karamura, D., Ssendege, R. and Kalyebara, R. (1999) Geographic Shifts in Highland Cooking Banana (*Musa* Sp., Group AAA-EA) Production in Uganda. *Int. J. Sustain. Dev. World Ecol.* **6**:45-59.

Harris, W.V. (1947) The Banana Borer. *East African Agriculture and Forestry Journal.* **13**:15-18.

Ingram, W.R. (1970) Pests of Banana. In: Jameson, J.D. (Ed), Agriculture In Uganda. Oxford, Uk, P.145.

Janssen, B.H. (1993) Report on a Consultancy Mission to the Lake Zone Farming System Research Project on Behalf of the Bukoba Nutrient Balance Study. Dept. Soil Science and Plant Nutrition, Wageningen Agricultural University, Wageningen, Netherlands.

Kashaija, I., Speijer, P.R., Gold, C.S. and Gowen S.R. (1994) Occurrence, Distribution and Abundance of Plant Parasitic Nematodes of Bananas in Uganda. *Africa Crop Science Journal.* **2**:99-104

Lahav, E. and Turner, D.W. (1983) Banana Nutrition. IPI-Bulletin No. 7, International Potash Institute.

Lekasi, J.K. (1998) Crop Residues as Mulches in Banana Based Croping Systems of Uganda. MSc Thesis, Makerere University, Kampala, Uganda.

Matovu, J.S. (1979) A Study of the Use of Two Organic Manures as Sources of Potassium. MSc Thesis, Makerere University, Uganda.

Mcnutt, D.N. (1974) A Review of Banana Weevil Control in Uganda, With Further Tests of Dieldrin Formulations. *East African Agriculture and Forestry Journal.* **30**:205-209

Murekezi, C. (1998) Influence of Coffee Husks on the Availability of Soil Nutrients and Pineaple Yield. MSc Thesis, Makerere University, Kampala, Uganda.

Myers, R.J.K, Palm, C.A., Cuevas, E., Gunatilleke, I.U.N. and Brossard, M. (1994) The Synchronisation of Nutrient Mineralisation and Plant Nutrient Demand. In: Woomer, P.L. and Swift, M.J. (Eds). The Biological Management of Tropical Soil Fertility. John Wiley and Sons, Chichester, UK.

Nakachwa, P. and Nabawanuka, J. (1988) Report on a Survey Conducted on the Bean-Banana Intercroping Association in Rakai and Mpigi Districts. Annual Report of Bean Research Programme, Kawanda Research Station, Kampala, Uganda.

Nkedi-Kizza, P. (1973) A Study of the Consumptive Use of Water by the Nakyetengu Banana (Musa Acuminata). MSc Thesis, Makerere University, Kampala, Uganda.

Ochwoh, V.O.A. (1977) The Effects of Organic Materials on Cation Exchange Capacity of Some Uganda Soils. MSc Thesis, Makerere University, Kampala, Uganda.

Okech, S.H.O. and Gold, C.S. (1996) Relationships of the Banana Weevil With its Host Plant and Soil Fertility. Ahi Technical Report Series No. 2. ICRAF, Nairobi, Kenya.

Rukazambuga, N.D.T.M., Gold, C.S. and Gowen, S.R. (1998) Yield Loss in East African Highland Banana (Musa Sp., AAA-EA Group) Caused by the Banana Weevil, *Cosmopolites Sordidus* Germar. *Crop Protection.* **17:**581-589.

Ortiz, R. and Vuylsteke, D. (1996) Improving Plantain- And Banana- Based Systems. In: Ortiz, R. and Akoroda, M.O. (Eds.), Plantain and Banana: Production and Research in West and Central Africa. International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria.

Sanchez, P.A., Palm, C.A. Szott, L.T., Cuevas, E. and Lal, R. (1989) Organic Input Management in Tropical Agroecosystems. In: Coleman, D.C., Oades, J.M. and Uehara, G. (Eds). Dynamics of Soil Organic Matter in Tropical Ecosystems. NIFTAL Project, Paia, Hawaii, USA.

Sarah, J.L. (1989) Banana Nematodes and Their Control in Africa. *Nematropica.* **19:**199-216.

Sikora, R.A., Bafokuzara, N.D., Mbwana, A.S.S., Oloo, G.W., Uronu, B. and Seshu Reddy, K.V. (1990) Interrelationship Between Banana Weevil, Root Lesion Nematode and Agronomic Practices, and Their Importance for Banana Decline in the United Republic of Tanzania. FAO. *Plant Protection Bulletin* **37:**151-157.

Simmonds, N.W. (1962) The Evolution of Bananas. Longman, London, UK.

Speijer, P.R., Gold, C.S., Karamura, E.B. and Kashaija, I. (1994) Assessment of Nematode Damage in East African Highland Banana Systems. In: Valmayor, R.V. (Ed). Banana Nematodes and Weevil Borers in Asia and the Pacific. INIBAP/ASPNET, Montpellier, France.

Speijer, P.R. and Kajumba, C. (2000) Yield Loss from Parasitic Nematodes in East African Highland Banana (*Musa* spp. AAA). *Acta Horticulturae.* **540:**453-460.

Ssali, H. (1973) Determination of Root Activity of Bananas (Nakyetengu cultivar) During Wet and Dry Seasons as Measured by Radioactive Phosphorus Uptake. M.Sc. Thesis, Makerere University, Kampala, Uganda.

Ssengooba, T. (1986) Survey of Banana Pest Problem Complex in Rakai and Masaka Districts: Preliminary Trip Report. Uganda Ministry of Agriculture, Kawanda Research Station.

Stover, R.H. (2000) Diseases and other Banana Health Problems in Tropical Africa. *Acta Horticulturae.* **540:**311-317.

Sumner, M.E. (1977) Aplication of Beufils Diagnostic Indices to Maize Data Published in the Literature Irrespective of Age and Conditions. *Plant Soil.* **46:**359-369.

Tisdale, S.M., Nelson, W.L. and Beaton, J.D. (1990) Soil Fertility and Fertilisers (Fourth Edition). Macmillan, NY.

Treverrow, N., Bedding, R.A., Dettman, E.B. and Maddox, C. (1991) Evaluation of Entomopathogenic Nematodes for Control of Cosmopolites Sordidus Germar (Coleptera: Curculionidae), A Pest of Bananas in Australia. *Annals of Apllied Bology.* **119:**139-145.

Turner, D.W. and Barkus, B. (1973) Loss of Mineral Nutrients From Banana Pseudostems After Harvest. *Tropical Agriculture.* **50:**229-233.

Tushemereirwe, W.K., Gold, C.S., Speijer, P.R. and Holderness M. (1993) Foliar Diseases of Banana in Uganda: Results From a Diagnostic Survey. *African Crop Science Journal.* **1:**145-150.

Van De Kop, P. J. (1995) The Role of Cattle in Nutrient Fluxes of the Banana-Based Agroecosystem of Bukoba District, Tanzania. Dept. of Agronomy and of Soil Science ond Plant Nutrition, Wageningen Agricultural University.

Van Der Eijk, J.P. (1995) Nutrient Losses Via Leaching in Bukoba District, Tanzania. Dept. of Soil Science and Plant Nutrition, Wageningen Agricultural University.

Voss, J. and Graf, W. (1991) On-Farm Research in the Great Lakes Region of Africa. In: Common Beans Research for Crop Improvement. (Eds.) van Schoonhoven, A. and Voysest, O. C.A.B. International, Wallingford, UK.

Vuylsteke, D. (1996) The East and Southern Regional Centre for the Improvement of Cassava, Banana and Plantain and the Banana Research Network for East and Southern Africa. In: Ortiz, R. and Akoroda, M.O. (Eds.), Plantain and Banana Production and Research in West and Central Africa. IITA, Ibadan, Nigeria.

Wilson, K.C. (1985) Mineral and Fertilizer Needs. In: Clifford, M.N. and Wilson, K.C. (Eds.) Coffee: Botany, Biochemistry and Production of Beans and Beverage. Croom Helm Ltd., London, UK.

Woomer, P.L., Bekunda, M.A. and Bwamiki, D.P. (1998) Site Characterization for Organic Resource Transfer Studies: The CENTURY Model Aproach. *African Crop Science Journal.* **6**:205-214.

Woomer, P.L., Bekunda, M.A. and Nkalubo, S.T. (1999) Estimation of Banana Yield Based on Bunch Phenology. *African Crop Science Proceedings.* **4**:1-10.

Wortmann, C.S., Sengooba, T. and Kyamanywa, S. (1992) Banana and Bean Intercroping: Factors Affecting Bean Yield and Land Use Efficiency. *Experimental Agriculture.* **28**:287-294.

Wortmann, C.S., Bosch, C.H. and Mukandala, L. (1993) The Banana-Bean Intercroping System in Kagera Region of Tanzania - Results of a Diagnostic Survey. Network on Bean Research in Africa, Occasional Publication Series, No. 6, CIAT, Dar es Salaam, Tanzania.

Wortmann, C.S., Bosch, C.H. and Mukandala, L. (1994(a)) Foliar Nutrient Analysis in Bananas of the Eastern Africa Highlands. *Journal of Agronomy and Crop Science.* **172**:223-226.

Wortmann, C.S., Karamura, E.B. and Gold, C.S. (1994(b)) Nutrient Flows From Harvested Banana Pseudostems. *Africa Crop Science Journal.* **2**:179-182.

Wortmann, C.S., Kirkby, R.A., Eledu, C.A. and Allen, D.J. (1998) An Atlas of Common Bean (*Phaseolus Vulgaris* L.) Production In Africa. Cali, Colombia. Centro Internacional de Agricultura Tropical (CIAT).

Wortmann, C.S. and Kaizzi, C.K. (1998) Nutrient Balances and Expected Effects of Alternative Practices in Farming Systems of Uganda. *Agriculture, Ecosytems and Environment.* 79:

Yost, D. and Eswaran, H. (1990) Major Land Resource Areas of Uganda. World Soil Conservation Resources, Soil Conservation Service, USDA. Washington DC, USA.

Youngquist, J. and Wortmann, C. (1998) Banana-Bean Intercroping in Eastern and Central Africa. In: Voysest, O. (Ed.). An Ecoregional Framework for Bean Germplasm Development. Documento de Trabajo. Centro Internacional de Agricultural Tropical (CIAT), Cali, Colombia.

Zake, Y.K., Bwamiki, D.P. and Nkwiine, C. (2000) Soil Management Requirements for Banana Production on the Heavy Soils Around Lake Victoria in Uganda. *Acta Horticulturae.* **540**:285-292.

Zake, J.Y.K., Nkwiine, C., Okwakol, M., Sessanga, S., Bwamiki, D.P. and Tumuhairwe, J.K. (1994) Soil Management for Sustainable Banana Productivity in Uganda. In: Diagnostic Survey on Key Constraints of Banana Production in Uganda. Working Doc., UNBRP, IITA, NRI.

Zake, J.Y.K., Nkwiine, C., Sessanga, S., Tumuhairwe, J. Okwakol, M. and Bwamiki, D. (1996) The Effect of Different Mulching Materials on Soil Properties and on Banana Productivity in Uganda. In: Rwakaikara-Silver, M.C., Bekunda, M.A. and Tenywa, J.S. (Eds.) Proceedings of the 14th Conference of the Soil Science Society of East Africa. Makerere University, Kampala, Uganda.

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Soil Fertility Management in the Lowland Humid Forest Zone

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Introduction

Climate and soils

The humid forest zone of Africa consists of three main areas: the Congo basin, between about 5° northern and 5° southern latitudes, extending as far east as lake Victoria; along the southern coast of West Africa ranging from approximately 5 and 9° northern latitudes; and the eastern coast of

Madagascar. Consistently high temperatures, high relative humidity, and heavy rainfall throughout the year characterize the climate. The annual rainfall usually ranges from 1,500 to 2,500 mm, but may reach much higher values in some areas. Annual precipitation exceeds or equals the potential return of moisture to the atmosphere through evaporation (Nieuwolt, 1977). Temperatures show very small annual ranges, which increase with distance from the equator, but remain almost everywhere between 5 and 10° Celsius and they increase with both elevation and distance from the coast. However, most of the humid forest zone in East and Central Africa lies in the lowland. In general, seasons in the humid tropics are determined by variations in rainfall (Nieuwolt, 1977). Most areas in the humid forest zone experience no more than four months with less than 200 mm of precipitation per year. The length of the growing season is at least 270 days (Jagtap, 1995).

Oxisols and Ultisols are the most abundant soils of the humid tropics, together covering almost two-thirds of the region. Oxisols are deep, generally well-drained red or yellowish soils, with excellent structure and little contrast between horizon layers. As a result of extreme weathering and resultant chemical processes, however, Oxisols are acidic, low in phosphorus(P), nitrogen(N), and other nutrients, and limited in their ability to store nutrients, but have relatively high soil organic matter content. Oxisols have low pH and low cation exchange capacity. They are deficient in major plant nutrients and often have toxic levels of Aluminium (Al) and Manganese (Mn). They may also suffer from sulphur (S) deficiency. N losses from leaching are high unless a continuous plant cover ensures rapid recycling. High Al saturation, which is toxic to plants and low levels of Calcium (Ca) in the subsoil, may result in limited rooting volume and increase the potential for moisture stress (Sanchez and Salinas, 1981). Trace element deficiencies may occur, especially in soils formed from basic rocks. Due to the extreme weathering, very low nutrient reserve, and a limited ability to hold soil nutrients, most of the nutrients in the ecosystems containing Oxisols are within living or dead biomass. However, due to their excellent physical properties, these soils can be suitable for a wide range of uses with proper management, soil amendments to overcome acidity, and the application of limiting nutrients.

Ultisols are usually deep, well-drained red or reddish soils, somewhat high in weatherable minerals than Oxisols but also acidic and low in nutrients. They are similarly low in plant nutrients and high in exchangeable Al. Nutrient reserves are concentrated in the surface horizon and their maintenance depends on continuous recycling through the vegetation unless fertilizers are added. Unlike Oxisols, they exhibit a marked increase of clay content with depth. They also usually contain high levels of aluminum, which is toxic to plants and severely restricts rooting depth. Ultisols are susceptible to erosion due to the less favorable physical properties in the surface layers and the degree of permeability in the argillic B-horizon. Compaction and loss of surface soil easily damages Ultisols when heavy equipment is used for land clearing or tillage operations (Lal, 1987). In general, the agricultural production potential of both Oxisols and Ultisols can be improved, as they respond well to fertilizers and good management practices.

Inceptisols and Entisols account for most of the remaining soils of the humid tropics. These are younger soils, ranging from highly fertile soils of alluvial and volcanic origin to very acidic and nutrient-poor sands. Inceptisols are the third most widespread soil type in the humid tropics. Three major kinds are important in the humid forest zone of Africa: Aquepts (poorly drained), Andepts (well drained, of volcanic origin), and Tropepts (well drained, of non-volcanic origin). Among the Inceptisols, Aquepts are dominant in humid forest zone of Africa. Most Aquepts or wet Inceptisols are of high to moderate fertility and support dense human populations in many parts of the world. However, in Africa large areas of wet Inceptisols (locally known as hydromorphic soils), long remained undeveloped because of human health hazards, although many of these hazards have been overcome and settlement has increased. Entisols are soils of recent development that do not show significant horizon layers. Within this soil type, well-drained, young alluvial soils (Fluvents) not subject to periodic flooding, are considered among the best soils for agriculture in the world. These soils are very suitable for intensive lowland rice production.

Vegetation and food crops

Although many humid tropic soils are acidic and low in reserves of essential nutrients, the constant warm temperatures, plentiful of rainfall and sunlight for most of the year permit, abundant plant growth. Under natural conditions the humid forest zone is characterized by lush vegetation giving an impression of highly productive systems. The natural vegetation consists broadleaf evergreen rainforests with little or no seasonal variations. The dry season, by definition limited to about two months, creates no moisture stress for the natural vegetation as it is supplied by moisture from the soil. However, water can be a limiting factor for crop production despite periods of abundant rainfall (Juo, 1989). Many humid forest areas have dry periods of sufficient length to adversely affect plant growth. Water shortages occur often where the soils have low water-holding capacities or have restricted rooting depth, but they can also affect areas with more favorable soil environments. Luxuriant forests growing on these predominantly nutrient-poor soils must possess an "efficient" mechanism for nutrient recycling and conservation. It has been suggested that such forests possess enhanced structural and physiological mechanisms for recycling and conserving nutrients.

Research has shown that undisturbed primary forests have well developed mechanisms for efficient recycling of the nutrients stored in its living biomass so that losses are minimal. These mechanisms are highly adaptive and can be identified both at structural and physiological levels in the natural vegetation. Clearing and burning the vegetation will cause a sudden release of nutrients tied up in the aboveground biomass. The released nutrients can be used by successional vegetation or cultivated plants for a short period. Under traditional cultivation systems, yields fall rapidly, the land is abandoned and secondary regrowth develops. The species composition of such regrowth varies, depending on the degree and frequency of burning and on surrounding vegetation. If burning is recurrent, grass usually replaces tree vegetation (Adedeji, 1984).

Alteration of forest cover and forest conditions through human intervention can range from marginal modification to fundamental transformation. At one extreme are forests that are slightly modified (through, for example, selective extraction, traditional shifting cultivation, or gradual substitution of perennial species) to maintain most of their cover, with little long-term impact on ecosystem components, processes, and regeneration rates. Deforestation represents the opposite extreme where the forest cover is replaced with other land use systems. Between these extremes, conversion happens to varying degrees, entailing changes in forest structure, species diversity, biomass, successional processes and ecosystem dynamics. Land or forest degradation occurs when these changes are of sufficient magnitude to have a long-term negative effect on productive potential. In many cases, the original forest is being eliminated and replaced with permanent agriculture, plantations, pasture and other developments. For example, according to Keatinge *et al.* (2001), much of the West African humid forest has almost disappeared with only pockets of forest remaining in some places. However, in Central Africa, there has been less deforestation due to the lower population density. Exposed soils, particularly following mechanical clearing, are subject to erosion, compaction, and crusting until a new vegetative cover of canopy is established (Lal, 1987).

Tropical root and tuber crops are in many ways the most preferred food crops of the lowland tropics and in general have a high degree of ecological adaptation to the humid tropical conditions. Root and tuber crops, especially cassava, yam, aroids, and sweet potatoes are extensively grown in the humid tropical zone although banana, plantain and groundnuts are also important food crops in the region (Keatinge *et al.*, 2001; Coursey and Booth, 1977). The high biological efficiency of root and tuber crops arises partly from the "architecture" of the crops (Coursey and Booth, 1977). Strength of other parts of the plant is not needed to support bulky roots and tubers. Increased size of the edible part need not therefore be associated with increased production of the non-edible tissue. In grain crops in contrast, a substantial fraction of total biomass is required to support the edible grains above ground. Some root crops such as cassava (*Manihot esculenta* Crantz) have the ability to withstand pests such as locusts, low soil fertility and poor husbandry. They are also adapted to intercropping; an important cropping system in the humid forest zone.

Over the centuries, agricultural systems and techniques have evolved to meet the special environmental conditions of the humid tropics. They include, a variety of multistrata agroforests, home gardens, shifting cultivation, managed fallows, modified forest systems, and even permanent cropping. Although these production systems are diverse in their particular adaptations, the successful ones tend to mimic the natural vegetation in such characteristics as: high nutrient use efficiency; maintenance of vegetative cover; a high level of diversity crops and crop varieties; complex intercropping patterns; and the integration of animals within the agroecosystem. But the maintenance of soil fertility is central to all production systems in the humid forest zone.

Soil Fertility Management

Nutrient cycling

The vegetation within the tropical humid forests thrives by retaining and efficiently recycling limited nutrients within the ecosystem. Root concentrations are generally in the topsoil. Therefore, when litter (leaves, twigs, branches, and whole trees) falls to the forest floor, the high quality litter decomposes rapidly, while the low-quality litter decomposes slowly. Mineralized nutrients are adsorbed by forest floor roots and adsorption by deep roots minimizes losses. Therefore, most of the nutrients are efficiently recycled, with minimal losses through leaching, denitrification, and volatilization. Understanding of the major processes responsible for nutrient cycling in this environment should provide the key to effective and sustainable soil fertility management.

The main processes which regulate soil fertility in the humid zones are the soil organic matter decay, the nutrient leaching and recycling, soil acidification, soil erosion and other processes related to soil management and agronomic practices. These processes can take place separately or in combination depending on the environment and human intervention. However, soil properties are in equilibrium with the vegetation as long as the forest remains undisturbed. The practice of shifting cultivation or slash and burn agriculture which is common in the lowland humid forest environment often changes the equilibrium by disrupting the continuous supply of litter and consequently interrupting nutrient recycling. Other more modern systems of agriculture and deforestation usually cause more problems if poorly implemented and managed.

Clearing and burning

The most common practice of changing the forest into food production involves slashing and burning the vegetation. The use of fire modifies the biological soil environment. When fire occurs, the temperature of the surface layers of the soil is raised. The actual heating rate and depth depends on the amount of moisture in the soil and the type of fire. Temperatures during the burn at the surface almost always exceed 100°C and can reach as high as 720°C for brief periods of time (Fehlberg, 1989; Andriesse and Koopmans, 1984; Kitur and Frye, 1983; Sertu and Sanchez, 1978; Brickmann and Vieira, 1971). The temperatures are dependent on the type and amount of biomass and the moisture content, all of which influence the intensity of the fire. Increases in temperatures in the soil are usually restricted to the top few centimeters, where they normally rise by 50-80°C above the temperatures before burning. These temperatures are high enough to modify the soil environment.

The burning of the aboveground organic materials usually combusts most nitrogen and organic acid components, returning inorganic cations to the soil in the ash, which has a liming effect. The amount of liming effect depends on the intensity of the fire and the thoroughness of the burning. The hot temperatures can also greatly reduce the amount of organic matter in the upper layers of the soil. For example, at temperatures of 200-300°C for 20-30 minutes, there may be as much as 85% reduction in organic matter (Fehlberg, 1989). Generally, most of the abiotic effects are short-term in nature. Under ideal conditions, regeneration of the vegetation rapidly begins the process of recovery. However, frequent fires can lead to more lasting change.

Depending on the dryness of the biomass, the weather and the amount of biomass, burning is described as complete or incomplete (Fehlberg, 1989). Temperatures are relatively low if the biomass burnt is either small or not completely dried. Low to medium burn temperatures, with ranges from 150-300°C at the soil surface, result in incomplete burn leaving some of the woody parts of the slash still intact. Theoretically, oxidation of carbon begins at a temperature of 150°C (Andriesse and Koopmans, 1984). Consequently SOM is affected by incomplete burning. SOM content in the top few cm decreases but addition from leaching of burned organic material may mask this process. As a result of these processes the carbon (C) content of the soil and the CEC may be even higher than before the burn. Burning may lead to increasing values of C, N, P, organic matter and CEC (Andriesse and Schelhaas, 1987). The content of plant available P increases slightly after burning as a result of the partial destruction of SOM. The influence of burning of slashed vegetation on N content due to volatilization has an important effect on soil nutrient supply. Andriesse *et al.* (1987), reported that with medium burn temperatures (300-400°C), the total N content of the top 2 cm decreased by 20-25% but that the ammonium content increased with lower temperatures of 200-250°C (Kitur and Frye, 1983; Sertu and Sanchez, 1978). In addition, burning may have a positive effect on the N cycle. Nitrifying bacteria responsible for NO_3 formation are partially inhibited in converting ammonium to nitrates. These changes result in increased soil fertility and improved conditions for crops.

In contrast, large amounts of dried biomass piled up would completely burn with high temperatures of up to 700°C at the soil surface (Andriesse and Schelhaas, 1987). These high temperatures may be detrimental to soil fertility. Temperatures between 400-600°C already cause a nearly total depletion of organic carbon and topsoil organic matter. High temperatures will lower carbon and organic P contents in the topsoil. About 80% of the total N contained in the litter and upper 2 cm mineral soil are reported lost at these burn temperatures (Andriesse and Schelhaas, 1987). Ammonium content decreases as oxide and carbonate formation is enhanced. Local ash accumulations under piled wood may increase pH values to above 10 and hinder or inhibit crop seed germination. Availability of P and K is correlated with the increase of temperature and also with the destruction of SOM.

Burning is more intense and thorough on sites with small size wood, which dry quickly and could easily burn. At the more mature sites, large trees form physical barriers to spreading of fire and therefore reduce the percentage of burn. For example, Van Reuler and Janssen (1993), reported 50% burn at a 4 year fallow site and 15% on a 20 year fallow site. Large trees are not normally slashed and the clearings have a limited size. These factors combined facilitate forest regrowth after the fields have been abandoned (Van Reuler and Jannsen, 1993).

Research data so far obtained from experiments on incomplete and complete burning indicate that low to medium temperatures are more beneficial for nutrient recycling. Soil properties such as available nutrients, SOM content and CEC are improved while there are negative effects at higher temperatures. In situations where the farm has to get rid of large amounts of biomass after clearing, the drying period of the slashed vegetation should be kept short. The fire will burn at a lower intensity and lower temperatures. However, any living plants or animals caught in the path of the fire are in danger (see managed bush fallows; page 169). Seeds of some plant species are killed, whereas others are either stimulated by breaking of specific dormancy factors or by creation of soil conditions that favor germination and establishment. In general, there is an immediate reduction in the population of nearly all soil-dwelling organisms following the fire. Many die as a result of the high temperatures but some are impacted by the changes in soil pH that follow the fire, or by the flush of certain nutrients that come from the burned organic materials. After the fire, there is a fairly rapid re-colonization, especially by bacteria that are stimulated by the increase in soil pH.

Cropping

The superior efficiency of the multistrata system in retaining nutrients can be attributed to the perennial root systems, the continuous nutrient uptake, the presence of a litter layer where nutrients are adsorbed or microbially immobilized, and the lower percolation rate due to the continuous presence of a transpiring canopy. A higher soil organic matter content and consequently cation exchange capacity in perennial systems should possibly be added to this list. More important may be the fact, at any given time, that at least some of the plants in the system should be actively growing and taking up nutrients, thereby reducing the nutrient concentration in the soil solution, and should have a transpiring canopy, thereby reducing water percolation.

Multistrata agroforestry systems are widespread in the lowland humid tropics of the world (Nair, 2001). The simpler systems such as commercial plantations are of major importance for the world markets. The more complex, home garden-like systems are locally important for the subsistence of smallholder farmers and contribute to the conservation of germplasm diversity of tree species and to maintenance of niches for fauna and flora in the agricultural landscape. According to Nair (2001), there is no clear-cut distinction between multistrata agroforestry and because what is referred to as home gardens in some situations may be referred to as multistrata in another, and vice versa. Therefore, the distinction below is meant to highlight two common traditional production systems that have attempted to mimic the natural vegetation (Lefroy, 1999).

There is little doubt that under humid tropical conditions, tree crops are better suited for the maintenance of soil fertility than annual crops. This is because permanent soil cover and perennial root systems of the trees provide continuous soil protection; a favorable environment for soil biological processes and more efficient nutrient cycling than systems based on annual crops. In order for agricultural production systems to be sustainable in the humid tropics, the following conditions need to be observed (Okigbo, 1981):

1. Nutrients lost during cultivation must be continuously replenished.
2. Favorable physical conditions of the soil must be maintained.
3. Soil must be kept constantly covered and erosion controlled.
4. Soil acidity and nutrient deficiencies and toxic constituents must be continually controlled.
5. Build up in pests, weeds and diseases must be prevented.

Many years of research and experience have produced various highly successful and stable management practices for perennial crop production. Similarly, in many generations of traditional wisdom and practical experience, farmers developed stable and viable multistorey home gardens production systems in the uplands (Soemarwoto, 1987). The particular methods that are most appropriate in any given locality will vary both within and among the humid forest regions. Local needs and opportunities, ecological circumstances, economic opportunities, and social and cultural mores as well as the status of land and water resources, will determine which methods are most suitable. Although certain technologies can be more freely introduced, they must be adopted to the inherent opportunities and limitations of local environments.

Home Gardens

Home gardens are examples of traditional agroforestry systems that involve the simultaneous cultivation of trees, shrubs, and other crops. They are typically a very diverse mixture of trees, shrubs, food crops, medicinal plants, and livestock tended within a multistoried structure around the homestead and carefully managed over generations. The gardens generally produce food, wood, fodder, and other subsistence products as well as cash crops (Nair, 2001; Beets, 1990; Fernandes *et al.*, 1985). Home gardens appear to have evolved concomitantly with the shifting cultivation and bush fallow systems. They are found within the vicinity of homesteads and comprise numerous multipurpose woody species in intimate multistoried associations with annual crops and small livestock. The multistoried structure and species diversity result in almost complete coverage of the soil by plant canopies, thereby promoting soil conservation.

Management

Soil fertility is maintained by the use of household refuse, crop residues and animal manure. The average size of home gardens is 0.68 ha with a range of 0.2 to 1.2 ha. An average size of 0.68 ha produces 125 kg of beans (184 kg ha^{-1}), 280 of parchment coffee (412 kg ha^{-1}) and 275 bunches of bananas (404 ha^{-1}) annually. Fuel wood production is estimated to be 1.2 m^3 yr^{-1} (1.5-3 m^3 ha^{-1} yr^{-1}) which is 1/4 to 1/3 of the household requirement (Fernandes *et al.*, 1984). The system has been recognized as a potentially sustainable form of land use with possible applications for the entire humid tropics. The continuous ground cover and high degree of nutrient cycling are the major factors that permit the home-gardens to remain sustainable. The various crop species and varieties in the home garden represent years of natural selection for survival and farmer selection for better production and quality. The species represent a good resistance to prevalent pests, compete well with weeds and have a generally high level of genetic variability (Fernandes *et al.*, 1984). The advantages inherent in multispecies and multistoried cropping systems include diversified production risk minimization, enhanced labor efficiency and continuous ground cover.

Based on the understanding of the ecology of mixed tropical plant communities, it is believed that tropical home gardens and other multistrata systems are ecologically sustainable (Nair, 2001). Evidence of sustainability (including the maintenance of soil fertility) of tropical home gardens is provided by their long-term existence on some sites. Although the mechanisms responsible for this sustainability have not been properly studied and quantified (Torquebiau, 1992), they include permanent soil protection as well as additions of nutrients and organic matter inputs such as domestic wastes, ashes and manure (Nair, 2001).

Socio-economics

The home gardens remain a mystery for the economists in that these systems that have flourished for a long time defy the economic standards and criteria that are widely used for measuring the efficiency of land-use systems and other production enterprises (Nair, 2001).

In addition to being nutritionally important, many of the tree-shrub species provide products of considerable economic value. The compound farms are also invaluable germplasm banks of at least the traditionally important multi-purpose tree/shrub species that are currently being destroyed in the forest zone (Okafor and Fernandes, 1987). Due to fragmented nature of land holdings, attempts to combine cash cropping with regular supply of foods for household use has led to operation of different field systems and diversified production units:

1. Compound farms involving multistoried cropping of staple food crops with multipurpose trees and small livestock in the immediate vicinity of the household.
2. Near fields close to the compound but with fewer crops than compound farms.
3. Outlying and distant fields often used to produce food or cash crops that are not suitable for growing within the multistoried home gardens.

Conclusions and research needs

Most studies of home garden systems have been mainly descriptive. Based on these studies, we have gained a fairly good understanding of the essential characteristics of the major types of tropical home gardens. The main conclusion is that, all tropical home gardens are similar in their structure and function. They involve an intimate association of different plant taxa forming a multistoried configuration of canopies and together they provide an enormous array of useful products mostly for home consumption (Nair, 2001). However, much has yet to be done to improve home garden management in areas such as improved shade tolerance of different crops, successional stages of home garden development, increased yields, fertility management, and establishment methods. The role of the animal component need to be carefully studied for example for fertility management, recycling of nutrients and household wastes via composts, pods and fish production.

Well-designed, medium to long-term, process-oriented soil fertility studies are necessary to enable us to define more clearly the conditions for the sustainability and productivity of tree crop-based land use systems in the humid tropics. However, soil research in multistrata agroforestry systems poses methodological difficulties, which are partly related to the spatial and temporal complexity and heterogeneity of these systems.

The following research questions deserve particular attention (Schroth, *et al.*, 2001):

1. How can multistrata systems be established most efficiently under conditions of infertile soils?
2. How can crop and tree species be arranged and managed for maximum complementarity of resource use in space and time?
3. How can soil biological processes that enhance soil organic matter build-up and improvement and stabilization of soil structure by roots, fauna and macroflora, be optimized in tree based land use systems?

Other potential improvements of the home gardens for high economical returns (Fernandes, *et al.*, 1985) include:

i. Replacing less productive trees or shrubs with fast growing N fixing species to provide increased fuel, fodder and green manure.
ii. Introduction of new crop varieties using the gene pool developed by natural and farmer selection.
iii. Using organic and inorganic fertilizers in order to enhance the productivity and sustainability of compound farms.

Additionally, the following improvements could be considered (Fernandes, *et al.*, 1985; Nair, 2001):

1. Propagation methods for certain species to enhance availability of the product throughout the year,
2. Selection of species for increased yields and quality products,
3. Introduction of species of high economic value from other regions,
4. Incorporation of species with multiple benefits such as green manure, natural insecticide and nematocide,
5. Evaluation of agronomic aspects and biophysical processes, particularly interactions among plant species,
6. Control and management of belowground biomass, and
7. Economic viability of the systems.

Jungle Cacao Plantations

One of the more traditional systems is the growing of cacao under partly cleared forest. Instead of completely clearing the forest before planting cacao seedlings, farmers clear strips in the undergrowth and the young cacao trees are planted in the middle of those strips. That way, the natural ecology is preserved, the cacao trees are shaded and the labor input for establishing the plantation is reduced. This type of cacao plantation called "jungle cacao plantation", is typically found in the humid agro-ecosystem in forest margins. One can distinguish jungle cacao plantation from commercial plantations by its size, the kind of forest clearing and land preparation, the type of management, the use of inputs, the yield, and the source of labor force. Generally a jungle cacao plantation averages around 1.5-2.5 ha. The plantation is often located in the forest margin near the village (a walking distance of less than 30 minutes). Access to the fields is through paths of cleared vegetation. The products are transported by head load or by small hand push carts.

An excellent review of a similar traditional cacao production system was conducted by Duguma *et al.* (2001). The cultural practice of cacao cultivation is said to be widespread in the humid West and Central Africa. The system involves planting cacao seedlings in the secondary forest or forest fallow that has been selectively cleared and planted to various types of food crops for one or two seasons (Duguma *et al.*, 2001). During land clearing, indigenous fruit, medicinal and timber tree species are deliberately retained both for their economic value and to provide shade for cacao plant. The clearing is done manually (with the exception of the use of chain saw to fell big trees), which together with the no-tillage method used when planting, causes minimum or no disturbance to the fragile soils. Intercropping with food crops is sometimes done to exploit the soil fertility and to increase shade for the cacao seedlings.

Management

To establish a new jungle cocoa plantation, the primary forest is cleared (but not burnt) with the help of hand tools such as machetes and axes. The understorey and the shrubs are cut down. Some small trees are felled but many large and useful trees such as *Irvingia gabonesis*, *Tetrapleura tetraptera* are left in place, since they will serve as shade to young cocoa trees. Since most trees are not felled, the plantation looks like a secondary forest and this is why it has acquired the name *"jungle cocoa plantation"*. Depending on the density of the retained natural tree species and mortality rate of the cacao seedlings, the system is enriched by planting additional tree crops, such as mango (*Mangifera indica*), African plum (*Dacryodes indica*), avocado (*Persea amaricanum*), guava (*Psidium guajana*), cola (*Cola nitida*), orange (*Citrus sinensis*), and mandarin (*Citrus reticula*). As the cacao tree and the other grow to maturity, the agroforest becomes a more diverse and structurally complex, closed-canopy multistrata system that resembles a natural forest.

The major management requirements of cacao agroforests are shade control, weeding, pest and disease control, harvesting of pods and processing of beans. Before planting, the cleared understorey vegetation including trees branches and stems are slashed but not burned. The cocoa population varies from 1200 to 1500 trees ha^{-1} depending on the type of soil. The seedlings are usually planted at the beginning of the rainy season.

In most cases, cacao is grown as a single crop. But in some areas one can find young cocoa trees under bananas (*Musa* sp.) as a shade tree. Sometimes in plantations located near the household, useful trees such as plum tree (*Dacryodes edulis*), mango (*Mangifera indica*), avocado (*Persea americana*), kola (*Cola acuminata*) may also be present. Inputs such as fertilizers are scarcely used. The only chemicals used are to protect the crop against diseases and pests.

Cacao agroforests are thought to remain productive and environmentally sustainable for up to 50 years, at a level comparable to long-term fallow or primary forest. Comparative assessment of selected top soil nutrients in the secondary forest and cacao-dominated tree-based home gardens of Southern Cameroon showed that soil pH, organic matter, Ca and Mg are greatest in cacao agroforest compared to that in secondary forest (Duguma *et al.*, 2001). These authors reviewed the production systems in Cameroon and concluded that cacao agroforest land use systems are superior to the competing food crop production system in terms of most environmental indices and natural resource management parameters that they considered.

Socio-economics

Yields in the traditional "jungle cacao" plantations are usually low, averaging about 300 kg ha^{-1} because the farmers do not apply any chemical fertilizers, despite positive results obtained in research stations and in estates with the use of NPK fertilizers. With good management of pests and diseases, the yield can rise up to 600 kg ha^{-1} of dry beans. This is still relatively low compared to 2000-2500 kg ha^{-1} dry beans one can obtain with optimum pest and disease management and judicious use of fertilizers on commercial plantations.

Labor constitutes the most important component in this type of exploitation. Labor is needed at all levels: forest clearing, land preparation, weeding, spraying, pruning, harvesting, breaking of the pods, fermenting and drying of the beans. This labor is mainly supplied by the family which is the only source of labor for small holdings. Since the family is involved in other farm activities, this may explain why the size of a jungle cacao plantation remains relatively small. The most severe problem faced by cacao farmers in the region is the occurrence of pests and disease.

Conclusions and research needs

The advantages of trees over annual crops in the humid tropics are well documented, such as reduced soil erosion, reduced soil fertility depletion and better nutrient cycling. This is because perennial crops are better than annuals in conserving soil. The frequency and intensity of cultivation is less than in arable farming and the nutrient input-output balance is more favorable. The most important reason however, is that trees cover the soil continuously. Shade ensures that erosion is limited and oxidation of organic matter is slow. In addition, most perennials are relatively more efficient converters of solar energy into products that are useful to man. They are also more efficient in the use of chemical inputs such as fertilizers, pesticides, and herbicides. The cacao plantations have the additional advantage over shifting cultivation or bush fallow systems in that, they are geared more towards cash production.

The magnitude of environmental benefits depends on the proportion of trees in the system: the more trees the greater the benefits. Often, however, the productivity of annual crops decreases as the woody perennial component of the system increases. In designing a system, it is important to decide on the relative importance of the immediate productivity or environmental benefits and of sustainability. This can be done by considering a series of possible combinations of annual crops and tree crops ranging from pure monoculture, at one end to pure forestry, at the other. Toward the agricultural end, the system produces more immediate agricultural products and towards the silvicultural end, sustainability is stronger and more long-term forestry products are generated (Beets, 1990).

Since cacao does not lend itself very well to mechanization, the first improvement can be done at the installation of the plantation by a suitable forest clearing. Large trees except some useful ones such as *Tetrapleura tetraptera* as *Irvingia gabonensis* should be reduced to an optimum number for right amount of shading and cacao population. Useful trees such as fruit trees (*Persea americana, Dacryodes edulis, Mangifera indica, Cola acuminata.*) and others could be planted to obtain 40-50% upper canopy. The use of mineral fertilizers may also assist in increasing cocoa yield. Given that a ton of cacao beans can remove 20 kg of N, 10 kg of P_2O_5 and 15 kg of K_2O, fertilization should be made in order to replace these quantities of exported nutrients. Results from research stations and cacao estates show yield increases from 300 kg ha^{-1} dry beans to more than 2000 kg ha^{-1} with the application of fertilizers. Optimal levels of application need to be determined.

Shifting cultivation

Shifting cultivation (also known as swidden, slash-and-burn, or slash-and-mulch agriculture) remains in wide use throughout the humid tropics. As traditionally practiced, shifting cultivation protects the resource base through efficient recycling of nutrients, conservation of soil and water, diversification of crops, and incorporation of fallow periods in the cultivation cycle. Fallows accumulate nutrients in their biomass and control weeds. However, traditional shifting cultivation systems are being disrupted, modified and replaced as population pressures rise and as migrants unfamiliar with the humid tropics or indigenous land use practices, attempt to farm on newly cleared land. Typically, this results in shortened fallow periods, fertility decline, weed infestation, disruption of forest regeneration, and excessive soil erosion.

Shifting cultivation refers to one of the most important traditional farming systems in the tropics in which relatively short periods of cultivation are followed by relatively long periods of fallow. Ruthenberg (1976), proposed a formula for classifying traditional farming systems:

$$R = \frac{C \times 100}{C + F}$$

Where,
R = Ratio (%)
C = Length of cultivation period
F = Length of fallow period

Lanly, (1985) proposed the following groupings:
R < 33 = shifting cultivation or long fallow agriculture.
R between 33-66 = short fallow, semi-permanent or stationary cultivation with occasional fallowing.
R > 66 = permanent cultivation

However, the meaning of the term "shifting cultivation" tends, in practice, to be broadened in two ways: Firstly, some documents and reports extend it to include short-fallow agriculture systems and secondly, others include under shifting cultivation, all types forestland encroachment by cultivators. In the following discussion, we have adapted Lanly's definition for convinience.

Shifting cultivation was once widespread throughout the world but is now confined to the tropics, particularly the humid tropics and the less accessible areas. The characteristics of shifting cultivation in the tropical world are remarkably similar in different areas. The system is usually characterized by a progression of different crops from year to year. An annual staple such as rice, maize or millet is often planted in the first year after clearing, then root crops such as cassava, sweet potatoes, yams and finally, bananas and fruit trees. Mixed cropping is the rule and it is from this practice and the high crop diversity, that most of the systems ecological stability is derived (Beets, 1990). Good shifting cultivators have learned through experience that the timing of all the activities, especially the fire make the difference between a sustainable and a degrading system (see clearing and burning; page 151).

Shifting cultivation works when the system is allowed enough time for natural successional processes to restore the soil fertility lost through disturbance and crop harvest. It is therefore, reasonable to conclude that the traditional practice cultivating for 2-3 years after clearing is to take advantage of the existence of temporarily high nutrient levels in the soil water and/or exchange complex of the soil. This may induce severe losses of nutrients and reduced crop yields if continued for too long without regeneration. Immediately following burning, nutrient mobility in the system is quite high, often resulting in high nutrient losses. Therefore, crops in this system need to quickly pick up the nutrients added from the ash or they will be leached or taken up by non-crop plant species. Depending on the soil type, climate and cropping practices, the rate of nutrient loss varies considerably.

Management

The shifting cultivation farmers cut and burn relatively small plots of forest and produce crops in the burned-over area. They grow crops on these plots for 2-3 years, until the nutrients are depleted and/or when weeds become a problem. The farmers then abandon the plots for 10-20 years, allowing the forest species to re-grow and replenish the soil fertility. The farmers move on to slash and burn another forested plot and repeat the process. A farmer may shift in turn five to ten such small plots before returning to clear and burn trees in the first one that was fallowed 10-20 years previously and restart a new cycle. After a cropping period the land is abandoned and will be re-cultivated after its fertility is judged to be restored, or sooner if other land is not available (Greenland 1974). In many parts of the world, due to increasing population the latter is the case (Van Reuler and Janssen, 1993).

Shifting cultivation has received a great deal of international attention because one of the suspected environmental consequences of the system is its contribution to global warming. It has been estimated that the tropical rainforests contribute substantial amounts of greenhouse gases from deforestation. Therefore, slash and burn agriculture could have global implications because of its contribution to these gaseous emissions as a result of the burning of the forest products and of the subsequent decay of trees and other unburned debris and of soil organic matter. Furthermore, slash-and-burn agriculture causes disturbance, if not loss, of the biological diversity accumulated for over a long period. The maintenance of the biodiversity is a matter of concern to all humanity. The biodiversity has multiple roles to play, which are increasingly being recognized, particularly in soil fertility management (Kotto-Same *et al.*, 1997).

The rationale for sustaining the shifting cultivation system is quite simple. The natural original forests and the fallowed areas are composed of different trees and other woody species which grow and provide several benefits for the agricultural crops. Under ideal conditions, there is a natural nutrient recycling and an optimal biomass production by the natural vegetation. The soil is protected against erosion and nutrients are continuously captured by tree root systems and recycled through litter and root decay. Slashing and burning the trees disrupts this equilibrium and exposes the soil to runoff and nutrient leaching and hence soil degradation. During the fallow period, the trees replenish the soil organic matter and consequently improve the soil structure. They also protect the soil from erosion and excessive water runoff and accumulate nutrients in their biomass and cycle them from deeper soil layers to surface layers where most crop roots are found. The nutrients that trees accumulate in their biomass are transferred to soil through litter fall and decomposition or ash after slash-and-burn.

Nutrient cycling and conservation mechanisms in tropical forest systems depend on the type of soil on which the forests grow. Tropical rainforests thrive on both fertile and infertile soils, but the total amount of nutrients accumulated in the plant biomass in a given forest system depends on the inherent fertility of the soil and the age of the forest. The most productive forests thrive on relatively fertile soils. They recycle and store large quantities of mineral nutrients. On the other hand, the forests growing on infertile soils are less productive and recycle smaller amounts of nutrients.

In primary forest ecosystems, two nutrient cycling mechanisms have been identified (Juo and Manu, 1996). The first mechanism involves internal cycling of nutrients released from the decomposing litter and captured by the root mat on the forest floor. The other mechanism involves the combination of recovery of mineral nutrients from the subsoil and saprolites. Primary forests established on strongly acidic and leached soils, such as those of the Congo Basin, depend on the internal cycle to meet their mineral requirements. The nutrients absorbed by the forest vegetation are derived from the litter decomposition and infiltration of surface water. The thick layer of root mat on the forest floor retains large amounts of water and available nutrients and facilitates nutrient uptake by the forest vegetation. In such forest ecosystems, over 80% of the N and P is held by the total plant biomass including leaves, branches, trunk and roots, while the bulk of Ca, Mg and K is held in the soil (Juo and Manu, 1996). The mineral nutrients released during the slash and burn may be lost through leaching and runoff if the soil system is unable to retain them. Nevertheless in the ideal slash and burn system, nutrients added to the small patch of manually cleared field are taken up by the food crop, captured either by the surrounding forest vegetation or by the living forest root mat remaining in cropped field. If however, these forests are transformed into large-scale production systems, the nutrient and organic pools become drastically reduced.

The availability of soil nutrients to plants is dependent on the flow of water through the soil system. It has been shown experimentally that water transport systems may occur in strongly weathered and highly permeable soils under forests (Juo and Manu, 1996). One is determined by macropores through which water drains rapidly during rainstorms. The other is determined by micropores through which water flows. Soluble nutrients released from decomposing litter are mainly retained in micropores that permit sufficient residence time for their uptake by plants. The presence of positive charges in the subsurface layers of many oxidic Oxisols and Ultisols might slow the movement of anions such as nitrates and sulfates. This retarded leaching process increases the residence time of nutrients, which in turn favors nutrient uptake by plants.

When the forest is slashed, the amounts of elements released through burning depend upon the total nutrient content in the biomass and the intensity of burning. When the slash-and-burn cultivator sets fire on the fallen vegetation, most of the large woody biomass remains uncombusted. Therefore, nutrients stored in the forest biomass are released both through the ash and the decomposition and mineralization of the plant residues. The amounts of nutrient elements in the ash have been estimated by several workers, using more intensive burning in slash and burn experiments (Kyuma *et al.*, 1985; Andriesse and Schelhaas, 1987). From these trials again, it has been shown that the quantities of nutrients gained by the soil after burning depend on the amount of each element in the ash and on the soil capacity to retain and store these nutrient elements in forms readily available to the crops. The total amount of nutrient inputs from the ash varies from one site to another and is influenced by several factors including the vegetation composition, the intensity of burning and the type of soil. Research findings have indicated that slash and burn might contribute significantly to the carbon dioxide in the atmosphere. Those gaseous losses of C and N and possible accumulation of carbon dioxide in the atmosphere, raise concerns regarding environmental conservation (Kotto-Same, *et al.*, 1997).

Burning of biomass leads to rapid increase of soil pH, exchangeable bases, effective cation exchange capacity and available P in the topsoil. In acid soils, the ash temporally neutralizes the soluble and exchangeable Al in the soil. This is a beneficial effect for the crop growth. The magnitude is influenced by the chemical composition of the ash, the mineralogy and charge characteristics of the soil. In strongly acidic soils containing oxides and kaolinite, like those of the Central Congo Basin, input of large amount of alkali and alkaline cations (Na, K, Ca, Mg) from ash can cause significant increase of soil pH and effective CEC. However, the leaching and crop harvest removal, taking place during the subsequent cropping cycles, might re-acidify the soil, because of the loss of the basic cations from the soil exchange complex. The rate at which the soil is re-acidified during the cropping phase would depend on the rainfall quantities and the seasonal distribution, the length and intensity of cultivation, and the level of conservation management. Moreover, such soil pH reversion might also take place during the fallow phase when a major portion of exchangeable are partially washed away by leaching and partially taken up by the fallow regrowth.

Very limited literature exists on the nutrient dynamics during the cultivation phase in the case of tropical forests. However, it can be stated that the important benefit of slash and burn is the rapid release of the mineral nutrients, such as Ca, Mg, K, and P, from the ash to the soil. This benefit may be short-lived if the soil system is unable to store this large addition of soluble nutrients against possible loss through leaching, runoff and erosion during the cropping phase. It is predictable that the amount and the cause of nutrient losses during the cropping cycles will depend on the crops and the site characteristics. According to Juo and Manu (1996), the decline of the ash-enriched nutrient pool of the soil during the cropping cycles may be accelerated under certain conditions including:

(a) Lack of continuous ground cover, which exacerbates erosion and runoff losses during rainstorms on slopping lands with less permeable soils.
(b) Increased frequency of clearing and cultivation, which leads to gradual destruction of soil macropore system, therefore decreasing the quantity of by-pass flow of rain water and increasing losses of mineral nutrients through leaching and runoff.
(c) Burning and cultivation, which lead to gradual destruction of the root mat, decomposition of the humified organic matter of the original forest ecosystem and reduction in the contribution of organic and microbial processes to nutrient cycling.

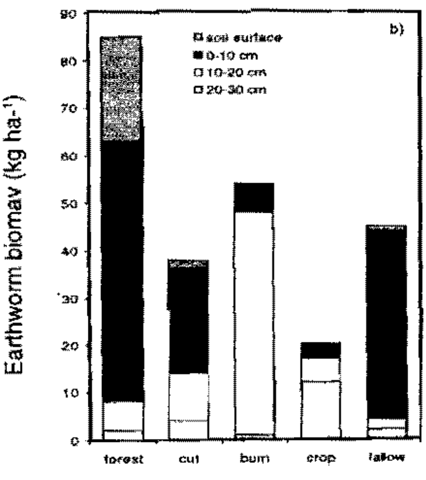
Considering the fallow from an ecosystem perspective, its main function is essentially the transfer of mineral nutrients from the soil back into the forest biomass. Because of the inevitable loss of mineral nutrients during the cropping cycles, recovery of the total nutrient stock in the entire ecosystem during the subsequent fallow phase is expected to be progressively smaller than that of the original forest ecosystem. Data from the Congo Basin (Eckholm, 1976), show that biomass accumulation reached a steady state after 15 years of fallow. By then, however, the total amount of biomass reached was only 35% of the biomass of the primary forest. These data suggest that the total amount of biomass of the secondary forest may take hundreds of years to reach the level comparable to that of the primary forest if the level of the total nutrient stock has been significantly reduced and the nutrient cycling and conservation mechanisms are disrupted by repeated cycles of slash and burn cultivation.

In the lowland humid tropics, mature secondary forest (15-20 years) can produce 300-400 tha^{-1} of above-ground biomass. This amount of biomass contributes approximately 1-2 tha^{-1} of N, 0.7-2.5 tha^{-1} of K, 2-

3 tha^{-1} of Ca, 300-800 Kgha^{-1} of Mg and 100-250 Kgha^{-1} of P to the soil (Bartholomew *et al.*, 1953; Kyuma *et al.*, 1985). However, the nutrient accumulation of the fallow vegetation is closely associated with species diversity, fallow length and inherent soil fertility. Perennial and tree legumes are good P and Ca accumulators. Leaves and branches are important nutrient sinks in young trees, but in older trees large quantities of nutrients are also stored in the trunks. It was found that tropical secondary forests (> 15 years) growing on high base status soils stored more nutrients, mainly N, P, K, Ca and Mg in their above-ground biomass and in surface soils (0 - 30 cm) than those growing on strongly acidic and leached soils (Nye and Greenland, 1960; Stromgaard, 1984; Kyuma *et al.*, 1985).

Soil biological processes are the drivers in nutrient cycling whatever the land use or management system. However, few studies have been undertaken so far to assess the effect of slash and burn practices on soil biological processes and the important contributing components in the humid zones of Africa. Niyungeko *et al.* (1995), studied the earthworm population dynamics in a slash and burn chronosequence in the humid forest in the Democratic Republic of Congo (formerly, Zaire). They found that the greatest populations of earthworms occur in the primary forest and the smallest in croplands which contained 24% of the worm population size and 23 % of the worm biomass compared to the original forest (Figure 5.1).

Figure 5.1. Earthworm population sizes and biomass in a slash-and-burn chronosequence nearby Kisangani



(J.N.M. Niyungeko, unpublished data)

The study produced some evidence of earthworm redistribution in response to burning. For example, the population size and the biomass of earthworms at the 10 - 20 cm soil depth increased following burning compared to that before burning. The epigeics which feed on the soil surface appear to be a very vulnerable component of the earthworm population. The forest litter contained 75 epigeics per square meter. These were tremendously reduced by the forest cutting and completely disappeared following burning. Furthermore, it appears that their populations are slow to recover during the fallow period.

Cutting, burning and cropping, each result generally in successive decline in earthworm population sizes. It is not easy to explain the rapid decline due to the forest cutting. It may be an effect of the sudden change in the microenvironment of the system ecology causing the migration of the earthworms to the undisturbed forest surrounding the slashed plot. However, the effects of burning, where surface litter is destroyed and soils heated to high temperatures and cropping, where surface soils are disturbed and vegetation composition altered, results in unfavorable habitat for earthworms.

In another study on termite population dynamics in the same slash and burn chronosequence, results showed that the forest contained 1538 termites m^2, the croplands 175 termites m^2, and one year old fallow 5450 termites m^2. Termite fresh biomass was 26.3, 6.4 and 127 Kg ha^{-1} for the forest, the cropland and the fallow respectively. When individual termite populations were compared, site-to-site variability remained high, in some cases with large numbers of termites found in soils following burning.

Figure 5.2. shows the changes in termite population and genera during land use change at one field site. The forest contains fewer individuals but more genera than the slashed forest, suggesting that the initial forest disturbance (felling trees and slashing understorey), provides a short-lived opportunity for some termites. Burning greatly reduced the termite population which after 12 weeks of maize and cassava cultivation failed to recover.

Overall, the net effect of forest conversion to agriculture was to reduce the number of termite genera from 6 to 2 and the total population by up to 95 %.

The impact of different land uses on termite populations is further illustrated in Table 5.1. The mean number of genera and percentage of active mounds for two field sites are presented for the land uses. The number of termite genera was reduced by 50% during the 18 weeks of land conversion. Each step of land preparation resulted in reduction of termite genera and the proportion of active mounds. There was a termite population recovery during the fallow interval, although the proportion of non-active termite mounds increased by 40%.

Figure 5.2. Termite population dynamics during the different land uses of slash-and-burn agriculture in Masako (Democratic Republic of Congo)

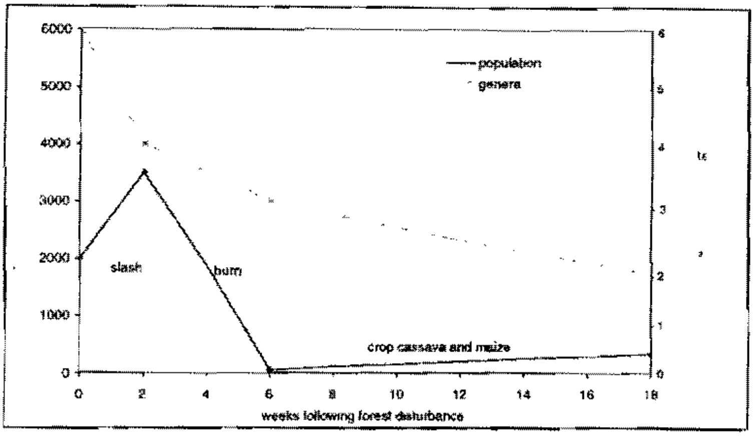


Table 5.1. Termite activities and number of genera during different stages of slash and burn agriculture

Parameter	Land Use				
	Forest	Cut	Burned	Cropped	Fallow
Weeks following forest disturbance	0	2	6	18	70
Total genera	5	3.5	3	2.5	3
Active mounds (%)	98	80	56	26	68

(J.N.M. Niyungeko, unpublished data)

The conclusion in terms of biodiversity is that termites are susceptible to land disturbance, but have some ability to recover during fallow intervals. The study dealt with the termites as an important functional group of soil organisms whose activities and biodiversity are subject to land disturbance. Hence, whether termites offer beneficial effects in terms of soil channeling or pose a risk through crop damage or litter removal, was not considered.

Socio-economics

Availability of labor determines which and when crops are grown and the amount of area is to be planted. In many cases the labor allocation will depend on the labor requirements for alternative activities. Since all the work is done manually, labor requirements depend on the characteristics of the natural vegetation and to a large extent, on whether the plot is planted for the first, second, or third time. Weeding requirements increase very rapidly with time after clearing and burning.

Based on the labor data from the Amazon basin of Peru (Rhoades and Bidegaray, 1987), it is estimated that one able man can only just handle 1 ha and a typical family about 2 ha, considering that many hours are lost travelling to and from the fields and that there are other needs for labor. Therefore, it would appear that shifting cultivation will remain a subsistence farming activity.

Shifting cultivation is an important production system in the humid forest zone. The system is quite sound ecologically under conditions of abundant land, but is under serious threat from population pressure and land scarcity. As land becomes scarce, there is general agreement that the system needs to be changed. However, there are no really sound and tested alternatives to the system, but many possibilities exist (Beets, 1990). For example, some agricultural technologies that have been developed for other farming systems can be of relevance as alternatives to shifting cultivation. Equally, components of other farming systems could also be considered for adoption. But the final package of the intervention, or alternative system as a whole, should be developed and tested together with farmers. When alternatives are considered, the following systems have ecological acceptability and economic viability in specific locations:

1. Regulated or planted fallow systems.
2. Agroforestry.
3. Smallholder farming with plantation crops.
4. Specializes commercial plantations.

Sustainable practices to improve productivity and conserve soil, water and biotic resources can provide farmers with alternatives to continued clearing of forests. For example, sustainable use of secondary forest fallows provides a viable alternative to primary forest clearing. However, it is important to note that improving shifting cultivation and the change from shifting cultivation to improved systems of land use comprises more issues than just technical problems. Labor requirements and efficiency in the change over, need to be given more emphasis than has been the case. In addition, improved techniques have to fit into the socio-economic conditions of the farming family. Otherwise these techniques will not be accepted. Available alternatives, regulated or planted fallows and alley cropping are the subject of the following sections.

Managed bush fallows

Extensive agricultural systems that rely on a fallow period to restore soil nutrient status between short periods of cultivation are generally described as shifting cultivation agriculture, slash and burn farming or swidden farming (Gleave, 1996). Earlier work concentrated on description, analysis and distribution of the systems at a variety of scales ranging from the local, to the general on the effects of the systems on the natural environment, particularly on the soil (Nye and Greenland, 1960) and on the transition to more intensive systems and the role of population on the transition. More recent work has refined the conclusions of earlier studies whilst also focusing on ways of improving the productivity of the systems by, for example, planting the fallow with nitrogen-fixing trees or shrubs or on designing improved systems to improve sustainability (Gichuru, 1994; 1991). Central to this work is the fallow period, its length and effects on soil fertility. A short fallow period is often taken to indicate environmental stress, pressure on resources or unsustainability of the system. Similarly, shortening fallow periods are taken to be indications of environmental degradation or increasing population pressure and declining sustainability. The planting of fallow, particularly with nitrogen-fixing species, speeds the process of fertility restoration thus shortening the period of optimum fallow length (Gichuru, 1994).

The bush fallow system has been considered the last phase in the intensification of shifting cultivation before the change to semi-permanent or permanent cropping (Langly, 1985). As the ratio between the length of the fallow and cropping phases declines, the bush fallow system is pushed closer and closer to the limits of its workability (Staver, 1989). A lengthened cropping period, a shortened fallow period, or increased weeding can set back the regeneration of trees and shrubs which is essential in the humid tropical climates to the restoration of potential productivity.

Management

Productivity and stability of bush fallow systems depend on fallow periods when trees and shrubs recycle nutrients from below the rooting zone of annual crops to the surface soil layer (Nye, 1958; Nye and Greenland, 1960). The period wherein the physical and chemical properties of the soil are restored, is the key to the long-term success of bush fallow systems (Ewel, 1976). However, when land becomes limiting and fallow periods are shortened such that adequate nutrient levels are not restored, the system deteriorates (Padwick, 1983). When soil fertility declines because fallow periods are too short, it is primarily because of exhaustion of N, P and K in the topsoil (Date, 1973; Nye and Greenland, 1960). The enhancement of the natural fallow vegetation by introduction of fast growing trees or shrubs is an attractive approach for shortening the fallow period or increasing the yield of subsequent crops (MacDicken, 1990).

Experiments on fallows date back to the 1930's with a well known example of the "corridor system" which was tried and applied by the Belgians in the Congo (now DRC). The system was founded on the principles of shifting cultivation (Eckholm, 1976). It was hypothesized that the fallow system could be improved by not relying totally on natural regeneration, but by planting particular species to shorten the fallow period. One such approach involves the introduction of new multipurpose or economic species to the cropping cycle or fallow period. In South-eastern Nigeria, where population density range as high as $1000/km^{2}$, there is a strong positive correlation between population density and the intensity of tree planting (Raintree, 1990). Studies show that both the type and age of the fallow greatly influence the fertility of the soil at the end of the fallow period (Padwick, 1983). Soil productivity generally increases with increasing fallow length when the appropriate tree or shrub species are present. Fast-growing species can be expected to restore soil fertility more quickly and vice-versa (Aweto, 1981). In order to be acceptable, fallow improvement species should yield high levels of the limiting nutrients and accumulate more organic matter than natural bush. Planted legume species have been shown to be effective in improving soil fertility (Juo and Lal, 1977; Kang and Wilson, 1987; Gichuru and Kang, 1989).

It is clear that the stability of shifting cultivation and bush fallow systems depend on fallow periods when trees and shrubs recycle nutrients and improve soil physical and chemical properties. But when land becomes limiting and fallow periods are shortened so much that adequate nutrient levels are not restored, the system deteriorates. Enhancement of the fallow vegetation would shorten the fallow period and increase crop yield. In the slash and burn system of land management, the vegetation is normally cleared and burned but this practice results in the loss of most of the N accumulated in the vegetation. Staver (1989), proposed a simple strategy for intensification of bush fallow systems; first to take into account farmer practices and secondly maintain the components that make the system function. Two case studies are presented below.

Legume species in the bush fallow

An experiment conducted in South-Eastern Nigeria to examine the contribution of *Tephrosia candida* and *Cajanus cajan* shrubs to improving the productivity of an acid soil showed that *Tephrosia candida* and *Cajanus cajan* increased surface soil organic carbon and total N levels over the natural bush. Pronounced differences in soil chemical properties were observed only at the surface layer (0-5 cm), (Table 5.2). Planted species produced higher organic C and total N compared with the natural bush plots. The most striking features were the differences in soil properties between the treatments in the surface layer. Concentration of nutrients was greater in the top 5-cm layer of all the treatments (Gichuru, 1991).

Table 5.2. Effect of fallow species on selected topsoil chemical properties at Onne, Southeastern Nigeria

Fallow species	pH (H_2O)	Org C (gkg^{-1})	Total N	Exchangeable Ca	Mg	K	Acidity
				(meq/100 g)			
	0-5 cm						
Natural bush	4.8	1.84	0.16	0.83	0.28	0.23	0.84
Cajanus cajan	4.6	2.21	0.19	0.68	0.20	0.17	0.78
Tephrosia candida	4.6	2.07	0.18	0.80	0.23	0.18	0.83
LSD (0.05)	0.15	0.23	0.011	NS	0.055	NS	NS
	5-15 cm						
Natural bush	4.4	1.10	0.12	0.35	0.10	0.11	2.40
Cajanus cajan	4.3	1.20	0.19	0.34	0.10	0.09	2.37
Tephrosia candida	4.3	1.12	0.11	0.32	0.10	0.10	2.28
LSD (0.05)	NS	NS	NS	NS	NS	NS	NS

(Gichuru, 1991)

In addition, N content of the ear leaf at tasseling stage of maize suggested that the main contribution of *Tephrosia* was available N. Similar trends were observed for both stover and grain nutrient status. There were significant positive correlation between grain yield and earleaf N (r=0.73**), grain N (r=0.51**), and stover N (r=0.54**). Significant correlations were also observed between grain yield and earleaf K (r=0.34*) earleaf, Ca (r=0.39*) and grain Ca (r=0.50*). However, the nutrient concentration and yield of dry matter maize (Table 5.3) was considered to give an integrated expression of soil fertility. *Tephrosia candida* improved soil fertility as indicated by vegetative growth, higher grain and stover yield and higher nutrient concentrations of the earleaf samples and in the grain and stover. *Tephrosia* plots had better vegetative growth and the maize plants were less susceptible to lodging compared with the natural bush and *Cajanus cajan* treatments. The better vegetative growth resulted in higher maize grain and stover yields and generally higher nutrient concentrations. The effect of *Tephrosia* was particularly pronounced with respect to N, which is a major limiting nutrient in these soils. Thus, *Tephrosia* shows a potential for improving soil productivity through N fixation.

Socio-economics

The beneficial effect of *Tephrosia candida* was particularly pronounced with respect to N, which is a major limiting nutrient in these soils. In addition, the higher levels of other nutrients recycled in the stover due to better maize crop are likely to further improve soil fertility in *Tephrosia candida* plots compared with the natural fallow. Thus, *Tephrosia candida* shows a potential for soil regeneration both through N, fixation and nutrient cycling. The lower concentration of bases in the soil under *Tephrosia candida* during the fallow is believed to be due to nutrients held in the vegetation (Jaiyebo and Moore, 1964).

Table 5.3. Effect of fallow species and the previous cropping system on maize grain and stover yield at Onne, Southeastern Nigeria

Fallow	Previous cropping system Sole maize		Cassava/maize	Mean
	Grain (kg ha^{-1})			
Natural bush	1217		693	955
Cajanus cajan	1071		835	953
Tephrosia candida	2953		1966	2459
Mean	1747		1165	
LSD (0.05)		279		341
	Stover (kg ha^{-1})			
Natural bush	1719		1547	1633
Cajanus cajan	1698		1532	1615
Tephrosia candida	2665		2467	2566
Mean	2027		1849	
LSD (0.05)		NS		342

(Gichuru, 1991)

Regeneration of a degraded Ultisol with Tephrosia candida

Tephrosia candida, a legume shrub known to nodulate well under acid soil conditions was compared with the natural bush regrowth, following 12 years of continuous cropping with lime application (Gichuru, 1994). Maize grain yields were significantly increased by *Tephrosia candida* compared to the natural regrowth fallow at all lime levels (Table 5.4). Overall, the yield increase due to the planted fallow being more than 200%. There was a strong interaction between the previous lime application and the fallow treatments indicating that the highest lime rate produced a significant effect on maize grain but only with *Tephrosia candida* fallow. Therefore, the natural bush regrowth appears to be less effective in soil regeneration even where soil is not far degraded as indicated by the very low yields in limed treatments following the fallow period.

Residual effects of liming following 12 years of continuous cropping were measurable in exchangeable Ca, acidity and effective cation exchange capacity (ECEC). The most pronounced changes due to the fallow treatments were observed in the top 5 cm of the soil (Table 5.5). Soil under planted species contained more organic C and total N, than under natural bush regardless of the previous lime treatment. The residual effects of lime after more than 15 years since application are quite remarkable and suggests a great potential for liming this acid Ultisol.

Table 5.4. Maize grain yields as influenced by fallow treatments and previous lime application

Lime rate	Fallow		
($t\ ha^{-1}$)	Natural bush	Tephrosia candida ($kg\ ha^{-1}$)	Means
0	675	1199	937
0.5	603	1414	1009
1.0	794	1204	999
2.0	888	1351	1119
4.0	761	2816	178
Means	744	1597	
SE	133.0		194.1

(Gichuru, 1994)

Table 5.5. Selected soil chemical properties of two contrasting lime treatments at the end of 12 years of continuous cropping at Onne Station

Depth (cm)	pH	Org C ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	Exchangeable Ca (me/100 g)	Exchangeable Mg (me/100 g)	Exchangeable K (me/100 g)	Total Acidity (me/100 g)	ECEC
Control (no lime)								
0-5	4.5	1.45	0.09	0.76	0.29	0.10	1.49	2.83
5-15	4.6	0.99	0.08	0.45	0.10	0.11	2.03	3.03
15-30	4.5	0.79	0.05	0.43	0.09	0.09	2.62	3.42
30-45	4.4	0.63	0.05	0.39	0.08	0.07	2.70	3.41
45-60	4.4	0.49	0.05	0.36	0.07	0.06	2.70	3.36
60-75	4.3	0.41	0.04	0.44	0.07	0.05	2.64	3.47
75-90	4.3	0.37	0.04	0.32	0.07	0.05	2.56	3.26
90-105	4.3	0.27	0.04	0.33	0.07	0.05	2.53	3.15
4 t lime ha^{-1}								
0-5	4.6	1.33	0.12	1.35	0.43	0.14	0.94	3.07
5-15	4.6	0.99	0.08	0.89	0.20	0.16	1.42	2.88
15-30	4.5	0.70	0.06	0.75	0.16	0.11	1.97	3.16
30-45	4.5	0.58	0.05	0.63	0.13	0.07	2.20	3.23
45-60	4.4	0.54	0.04	0.55	0.10	0.06	2.34	3.24
60-75	4.3	0.50	0.05	0.49	0.09	0.06	2.24	3.21
75-90	4.3	0.38	0.04	0.44	0.07	0.05	2.21	3.08
90-105	4.3	0.39	0.05	0.43	0.07	0.05	2.00	2.75

(Gichuru, 1994).

Conclusions and research needs

One of the most challenging problems in the improved fallow approach is the establishment of the legume species into the bush fallow. Preliminary studies have shown that *Tephrosia candida* can be established in the humid forest zone by broadcasting seeds just before the final weeding of a cassava crop, at the end of the cropping cycle, without additional labor cost or reduction in cassava yield. A study undertaken to determine economical methods of introducing *Tephrosia candida* in bush fallow systems under farmers' conditions, compared the establishment of *Tephrosia candida* in cassava-based production systems with or without the cassava crop. Two methods were tested:

i) Seed broadcast at final weeding of food crop, and
ii) Planting seeds at the end of the cropping phase.

The first method involves broadcasting *Tephrosia candida* seeds before weeding. The weeding process incorporates the broadcasting seeds into the soil without additional labor. Tephrosia seedlings then grow in a favorable environment with reduced weed competition. *Tephrosia candida* established at the time of third and final weeding would not affect the yield of cassava. After cassava harvest, Tephrosia is left to grow during the fallow period. The second method of planting *Tephrosia candida* involves dribbling as in maize or cowpea planting, at depths of about 1 cm. Although Tephrosia can be planted anytime except during the dry months, it appears to establish best when planted during the peak rainy period. Ideally, seeds should be planted at the onset of the fallow period.

After the Tephrosia fallow, land is cleared and cropped as practiced in traditional bush fallow systems. After cropping, the land goes back to Tephrosia fallow again. The fallow/cropping combination can be 1 year/1 year, 2 years/1 year, 2 years/2 years, 1 year/2 years, or any other combination depending on the effectiveness of the fallow and whether or not external chemical inputs are applied. The longer the fallow period the greater the soil improvement and therefore, reduced requirements for external inputs. However, there is need to determine the optimum fallow length using various species, with emphasis on economic viability.

Alley Cropping

A major concept of the alley cropping technology is that trees "pump up" and recycle nutrients from deeper soil layers as well as N fixation by legumes thus reducing the level of external inputs. Agroforestry (Lundgren and Raintree, 1983; Nair, 1984), has received a great deal of attention as a possible solution to production problems of the humid tropics. Alley cropping, also known as hedgerow intercropping, is a production system in which food crops are grown in alleys formed by planted hedgerows. Alley cropping integrates on a continuous basis, the soil-restorative attributes of the fallow with arable cropping through simultaneous hedgerows of perennial trees or shrubs (Beets, 1990). The hedgerows are periodically cut back and pruned during the cropping season to prevent shading, reduce competition with the companion crops and to provide green manure and mulch (Kang *et al.*, 1984). The prunings (leaves and twigs) are applied to the soil as mulch. This creates a favorable microclimate and provides upon decomposition, nutrients for crop growth. The bigger branches can be used as stakes or firewood. Kang *et al.* (1984), described alley cropping as a stable alternative to shifting cultivation, which retains the basic features of bush fallow, one of which is to provide shade and pruning that suppress undergrowth, while fixing atmospheric nitrogen. The success of alley cropping depends on some technical factors such as the use of suitable woody species, the successful establishment of the hedgerows and their appropriate management (Kang *et al.*, 1990) and the design in terms of spacing, periodicity of pruning, etc. The woody species used, which mostly are legumes, play a productive and or protective role depending upon the dominant function(s) of the species (Nair *et al.*, 1993). The productive role includes production of food, fodder, firewood and various products. The protective role stems from the soil improving and conserving functions of woody perennials.

The woody species improve soil conditions through the addition of organic matter from litterfall, prunings and dead and decaying roots; the modification of soil porosity and infiltration rates leading to reduced erodability of soil and improving the efficiency of nutrient cycling within the soil-plant system (Nair, 1984). The presence of more plant cover on the soil, either alive or dead, also reduces the runoff and the impact of raindrops on the soil and thus minimizes splash and sheet erosion. Other protective functions of woody perennials include their role as live fences, shelter belts and windbreaks.

Management

The alley cropping tree species should be easy to establish, must have a deep root system, fast growth, tolerance to pruning, ability to coppice vigorously and high foliage productivity. The trees undergo frequent pruning aimed at reducing the competition with the companion food crops for light and soil resources and to promote biomass production. At the initial cutting back, the wood is removed while the small branches and the leaves are left as mulch in situ to decompose.

However, fast growing species require high labor demand for maintenance. In a three-year alley cropping period, fast growing *Gmelina arborea* needed as much as 323 person-days ha^{-1} for management as compared to 195 person-days ha-1 for slow growing *Dactyladenia barteri* during the same period (Ruhigwa *et al.*, 1994). The characteristic of growing fast did not give *Gmelina* any advantage in terms of total dry matter yield. Such woody species have no advantage for alley cropping. After the initial cutting of the woody species, regular prunings are carried out at different heights and frequencies depending on tree and/or food crop growth and the branching patterns of the hedgerows. Various pruning heights and intensities are applied to trees in alley cropping systems. Investigations showed that the height and intensity of pruning affect the biomass production and nutrient content of hedgerow prunings (Kang *et al.*, 1990). The combination of pruning height (25, 50, 75, 100 and 150 cm) and pruning intensity (monthly, bi-, tri-, and six-monthly) indicated that the biomass, dry wood and N yield *of Leucaena leucocephala, Sesbania sesban and Gliricidia sepium* increased with increasing pruning height but with decreasing pruning frequency. The pruning regime however, affects the survival rate of hedgerows differently. The survival rate of some hedgerows such as *Gliricidia* and *Sesbania* was negatively affected by intense pruning while that of *Leucaena* plants was not affected.

Responses by annual food crops to hedgerow pruning height and intensity have an inverse relationship with yield. Maize and cowpea yields increased with increased pruning frequency but decreased with pruning height. Despite the fact that with too frequent prunings of *Leucaena* the young loopings have higher N content, the amount of N yield depends on biomass produced. However, for the alley cropping system, where the emphasis is to optimize organic matter yield, nutrient cycling and yield through the hedgerow pruning necessary for maintaining the productivity of the fragile tropical soils (Kang and Juo, 1983), too frequent prunings, despite its positive effect on the associated crop yields, is less satisfactory. Alley cropping may contribute to the maintenance of soil fertility under annual cropping through improved nutrient cycling, but the system's total labor and possibly, capital requirements are likely to be greater than those with shifting cultivation.

Systems based on annual crops are likely to be less nutrient-efficient and sustainable than systems based on perennial crops, due to reduced fixation and transfer of N to the crops, the tendency of the trees to compete for and sequester nutrients and relatively high P requirements of the crops. However, the nutrient cycling capacity seems to be directly related to soil type, genotype and hedgerow species. A balance between nutrient removals and additions can be achieved by reducing the quantity of nutrients and products exported or replenishing nutrient removed.

Agroforestry systems in which large quantities of nutrients are removed in harvested productions are unlikely to be sustainable without fertilization. This is particularly true for acidic and infertile tropical soils. On infertile soils, the ability of agroforestry systems to significantly increase nutrients through enhanced nutrient recycling or nitrogen fixation appears to be limited, mainly due to the low levels of available nutrients and high levels of elements toxic to plant growth (Palm *et al.*, 1991; Szott *et al.*, 1991b). On fertile soils, nutrient deficiencies may also occur under high levels of nutrient removal.

Results usually show that the application of inorganic N fertilizers considerably increases yields of alley cropped crops. But the response to fertilization of alley cropped food crops varies with the hedgerow species used. The fertilization of alley cropped maize with *L. leucocephala* for instance increased grain yields by up to 1000 kg ha^{-1} but smaller increases were obtained with *Gliricidia sepium*, *Flemingia macrophylla*, or other alley cropping species (Szott and Kass, 1993). Responses to other nutrients in alley cropping have also been reported. The application of 30 and 60 kg of P increased the pole bean (*Phaseolus vulgaris*) production in N-fertilized *S. sesban* alley cropped systems (Yamoah and Burleigh, 1990). The beneficial effects of fertilization are sometimes delayed. A response to low levels of P (25 kg ha^{-1} $year^{-1}$) in *Inga edulis*, *Cassia reticulata*, or *G. sepium* alley cropping systems on an Ultisol were observed only in seventh and tenth cowpea, and eleventh rice crops of an eleven-crop-long sequence (Salazar, 1991). Similarly, alley cropped rice and cowpea with *I. edulis* in combination with 50 kg N, 25 kg P, 20 kg K, 35 kg Ca, and 16 kg Mg ha^{-1} $crop^{-1}$ on an Ultisol resulted in significantly greater yields in fertilized, as compared to the unfertilized treatment in the fourth through to the seventh crops of a seven-crop-long sequence. These observations support the argument that prunings alone, especially on infertile soils, cannot sustain productivity of continuous alley cropping (Palm *et al.*, 1991; Szott *et al.*, 1991a,b)

Direct fertilization as well as liming of alley cropping systems improves pruning biomass. Pruning production of *L. leucocephala* and *Faidherbia albida* (Syn. *Acacia albida*) responded to N (Hill, 1970; Stewart and Gwaze, 1988). Biomass of *S. sesban*, *Calliandra calothyrosus*, *L. leucocephala* and *Markhania lutea* increased due to lime with manure additions (Yamoah *et al.*, 1989). Sometimes, manure application results in little response of pruning production as observed with *I. edulis*, *Erythrina* sp., or *Codariocalyx gyroides* to lime or lime + P on an acidic infertile Ultisol (Szott, 1987).

Nutrients in litterfall and pruning, unless brought in through cut-and-carry, are merely recycled and are not true additions to the systems. The application of inorganic fertilizers, on the other hand, represents a true addition. The quantity of nutrient recycled through prunings and litterfall can vary greatly depending on climate, soil type, tree species, spacing, and management techniques.

In alley cropping, it is unlikely that high demand for nutrients, especially N, will be met solely by the prunings of the hedges, since nutrient demand appears to exceed the capacity of the trees to provide N and other elements. However, positive effects of fertilization may be less than expected due to the negative relationship between N fixation and quantity of inorganic N applied, the increased probability of N loss through leaching and volatilization, and the tendency of the trees to compete for and sequester nutrients such as P.

Fertilization is apt to increase the amount of nutrient contained in pruned materials or in litter (Szott *et al.*, 1991a). In the absence of fertilization, tree based inputs and nutrient cycling may sustain the productivity of low-nutrient demanding agroforestry systems, such as shaded perennial crops and home gardens. The pruning production, the response to fertilization (lime or fertilizer application) and nutrient concentration of prunings depend upon the species and the soil type. For example, pruning production by *I. edulis* and *Erythrina* sp. did not respond to one application of 2.5 tons lime ha^{-1}, while *Cassia reticulata* and *G. sepium* showed little response to low rates (11-25 kg ha^{-1}) of applied phosphorus (Szott, 1987; Szott *et al.*, 1991a).

Prunings of *Inga, Erythrina, Cassia*, and *Gliricidia* are potentially capable of supplying most of the macronutrients required for moderate production levels of upland rice. Quantities of some nutrients supplied in prunings compare favorably with the amounts required for an average upland rice grain yield of 2 tons ha^{-1} for Ca (20 vs. 5 kg Ca ha^{-1}) and Mg (6 vs. 3.4 kg Mg ha^{-1}), but not those of N (66 vs. 55 kg N ha^{-1}), P (6 vs. 10 kg P ha^{-1}) with K accumulation being slightly inferior to the demand (33 vs. 37 kg K ha^{-1}). Based on nutrient budgets, the recycling potential of these alley cropping systems is therefore inadequate for P and K and marginal for N. These balances would be even less favorable if more nutrient demanding crops like maize are used or if higher levels of yield are expected. As an example, in more fertile Alfisols, the P content of *L. leucocephala* prunings (Kang and Wilson, 1987), is inadequate for one crop of maize.

The ability of agroforestry systems to enhance nutrient availability on infertile soils is very limited compared to systems on fertile soils. On both, however, agroforestry systems can play an important role in reducing nutrient losses. Litter production and quantities of nutrients in litter are greater on fertile than on infertile soils. However, management techniques for accelerating nutrient fluxes through pruning appear to hold promise for increasing plant productivity on the latter soils.

Socio-economics

Economic studies have indicated that alley cropping is more profitable than conventional farming with maize (Verinumbe *et al.*, 1984; Ngambeki, 1985) and an economical technology when farming intensity increases due to increased population density (Ehui *et al.*, 1990). In another study, alley cropping using *L. leucocephala* was found uneconomical when only crop yields were considered. But it out-performed monoculture of annual crops when the value of staking material provided by the hedges was included in the economic calculations (Mittal and Singh, 1989). Ruhigwa *et al.* (1994), also evaluated the economic potential of alley cropping to supply in situ mulch for plantains in relation to cut-and-carry mulching systems. Labor for land clearing, pruning and weeding the alley cropped plots was compared to labor for clearing, mulching, control of sprouting of *Pennisetum purpureum* (elephant or napier grass) mulch in addition to its production transport costs. The labor requirement in all the three years of mulching plantains was highest in *Pennisetum* mulched plots and lowest in alley cropped plots. The labor for mulching with *Pennisetum* was 4 to 7 times more than that of pruning the hedgerows. Although the *Pennisetum* mulched plots produced the highest plantain bunch yields (24.4 - 31.5 tons ha^{-1} against 53.5 tons ha^{-1}), the cost of extra land needed to produce the mulch in addition to its transport and management resulted in negative net revenue over a three-year cropping period. The conclusion is that alley cropping using suitable hedgerow species as in situ mulch source is more profitable than a cut-and-carry mulching system.

The economic benefit of using legumes vs. inorganic fertilizers as an N source rests chiefly upon the trade-off between labor and inorganic fertilizers. The labor cost in alley cropping is so high such that, for example, in Costa Rica, fertilizer prices would have to increase about six times in order to balance the extra labor costs involved in alley cropping (Hernandez *et al.*, 1995). It is important to note that in many cases, the decision about fertilizer use is an economic rather than a technical one. However, the efficiency with which available nutrients are taken up by crops can be improved and unproductive nutrient losses reduced, through the design and management of suitable land use systems. Where suitable crop associations increase farmers' income, fertilizers may become more easily accessible. The management of soil physical and biological properties is however, more complex and much less understood than nutrient management.

Conclusions and research needs

To date, much of the work on alley cropping has been in the context of continuous cropping. The emerging picture is that the system is not sustainable, on acid, infertile soils without additions of chemical fertilizers. In this context, there is not yet sufficient evidence to support sustainability of the systems. Therefore, long-term research is still needed. This effort must also be undertaken under intercropping, the most common tropical food production system. Studies of the long-term dynamics and internal cycling of nutrients contained in the hedgerow prunings are also required. Selection and improvement of acid-tolerant germplasm is very important and should continue. It may also be necessary to select for plant characteristics that are favorable in mixed-species systems. The suitability of alley cropping as well as other agroforestry systems will vary with the biological and socioeconomic environment at a given site. The latter factors should also be considered in the formulation of research in alley cropping. The main disadvantage of most agroforestry systems is that they are quite labor intensive and in the case of alley cropping, the level of management is relatively high. In addition, farmers might be unwilling to plant and maintain trees solely for the purpose soil fertility amelioration.

Experiments on alley cropping have lead to the conclusion that, although there is obviously scope for alley cropping, its potential is restricted to certain environments, and certain conditions. In dryer areas the scope is considerably restricted because of the limited ability of the common alley cropping tree species to produce enough dry matter in such environments (Beets, 1990). Failure of the system may also be due to other factors: infertile soils that are unable to produce enough biomass, poor management of hedgerows that results in excessive competition between the trees and crops, and the use of species that are not suitable for the particular environment.

Acknowledgements

The authors would like to acknowledge the contributions to this chapter that resulted from comments and suggestions from reviewers and the editors.

References

Adedeji, F.O. (1984) Nutrient cycles and successional changes following shifting cultivation practice in moist semi-deciduous forests in Nigeria. *Forest Ecology and Management.* **9:** 87-99.

Altieri, M.A. (1987) Agroecolgy: *The Scientific Basis of Alternative Agriculture.* Westview, Boulder, CO.

Andriesse, J.P. and Koopmans, T.H. (1984) A monitoring study on nutrient cycles in soils used in shifting cultivation under various climatic conditions in tropical Asia. I. The influence of simulated burning on form and availability of plant nutrients. *Agric. Ecosyst. Environ.* **12:** 1-16.

Andriesse, J.P., and Schelhaas, R.M. (1987) A monitoring study on nutrient cycles in soils used in shifting cultivation under various climatic conditions in tropical Asia. II. Nutrient stores in biomass and soil. *Agric. Ecosyst. Environ.* **19:**285-310.

Aweto, P.M. (1981) Secondary succession and soil fertility restoration in southwestern Nigeria. III. Soil and vegetation interrelationships. *J. Ecology.* **69:** 957-963.

Aweto, A.O. (1988) Effects of shifting cultivation on a tropical rain forest soil in South-Western Nigeria. *Turrialba.* **38 (1):** 19-22.

Beets, W.C. (1990) *Raising and Sustaining Productivity of Small-holder Farming Systems in the Tropics.* 738p. AgBe Publishing, Alkmaar, Holland.

Brand, J. and Pfund, J.L. (1998) Site-and watershed-level assessment of nutrient dynamics under shifting cultivation in Eastern Madagascar. Agriculture, *Ecosystems and Environment* **71:** 169-183.

Brickmann, W.L.F. and Vieira, A.N. (1971) The effect of burning on germination of seeds at different soil depths of various tropical tree species. *Turrialba.* **21:** 77-82.

Couesey, D.G. and Booth, R.H. (1977) Root and tuber crops, PP. 75-90. In: Leakey, C.L.A. and Wills, J.B. (eds). *Food Crops of the Lowland Tropics.* Oxford University Press, Oxford.

Date, R.A. (1973) Nitrogen, a major limitation in the productivity of natural communities, crops and pastures in the Pacific area. *Soil. Biol. Biochem.* **5:** 5-18.

De Rouw, A. (1995) The fallow period as a weed-break in shifting cultivation (tropical wet forests). Agriculture, *Ecosystem and Environment.* **54:** 31-43.

Doran, J.W. (2002) Soil health and global sustainability: translating science into practice. Agriculture, *Ecosystems, and Environment.* **88:** 119-127.

Duguma, B., Gockowski, J. and Bakala, J. (2001) Smallhoder cacao (*Theobroma cacao* Linn.) cultivation in agroforetry systems of west and central Africa: challenges and opportunities. *Agroforestry Systems.* **51:**177-188.

Duguma, B., Kang, B.T. and Okali, D.U.U. (1988) Effect of pruning intensities of three woody leguminous species grown in alley cropping with maize and cowpea on an Alfisol. *Agroforestry Systems.* **6:** 19-35.

Eckholm, E.P. (1976) *Losing Ground: Myth and Reality in the Humid Tropics.* Norton, New York.

Ehui, S.K., Kang, B.T. and Spencer, D.S.C. (1990) Economic analysis of soil erosion effects in alley cropping, no-till, and bush fallow systems in South-Western Nigeria. *Agricultural Systems.* **34:** 349-368.

Ewel, J.J. (1999) Natural systems as models for the design of sustainable systems of land use. *Agroforestry Systems.* 45: 1-21.

Ewel, J.J. (1976) Designing agriculture ecosystems for the humid tropics. *Annu. Rev. Syst.* **17:** 245-271.

Ewel, J., Buresh, C., Brown, B., Price, N. and Raich, J. (1981) Slash and burn impacts on a Costa Rican wet forest site. *Ecology.* **62:** 816-829.

Fehlberg, H.G. (1989) Shifting cultivation: Some management aspects for its management pp. 381-394. In: van der Heide, J. (ed.) *Nutrient Management for Food Crop Production in Tropical Farming Systems.* Institute for Soil Fertility (IB), Haren, The Netherlands.

Fernandes, E.C.M., Oktingati, A. and Maghembe, J. (1984) The Chagga home gardens: A multistoried agroforestry cropping system on Mt. Kilimanjaro (Northern Tanzania). *Agroforestry Systems.* **2:** 73-86.

Floyd, B. (1969) Eastern Nigeria: A geographical review. MacMillan, London.

Friesen, D.K., Juo, A.S.R. and Miller, M.H. (1983) Residual value of lime and leaching of calcium in a kaolinitic Ultisol in the high rainfall tropics. *Soil Sci. Soc. Am. J.* **46:** 1184-1189.

Fujisaka, S. and Escobar, G. (1997) *Towards a practical classification of slash-and-burn agricultural systems.* pp. 1-16 in Rural Development Forestry Network Paper 21c, ODI, Portland House, Stag Place, London SW1E 5DP, UK.

Gichuru, M.P. (1994) Regeneration of a degraded Ultisol with *Tephrosia candida* in the humid forest zone of South-Eastern Nigeria. *Interciencia.* **19(6):** 382-386.

Gichuru, M.P. (1991) Residual effects of natural bush, *Cajanus cajan* and Tephrosia candida on the productivity of an acid soil in South-Eastern Nigeria. *Plant and Soil.* **134:** 31-36.

Gichuru, M.P. and Kang, B.T. 1989. *Calliandra calothyrsus (Meissn.)* in an alley cropping system with sequentially cropped maize and cowpea in South-Western Nigeria. *Agrof. Syst.* **9:**191-203.

Gleave, M.B. (1996) Length of the fallow period in tropical fallow farming systems: a discussion with evidence from Sierra Leone. *Geographical Journal.* **162:**14-24.

Gliessman, S.R. 1991. *Agroecology: Researching the Ecological Basis for Sustainable Agriculture.* Springer-Verlag, New York.

Greenland, D. 1974. Evolution and development of different types of shifting cultivation. *FAO Soils Bulletin.* **24:**5-13.

Hernandez, I., Kass, D.L. and Camacho, Y. (1995) Economic evaluation of alley farming of maize/beans with *Erythrina poeppigiana* in Costa Rica. pp. 472-479. In: Kang, B.T., Osiname, O.A. and Larbi, A. *Alley Farming Research and Development.* Proc. of an International Conference on Alley Farming, 14-18 September, 1992, Ibadan, Nigeria.

Hill, G.D. (1970) Studies on the growth of *Leucaena leucocephala.* Effect of clean weeding and nitrogen fertilization on early establishment. *Papua and New Guinea Agricultural Journal.* **22:** 29-30.

Jagtap, S.S. (1995) Environmental characterization of the moist lowland savanna of Africa. p. 91-109. In: Kang, B.T. *et al,* (eds). *Moist savannas of Africa: Potentials and constraints for crop production.* IITA, Ibadan, Nigeria.

Jaiyebo, E.O. and Moore, A.W. (1964) Soil fertility and nutrient storage in different soil-vegetation systems in tropical rainforest environment. *Tropical Agric. (Trin).* **41:** 130-138.

Juo, A.S.R. (1989) New farming systems development in the wetter tropics. *Exp. Agric.* **25:** 145-163.

Juo A.S.R. and Lal, R. (1977) The effect of fallow and continuous cultivation on the chemical and physical properties of an Alfisol in western Nigeria. *Plant and Soil.* **47:** 567-584.

Juo, A.S.R., and Manu, A. (1996) Chemical dynamics in slash and burn agriculture. *Agric. Ecosyst. Environ.*, Special Issue. **58:** 49-60.

Kang, B.T. and Juo, A.S.R. (1983) Management of low activity clay soils in tropical Africa for food crop production. In: Beinroth, F.H., Neel, H. and Eswarn, H. (eds). *Proc. of the Fourth international Soil Classification Workshop,* Kigali, Rwanda, Brussels: ABOS-AGCD.

Kang, B.T., Reynolds, L. and Attra-Krah, A.N. (1990) Alley farming. *Advances in Agronomy.* Vol. 43, pp. 316-359.

Kang, B.T. and Wilson, G.F. (1987) The development of alley cropping as a promising agroforestry technology. pp. 227-243. In: Steppler, H.A. and Nair, P.K.R. (eds). *Agroforestry: A decade of development.* International Council for Research in Agroforestry, Nairobi, Kenya.

Kang, B.T., Wilson, G.F. and Lawson, T.L. (1984) *Alley cropping: a stable alternative to shifting cultivation.* International Institute of Tropical Agriculture, Ibadan, Nigeria, pp. 22.

Keatinge, J.D.H., Breman, H. Manyong, V.M., Vanlauwe, B. and Wendt, J. (2001) Sustaining soil fertility in west Africa in the face of increasing pressure for agricultural intensification. p 2-22. In: Tian, G. *et al.* (eds.) *Sustaining soil fertility in West Africa.* SSSA Spec. Publ. 58. SSSA and ASA, Madison, WI.

Kitur, B.K., and Frye, W.W. (1983) Effects of heating on soil chemical properties and growth and nutrient composition of corn and millet. *Soil Sci. Soc. Am. J.* **47:** 91-94.

Kotto-Same, J., Woomer, P.L., Appolinaire, M. and Louis, Z. (1997) Carbon dynamics in slash-and-burn agriculture and land use alternatives of the humid forest zone in Cameroon. *Agriculture, Ecosystem and Environment.* **65:** 245-256.

Kyuma, K., Tulaphitak, T. and Parintra, C. (1985) Changes in soil fertility and tilth under shifting cultivation. I. General description of soil and effect of burning on soil characteristics. *Soil Sci. Plant Nutr.* **31:** 227-238.

Lanly, J.P. (1985) Defining and measuring shifting cultivation. *Unasylva.* **27(147):** 17-21.

Lal, R. (1987) Managing soils of sub-Saharan Africa. *Science.* **236:**1069-1076.

Lefroy, E.C., Hobbs, R.J., O'Connor, M.H. and Pate, J.S. (eds.) (1999) Agriculture as a Mimic of Natural Ecosystems. Kluwer, Dortrecht, The Netherlands. 438pp.

Lundgren, B. and Raintree, J.B. (1983) Sustained agroforestry. In: Nestel, B. (ed). *Agricultural Research for Development: Potentials and Challenges in Asia.* ISNAR, The Hague.

MacDicken, K.G. (1990) Agroforestry management in the humid tropics. In: MacDicken, K.G. and Vergara, N.T. (eds.). *Agroforestry: Classification and Management.* Pp. 98-149. Wiley, New York.

Mittal, S.P. and Singh, P. (1989) Intercropping field crops between hedgerows of *Leucaena leucocephala* under rainfed conditions in Northern India. *Agroforestry Systems.* **8:** 165-172.

Nair, P.K.R. (2001) Do tropical home gardens elude science or is it the other way around? *Agroferstry Systems.* **53:** 239-245.

Nair, P.K.R. (1984) Classifications of agroforestry systems. *Agroforestry Systems.* **3:** 97-128.

Ngambeki, D.S. Economic evaluation of alley cropping *Leucaena* with maize-maize and maize-cowpea in Southern Nigeria. *Agricultural Systems.* **17:** 243-258.

Nieuwolt, S. (1977) *Tropical Climatology: An Introduction to the Climates of the Low Latitudes.* John Wiley & Sons, Chichester. 207p.

Nye, P.H. (1958) The relative improvement of fallow and soils in storing plant nutrients in Ghana. *West Africa Sci. Assoc.* **4:** 31-41.

Nye, P.H. and Greenland, D.J. (1960) Soil under shifting cultivation. *Tech. Communication* 51. Commonwealth Bureau of Soils, Farnham, UK.

Norgrove, L., Hauser, S. and Weise, S.F. (1998) Effects of crop density by earthworms and implications for nutrient cycling in a tropical intercropping system. *Pedobiologia.* **42:** 267-277.

Okafor, J.C., and Fernandes, E.C.M. (1987) Compound farms in South Eastern Nigeria: A predominant agroforestry home garden system with crops and livestock. *Agroforestry Systems.* **5:** 153-168.

Padwick, G.W. (1983) Fifty years of experimental agriculture. II. The maintenance of soil fertility in tropical Africa: A review. *Expl. Agric.* **19:** 293-310.

Palm, C.A., McKerrow, A.J., Glasener, K.M. and Szott, L.T. (1991) Agroforestry in the lowland tropics: is phosphorus important? In: Tiessen, H., Lopez-Hernandez, D. and Salcedo, I. (eds.). *Phosphorus cycles in Terrestrial and Aquatic Ecosystems*. pp. 134-141. Regional Workshop No. 3. South and Central America. Scientific Committee on Problems of the Environment (SCOPE) and United Nations Environmental Programme. Saskatchewan Institute of Pedology. Saskatchewan. Canada.

Prinz, D. (1986) Increasing the productivity of small-holder farming systems by introduction of planted fallows. *Plant Research and Development*. **24:** 31-56.

Raintree, J.B. (1990) Theory and practice for agroforestry diagnosis and design. pp. 58-97. In: MacDicken, K.G. and Vergara, N.T. (eds.) *Agroforestry: Classification and Management*. Wiley, New York.

Rhoades, R.E., and Bidegaray, P. (1987) *The farmers of Yurimaguas: Land-use and cropping strategies in the Peruvian Jungle*. International Potato Center, Lima, Peru.

Ruthenberg, H. (1976) *Farming Systems in the Tropics*. Clarendon Press, Oxford. 366pp.

Ruhigwa, B.A., Gichuru, M.P. Spencer, D.S.C. and Swennen, R. (1994) Economic analysis of cut-and-carry and alley cropping systems of mulch production for plantains in southeastern Nigeria. *Agroforestry Systems*. **26:** 131-138.

Salazar, A.A. (1991) Phosphorus fertilization in an alley cropping system in upland soils of the Peruvian Amazon basin. MS thesis. Soil Science Department. North Carolina State University. Raleigh. NC. 82 pp.

Sanchez, P.A. (1991) Alternatives to slash and burn: A pragmatic approach to mitigate tropical deforestation. Paper presented at the Conference on Agricultural Technology for Sustainable Economic Development in the New Century: Policy Issues for the International Community, World Bank, Airlie, Virginia, October 23,1991.

Sanchez, P.A. and Salinas, J.C. (1981) Low input technology for managing Oxisols and Ultisols in tropical America. *Adv. Agron*. **34:** 279-406.

Schroth, G., Lehmann, J., Rodrigues, M.R.L., Barros, E. and Macedo, J.L.V. (2001) Plant-soil interactions in multistrata agroforestry in the humid tropics. *Agroforestry Systems*. **53:** 85-102.

Schroth, G., Kolbe, D., Pity, B. and Zech, W. (1995) Searching for the criteria for the selection of efficient tree species for fallow improvement, with special reference to carbon and nitrogen. *Fertilizer Report*. **42:** 297-314.

Sertu, S.M., and Sanchez, P.A. (1978) Effects of heating on some changes in soil properties in relation to an Ethiopian land management practice. *Soil Sci. Soc. Am. J.* **42:** 940-944.

Staver, C. (1989) Shortened bush fallow rotations with relay-cropped *Inga edulis* and *Desmodium ovalifolium* in wet central Amazonian Peru. *Agroforestry Systems*. **8:** 173-196.

Stewart, H.T.L. and Gwaze, D.O. (1988) *Effect of fertilizer and sowing date on establishment and early growth of direct-seeded Acacia albida in Zimbabwe*. Nitrogen Fixing Tree Research Reports. **6:** 40-42.

Strogaard, P. (1984) The immediate effect of burning and ash-fertilization. *Plant Soil*. **80:** 307-320.

Szott L.T. (1987) Improving the productivity of shifting cultivation in the Amazon basin of Peru through the use of leguminous vegetation. Ph.D. dissertation. Soil Science Department. North Carolina State University. Raleigh. NC. 168 pp.

Szott, L.T., Palm, C.A. and Sanchez, P.A. (1991a) Agroforestry in acid soils in the humid tropics. *Advances in Agronomy*. Vol. **45:** 275-301.

Szott, L.T., Fernandez, E.C.M. and Sanchez, P.A. (1991b) Soil-plant interactions in agroforestry systems. *Forestry Ecology and Management*. **45:** 127-152.

Tel, D. and Rao, P. (1982) Automated and semi-automated methods for soil and plant analysis. IITA manual Series No. 7. *Intern. Inst. Trop. Agri.* Ibadan, Nigeria.

Torquebiau, E. (1992) Are tropical agroforetry home gardens sustainable? *Agriculture, Environment, and Ecosystems*. **41:**189-207.

Van Reuler, H. and Janssen, B.H. (1993) Nutrient fluxes in the shifting cultivation system of South-West Côte d'Ivoire. I. Dry matter production, nutrient contents and release after slash and burn for two fallow vegetation. *Plant and Soil*. **154:** 169-177.

Van Reuler, H. and Janssen, B.H. (1993) Nutrient fluxes in the shifting cultivation system of South-West Côte d'Ivoire. II. Short-term and long-term effects of burning on yield and nutrient uptake of food crops. *Plant and Soil*. **154:** 179-188.

Verinumbe, I., Knipscheer, H. and Enabor, E.E. (1984) The economic potential of leguminous tree crops in zero-tillage cropping in Nigeria: a linear programming model. *Agroforestry Systems*. **2:** 129-131.

Watson, G.A. (1983) Development of mixed tree and food crop systems in the humid tropics: A response for population pressure and deforestation. *Exp. Agri.* **19:** 311-332.

Wiersum, K.F. (1986) Intensification of shifting cultivation in Africa, land-use and forest conservation. *Agricultural Science*. **34:** 485-488.

Yamoah, C.F. and Burleigh, J.R. (1990) Alley cropping *Sesbania sesban* (L.) Merill with crops in the highland region of Rwanda. *Agroforestry Systems*. **10:** 169-181.

Zinke, P.J., Sabhasri, S. and Kunstadter, R. (1978) Soil fertility aspects of Lau forest fallow system of shifting cultivation, pp. 134-159. In: Kunstadter, R., Chapman, E.C. and Sabhrasri, S. (eds.) *Farmers in the Forest*. The University of Hawaii Press, Honolulu, HI.

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6

Potential for Changing Traditional Soil Fertility Management Systems in the Wet Miombo Woodlands of Zambia: The Chitemene and Fundikila Systems

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Introduction

Although there are many types of traditional shifting cultivation systems in the wet miombo region of Zambia (Haug, 1981, Stromgaard, 1989) the most common systems are chitemene, a slash-and-burn or ash fertilisation system and the fundikila grass-mound system. Both systems have been well described by several authors (Peters, 1950; Trapnell, 1953; Stromgaard, 1989).

Shifting cultivation is a term used to describe agricultural systems that involve an alternation between cropping for a few years on selected and cleared plots, by means of slash-and-burn, and by use of hoe and only minimal use of a plough and a lengthy period when the soil is rested (Sanchez, 1976; Ruthenberg, 1980). Cultivation consequently shifts within an area that is otherwise covered by natural vegetation. The intensity of shifting cultivation varies widely. A relatively simple and appropriate criterion of land-use intensity is the relation between the period of cultivation and the period of fallow (Ruthenberg, 1980). In terms of total area, shifting cultivation is the predominant agricultural system in the high rainfall zone (HRZ) of Zambia with annual precipitation of over 1000 mm during 5 months. The region is predominately covered with miombo woodlands.

Large areas of the savanna region in Central, Eastern and Southern Africa are covered with woodland vegetation known as miombo (Araki, 1992), which covers part of Democratic Republic of Congo, Tanzania, Zambia, Zimbabwe, Malawi and Angola. The transformation of large areas of woodland to cultivated land could have implications for biodiversity conservation, regional hydrology, land-atmosphere radiation fluxes and global carbon dynamics through transferring carbon from a terrestrial store to the atmosphere.

Miombo woodland is also referred to as an Open Forest type of vegetation mainly dominated by principle trees of two genera *Brachystegia, Julbernardia* and *Isoberlinia* species forming a single-storey woodland with a light but closed canopy, usually attaining a height of 15-20 m (Stromgaard, 1988 and Araki, 1992) for mature woodland. Under the canopy there are a few scattered herbaceous shrubs and the ground flora is a mixture of grasses dominated by *Hyparrhenia* and *Digitaria* species that usually grow to a height of about 1-2 m under the light woodland canopy (Stromgaard, 1988 and Araki, 1992). Destruction of this woodland will eventually result into grassland type of vegetation normally referred to as chipya, dominated by fire-hardy trees. Chipya varies from open grass-herb communities dominated by grass of the genera *Andropogon* and *Hyparrhenia*, to open woodland communities with groups of scattered individual trees predominately *Syzygium guianense* spp. *macrocarpum* (Stromgaard, 1988). In a detailed study of woodlands in Northern Zambia, Lawton (1978) proposed that in the absence of fire chipya would be replaced by *Brachystegia-Julbernardia* woodland probably through a transition type of vegetation, dominated by *Uapaca* spp.

Soils in the wet miombo woodland, are generally low in inherent fertility, shallow and slightly acidic, having quartz rubble or laterite underneath, providing little support for permanent agriculture. The local farmers have adjusted their agricultural systems to available resources. In this region of Northern Zambia, where the shifting cultivators depend on woodlands as an agricultural fallow crop, deforestation is prevalent under the growing population pressure. In addition, poor soils in the miombo woodland coupled with slow regrowth rate of the *Brychystegia* woodland make the system vulnerable to over utilization, degradation and possible deforestation. Chidumayo (1987), reports that the increasing population in the region is part of the cause of deforestation, which has resulted to some extent in the reduction of (i) the fallow periods, (ii) the per person woodland requirement from 1.1 ha to 0.53 ha, and (iii) the frequency of clearing new chitemene gardens. However, it is not clear yet what the current fallow period is and is unlikely to be a single value, but vary considerably depending on soil type, vegetation, climate and distance from settlements. Araki (1992) reports that the fallow periods which were traditionally 50-70 years have been reduced to as few as 10 years, Peters (1950) reports 35 years, Trapnell (1953) 20 years, Allan (1967) 22-25 years, and Mansfield *et al.* (1976) reports 20-30 years. "Consequently, the diminishing wood resources have artificially increased the population carrying capacity from 18.7 to 2.4 persons km^{-2}", (Chidumayo, 1987). Mansfield *et al.* (1976) estimated that the carrying capacity of the *chitemene* system is between 2 and 4 persons km^{-2} depending on the amount of suitable land available. Lack of suitable woodland leads to clearing of larger areas and hence reduction of the fallow period. Both of these factors lead to increasing forestry degeneration over time.

The most widespread soils of the region, Oxisols and Ultisols, lie on the Tertiary land surface (Singh and Goma, 1995). The soils are strongly leached, have little or no primary minerals, are predominantly acidic (pH ($CaCl_2$) < 4.5), with a clay fraction mineralogy dominated by kaolinite and variable amounts of oxides of iron and aluminium. Aluminium saturation is high sometimes exceeding 60 % in the sub-soil. The soils have low organic matter content, medium to high P fixation capacity (Singh, 1989) with wide spread inherent P deficiency (3 - 12 ppm Bray-I P), low content of nitrogen, sulphur, potassium, low CEC (< 15 cmol kg^{-1} soil) and are therefore generally very poor in plant available nutrients. Generally, the region has great agricultural potential of becoming the maize-belt of Zambia inspite of the highly leached and acidic soils which make it extremely difficult to sustain yields economically over time. The region has good and reliable rainfall, numerous perennial rivers and lakes suitable for providing irrigation water and has optimum temperature for plant growth throughout the year. The rest of the country has severe drought problems. The soils have good physical properties and it is generally considered, that provided chemical constraints can be ameliorated, the agricultural potential of the area could be improved.

It has been observed by various workers that arable production on tropical Ultisols and Oxisols, whether under traditional shifting cultivation or intensive farming, can lead to a decline in soil fertility due to a rapid decrease in soil organic matter, hence N supply, and the removal of elements such as P, K, Ca, Mg, and S (Sanchez *et al.*, 1982). Nutrients depletion rates vary with soil properties. The proportion of nutrients lost is normally greater in sandy soils, but the total loss is greater in clayey soils (Sanchez *et al.*, 1997). According to the authors, this is largely because soil organic matter (SOM) particles are less protected from microbial decomposition in sandier soils than loamy or clayey ones. The smallholder farmers in the region do not need low-input, low-output systems that do not address poverty alleviation. Given the limitations of the extremes of either pure organic inputs or pure inorganic inputs and the increasing population pressure there is an increasing need for a more robust approach that provides potential alternatives and increases the basket of options available to farmers and policy makers. The objective of this chapter is to review the status of the traditional shifting cultivation systems and the technologies that are potential alternatives for changing the traditional agricultural systems (chitemene and fundikila) in the wet miombo woodlands of Zambia. The chapter also focuses on the people's economic and social circumstances that might constrain or encourage uptake and how best to assist them adopt a more understanding position of these practices to sustain yields over time. The goals can only be achieved by an integration of indigenous farming systems with modern technological farming systems.

Traditional agricultural systems and their adaptive characters

The main traditional form of land use in the miombo region of Zambia involves cultivation of small fields of fingermillet (*Eleusine coracane*), sorghum (*Sorghum vulgare*), cucumber, pumpkin, cassava (*Manihot esculenta*), maize (*Zea mays*), groundnut (*Arachis hypogea*) beans (*Phaseola* spp) and pulses, either under some form of shifting cultivation or semi-permanent agriculture, usually involving ash fertilisation and hand hoe cultivation. Over the last 70-80 years the cultivation of cassava and maize has spread in the region (with maize being grown primarily on the semi-permanent gardens), while the growing of fingermillet has declined (Moore and Vaughan, 1994). Research conducted in the region indicates that soil fertility, particularly as it relates to exchangeable bases and soil structure declines rapidly over 2-5 years under normal arable conditions. Shifting cultivation is often a technology of expediency where farmers seek to employ agricultural technologies that work best for them under prevailing circumstances (Spencer, 1966). In other cases it is a land-use system that may belong to the past but is still carried on because the transition to more productive land-use systems demands more favourable market prices, improved access to markets, agricultural credit and inputs, infrastructure, knowledge and time (Ruthenberg, 1980). The local resource-poor farmers in the region practise shifting cultivation chitemene and fundikila semi-permanent grass-mound system being the systems adapted in response to ouside pressure over time to suit the environment and locally available resources. Here a distinction on their applicability is made between the two most dominant traditional shifting cultivation systems in the wet miombo woodland of Zambia with respect to their impact on the ecosystem.

Chitemene, slash-and-burn system

Chitemene is a traditional shifting cultivation system of land management most common in the wet miombo woodland of Zambia in areas where trees are still in abundance. It is a form of 'slash-and-burn' cultivation or ash-culture, but unique in that the lopped area is much larger than the cropped area. Stromgaard (1989) recognizes three types of chitemene, slash-and-burn systems:

(1) Large-circle chitemene, practiced by the Bemba community where the woodland is felled, trees are chopped in a larger area (the outfield) and the slash piled in a smaller area (the infield) and burned.

(2) Small-circle chitemene practiced by the Lala: the trees are not chopped but cleared-felled and a larger woodland area is cut to establish the future garden.

(3) Block chitemene is the agricultural system of the Lamba which is a variant of the large-circle chitemene. In contrast to the other two chitemene types, more than half the land is under cultivation in the cleared area. In some cases, the whole of the cleared area might be covered with brush wood and burnt as a "block". In cases where not all the cleared land is burned, cultivation is not limited to the burned areas only.

However, there is considerable variation of ratio of cultivated land and cleared area, some of which relates to the type of *chitemene* and some to the duration of the fallow period and hence the amount of biomass that accumulates during the fallow. In the large-circle *chitemene*, with one large ash-circle the ratio of cultivated land to cleared area Araki (1993) estimated to be 1:6, Stromgaard (1984, and 1989) gives 1:5-1:8, and 1:12 respectively, while for small-circle *chitemene*, Peters (1951) gives 1:10/1:23, depending on the length of the fallow period, and Stromgaard (1989) again gives the ratio of 1:26.

The cultivation starts with the selection of a field site, the most important criterion being quantity of available wood material for burning and botanical composition of the ground cover (Stromgaard, 1985). Clearing and preparation of the selected area starts at the end of rainy season (May - July). The cutting of trees is exclusively a male activity. In some parts of the region people climb the trees, chopping off the branches, leaving only the trunks in the large circle chitemene. In other areas they cut the whole tree at waist or shoulder height. This is small-circle chitemene where trees are felled over a large area and several small ash-circles are made. In both types of chitemene when the trees and branches have been cut, the women collect and pile them in a special way, preparing the field for burning.

The burning takes place just before the on-set of the rains, about late October or early November and leaves a thick layer of ash. The field is then ready for planting. Fingermillet (*Eleusine coracane*) is always grown during the first year, usually mixed with some minor crops. The other crops in the intercrop are referred here as 'minor' in the sense that usually they are not as numerous or have the same biomass as fingermillet. The first crop planted is generally pumpkins, cucumbers or squashes which are scattered on the edges of the field. Cassava (*Manihot esculenta*) cuttings are planted dotted in the entire field and fingermillet is broadcast later. Maize (*Zea mays L.*), sesame, sorghum (*Sorghum vulgare*) or bulrush millet may also be planted mixed with the fingermillet in the first year. Under the system several sequences of cassava, fingermillet, beans, groundnuts (*Arachis hypogea*) and bambara nuts are grown.

By and large when an area is opened up for agriculture, cultivated and then abandoned to fallow, the soil undergoes a series of chemical and structural changes, the magnitude of which is soil-dependent. The period required for soil fertility restoration by natural regeneration in the *chitemene* system depends on the composition of the vegetation, the soil type, climate and frequency of bush fires. The time needed depends also on how the vegetation was cut, the relative duration of the cultivation and the fallow periods. If the trees are lopped, as is done in 'large-circle *chitemene*', regeneration is faster than when they are clear-felled, as in 'small-circle' and 'block' *chitemene*. Generally, the continuous use of the land extends over 4 - 6 years alternating with many years of bush fallow. Trapnell (1953) estimates a sufficient period for woodland regrowth to be about 20 years. Allan (1965) thinks 22-25 years and Mansfield *et al.* (1976) estimates 20-30 years to regenerate the fertility of the soil on natural vegetation. Premature clearing of fallow woodland could result in declining yield per hectare, which forces shifting cultivators to increase the area of clearings. This increases the risk of degradation of the soils thereby creating environmental and ecological problems.

Chidumayo (1987) reports that the sustainabilty of shifting cultivation systems hinges on the balance between the population of cultivators and the availability of suitable woodland. He further suggest that increasing population in the shifting cultivation land use system results in either the adoption of other less wood-dependent agricultural practices, or a reduction in the length of fallow periods which are required for the regeneration of natural woodland. There is need for a strong land-use policy to avoid improper use of land. Land must be used according to its suitability and communities should be advised accordingly. Soil and erosion degradation already affect most farmland in Zambia (Veldkamp, 1987a) and per capita food production is inadequate and declining. Because of population pressure and soil resource limitations, only increased yields per hectare may lead to sustained and improved household food security in the region.

Sustainable farming systems cannot be established on depleted, highly weathered soils until enough nutrients have been replenished to the system to maintain soil fertility, vigorous plant growth and food production.

Some ecological effects of the *chitemene* land-use system

A large proportion of nutrient reserve of the system is contained in the above-ground phytomass which is released by burning. Cultivation is confined to the burnt patch (Haug, 1981), where the ash layer forms an excellent seed bed and helps to overcome the inherently low soil fertility and high acidity, by increased contents of P, K and Ca in the soil. The effect of heat is thought to change P from unavailable to available form (Banyard, 1968). In addition the heat from the burning controls weed growth. Some of the nutrients released are utilised by food crops and some are lost in water runoff and leaching or through volatilisation. Reports from other parts of the world indicate that the losses of nutrients due to leaching increase with burning depending on the soil type, topography, rainfall pattern and the burning regime.

Woodland surrounding human settlements suffer various human interference such as *chitemene* cutting, and fuelwood or charcoal production. The fallow period of the outfield is usually shorter than what some researchers have estimated (Araki, 1992; Peters, 1950; Trapnell, 1953; Allan, 1965; Mansfield *et al.*, 1976). Since regeneration of woodland takes place through coppice regrowth, the crown becomes smaller and finely divided compared with that of semi-mature woodland. The reduction of the biomass due to shortening the fallow period seems to affect the amount of ash produced and hence the low yield of fingermillet.

"The *chitemene* shifting cultivation system is especially suited to the inherently infertile, leached and acid soils of Northern Zambia because it enhances the yield of fingermillet due among other things to the flush of N", (Chidumayo, 1987), released by rapid decomposition of humus at the beginning of the rains. Studies on the effect of heat versus ash aspect on soil acidity amelioration indicate beneficial effect of burning in the traditional slash-and-burn system of cultivation in reducing soil acidity. The liming effect and quick release of nutrients produced by burning are important. The effect of heat per se changes P from unavailable to available form (Banyard, 1968). It also produces a porous fine seed-bed and controls weeds, at least in the first two cropping seasons. In experiments conducted in Northern Zambia (Banyard, 1968) four treatments were applied (1) normal chitemene ash garden with 21.14 tonnes of wood pile burned and ash retained on plot; (2) 21.14 tonnes of wood pile burnt on iron sheets but ash removed; (3) no wood pile but received ash from burnt without ash plot from treatment 2, and (4) no wood pile, no ash and vegetation cleared before planting. The results demonstrated that the soil fertility was increased through burning, as well as by the addition of ash (Table 6.1). According to these experiments, the soil N content in all the plots was similar before burning (70-80% in ammonium form, NH_3-N, and 20-30% in nitrate form, NO_3-N). The burning treatment occured after 22 mm of rainfall, by which time the non-*chitemene* and ash plots had lost about 10% of the NO_3-N, while NH_3-N increased by 40-50% on the other plots. There was a further loss of 30% NH_3-N in the non-*chitemene* plot following planting, which was done after 262 mm of rainfall and the NH_3-N in the ash plot soil decreased by over 50%, while the soil in the burnt and *chitemene* plots showed a further increase of up to 15% in NH_3-N. In contrast, soil samples from the non-*chitemene* and ash plots in which microbial activity was controlled using toluene had over 60% more NH_3-N than in the untreated samples mentioned above. The increase in NH_3-N in the toluene soil samples from the burnt and *chitemene* plots was apparently not significantly different from the untreated samples (Chidumayo, 1987).

Table 6.1. Yield of fingermillet and the quantity of mineral nitrogen present in the soil (NH_3-N + NO_3-N) at different combinations of burning and addition of ash.

Sample Plot (0.0101 ha)	Treatment	Yield (kg ha^{-1})	Mineral Nitrogen (mg kg^{-1} soil) <— (NH_3-N + NO_3-N) —> Before burning	Soon after burning	64 days after burning
Burnt with ash	Normal *chitemene* ash garden with 21.14 tonnes of wood pile burnt and ash retained on plot.	1177	22.50	27.00	29.00
Burnt without ash	21.14 tonnes of wood pile burnt on iron sheets but ash removed.	943	17.75	30.50	35.75
Ash only	No wood pile but received ash from burnt without ash plot (above).	579	15.25	24.50	12.50
Non-*chitemene* (Cleared, no burn & no ash) Control	No wood pile, no ash and vegetation cleared before planting.	268	18.75	16.25	12.50

Source: Banyard, 1968

According to Chidumayo (1987), "the heat generated by burning *chitemene* wood piles initially increased the amount of NH_3-N in the soil which was subsequently retained. In the absence of burning and therefore with greater microbial activity, there was a rapid loss of soil N, which was unavailable later in the growing season. *Chitemene* burning regulated the soil N cycle by suppressing microbial activity, but allowing the steady and continual release of NH_3-N throughout the growing season for fingermillet".

Stromgaard (1984) has also shown that "the content of major nutrients (N, P, K, Ca, Mg) in the top 50 cm of the soil increases following the burning of piles of woody vegetation. Thus, the burning of *Chitemene* wood piles, apart from regulating the N cycle, enhances the supply of other nutrients. It has been estimated that the concentration of N, P, and K derived from the burning of about 110 tonnes, fresh weight, of wood biomass on a *chitemene* ash infield is equivalent to the average application of 1310 kg N ha^{-1}, 41 kg P ha^{-1} and 606 kg K ha^{-1} (Stromgaard, 1984). There is no immediate increase in P down the soil profile, presumably because this is a relatively immobile element; in contrast, there is an immediate increase in K, even in the absence of rain within 24 hours of burning. The burning also delays the oxidation of ammonia to nitrate and the conversion of nitrite to nitrate (Stromgaard, 1984). The planting of fingermillet in *chitemene* shifting cultivation is normally done some weeks after burning, perhaps to coincide with, and to take advantage of, the release of nitrates".

In other studies conducted in Zambia (Stromgaard, 1989) as well as in other parts of the tropics (Zinke *et al.*, 1978; Kang and Lal, 1981), indicate that burning resulted in an increase in soil pH, P and available bases, but the increase was short lived. More recent research also support this view. Steinshamn (1984) reported that soil pH and the concentration of available bases, after reaching a peak two to three months after burning, started decreasing about four months after burning.

Table 6.2. demonstrates the fertilising effect of the wood ash. The increase in CEC value with depth under formerly burned vegetation is not followed by a corresponding change in the amount of exchangeable bases. The concentration of these decrease with depth and the whole variation in CEC value is attributed to a variation in H^+ (Stromgaard, 1985). The beneficial effect of fire and ash on CEC was still apparent after 16 years, although the exchangeable cations have either been removed by the crop, recaptured by the vegetation, or leached out of the soil profile. Apparently, the burning of miombo forest under shifting cultivation system and the ensuing build-up of nutrients in the fallow vegetation follows a fixed pattern. The previous burn ensures a reasonably high CEC value in the soil, which is still detectable 16 years after burning and this seems to be necessary for the retention of cations which become mobilised under the next cycle of burning under shifting cultivation (Stromgaard, 1985).

Table 6.2. Soil parameters before clear-felling and after the controlled burning of old *miombo* regrowth, completely cleared 16 years before. Branches piled in the centre of the cleared plot

Parameter	Depth (cm)	pH ($CaCl_2$)	Total N (%)	Org. C (%)	Avail. P (ppm) (Bray I)	Exchangeable cations Cmol$_c$ kg^{-1} soil Ca	Mg	K	CEC
Before Burning	0-10	5.8	0.07	0.64	1.50	0.75	0.37	0.14	2.88
	10-20	5.7	0.05	0.37	4.38	0.60	0.25	0.10	3.04
Immediately	In ash	10.4	-	1.40	63.0	11.51	19.8	17.61	10.38
After Burning	0-10	6.9	-	1.15	63.0	3.91	1.4	1.01	6.10

Source: Stromgaard, 1985

Sanchez (1976) also reports that, in other slash-and-burn agricultural systems in the tropics, the basic cations in the ash cause dramatic increases in exchangeable Ca, Mg, and K levels after burning. These are followed by a gradual decrease during the cropping period due to leaching and crop uptake.

Crop growth and yield in the slash-and-burn system depends on the length of fallow periods, parent material of the soil and its physical and chemical properties. Without additional input, the yield of maize crop in the third year after burning of a secondary *miombo* forest declined drastically (SPRP Annual Report, 1987). Similar observations were made by Cooper *et al.* (1986) in South West Nigeria.

In addition to decline in chemical fertility and acidity development, weed infestation is another major factor causing yield decline which forces the farmers to shift to a new site. Schultz (1976) observed that it is the build up of weeds rather than soil exhaustion *per se* which lead to cessation of the cultivable fields in the traditional shifting cultivation systems.

Soil physical properties

It is widely believed that clearing and burning cause a deterioration of soil physical properties. The evidence shows, however, that this effect is dependent on soil type, climate, clearing and burning regime and cropping practices. Reducing forest biomass by tree clearing in the *chitemene* cultivation system affects soil temperature. In some cases soil surface temperatures can reach levels sufficient to sterilise the soil to the depth of several centimetres. This affects the nitrification of ammonia to nitrate in the soil, which was delayed by about four weeks probably due to decreased activity of soil fauna (Tveitnes, 1986; Chidumayo, 1987; Stromgaard, 1984). According to Tveitnes (1986), these changes were more pronounced in the surface than in the subsoil. It has been reported that generally shifting cultivation in disequilibrium results in a gradual deterioration of soil tilth and soil structure due to intensive mining of nutrients which leads to weed infestation, erosion, down stream siltation and flooding, and dramatic ecological changes and loss of biodiversity. This is probably due to rapid decline in the organic matter content of the soil (Sanchez *et al.*, 1997).

Runoff and Soil erosion

Despite changes in soil water balance, surface runoff losses are generally low in the *chitemene* cultivation system during the cultivation period (4-6 years). This is probably due to increased water percolation as a result of increased pore space brought about by burning of soil organic matter in the top layer of the soil. There is no evidence of any available soil erosion losses data from *chitemene* fields in Zambia. Lal (1981) also found that water runoff and soil erosion were negligible in plots cleared by traditional farming methods partly due to relatively rapid growth of cover in form of crops. Erosion proceeds only where there is no crop canopy to protect the soil. In traditional shifting cultivation, the soil is devoid of a canopy for just a few weeks. The abundant debris in the form of trunks, branches, pieces of charcoal and ash protects most soils during this critical period (Sanchez, 1976). In areas where population pressure have decreased the fallow period, the problem of erosion may be critical when the land is exposed because of poor crop stands.

Fundikila, grass-mound system

In areas of the wet miombo region of Zambia where grasslands are more dominant than woodlands or where the area has become deforested due to rapid increase in population (Stromgaard, 1989), another farming system is practised. It is a somewhat semi-permanent system locally known as fundikila or grass-mound system where grass, usually of low quality, *Hyparrhenia* spp. and *Pennisetum* spp., (Stromgaard, 1988, 1990) is buried in mounds of various sizes and shapes at the end of the rain season. Beans may be planted immediately on early made mounds in some cases, which ripen before the end of the rainy season when they are harvested but with the mounds being left intact. The last-made mounds are often left bare. At the start of the following planting season the mounds are levelled and the compost is spread evenly to give a fairly uniform seed bed. In this way the grass-mounds are assumed to act as a form of compost, supplying the new crop with nutrients. On the patches where excess grass and shrubs were burned "delicate" but minor crops such as cucumbers, pumpkins or squashes are planted.

The cropping pattern follows a well designed system in order to enhance soil fertility and is based on annual rotation of crops for 4-6 years, depending on soil type, succeeded by long fallow periods. Nutrient depletion varies with soil properties. On clayey and or on relatively fertile soil the cropping period is longer than in the other soil types, normally more than five years. Mansfield (1973) reported that the required fallow period for the soil recovery in this system is about 15-20 years and Allan (1965) also found that the fallow period should not be less than 8 years on the best soils. Trapnell (1953) reported that the land is considered ready for recultivation when the weeds from former cultivation has disappeared and *Hyparrhenia* spp. have become dominant again.

The cropping pattern varies from area to area and from household to household, but generally most households plant fingermillet in the first year. Fingermillet is normally followed by beans. In the second season, a variety of crops may be grown which include maize, beans, sorghum, and groundnut. In some cases, the fields may be mounded every second year, and the crop planted on the mounds. In the third cropping season most farmers plant fingermillet again followed by mixed beans. At this time some farmers would start abandoning the fields. In the fifth cropping season a number of farmers would still plant a bean crop while others would plant other crops. There might be another harvest of a cereal crop in the fifth year, after which the field is left fallow. The number of households abandoning the fields after the fifth year increases tremendously. It has been estimated that the fundikila cultivation system is able to support 20-40 persons km^{-2} (Mansfield *et al.*, 1976), considerably more than in the *chitemene* system. This is because in the latter system adequate biomass is required so trees need to be chopped in a much larger area, piled in a small area and burned to establish the future garden.

The main reason for cessation of the cultivation of land under the *fundikila* system is the reduction in crop yields as a result of decline in soil fertility and to a lesser extent due to high weed infestation (Stromgaard, 1990). Another concern among farmers is the high incidence of termite attack that destroy their field crops (Sokotela, *et al.* 1995). Farmers associate termite activity with organic matter depletion in the soil. The farmers usually put such lands under fallow since they have no access to expensive pesticides.

Impact of fundikila grass-mound system on the environment

Soil fertility

On highly leached, infertile and acidic soils, soil degradation is possible if the input or output balance of nutrients is not maintained due to shorter fallow periods. In deforested areas, where nutrient conservation and recycling capacity in the miombo ecosystem are broken, there is no tree canopy to lessen the impact of raindrops on the soil surface nor is there a network of roots to absorb nutrients. The nutrients released during decomposition are easily leached out and are not available for succeeding crops (Stromgaard, 1989). Soil degradation is the consequence of these processes. In the fundikila grass-mound-based system crop yield levels are generally low. Soil fertility is depleted and the fallow becomes primarily dominated by the nutrient poor *Hyparrhenia* grass spp. The other important concern among farmers is the high incidence of vermin, particularly termites, that destroy their field crops. This is attributed to the depletion of plant nutrients.

Researcher designed, farmer-managed trials were conducted to study the concerns of decreasing soil fertility as a consequence of shifting cultivation in Northern Zambia. Nine farmers were selected from two localities. Three treatments were used:

(1) Farmer practice (grass-mound only),
(2) Farmer practice plus kraal manure, and
(3) Farmer practice plus full recommended fertilizer rate.

Application rates and source of fertilizers were a basal dressing 200 kg ha^{-1} compound fertilizer (20:10:5:10%) containing S applied to treatment plots receiving full fertilizer rates. Kraal manure had a concentration of 1.5% N and manure of 40 kg N ha^{-1} equivalent was applied to the manure-treated plots. The cultivation was as per individual farmer's practice except for the kraal manure and fertilizer application treatment.

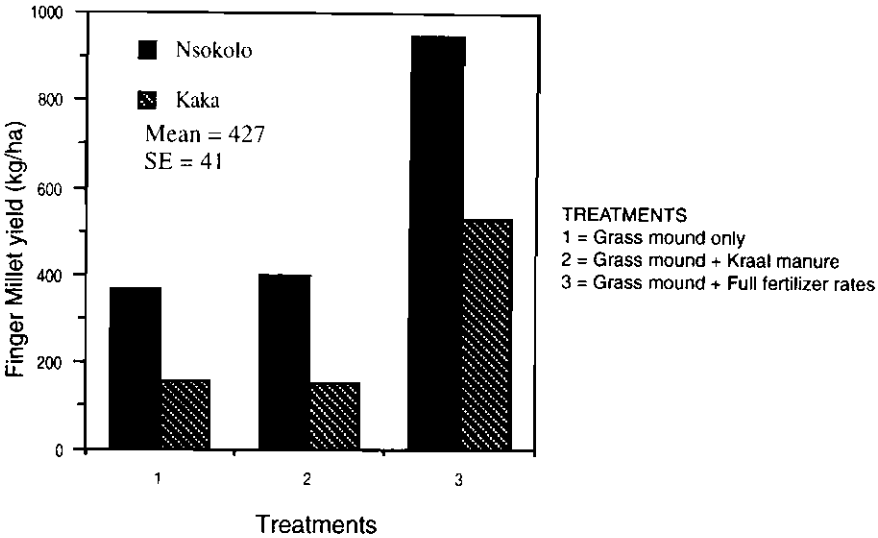
The results given in figure 6.1 indicate that fingermillet yield showed significant yield differences between treatments and both sites for the addition of full fertilizer rate (Goma *et al.*, 2001). At both sites there was no significant effect on application of kraal manure compared to farmer's practice for fingermillet (Goma *et al.*, 2001). This could be attributed to immobilization of soil nitrate, rendering it unavailable for plant uptake due to poor quality of the *Hyparrhenia* grass. Application of compound inorganic fertiliser (NPK+S) provided favourable conditions for plant uptake as these nutrients were inherently deficient in the soil. Generally, the soils in Kaka were less responsive to mineral fertilizer additions. This could partly be due to dry spells experienced in the area or to poor soil fertility.

Weed infestation

Trapnell (1953) and Schultz (1976) both postulate that weed infestation, rather than soil exhaustion, is the primary cause of farmers abandoning their plots in the fundikila grass-mound system. In recent surveys conducted in Kaka and Nsokolo areas in Mbala district of Northern Zambia, it was apparent that the major reason for cessation of the cultivation of land under this system was cited as mainly reduced yields due to decline in soil fertility and to a lesser extent due to high weed infestation (Sokotela *et al.*, 1995). The results confirm the findings of

Sanchez (1995), who also reports that in the miombo woodlands which harbour unique animal biodiversity soil-fertility depletion decreases above- and below- ground biodiversity and increases the encroachment of forests and woodlands in response to the need to clear additional land.

Figure 6.1. The effect of kraal manure and inorganic fertilizer application on the yield of fingermillet (on-farm trial)



Source: SPRP, 1997

Soil erosion

The soil is more disturbed in this system of cultivation than in the *chitemene* system because most sub-soil remains without canopy to cover over a longer period, hence soil compaction may be created, some soil loss may be expected, especially in areas with high wind velocity and a short fallow period. There are no quantitative data on soil erosion losses in the region but some examples of degraded soils have been observed in the field which could be due to soil structural deterioration and compaction as a result of the exposure of subsoil layer to high temperatures for a long period of time.

Intensification and Soil Management Options

During the last few decades, the traditional shifting cultivation system in the region has undergone rapid changes due to various factors including increased human population, changes in markets, employment opportunities, human movement and migration patterns, availability and cost of inputs, withdrawal of subsidies on fertilizers and transport. Much of the *miombo* woodland has been and continues to be, modified by people, principally through the removal of woodland cover (Campbell *et al.*, 1996), which has resulted in shortening of fallow periods, inadequate soil fertility regeneration and increased land degradation. Human activities are therefore important in the dynamics of miombo ecosystems (Morris, 1970). Since the early sixties research efforts have been undertaken in Zambia, to find potential alternatives to shifting cultivation for the wet miombo region of Zambia dominated by acid soils, where increasing demographic pressure is threatening the traditional slash-and-burn agricultural system. Emphasis is being directed to production systems that are affordable by small-scale farmers as most of them cannot afford the use of costly inputs such as mineral fertilisers.

Management of soil fertility is an important factor in achieving sustainable agriculture. This applies particularly where farmers run out of new cultivable land and will have to increase productivity on existing land holdings in order to raise production levels. In some parts of Zambia, particularly the southern region, deterioration and impoverishment of soils have led to a rapid decline of production potentials of most land. Consequently, future strategies for agricultural development must increasingly aim at conserving and improving productivity of existing land. Farmers' awareness and knowledge of methodologies for sustainable agricultural production, of optimal levels of chemical and organic fertiliser use, are key elements of such strategies. Most smallholder farmers in the region appreciate the value of fertilizers, but they are seldom able to apply them at the recommended rates and at the appropriate time because of high cost, lack of credit, delivery delays and low and varied returns mainly because of poor or low producer price for cereals as well as high risk. Such constraints are largely due to the lack of an enabling policy environment, particularly in rural areas caused by the deficient road and market infrastructure. Furthermore, since fertilizer recommendations are normally formulated to cover broad areas with diverse soils, farmers also lack information about the best fertilizer to use for their particular fields and cropping practices, making the crop response to fertilizers more erratic and less profitable.

In both acid and non-acid soils, continuous cultivation of food crops is possible with judicious use of lime, fertilisers, crop rotation and soil conservation practices (Kang *et al.*, 1981; Sanchez *et al.*, 1982; Lal, 1987). But it is unlikely that the majority of farmers in the region can readily switch from shifting cultivation to continuous production systems because of the cost of the external inputs needed to sustain continuous cropping. Alternative systems that are affordable and profitable might be useful as a first step to more permanent land-use system options. A new comprehensive approach in research and development with specific focus on soil fertility restoration is necessary to reverse the process of soil nutrient depletion and increase agricultural outputs with minimum negative impact on the ecosystem.

Some potential options to traditional agricultural systems

One of the biggest challenges facing agriculturalists at the moment is to develop soil fertility restoration and nutrient saving and conservation technologies that are profitable, agronomically effective and socio-economically feasible and adaptable within the clientele resource constraints. The improvement of the traditional shifting cultivation systems, *chitemene* and fundikila, has been neglected due to the concentration on the hybrid-maize and fertiliser based economy in the past when the government used to subsidize fertilisers. The removal of fertilizer subsidies as part of the Structural Adjustment Programme (SAP) in the last decade has tripled or quadrupled fertilizer prices in relation to crop prices. Structural adjustment programmes, even though aimed at supporting the agricultural sector, appears to have a negative influence on soil fertility management in Zambia. Policies play important roles in agricultural development. Whereas some directly influence investment decisions in soil fertility management, others impact them indirectly. Recent studies in Tanzania and Zambia (NLH, 1995), prove that the abolition of fertiliser subsidies led to an extensification of agricultural production. Farmers return to soil mining and expand cultivated land with all the detrimental effects on the environment. It is therefore doubtful, whether liberalisation of agricultural market alone is the panacea of the crisis of agriculture in Zambia.

Following the diagnostic and design (D&D) exercises in the high rainfall area of Zambia (Huxley *et al.*, 1986; AFRENA, 1989; Mattsson, 1989) alley cropping was recommended as a potential agroforestry intervention for both the *chitemene* and fundikila systems. It was hoped that the use of fast growing leguminous trees to supply N and organic matter and to mobilise nutrients from deeper soil layers, would help to maintain soil fertility for longer periods in an extended cropping period and to ensure faster regeneration of fertility in a shortened fallow period.

The combination of green-manuring and alternating cereal crops with legumes in the fundikila system, help to slow soil fertility degradation. There is evidence that the fundikila traditional cropping system is able to support crop production (Stromgaard, 1989) for a cropping period of 3-5 years and the fallow period is traditionally up to 20 years (Mansfield, 1973). Due to poor nutritive quality and slow decomposition rate of the grasses used in the grass-mound system, crop yields are usually very low during the first cropping season. With such low-quality plant material, there is likely to be substantial initial immobilization of nitrate by soil microbes. This could initially pose problems to high-N demanding crops such as cereals, hence perhaps why farmers plant beans first. This might help conserve N which would be released in second and subsequent years as the microbial biomass turns over and the C:N ratio falls.

The smallholder farmers in Zambia do not need low-input, low-output systems that do not address poverty alleviation. Given the limitations of the extremes of either pure organic inputs or pure inorganic inputs, it is time for a more robust approach that provides fresh alternatives and increases the basket of options available to farmers and policy makers. The agricultural scientists therefore, can facilitate the process by seeking to create the space and opportunity for farmers to take up these options that they feel will work best for them at the moment and retain those elements of their traditional systems with which they are knowledgeable, comfortable and experienced. The development of sustainable semi-permanent or permanent farming system in the region must build on the transformation of the existing farming systems. There are two distinct agroforestry systems at both low and medium-input technological levels: alley cropping and planted or improved fallows to improve regeneration of soil fertility. These systems are likely to be site specific, however.

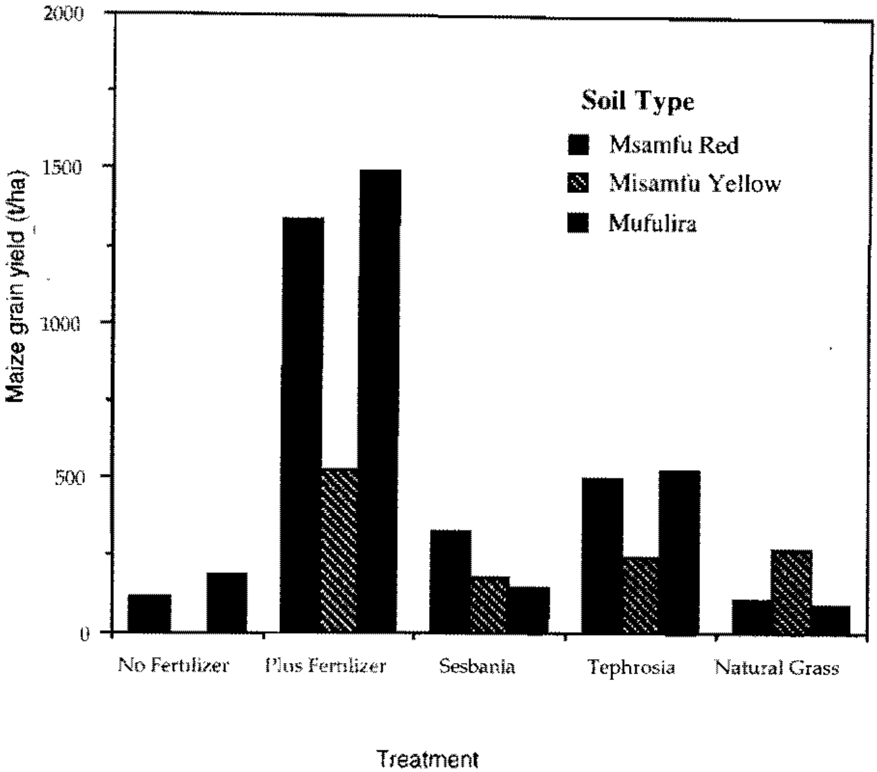
Planted Fallows

Some experiments on affordable cropping system was conducted at Misamfu Research Centre to serve as a transition technology between shifting and continuous cultivation for acid soils. Various fast growing leguminous annual cover crop species; *Crotalaria*, *Mucuna*, *Dolichos* and *Stylosanthes* which were tested had positive influence on soil fertility particularly with low inputs of lime and P.

Several woody leguminous species have also been evaluated at Misamfu Regional Research Centre as alley cropping system for soil fertility improvement. *Leucaena leucocephala* and *Gliricidia sepium* performed well with liming and P application. *Sesbania sesban* performed poorly although it does very well in the Eastern Province of Zambia where soils are relatively better than those in the high rainfall zone of Zambia. Other species, *Leucaena diversifolia*, *Grevillea robusta*, *Acacia confusa*, *Acacia albida*, *Acacia mearnsii*, *Albizia falcataria* and *Calliandra calothyrsus* and shrub type *Cajanas cajan* (pigeon peas), seem to be promising in that they produced substantial amount of biomass.

Results from field trials showed that maize yield was higher following leguminous cover crops. Forage legumes are well recognised as capable of improving soil fertility through symbiotic N_2 fixation to the extent that the non-legumes subsequently grown benefit from the residual fertility. *Medicago* or annual *Trifolium* species are estimated to contribute about 50 to 70 kg N ha^{-1} for the subsequent crop (SPRP, 1996).

Figure 6.2. The effect of improved fallow on maize yield



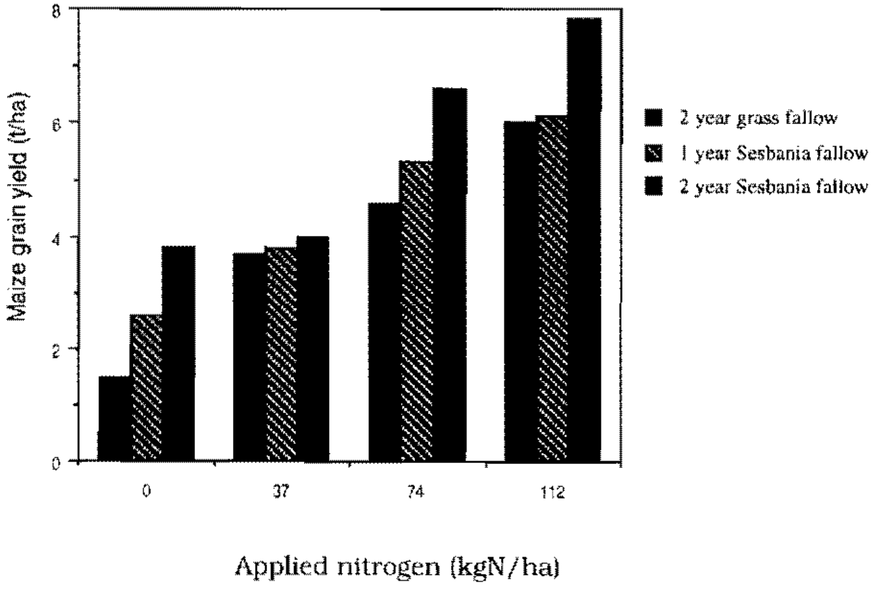
Source: SPRP Annual Report, 1997

The results on the response of maize in an improved fallow experiment conducted on three soil types in Northern Zambia are shown in Figure 6.2. The results indicate that *Tephrosia vogelii* plots out-yielded *Sesbania sesban* at Misamfu on Misamfu red and Misamfu yellow soil series, both belong to the Oxisol order, and Mufulira soil series (Ultisol). The natural grass fallow gave higher maize yield than the control plots on Misamfu yellow soil series. Continuous maize with fertiliser gave the highest yield on Mufulira soil series followed by Misamfu red soil series, while continuous maize without fertiliser was a total failure at all the sites. These results demonstrate that addition of organic manures will only rarely provide the productivity boost needed by smallholders, hence the need to be combined with the judicious use of chemical fertilisers..

Generally, the results confirm earlier findings that it is probably not possible to grow maize continuously on most soils without inorganic fertiliser application (Singh and Goma, 1995). Moreover, farmers traditionally have not tried to grow maize or any other crop continuously, but have rotated their crops with fallow. These old and already highly leached soils are frequently damaged through lengthy exploitation without adequate fertility replenishment. The soils present a particular challenge for fertiliser management. The efficiency of fertiliser use is typically unsatisfactory, often related to inadequate levels of soil organic matter and nutrient imbalances, caused by the farming systems.

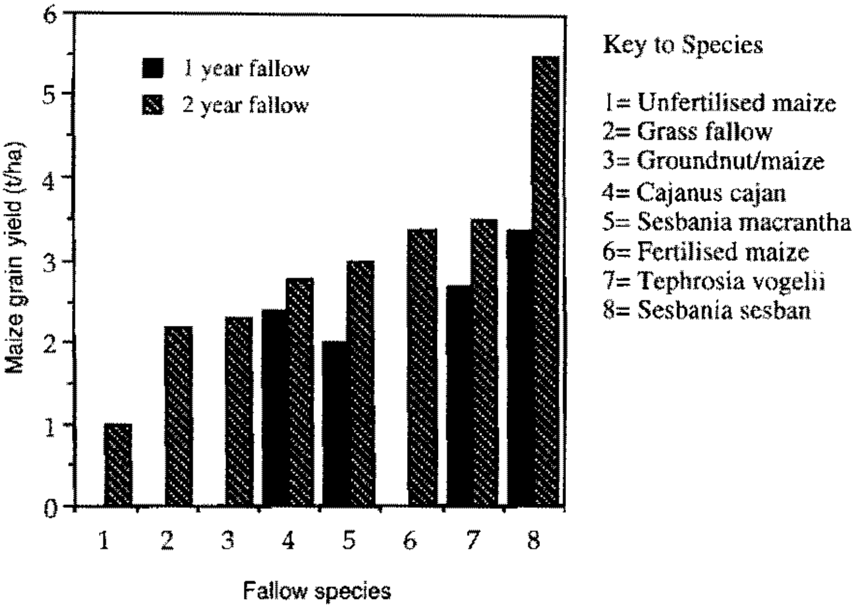
The rapid introduction of organic materials to smallholder agriculture is needed, through the combination of formal science and indigenous knowledge. Improved fallows are probably the most exciting developments for soil fertility improvement. Improved fallow experiments conducted in Eastern Province of Zambia both on-farm and on-station showed that fallows with *Sesbania sesban* performed very well. *Sesbania sesban* planted fallows of 1 to 3 year rotation continued to show potential in increasing maize yields with or without the application of inorganic fertilisers (Figs. 6.3). Other multi-purpose tree species (MPTs) such as *Tephrosia vogelii* and *Sesbania macrantha* have shown promise for 1 and 2 year fallows (Figure 6.4).

Figure 6.3. Maize yield response following Sesbania and grass fallow at 4 levels of N - application



Source: Kwesiga and Phiri, 1995

Figure 6.4. The effect of short rotation fallow on maize grain yield without inorganic fertilizer after 1 or 2 years fallow.



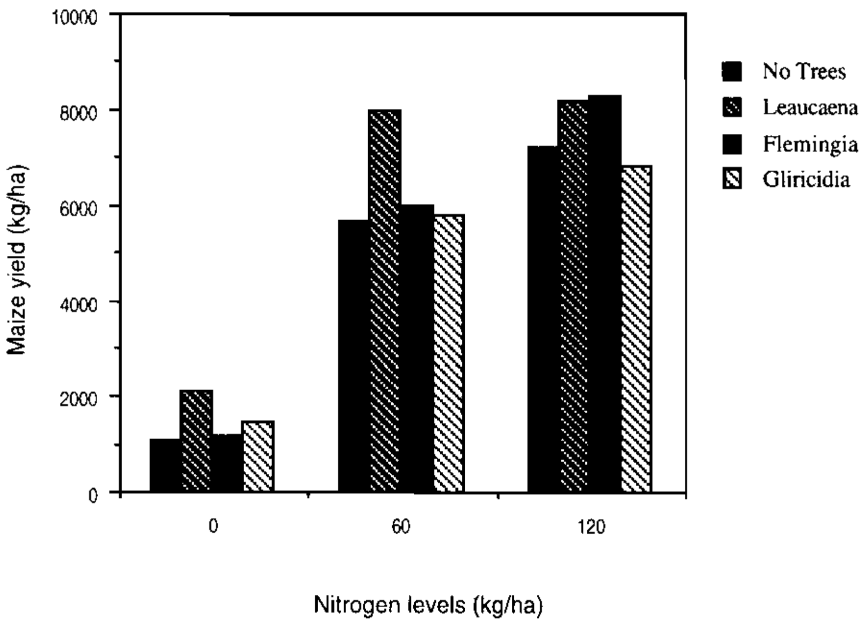
Source: Kwesiga and Phiri, 1995

Alley Cropping System

Three experiments were established at Misamfu Research Centre to evaluate the potential of alley cropping in maize production on low fertility, acidic soils (Ultisol). *Leucaena leucocephala*, *Flemingia congesta*, *Sesbania sesban*, *Albizia falcataria*, *Cassia spectabilis*, and *Gliricidia sepium* were grown in alley with hybrid maize and soyabean. All the trials received 40 kg P ha^{-1} and 30kg K ha^{-1} fertilizer; N was applied at three rates; 0, 60, 120 kg/ha as subplot treatment. One trial was limed (2 t/ha dolomitic lime) uniformly once at the beginning of the experiment.

The results in Figure 6.5. indicate that incorporation of *Leucaena leucocephala* prunings resulted in an increase in maize yield of up to 95 %, with a smaller increase being produced by *Flemingia congesta*. There was a good correlation between the quantity of biomass prunings applied and the proportional increase in maize yields over the control treatment. The lack of effect of most of the tree species on crop yields was attributed to low biomass produced. *Sesbania sesban* and *Albizia falcataria* were found not to be suitable species for alley cropping and were replaced by *Gliricidia sepium* and *Flemingia congesta*. However, though these species coppice well and are perennial they were found not to provide sufficient N from their prunnings to increase maize yields (SPRP, 1990). *Leucaena leucocephala* could be a suitable alley cropping species as a means of maintaining soil fertility where soil acidity is low or when the soil is limed, but this may not be feasible to the resource-poor farmers.

Figure 6.5. The effect of organic and inorganic fertilizers on the yield of maize on an Ultisol, Misamfu Research Centre, Kasama, Zambia



Source: SPRP, 1990

An economic analysis showed that alley cropping with limed *Leucaena leucocephala* was only profitable when nitrogen fertiliser costs were in relation to maize prices (Matthews *et al.*, 1992). However, lime is both expensive and difficult to obtain and transport for most small scale farmers in the region is scarce and is therefore not a practical recommendation. In order for alley cropping to be a viable, affordable and profitable technological package, future alley cropping research should increase the genetic base by screening a wider range of tree species, including other species or provenance of *Leucaena*, for acid tolerance and higher biomass production.

Limitations to Alternative Agriculture

Complete replacement of the expensive chemical fertilisers may not be the best solution. First, organic fertilisers may not contain certain plant nutrients or not in enough quantities. The nutrient imbalance requires correction through supplemental soil treatment with mineral fertilizers. Second, mineral fertilisers in combination with organic fertilisers tend to enhance the decomposition process of the latter whose breakdown would, otherwise, be too slow for the crop to benefit. Slow decomposition rates delay plant nutrient release to the soil and results in poor crop performance. Finally, since organic fertilisers generally contain low levels of plant nutrients, very large amounts may have to be applied to supply a crop with adequate N, for example. Mineral fertilisers often contain 20-40 times the nutrient content of manure.

The best fertiliser management regime would be to use both types of fertilisers in combination as far as possible. When both types of fertilisers are used together, they tend, to some extent to compensate for each other's inadequacies. For instance, the inability of mineral fertiliser to improve soil structure can be compensated for by the presence of organic fertiliser. In the same way, the inability of organic fertiliser to supply certain elements or enough of them will be compensated for by the presence of chemical fertiliser. However, on relatively fertile soils and when dealing with low nutrient-demanding crops such as food legumes, which are able to fix atmospheric N, use of organic fertiliser alone may suffice.

Since animal manure is found only in relatively small quantities in the region, green manuring with various leguminous plant materials, composting, sound crop residue management practices and improved *fundikila* with perennial legumes like *Stylosanthes* must be encouraged.

Summary and Research Priorities

Major management constraints of most soils in Zambia are related mostly to poor soil fertility and aluminium toxicity. These production limiting constraints have obliged the resource-poor farmers to adopt shifting cultivation systems of agriculture. Recently, the availability of new cultivable land has decreased, which has forced farmers to encroach onto marginal and fragile lands for cultivation resulting in reduced fallow periods. This increases the risk of degradation of the already fragile land. The sustainable use of these soils requires adequate inputs of nutrients and soil amendments in the form of inorganic and organic fertilisers and lime. The rapid reintroduction of appropriate and affordable technologies to smallholder agriculture is required, through the combination of formal science and indigenous knowledge. Improved fallows and the use of more acid tolerant crops are probably potential alternative technologies for soil fertility amelioration.

Fertiliser use is the new approach to overcome soil fertility depletion and is one of the factors responsible for a large part of food production increases in other parts of the world such as Asia, Latin America and the temperate region, as well as in the commercial farm sector of Sub Saharan Africa. Fertiliser use is viewed as a recurring cost of production. It is only feasible if farmers can sell their surplus production at a profit. This is part of the problem that farmers in places like the wet miombo woodlands of Zambia face, they are far from the main markets, with all that this entails. It is expensive to transport their produce to those markets themselves, so they generally have to accept low prices because someone else will bear the transport costs hence non-availability of agro-inputs in the area and if available, the cost is beyond the reach of these farmers. Their scale of operation is generally so small that they cannot benefit from the economies of scale; if anything they are functioning at diseconomies of scale. Under such circumstances, the author feels that we should be helping the farmers use and develop their indigenous technologies until some of the larger structural problems can be addressed, at which point the farmers are likely to adopt the new technologies without having to be encouraged to do so. Adopting a more understanding position on practices such as *chitemene* and fundikila would be a good start.

Sustained agricultural production can be achieved only by a proper use of soil resources, which includes the maintenance or enhancement of soil fertility. Under conditions of sedentary agriculture without significant changes in farming practices, of low yields and limited crop residue availability for the purpose of soil fertility maintenance and poor availability and high cost of inorganic fertilisers, the nutrient reserves of the soils are being depleted.

Future research priorities must, therefore, be based on farmers' resource constraints rather than on single commodity research since the major target group are small-scale farmers, among whom the practices of shifting cultivation are most prevalent. In order to achieve this, farmers should be involved early enough in the research process and on-farm trials of recommended low-input technology should be encouraged among farmers. Currently amongst the farmers in the region, there seems to be a transfer gap rather than a technology gap, therefore, there is a need for participatory technology testing under farmer's specific conditions. However, in certain areas we still need some new technologies but these must be through participatory technology development (PTD) approach. This is essential if the research technologies developed or being developed are to stand the test of time.

Chitemene shifting cultivation appears to have been developed with the implicit objective of ensuring the regulated release of soil nutrients for optimum crop production in soils that are relatively infertile.

The following proposed research thrusts are potential options needed to improve management strategies which could stave off the declining per capita food production:

- *Tree species and provenance screening.* Improved fallow involving leguminous trees seem to be a potential technology to address the problem of declining soil fertility in the wet miombo region of Zambia. Trials so far conducted have shown that of all the tree species tested, only *Leucaena leucocephala* has given a positive benefit to crop yields. However, this was limed at 2 t ha^{-1} at the time of establishment but generally, *Leucaena* does not perform well on acid soils. Acid tolerant leguminous tree species have not been identified yet. Lime is also expensive and not always available to small-scale farmers. Therefore, there is need to screen various tree species and provenance of *Leucaena* and other tree species for tolerance to the high acidic soil conditions in the region to achieve good biomass production without liming. In addition, management trials aimed at finding management practices that will maximise biomass production, increase benefits to companion crops and reduce competition, should also be conducted.

- *Screening of local species to test for their suitability in the alley cropping system.* Trees and shrubs have many roles to play in tropical land use systems and wood perennial legumes are an extensive and important group to consider. Many legumes fix N and have their own importance to contribute: some are deep rooted and act as nutrient-pumps while others have mycorrhizal affiliation - a symbiosis which provides nutrients to the trees. Some have uses as traditional medicines, insecticides, fish poison. Evaluation of these for alley cropping can be an added advantage as these are more adapted to the local environment.

- *Effect of rate of biomass application on crop production.* In earlier alley cropping experiments at Misamfu Research Centre prunings from hedgerows of trees were used to improve and sustain yields of crops grown in alleys between hedgerows (Figure 6.5). It has been difficult to establish quantitatively the effect of the pruning application on the crop yield because of large variation in soils and biomass production from the trees in these trials. It is therefore considered beneficial to establish a trial where a crop receives known quantities of biomass and then measure the response of the crop.

- *Nutrient cycling under alley cropping systems.* Some research studies conducted in the region demonstrated that there was no benefit in

growing trees and crops in close association. In some cases there was even a depression of yield by the presence of trees. The tree species used were able to grow reasonably well and produced adequate quantities of biomass, but this did not seem to be able to benefit the crop. It is possible that many of the nutrients particularly nitrogen, could have been lost from the system, either by leaching or volatilisation to the atmosphere. A knowledge of *in-situ* rates of N fixation, quantity fixed and the subsequent fate of N fixed within Alley Cropping systems may help to design new techniques in alley cropping management to reduce losses.
In-situ rates of N-fixation of some leguminous tree species can be estimated using some sophisticated techniques such as the ^{15}N natural abundance technique and the ^{15}N isotope dilution technique.

- *On-farm establishment of tree species for fodder and alley cropping trials.* Animal husbandry is found in some parts of the region. Non-availability of high quality fodder is considered as a constraint for improving animal production especially during the dry season when grass is scarce. It has been documented in West Africa that the Fulani cattle spend 5% of their feeding time on browse during the rainy season and 15-20% during the dry season (Kang and Lal, 1981). This clearly indicates that animals mainly survive on fodder during the dry season and hence the need for developing good protein-rich fodder. More research need to be conducted to establish fodder banks on farmers' fields.

- *Synchronisation of green manure incorporation.* The release of nutrient from above ground-inputs and roots can be synchronised with plant growth demands. The synchrony principle is based on understanding the way that the processes of organic matter decomposition and nutrient uptake by plants are integrated to ensure efficient nutrients cycling in ecosystems; its aims are to improve the efficiency of nutrients cycling in agricultural systems by manipulation of these processes, in particular by management of organic matter inputs, with or without interaction with inorganic fertilisers.
Previous work at Misamfu Research Centre has shown that over a period of time (5-6 years), the soil physical and chemical characteristics deteriorate progressively when the same piece of land is cropped even under rotation and use of a good fertiliser practice. Soils in this region are acid-prone and easily become more acidic with addition of nitrogenous fertilisers without liming programme. The level of organic matter also drops with time.
Therefore, in order to build up or maintain soil fertility, the introduction of a green manure could be a cheap and viable option. Since traditional small-scale farmers often have limited labour and

land resources and cannot afford to raise a green manure during the dry season, it is felt that the green manure could be grown together with a food crop and incorporated sometimes during the course of the growing season. Another important aspect would be to determine the best time to plant and incorporate the green manure for maximum benefit to the crop.

Mycorrhiza-tree association studies. Leguminous species require large amounts of phosphorus (P) for growth, nodulation and N fixation. Consequently they are often unable to grow on acid soils with low available P. Other researchers have found exciting and dramatic association between P absorption and a specialised group of fungi called vesicular arbuscular mycorrhizae (VAM). In particular, mycorrhizal infection usually increases the efficiency of nutrient absorption by its host, from which the fungus obtain carbon compounds. Research has shown that effective associations between many leguminous species and mycorrhizal fungi significantly improve growth and N_2 - fixation relative to non-mycorrhizal plants in P deficient soils. Research need to be established to find out the predominant mycorrhizal fungi associated with species commonly used in agroforestry and the effects of mycorrhizal inoculation on survival and P uptake of some leguminous species.

Nutrient management - Rock phosphate initiative. After N, P is the most limiting element for crop growth throughout the tropics. While it is available in a variety of chemical forms as a fertiliser, it is often too expensive for small-scale farmers (Sanchez *et al.*, 1995). To improve the N status of tropical soils, we can incorporate legumes into our cropping systems to take advantage of the association with N_2- fixing rhizobacteria. However, there are no known equivalents for P (Sanchez *et al.* 1995).

Farmers can use two basic strategies to meet the phosphorus requirements of their crops; find other indigenous sources or improve the availability of the phosphorus that does exist. Two major alternative sources are animal manure and indigenous RP. Cattle manure usually ranges between 0.2 and 0.4% P_2O_5 (Mishra and Bangar, 1986). Rock phosphate deposits exist in the region and other parts of Zambia.

The agronomic effectiveness of several types of rock phosphate (RP) is highest for acid soils that have low P and Ca levels, but it has not been an effective source of P in neutral or alkaline soils. Compared to water soluble P fertilisers, RPs are generally considered less effective, presumably because their limited solubility does not maintain a sufficiently high level of P in the soil solution. A variety of micro-organisms are known to solubilize different insoluble

inorganic phosphates. These include fungi, bacteria and actinomycetes. Many trials have been conducted with inoculation of soils, crops and the phosphorus itself with the various microbes. Some researchers have investigated biological methods to make the RP more soluble, affordable and profitable. Researchers in Kenya and India have had good results when they added the RP while starting compost piles. The important mechanisms involved in the dissolving of insoluble phosphates in soil include formation of organic acids and chelating substances. During composting, there is concentrated microbial activity and significant amounts of organic acids and chelating substances are produced (Mishra and Bangar, 1986).
Adding RP to compost is one method farmers might use to better utilise the limited P available to them. Responses will depend on the composition of the RPs and soil types. Application of phosphate rock is of interest to the agricultural systems that are affordable, because phosphate rock is less expensive than ordinary water soluble super phosphate and releases P quickly in the very acid soils. The use of acid-tolerant crops may permit more efficient utilisation of P from RP, because the plants will grow under the acid conditions that promote the dissolution of apatite.

Screening and Selection of Crop Genotypes for tolerance to both aluminium toxicity and low phosphorus levels: Soils of the high rainfall area of Zambia have problems of low natural soil fertility and P availability to plants is low. Aluminium toxicity and P deficiency always occur together, although they are often studied separately (Singh and Goma, 1995). Under acid soil conditions, where it is difficult to separate the detrimental effects of aluminium from those of low P availability, the differences in aluminium tolerance among species or varieties seems to be positively correlated with differences in P translocation rates in the presence of Al (Foy, 1974). It is well documented that differences exist among crop species and varieties in tolerance to low levels of available P in the soil. It has also been reported about the possibility of dual tolerance to both Al and low P (Salinas and Sanchez, 1996). Limited evidence indicates that the species or varieties which are tolerant produce maximum yields at lower levels of applied P and or lime than do the sensitive species or varieties. Fertilisers can correct soil limitations but their high cost and the uncertain economic return are a factor of high risks inherent in agriculture in the region for small-scale farmers, who have no resources or access to credit facility. Currently, local farmers have clearly taken up hybrid maize. However, the attributes of these hybrids are not well suited to the climate, soils and management conditions of the region and the cost is beyond the reach of the local farmers. The exploitation of the genetic variability of genotypes with different features could be a potential strategy that would make feasible the production systems of resource poor small-scale farmers in view of the high price of fertilisers and lime. The screening programme must incorporate promising major crop genotypes, grown in the region, with dual tolerance to both low levels of available soil P and high Al saturation for incorporation into breeding programmes. This would enable these resource poor farmers to effectively and economically utilise low-fertility, acid soils of the region where P and Al toxicity are some of the major limiting factors for maize production. In addition, it is not just cultivars that are tolerant of acid soils that are needed, but also the ones that can handle high levels of Al in the soil (not necessarily aluminium-accumulators, as the aluminium would be released into the soil when the foliage decompose).

- *Increase efficieny of external inputs*: The efficiency of mineral fertilizers is quite low in most cropping systems in Africa due to soil conditions, eratic and low rainfall and poor crop and soil management. In order to make fertilizers more profitable, future research need to focus more on developing strategies for a higher efficiency of these external inputs.

References

Agricultural University of Norway. (1995) Structural adjustment policies and environmental degradation in Tanzania, Zambia and Ethiopia. *Preliminary Seminar Report, 9-10 January 1995. The Ecology and Development Programme*. NLH, Ås, Norway.

Allan, W. (1967) *African Husbandman.* Oliver and Boyd, Edinburgh.

Araki, S. 1993. Effect on soil organic matter and soil fertility of the *chitemene* slash-and-burn practice used in northern Zambia. In: Mulongoy, K. and Merckx, R. (eds), *Soil Organic Matter and Sustainability of Tropical Agriculture,* John Wiley, Chichester, UK. pp. 367-375.

Araki, S. (1992) The Role of *Miombo* Woodland Ecosystem in *Chitemene* ShiftingCultivation in Northern Zambia. *Japan InfoMAB No. 11*. Centre for AfricanArea Studies, Kyoto University, Japan.

Banyard, S.G. (1968) *Mpika District Forest Management Book*. Forestry Department, Ndola.

Campbell, B., Frost, P. and Byron, N. (1996) Miombo woodlands and their use: Overview and key issues. In: Campbell, B. (ed), *The Miombo in Transition: Woodlands and Welfare in Africa.* Centre for International Forestry Research, Bogor, Indonesia.

Chidumayo, E.N. (1987) A shifting cultivation land use system under population pressure in Zambia. *Agroforestry Systems*. **5:** 15-25.

Chidumayo, E.N. (1988a) Estimating Fuelwood Production and wood in regrowth dry miombo woodland in Zambia. *Forest Ecology and Management.* **24(1):** 59-66

Cooper, D.C., Lal, R. and Classen, S.L. (1986) In: Lal, R, Sanchez, P.A. and Cummings, R.W. Jr. (eds). *Land Clearing and Development in the Tropics.* Balkema, Rotterdam, The Netherlands. pp. 149-158.

Foy, C.D. (1974) Effects of Aluminium on Plant Growth. In: Carson, E.W. (ed). *The Plant Root and its Environment.* pp. 601-642, University Press of Virginia, Charlottesville, USA.

Fresco, L.O. (1986) Cassava in Shifting Cultivation. *A Systems Approach to Agricultural Technology Development in Africa.* Royal Tropical Institute, Amsterdam, The Netherlands.

Goma, H.C., Rahim, K., Nangendo, G., Riley, J. and Stein, A. (2001) Participatory studies for agro-ecosystem evaluation. *Agriculture, Ecosystem and Environment* **87:** 179-190.

Haugh, R. (1981) Agricultural Crops and Cultivation Methods in the Northern Province of Zambia. M.Sc. Thesis, Agricultural University of Norway. Occasional Paper No. 1.

Huxley, P.A., Rocheleau, D.E. and Wood, P. (1986) *Farming Systems and Agroforestry research in Northern Zambia: Phase I Report,* Diagnosis of Land-use problems and research indications, ICRAF, Nairobi, Kenya.

Kang, B.T. and Lal, R. (1981) *Tropical Agricultural Hydrology,* Lal, R. and Russell, E.W. (eds). John Wiley, New York.

Kang, B.T., Wilson, G.F. and Sipkens, L. (1981) Alley cropping maize and leucaena in Southern Nigeria. *Plant and Soil.* **63:** 165-179.

Kwesiga F. and Kamau, I.N. (eds). (1989) Agroforestry Potential in the Unimodal Uplands Plateau of Zambia. *Agroforestry Research Network for Africa, Report No. 7., ICRAF,* Nairobi, Kenya.

Kwesiga, F. and Phiri, D.M. (1995) Agroforestry based cropping systems. *National Symposium Proceedings On: A systems Approach to Long-term Soil Productivity,* February, 7-10, 1995. Lusaka, Zambia.

Lal, R. (1987) *Tropical Ecology and Physical Edaphology.* Wiley, New York, USA.

Lal, R. (1989) Soil Management options in the tropics as alternatives to slash-and-burn. *Soil Technology.* **2:** 253 - 270.

Lawton, R.M. (1978) A study of the dynamic ecology of Zambian vegetation. *J. Ecol.* **66:** 175-198.

Mansfield, J.E. (1973) Summary of Agronomic Research Findings in Northern Province, Zambia. Land Resources Division, England.

Mansfield, J.E., Bennett, J.G., King, R.B., Lang, D.M. and Lowton, R.M. (1976) Current land-use, Land resources of the Northern and Luapula Provinces, Zambia. A reconnaissance assessment. *Land Resource Study No. 19. Vols. 1-6,* Ministry of Overseas Development, Surbiton, Surrey, England.

Mattsson, L.E. (1989) Agroforestry diagnosis in Mambwe area, Northern Province of Zambia: Assessment of Constraints and Potentials to Agricultural Production Systems in Nsokolo watershed with targets for agroforestry research and development. Ph.D. Thesis, AUN, Ås, Norway.

Mapiki, A. (1988) Some special features of red soils of the high rainfall area of Zambia with reference to their fertility and management problems. In: Nyamapfene, K., Hussein, J. and Asumadu, K. (eds). *The Red Soils of East and Southern Africa,* Proceedings of an International Symposium, Harare, Zimbabwe, 24-27 February 1986, IDRC Manuscript Report 170e. pp. 368-389.

Matthews, R.B., Lungu, S., Volk, J., Holden, S.T. and Solberg, K. (1992) The potential of alley cropping in improvement of cultivation systems in the high rainfall areas of Zambia II. Maize production. In: *Agroforestry Systems*. **17:** 241-261.

Mishra, M. and Bangar, K. (1986) *Biological Agriculture and Horticulture*. **3:** 331-340.

Moore, H.L. and Vaughan, M. (1994) *Cutting Down Trees: Gender Nutrition, and Agricultural Change in the Northern Province of Zambia*, 1890-1990. Heinemann, Portsmouth, NH.

Morris, B. (1970) Nature and origins of *Brachystegia* woodland. *Commonwealth Forestry Review*. **49:** 155-158.

Peter, D.V. (1950) Land Usage in Serenje District. *Rhodes-Livingstone Paper No. 19*. The Institute for African Studies, University of Zambia. Manchester University Press.

Richards, P. (1985) *Indigenous Agricultural Revolution*. Unwin Hyman, London.

Ruthenberg, H. (1980) *Farming Systems in the Tropics*. Clarendon Press, Oxford.

Salinas, J.G. and Sanchez, P.A. (1996) Soil-Plant relationships affecting varietal and species differences in tolerance to low available soil phosphorus. *Ciencia E Cultura*, 28 (2), Fevereiro.

Sanchez, P.A. (1976) *Properties and Management of Toils in the Tropics*. John Wiley, New York.

Sanchez, P.A., Shepherd, K.D., Soule, M.J., Place, F.M., Buresh, R.J., Izac, A.M.N., Mokwunye, A.U., Kwesiga, F.R., Ndiritu, C.G. and Woomer, P.L. (1997) Soil Fertility Replenishment in Africa: An Investment in Natural Resource Capital. *Replenishing Soil Fertility in Africa*. SSSA Special Publication No. 51, pp1-46.

Sanchez, P.A., Bandy, D.E. and Villchica, J.H. (1982) Amazon Basin Soils: Management for Continuous Crop Production. *Science*. **216:** 821-827.

Sanchez, P.A, Izac, A.M., Valencia, I. and Pieri, C. (1995) Soil Fertility Replenishment in Africa: *A concept Note (Draft)*. ICRAF, Nairobi, Kenya and World Bank, Washington D.C.

Schultz, J. (1976) *Land Use in Zambia*. Afrika-studien. Welt-Vorum verlag, München.

Singh, B.R. (1989) Evaluation of liming materials as ameliorants of acid soils in high rainfall areas of Zambia. *Norwegian J. Agric. Sci.* **3:** 13-22.

Singh, B.R. and Goma, H.C. (1995) Long-term Soil Fertility Management Experiments in Eastern Africa. pp 347-382. In: Lal, R. and Stewart, B.A. (eds). *Advances in Soil Science: Soil Management Experimental Basis for Sustainability and Environmental Quality*. CRC Press, Inc. Lewis Publishers.

Sokotela, S.B., Mwalongo, B. and Mwakalombe, B. (1995) Biological Soil fertility Management in Northern Zambia: An On-farm diagnosis and characterisation study. Paper presented at a workshop on Nutrients Cycling and Soil Fertility Management in Africa. Held at Soddo, Weilata, Ethiopia. 26 November-2 December, 1995.

Spencer, J.E. (1966) *Shifting cultivation in Southern-Eastern Asia*. University of California Press, Berkley and Los Angeles, USA.

SPRP Annual Reports. (1983-86, 1987, 1988, 1989, 1990, 1996, 1997) Soil Productivity Research Programme, Misamfu Regional Research Centre, Ministry of Agriculture, Food and Fisheries, Kasama, Zambia.

Steinshamn, H. (1984) The effect of chitemene on soil fertility and changes on some soil parameters during the first cropping season in two field trials at

Misamfu Regional Research Station, Kasama. MSc. Thesis. Agricultural University of Norway.

Stromgaard, P. (1984) The immediate effect of burning and ash fertilisation. *Plant and Soil.* **80:** 307-320.

Stromgaard, P. (1985) Biomass, growth, and burning of woodland in a shifting cultivation area of South Central Africa. *Forestry Ecology and Management.* **12:** 163 - 178.

Stromgaard, P. (1988) Soil and vegetation changes under shifting cultivation in the miombo of East Africa. *Geogr. Ann.* **70B(3):** 363 - 374.

Stromgaard, P. (1988) The grassland mound-system of the Bisa-Mambwe of Zambia. *Tools and Tillage*, Vol. VI: 1, pp. 33-46. National Museum of Denmark, Copenhagen.

Stromgaard, P. (1989) Adaptive Strategies in the breakdown of shifting cultivation: The Case of the Mambwe, Lamba, and Lala of Northern Zambia. *Human Ecology.* **17:** 427 – 444.

Stromgaard, P. (1990) Effects of mound-cultivation on concentration of nutrients in a Zambian miombo woodland soil. *Agriculture, Ecosystems and Environment.* 32:295-313.

Stromgaard, P. (1990b) Effects of mound-cultivation on concentration of nutrients in a Zambian miombo woodland soil. *Agriculture, Ecosystems and Environment.* **32:** 295-313.

Trapnell, C.G. (1953) The soils, vegetation and agriculture of North-Eastern Rhodesia. *Report of the Ecological Survey.* Government Printer, Lusaka, Zambia.

Tveitnes, S. (1986) *An outline of soils and soil fertility in the high rainfall areas of Zambia.* Report on Phase I. Part I. Noragric, Agricultural University of Norway.

Veldkamp, W.J. (1987a) Reconnaissance/semi-detailed semi-quantified land evaluation system for non-irrigated (rainfed) agriculture. *Soil Survey Unit, MAWD.* Government of the Republic of Zambia.

Zinke, P.J., Sabasri, S. and Konstadter, P. (1978) In: Konstadter, E., Chapman, E.C. and Sabasri, S. (eds). *Farmers in the Forest.* East-West Centre, Honolulu.

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Soil Fertility Management in Semi Arid Areas of East and Southern Africa

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Introduction

The arid and semi-arid areas of sub-Saharan Africa occur mainly around latitudes 10 to 15°N in West Africa and roughly 10 to 30°S in Southern Africa. In addition, there is also a large arid and semi-arid region in the Horn of Africa and in East Africa. Another large dry region exists in South-Western and South-Eastern Africa, consisting of a semi-arid strip that runs roughly North-South inland of the Namib Desert, eastwards in a broad belt through Botswana, then South through the center of South Africa. Smaller semi-arid areas are also found in Zimbabwe, Mozambique and Madagascar. These semi-arid regions in sub-Saharan Africa are experiencing the greatest population change, compared with the high potential agricultural areas, with a natural rate of increase of 3.5 to 4% in East Africa and a higher actual growth rate due to migration from the crowded fertile areas of the highlands. Farm sizes in these regions are thus getting smaller, ranging from 1.5 to 17 ha per household (McCown and Jones, 1992), in East Africa. In Southern Africa the natural population growth rate is between 3 and 3.5% (SACCAR, 1997), and the land size of an individual household ranges from 0.5 to 25 ha with an average of 3 ha in Zimbabwe and Zambia. Traditionally, farmers in the semi-arid areas of East and Southern Africa have always grown maize (*Zea mays* L.), beans (*Phaseolus vulgaris* L.), sorghum (*Sorghum bicolor*), millets (*Pennisetum americanum* and *Eleusine coracana*), cowpeas (*Vigna unguiculata*) and pigeon peas (*Cajanus cajan*). The migrants into the semi-arid regions have traditionally brought along with them crops more suited to the high potential regions, with no requisite change in production technology to optimize the production of these crops in the semi-arid regions.

Semi-arid regions have a low rainfall of approximately 350 to 650 mm per annum, which is usually erratic, and unreliable. In Kenya, these areas receive rainfall with recordings as low as 342 mm per annum (Nadar and Faught, 1984a) and even lower amounts below 300 mm per annum are recorded in the unimodal rainfall system of Southern Africa, especially in Botswana, Zimbabwe, South Africa and Namibia. The probability of crop failure in semi-arid regions may therefore be quite high during years of below average rainfall because inadequate moisture would limit crop growth in addition to unavailability of nutrients. There is need, therefore to understand other contributory factors to successful agriculture in these dry environments, mainly those pertaining to soil fertility and water management.

There is widespread cultivation of semi-arid lands in sub-Saharan Africa. The topography is variable and areas with slopes as high as 30% or more are commonly used for crop production and are susceptible to severe soil erosion, nutrient depletion and consequently nutrient imbalances. Many of the soils in the arid and semi-arid lands (ASAL) of East and Southern Africa are deficient in some essential mineral nutrients especially phosphorus and nitrogen. Crop yields are thus declining in many areas because of reduced soil fertility resulting from continuous cropping with little or no inputs of nutrients.

Mixtures, intercrops or polycultures characterizes crop production in the semi-arid areas. There are many variations of intercrops, the common ones being mixed, row, strip, and relay cropping (Vandermeer, 1990). These variations depend on the sowing date, spatial arrangement and the degree of physical association of the crop species grown together. A common reason for the frequent use of intercrops is that they produce a system capable of dealing with environmental variability, or that the system is a strategy of risk avoidance (Francis and Sanders, 1978). It is argued that if two or more species are grown together, where each has a different growth requirement and different growth cycle, there may be an increased possibility of obtaining some yield, at least in one of them, under adverse growth conditions as common in the arid and semiarid areas. The legume in a polyculture is a source of protein in human diets for cash-limited peasant families. The legume stover is also a protein source in animal feeds. Livestock production systems also dominate many of the ASAL. The judicious use of agricultural inputs and implements, reducing nutrient losses and improving nutrient cycling in crop-livestock systems is therefore key to the development of sustainable agriculture in these semi-arid regions.

In this chapter we begin with a section on constraints to soil fertility management under cropping systems characteristic of semi-arid areas focusing on East and Southern Africa. Where necessary, appropriate comparisons between the semi-arid and subhumid, and humid agro-ecological zones are made to bring out desired contrast. To aid in the projection of this contrast between the semi-arid zone and other zones, examples in some sections of this chapter are drawn from elsewhere in Africa or in the world. Following the presentation of soil fertility management constraints, we discuss intercropping in semi-arid areas, and nutrient supply in cereal crop rotations and other dryland cropping situations. In the sections that ensue, one of the cornerstones of soil fertility maintenance or improvement, namely crop-livestock interaction, is discussed emphasizing manure use in more detail than in any of the other sections of this book.

Soil Fertility Management in Semi-arid Areas

Soil fertility management in semi-arid areas is mainly constrained by inadequate moisture and lack of resources for purchases of inputs, particularly the very expensive mineral fertilizers that are usually imported. This problem is compounded by the nutrient removals, which in turn exacerbate the problem of soil fertility decline. The nutrient removals arise from continuous cropping, without adequate replenishment and soil erosion. Nutrient imbalances and deficiencies are therefore common in most soils of these regions.

Nutrient deficiencies

Many of the soils in the semiarid zones of Eastern and Southern Africa are deficient in some essential mineral nutrients especially phosphorus (P) and nitrogen (N) (Okalebo, 1987; Siderius and Muchena, 1977; Keating *et al.*, 1992; Hikwa *et al.*, 1998). Low soil fertility (especially P and N deficiency) is a major biophysical constraint to successful agriculture in semiarid areas of East and Southern Africa (FAO, 1971; Yates and Kiss, 1992;).

In the Eastern Province of Zambia (Katete and Chipata districts), an area typical of the Miombo woodlands of Southern Africa, declining N fertility was identified as a major constraint to maize production while P was not (Ngugi, 1988). More than 60% of the sandy soils found in Zimbabwe are planted to continuous maize monoculture with crop residues mostly removed to feed livestock, as is common elsewhere in Eastern and Southern Africa. Mukurumbira and Nemasasi (1998), noted that this practice might result in both macro and micronutrient deficiencies in these sandy soils. Trace element deficiencies, especially of zinc (Zn) and molybdenum (Mo) may also become limiting under continuous cultivation, as commonly applied mineral fertilizers do not usually supply these nutrients.

A better understanding of nutrient imbalances induced by pH and other applied nutrients is important in managing soil fertility. For instance, trace elements such as Zinc and Molybdenum affect maize growth, yet they become unavailable at pH greater than 5. Boron availability is decreased by liming and dry conditions but deficiency is amplified by inadequate natural supplies from parent rock and by leaching in sandy soils (Mukurumbira and Nemasasi, 1998). Overliming and high P applications have been shown to reduce the availability of Zn to crops grown on sandy soils in Zimbabwe (Mukurumbira and Nemasasi, 1998). High levels of N and P may also induce copper deficiency by interference with translocation under marginal deficiency situations (Tanner, Cooper, Madziva and Vere, 1981). Tanner (1973) attributed the increase of the Zn deficiency problem in Zimbabwe to changeover from the use of manures, which contain Zn to inorganic fertilizers. This suggests that part of the problem of nutrient deficiencies can be addressed through judicious use of organic inputs. Studying the efficacy of combinations of organic and inorganic sources of nutrients on maize growth, Nyathi (1997) concluded that synergism or complimentarity existed only when combinations of inputs to sandy soil included inorganic fertilizers.

Inherently infertile soils require external inputs of fertilizer materials for sustained fertility and productivity especially under continuous cropping (Nyathi, 1997). Chemical properties, typical of sandy soil in Eastern and Southern Africa particularly common in most parts of Zimbabwe are presented in Table 7.1 Soils are strongly acidic with an average pH of 4.9 for the 0 to 15 cm depth (Table 7.1). In addition, the predominantly sandy soils in the semiarid zone predispose any soil amendments to reduced effectiveness because of their low water holding capacity and low organic matter content. Soil fertility management has to focus on supplying inputs from external sources to improve organic matter content of sandy soil and consequently its capacity as a repository for nutrients.

Nutrient depletion

One of the major constraints to soil fertility management in semi arid areas is depletion of nutrients through continuous cultivation without adequate nutrient replenishment. The continuous cultivation exposes soil organic matter (SOM) to oxidative processes, since in most cases there is a reduced biomass input (Shepherd and Soule, 1998) and failure by users to judiciously manage soil nutrient reserves. Decomposition of organic matter has an impact on the capacity of soil to retain nutrients. SOM plays a key role in soil fertility replenishment but the linkages between degradation and soil carbon sequestration and nutrient retention are complex. Some forms of tillage, particularly in arid and semiarid areas encourage oxidation of organic matter throughout the profile resulting in release of carbon to the atmosphere rather than its build up in the soil (Nabhan, 1997). This leads to reduced biomass production from crops or pastures and lower carbon inputs to the soil in subsequent periods (because less root matter, leaf litter and less crop residues are returned to the soil).

Table 7.1. Chemical properties of sandy soil at Makoholi Experiment Station, Zimbabwe

	Soil depth (cm)	
	0-15	15 - 30
	[1]mLS	[2]mSal
Texture		
Gravel (%)	1	3
Coarse sand (%)	18	17
Medium sand (%)	31	26
Fine sand (%)	36	31
Silt (%)	10	8
Clay (%)	4	18
pH (0.1M CaCl2)	4.9	4.9
Mineral nitrogen (ppm)	6.5	5.0
Mineral nitrogen after seven weeks incubation (ppm)	14.8	11.5
Resin-extractable phosphorus (ppm)	7.7	6.7
Exchangeable cations (ammonium acetate)(meg / 100 g dry weight soil)		
Potassium	0.09	0.08
Calcium	1.06	1.07
Magnesium	0.45	0.43
Total Exchangeable bases	1.60	1.58

After Nyathi, 1997

1 mLS = medium loamy sand
2 mSal = medium sandy loam

Surveys in communal areas of Zimbabwe revealed that 44% of the 500 crop fields that were sampled had depleted levels of at least one nutrient (Mushambi *et al.*, 1997). Normally such soils are characterized by multiple nutrient deficiencies of N, P and S and at advanced stages by the depletion of Mg and Zn (Grant, 1970). Smaling *et al.* (1997), chronicled nutrient depletion in five African regions according to the severity of the problem with East and Southern Africa occupying first and third positions, respectively, in a scale where one is the worst case scenario. High nutrient depletion is attributed to high outflow of nutrients in harvested products, erosion and to the relatively inherently infertile Alfisols that are predominantly sandy as described for Southern Africa where they are dominant (Chapter one). Nutrient depletion rates vary with soil properties. The proportion of nutrients lost is normally greater in sandy soils but the total nutrient loss is greater in clayey soils (Sanchez *et al.*, 1997). This is largely because soil organic matter particles are less protected from microbial decomposition in sandier soils than in loamy or clayey ones (Swift *et al.*, 1994). Sanchez *et al.* (1997), noted that this is one major difference between the nutrient-depleted high potential zones of Eastern and Southern Africa with predominantly loamy and clayey soils, and semiarid zones of West, East and Southern Africa with predominantly sandy soils. There appears to be a significant decline in soil fertility with time, regardless of the original nutrient status further reinforcing the need to judiciously manage soils through well-defined strategies that work towards nutrient replenishment. This requires that fertility management especially of sandy soils has to pay attention to manipulation of organic matter levels to allow for increased retention of nutrients.

Soil scidity, sodicity and salinization

Of the approximately 2976 million ha of total land area in Africa, 2146 million ha are classified as problem soils of which 72% are affected by different fertility constraints such as soil acidity, vertic properties, shallowness, salinity, poor drainage and low fertility. About 490 million ha in Africa are affected by different types of soil degradation (Mashali, 1997). In rainfed areas, fallow periods are declining below safe limits. In Zimbabwe, it is estimated that 30% of croplands in the communal areas have been fallowed or abandoned due to depleted soil fertility (Anderson *et al.*, 1993). On irrigated lands, improper use and system management not only detract attainment of sustainable agricultural production but also cause land to be withdrawn from cultivation because of salinity, sodicity, compaction and infertility (Nabhan, 1997). Marginal land and problem soils with severe production constraints are put under cultivation without adoption of efficient water and soil management practices (Mashali, 1997).

Soil acidity

The sandy soils in Zimbabwe are highly weathered, weakly buffered and acidic (Grant, 1970). Dhliwayo *et al.* (1998), noted that 70% of soils from eight sampled communal areas in the semiarid zone of Zimbabwe were extremely to very strongly acid with Al saturation of more than 20%, a level toxic to maize plants. In these soils which are moderately leached, Mo becomes unavailable at pH values below 4.8 (0.01M Ca Cl_2), a sharp contrast with granite derived soils which usually supply adequate Mo for normal maize growth at these pH levels (Tanner and Grant, 1974). Grant (1971) reported that 32% of light colored soils of Zimbabwe derived from siliceous rocks and 31% of red soils from basic rocks had pH values of 4.2 or less. In South Africa, naturally occurring acid soils affect more than 15% of total land area and soil analyses trends indicate increasing acidification and that almost 14% of total arable land is likely to be affected by some degree of subsurface acidity (Beukes, 1997; Farina 1997).

A usual remedy is the application of lime to correct acidity of soils. Farmers are often forced to neglect soil care when economic returns from agriculture are too low to justify investment in soil fertility maintenance. Liming to ameliorate soil acidity is in this category. Dhliwayo *et al.* (1998), however, recommended that high lime applications should be split such that half of the recommended amount is applied during the first year and the other half in a subsequent season. This should be done to avoid upsetting the nutrient balance in the weakly buffered sandy soils characteristic of most of the semiarid zones of East and Southern Africa. Another possible approach could be to tailor plants to suit the environment. The main component of managing soil acidity for plant growth is the selection of productive varieties that are tolerant to Al toxicity (Sanchez and Salinas, 1981). Al ions directly damage roots and reduce nutrient and water uptake, and acidity causes poor nodulation in legume crops (Beukes, 1997). Plant species and genotypes within species differ widely in their tolerance to excess Al and some of these differences are genetically controlled (Foy, 1988). This appears to offer a timely opportunity for deliberate manipulation to engineer plants suited to specific problem environments or ecological hot spots.

Salinization/waterlogging/sodication

Soil salinization is the accumulation of excess salts in the rhizosphere (rooting zone) resulting in partial or complete loss of soil productivity and eventual disappearance of vegetation (Mashali, 1997). Salinization refers to all types of soil degradation brought about by the increase of salt content in the soil and can also be caused by incursion of sea water into coastal areas (Nabhan, 1997). It covers the build-up of free salts and sodication due to the development of dominance exchange complex by sodium. The sodication process involves the presence of soluble sodium salts in the soil solution and their adsorption on the exchange complex (Mashali, 1997). Salinization in Africa is one of the degradation processes affecting large tracts of land in arid and semiarid zones. There are approximately

79.5 million ha of salt and sodium affected soils in sub-Saharan Africa (FAO, 1986). Salinity and sodicity affect soil chemical properties making soil unfit for conventional crop production (Nabhan, 1997).

In Zimbabwe, saline and sodic soils are found in areas of low rainfall and high temperatures (Mushambi *et al.*, 1997). Irrigation is used to supplement natural rainfall for main season (summer) crops and to supply water for winter crops in the dry season. Human induced salinization is the result of improper irrigation, soil and water management. The two types of water that may give rise to salinity problems are: regenerative waters (that is underground water), and drainage water from irrigated land (du Toit, 1991 quoted by Mushambi *et al.*, 1997). Underground water in low rainfall areas has more dissolved salts than that in high rainfall zones due to high evaporation and evapotranspiration rates (high temperatures). An assessment in Zimbabwe of 204 samples of irrigation water from different tobacco growing districts indicated that 95% of the samples had low to medium salinity (Mushambi *et al.*, 1997).

Water logging is the lowering in land productivity through the rise in groundwater close to the soil surface (Nabhan, 1997). Waterlogging is linked to salinization as both are often brought about by incorrect irrigation management. A complete solution to the problem of waterlogging and salinity requires comprehensive drainage works to remove the excess groundwater but is expensive. With the drive by governments to increase crop production through irrigation to match the rapid and alarming increase in population growth rate (currently averaging 3% per annum) in the East and Southern African region, various problems of salinization and/or sodication are bound to increase in future. Studies indicate that growing forage plants on salt affected soils to remove excess salt is feasible and economical (Szabolcs, 1992; Malcolm, 1992; Davidson and Galloway, 1993). Given the recent advances in biotechnology for the selection of salt-tolerant plants, it is likely that this major obstacle will be overcome by the use of these techniques.

Soil erosion

The impact of soil erosion and soil processes it affects including crop responses are described in documents by the FAO-sponsored Erosion-Productivity Network which since its inception in 1984 has used a standardized design to generate comparative data from different soils and agro-ecologies (Stocking, 1984).

The soil in most agricultural land of Zimbabwe has been reduced to its minimum agricultural potential through degradation of soil structure seriously limiting yields and substantially increasing inputs. Of the total land area of Zimbabwe, 13% is classified as severely eroded (Whitlow, 1988). As a product of soil erosion, it was estimated that $1.5 billion

(Zimbabwe dollar) worth of N and P and 2.5 billion tons of organic matter essential for soil stability and fertility were lost every year in Zimbabwe (Stocking, 1986). In Zimbabwe it is estimated that the rate of soil loss from land ploughed annually is in the order of 50 t ha^{-1} yr^{-1}, and that one third of seasonal rainfall is lost as surface runoff with up to 50% of applied fertilizers washed off the land (Elwell and Stocking, 1988).

On a more positive note, Tiffen *et al.* (1993), describes a success story in semi-arid Kenya on environmental recovery in the dry plains of Machakos, South East of Nairobi. Their work draws a positive picture of the adaptive response by smallholder farmers to changes in land availability, agricultural outputs and labour markets, technological options and institutional innovations, and farmers' ability to invest in the agricultural resource base.

Inadequate Fertilizer Use

Intensification of production systems requires an increased supply of nutrients. Monitoring of soil nutrient balance and supply to plants, control of losses, arresting depletion and ensuring accumulation are essential for increased productivity. The average world fertilizer consumption during the period 1990-1993 was 131 million metric tons (MMT) of nutrients that declined to 130 million MMT in 1995-1996 (Nabhan, 1997). Africa comprising 58 countries accounts for only 2.6% of world fertilizer consumption and the share of sub-Saharan Africa is only 1.2% equivalent to 2.16 MMT in 1993 compared to 51.2 MMT for the Far East developing countries and 5.4 MMT in the Near East. With the exception of twelve major fertilizer consumers in Africa (Algeria, Egypt, Kenya, Libya, Malawi, Morocco, Nigeria, South Africa, Sudan, Tunisia, Zambia and Zimbabwe), the average fertilizer use is below 10 kg nutrients per ha of arable land in most of sub-Saharan Africa compared to 130 kg/ha in the Far East and 60 kg/ha in the Near East and 90 kg/ha as a world average. About 63% of the regional total of fertilizer consumption in Africa is accounted for by Egypt, Morocco and South Africa (Nabhan, 1997). Fertilizer consumption during 1975 to 1990 had been growing at nearly 5% in East Africa and 1.7% in Southern Africa. Structural adjustment policies of many governments in East and Southern Africa have led to a great disparity and stagnation in fertilizer consumption among countries since the late 1980s (Simpson *et al.*, 1996). About 87% of N fertilizer is produced in South Africa and Nigeria and very small units are operational in Zimbabwe, Senegal, Mauritius and Zambia. South Africa and Nigeria produce 85% of the continental P fertilizer needs (Nabhan, 1997).

Water deficits and crop growth

In Kenya, the semi-arid agricultural areas receive very low bimodal rainfall, with recordings as low as 342 mm per annum (Nadar and

Faught, 1984)), and even lower amounts are recorded in the unimodal rainfall system of Southern Africa, especially in Botswana, Zimbabwe, South Africa and Namibia (SACCAR, 1997). The probability that the rainfall is less than two thirds of potential evaporation in the rainy season varies between 60 to 80%. It is generally assumed that rainfall equaling two thirds of potential evaporation (approximately 367 mm in a four months growing season) is the minimum required by annual crop plants like maize and beans with a growing period of approximately three months. Rainfall less than half of the potential evaporation (approximately 275 mm within 4 months) in the growing season will lead to crop failure (Nadar and Faught, 1984). The probability of crop failure in semi-arid regions may therefore be quite high during years of below average rainfall.

Farmers in the East and Southern African region use various water capture strategies aimed at reducing runoff on the soil surface and those that encourage infiltration. These include terracing on steep slopes particularly but not exclusively in Kenya, contour bands including dead level contours now becoming popular in Zimbabwe, storm drains and other water harvesting techniques such as tied ridges and basins constructed in a field of growing crops to encourage water infiltration and retention. Tiffen *et al.* (1993), elaborated on the excellent progress that has been made in Kenya (Machakos) in reducing soil erosion by contour banks and terracing. Terracing of the croplands using hand-dug contour trenches and banks was long adopted by farmers in Kenya and is known in Kiswahili as 'fanya juu' terraces (Simpson, Okalebo and Lubulwa, 1996). Tiffen and Mortimore (1994), further elaborated that any deleterious effects of changes in the nature of the resource base (due to cultivation and cropping) have been more than offset by improvements due to terracing, and other conservation measures and that farmers have learned how to manage the resource better. The progress made in the conservation of soil and water has, however, by increasing the supply of soil moisture actually increased the potential for 'mining' of the remaining soil nutrients by crops (Simpson *et al.* 1996). With inherently low soil fertility, most of the soils in the semi-arid areas of East and Southern Africa may produce short term gains in crop yields when appropriate water harvesting techniques are used but will accentuate the problem of low soil fertility in the long term.

Cycles of drying and rewetting of soil greatly stimulate N mineralization (Birch, 1958, also see CABI, 1994). In semi-arid zones this release of nutrients may be unsynchronized with plant uptake due to immature roots or insufficient moisture to allow uptake to occur (Nyathi, 1997). Cycles of increasing soil degradation arising from episodic events such as storms and fires have led to situations of diminishing organic matter levels and nutrient status of soils in the semi-arid areas. With reduced soil organic matter, infiltration rates for rainwater are lowered, runoff increases carrying with it the relatively nutrient-rich top layer. Both valuable soil and potentially productive water are lost (Simpson *et al.*, 1996) to silting dams, lakes, rivers and oceans. Nitrogen fixation has also been reported to decrease with water deficits via poor root nodulation and an observed drop in nitrate reductase activity (Salisbury and Ross, 1992). This would affect plant growth negatively in semi-arid areas.

Biological nitrogen fixation in cropping systems

On a worldwide basis, the demand for fertilizer nitrogen cannot be met by the use of chemical fertilizers (Postgate, 1987). Therefore, biological nitrogen fixation (BNF) is an important source of soil nitrogen in the soil-plant-environment system, particularly for farmers in developing countries where farm family incomes are low and preclude the wide use of commercial inorganic N sources. The use of BNF is widely recognized in Kenya, Malawi, Zambia, South Africa, Tanzania, and Zimbabwe and to a lesser extent in the other countries of East and Southern Africa as a practical way of increasing nitrogen availability to plants. To this end, the Microbiology Research Centre (MIRCEN) in the University of Nairobi and the Soil Productivity Research Laboratory of the Department of Research and Specialist Services in Marondera (Zimbabwe) have been for a decade and more actively involved in the production, evaluation and marketing of legume inoculants.

Where legume/cereal intercrops are involved, the possibility of nitrogen transfer from the fixing legume to the cereal, or the sparing of mineral N by the fixing legume which in turn increases N availability to the cereal can increase crop growth and yield per unit land area. However, BNF is a process that requires a high energy input. Energy in the form of adenosine triphosphate (ATP) is required to transform atmospheric N_2 to NO_3^- , in addition to the much higher requirements for Mo^+ and Fe^{3+} for N_2 fixation. Other extra requirements for fixation include a greater enzyme requirement by the bacterium, and the requirement for a greater time to regenerate enzymes for NO_3^- assimilation. These extra requirements for N-fixation are well documented by Raven (1985) and Sprent (1994).

In theory, therefore, atmospheric fixation of nitrogen has a high energy and water cost to the fixing plant (Raven, 1985). Thus, in semi arid regions, where nutrients and water shortages are common, the relatively high energy requirements for N_2 fixation may reduce the maximum potential yield for fixing plants compared to plants assimilating mineral N_2 (non-fixing). Based on this information, a N_2 fixing legume plant or any other in a mixture with a cereal crop may not be the most efficient way of utilizing the scarce supplies of water for food production in semi-arid areas of East and Southern Africa. There is, however, experimental evidence to demonstrate that intercropping with legumes is successful only for a few legumes such as cowpea (*Vigna unguiculata*) and pigeon pea (*Cajanus cajan*), in years of average rainfall, and the legumes have been shown to fix N_2.

Intercropping in Semi-arid Areas

Intercropping is defined as the cultivation of two or more species of crops to the extent that the crops interact biologically (Vandermeer, 1990). Common terminology used interchangeably with intercrops include polycultures and mixtures. Intercropping is commonly practiced to closely similar or equal extent in semiarid and subhumid zones using cereal, leguminous and other crop varieties. The focus of discussion in this section is on semiarid zone intercropping practices.

There are many variations of intercrops, the common ones being mixed, row, strip, and relay cropping (Vandermeer, 1990). These variations depend on the sowing date, spatial arrangement and the degree of physical association of the crop species grown together. Intercropping is a very common practice. In Africa, 98% of cowpeas (*Vigna unguiculata*) are grown as mixtures while in Colombia, 90% of beans (*Phaseolus spp.*) are cultivated in intercropping systems (Guttierrez *et al.*, 1975). Agricultural land devoted to intercropping varies between 17% in India to 94% in Malawi (Edje,1979). In 1923, before the advent of mechanized agriculture, as much as 57% of soybean acreage was grown as an intercrop with maize in Ohio, U.S.A. (Thatcher, 1925). This probably emphasizes the age-old importance of intercropping as a practice that has harbored hidden benefits that have not been clearly substantiated by research.

A common proposal for the frequent use of intercrops is that they produce a system capable of dealing with environmental variability, or that the system is a strategy of risk avoidance (Francis and Sanders, 1978). It is argued that if two or more species are grown together, where each has a different growth requirement and different growth cycle, there may be an increased possibility of obtaining some yield, at least in one of them, under adverse growth conditions. In many parts of Kenya, Zimbabwe, Zambia and Malawi for instance, farmers will plant maize and bean polycultures, expecting a reasonable maize grain yield and a considerably reduced bean yield, such that the bean is considered a bonus (Fisher, 1977). The legume in the polyculture is a source of protein in human diets for cash-limited peasant families. Common dishes often consist of cereal-legume mixtures. The legume stover is also a protein source in animal feeds.

A survey of Machakos area in Eastern Kenya, dominated by a semi-arid climate, revealed that almost all farmers practiced mixed cropping, especially during the short rainy season (Marimi, 1975), while other reports indicate that 95% of farming land in other marginal areas of

Kenya was under intercrops. Most of the intercropping research in Kenya, however, has been carried out in the high and medium potential areas and in the relatively wetter and cooler areas of semi-arid Kenya such as Katumani and the surrounding areas (mean annual air temperature 19.5°C, mean annual rainfall 655 mm) (Nadar, 1980). In the drier areas of Kenya, for instance Kiboko (mean annual air temperature 23.5°C, mean annual rainfall 500 mm), most of the research on intercrops has been on agroclimatic analysis and/or modeling (Stewart and Faught, 1984; Keating *et al.*, 1992).

Limitations of intercropping

When two species are grown together within the same environment, their interaction can be synergetic or competitive. In semi-arid regions, there may be competition for limiting supplies of nutrients and water. Intercropping may also affect the amount and quality of light available to the components of the mixture. For instance, maize and beans while grown together form different canopies and the taller maize could shade the bean plants. The qualitative and the quantitative radiation interception therefore differ between monocultures and polycultures, particularly for legumes and the shading effect of the cereal, affect the utilization of light for photosynthesis (Kimani 1994). These and many other crop competition issues, as well as the choice of legume intercrop need more attention from researchers who should find answers to be able to unambiguously advocate intercropping as a viable agricultural production practice in these areas.

One of the major difficulties to understanding the advantages or disadvantages of intercrops is the absence of appropriate ways for assessing the performance of the components of a mixture relative to the monocultures. The Land Equivalent Ratio (LER), a function of land area, is the most commonly used measurement to judge the effectiveness of an intercrop (Mead and Willey, 1980). The objectives of intercropping may not necessarily be related to increased biomass or grain yield, but could be related to socio-economic factors such as risk aversion or a combination of this and other factors such as improving soil fertility over time through inclusion of legumes or agroforestry species. The planting pattern which produces the highest physiological advantage cannot always be the one used by the farmer because his/her choice is likely to be influenced by other considerations such as preferences for a specific component, convenience in sowing, weeding and harvesting (Natarajan, 1989). There are situations where the farmer would not accept a loss in yield from one of the components. Willey (1979) points out that different intercropping situations may have to satisfy different requirements for them to be advantageous, and it is important that research aimed at improving an intercrop recognizes these requirements. For example, in Zimbabwe, a row pattern in a maize - cowpea intercrop which produces more cowpea but reducing the maize yield drastically will be less preferred than the one that largely favors higher maize yields and some additional yield of the legume (Natarajan, 1989).

Soil fertility and nutrient dynamics under polycultures appears more complex than under cereal crop rotations and requires the attention of multi-disciplinary research teams that would at least include agro-ecologists, agronomists and soil scientists. Under crop rotation, it is possible to precisely measure nutrient requirements of the next crop while simultaneously determining what has been used or contributed by a previous crop, a much simpler operation than dealing with intercropping situations.

Nutrient supply in cereal crop rotations and other dryland cropping situations

Numerous studies have been conducted in ASALS of Eastern and Southern Africa to determine the effect of inorganic and organic inputs on crop yields (Stewart and Faught, 1984; Probert and Okalebo, 1992; Nyathi, 1997; Jeranyama *et al.*, 1998). Most of these studies have confirmed the widespread deficiency of N and P in soils and the necessity of these nutrients for healthy plant growth in the ASALS of Eastern and Southern Africa. On examining the results of experiments conducted to determine the effects of various levels of N and P (30 kg N and 20 to 60 kg P ha^{-1}) on the yield of maize and cowpeas grown in a rotation at five sites in the ASALS of Kenya, Probert and Okalebo (1992), concluded that N and P combinations gave yields higher than the control and N only treatments at all sites reflecting the combined importance of N and P in maize nutrition in the ASALS of Kenya (Table 7.2). A similar conclusion was reached by Nyathi (1997), following a study in Zimbabwe in which the effects of N and P levels on a maize monocrop grown on a sandy soil were considered. Grant (1981), demonstrated that it was difficult to obtain good crop yields from sandy soils without regular application of mineral fertilizer, manure, and lime in Zimbabwe. Although water may be the major limiting factor to crop growth in semi-arid areas, these studies show that nutrients also play a key role in increasing or limiting yields depending on the amount of rainfall.

A legume cover crop may contribute N to a subsequent non-leguminous crop, reducing N fertilizer needs by 100 kg N ha^{-1} and more in some cases (Giller and Wilson, 1991; Hesterman, Griffin, Williams, Harris and Christenson, 1992). Badaruddin and Meyer (1989), however, cautioned that cover crops may also deplete the soil moisture necessary for grain production in semi-arid areas while Jeranyama *et al.* (1998), emphasized that they can also compete for light and nutrients with the revenue crop. Strategies for water conservation in soil cultivated for crop production should include selection for those green manure cover crops that enhance water use efficiency.

Table 7.2. The Effect of N and P Fertilizer on the Yield of Maize (kg grain ha^{-1}) in the short rains season in Eastern Kenya

Treatment	NDFRC Katumani	Ithookwe Sub-Station	Makava Farm	Kyengo Farm	Mutua Farm
Control	2436	2416	480	590	497
N	3474	3481	918	3860	1993
N+P*	3759	4304	1665	4540	3150
LSD (P<0.05)	859	779	376	416	450

Sources: Okalebo, 1987; Probert and Okalebo, 1992
*Means of P application rates of 20, 40 and 60 kg P/ha, apart from Mutua Farm where rates were only 20 and 40 kg P/ha.
The LSD values are for comparing the control or the N treatments with N + P treatment.

Legumes are very important in African cropping systems. As pointed out earlier in this chapter they are often not only intercropped with cereals but are also grown as sole crops in cereal-legume rotations. Legumes are a major source of protein, particularly to smallholder farmers (Karanja and Wood, 1988). The commonly grown legumes in East and Southern Africa are common beans, cowpeas, pigeonpeas, bambara nuts and groundnuts. Through rotations legumes serve as a break crop against root diseases and also contribute to residual soil N (through decay of roots, nodules and leaf litter) for subsequent cereal crops (Nadar and Faught, 1984a). At Kyengo Farm (Wamunyu in Kenya) Simpson *et al.* (1992), reported that the cowpeas, pigeonpeas and lablab grown for two seasons in a rotation with maize left behind an additional 40 kg N ha^{-1} in the soil profile. This N quantity was only adequate to increase subsequent maize yield by 300-400 kg ha^{-1}. Perhaps the modest increase arose from the common practice in the region, where the legume's entire above ground biomass including some roots were removed from the soil and used as livestock feed, thus removing most of the N associated with the legume biomass. This reflects that the legumes alone will not solve the problem of sustaining soil fertility in semi-arid areas where both human and livestock populations are already exacting immense pressure on the land which has to continue to support their sustenance.

To determine the phosphate fertilizer requirement for cowpeas, a field trial was conducted at Kyengo Farm, Wamunyu (Kenya) during the 1988 short rains (SR). Phosphate was applied at 0, 20, 40 and 60 kg P ha^{-1} as single superphosphate. To study the residual effect of P fertilizer in a succeeding crop, cowpeas were replanted in 1989 long rains (LR) without further application of P; but only nitrogen was applied at 60 kg ha^{-1} and the second cowpea crop planted very close to the original rows.

The first cowpea crop experienced a wetter than average season (rainfall from planting to harvest was 415 mm at Kyengo Farm in 1988 SR). Cowpeas responded to phosphorus with grain yields increasing with rates of P (Table 7.3). In 1989 LR the rainfall was unevenly distributed with only 8 mm received after the end of April. On this sandy soil, moisture was limiting production due to poor storage, hence the residual effects of P added to the preceeding crop were not substantial (Table 7.3). Inadequate soil moisture reserves do not favour the dissolution of fertilizer in soils, and thus limit plant uptake.

Table 7.3. The effect of N and P Fertilizers on the Yield of Cowpeas at Kyengo Farm, Wamunyu (Kenya) in the 1988 short rains (SR) and the 1989 long rains (LR)

Treatment	1988 SR Grain (kg ha^{-1}) oven-dry	1989 LR Grain (kg ha^{-1}) oven-dry
Control	1010	98
N	1100	248
N+P*	2240	375
LSD (P<0.05)	413	96

Source: Probert and Okalebo, 1992
* Means of P application rates of 20, 40 and 60 kg ha^{-1}
LSD's are for comparing the N or the control treatments with N+P.

Crop-Livestock Interactions in Mixed Farming Systems

This section presents an integrated view of nutrient cycling in selected mixed farming systems of East and Southern Africa with some examples also drawn from West Africa to illustrate some fundamental characteristics of systems common in Africa. First, a general view of crop-livestock interactions is presented to highlight possible benefits, synergies and problems arising from interaction of crop and livestock enterprises within semi-arid settings.

Characteristics of mixed crop-livestock farming systems in semiarid zones

Mixed crop-livestock farming systems are characteristic of large areas of Africa (Allan, 1965; UNESCO, 1979). Cattle are the most widely used livestock for cultivation in most parts of Africa while in India both cattle and buffaloes are used as sources of draft power. In most of sub-Saharan Africa, animal power for cultivation has been introduced during the present century unlike for example, in North Africa where animal traction has been in use since the time of the Egyptian Pharaohs. Domestic animals (cattle, camels, goats, sheep, horses, mules and donkeys) have played an outstanding and central role in the entire history of mankind by providing food, fuel, manure, transport and clothing.

Livestock farming is a necessary complement to crop cultivation in many mixed farming systems and a key factor in the ecological balance, as well as an important safeguard against risk for the farming household. The importance of animal products in the balance of seasonal fluctuations of food availability from other sources, or in the case of total crop failure should not be underestimated. The goat, for example, often called the poor man's cow, and blamed for destroying the environment (because it is the last one to be seen when all else has succumbed to drought) does in fact have an important function in the survival of a large number of the rural population in East and Southern Africa through provision of milk and timely meat supplies following a drought. The increase in agricultural productivity through the use of animal draught power and the provision of manure are indirect effects but very critical inputs to enhancing social security and soil fertility for the smallholder farmer

The role of livestock in improving soil fertility and productivity

In many African countries, fertilizer prices have escalated due to the removal of subsidies as part of government structural adjustment programs. One of the outcomes of such policies is the greatly reduced use of this input in agricultural production. Instead, livestock manure is the main input for improving soil fertility particularly in semi-arid regions and has potential to improve crop yields considerably. This has been shown in several studies and reviews (Haque, 1993; Probert *et al.* 1995; Murwira *et al.*, 1995;) and for humid and sub-humid areas of East Africa (Kimani *et al.*, 1999; Lekasi *et al.*, 1998; Lekasi *et al.*, 2001).

The demonstrated benefits of manure include increase in soil pH, water holding capacity, hydraulic conductivity, infiltration rate and decreased bulk density. Manure can be an important source of nutrients, especially nitrogen (N), phosphorus (P) and potassium (K). The quantities of manure available are, however, often inadequate to maintain soil fertility and crop yields. The quality is also often poor. This can, however, be improved. Results of a survey of farmer practices in the Masvingo Province of Zimbabwe showed that a majority (86%) of surveyed farmers mixed woodland leaf litter with manure or with manure and fertilizer before application to crop fields (Nyathi, 1997). In the short term, manure forms a reserve pool of mineralizable nutrients that will be available for plant uptake in future seasons. In general, manure has the long-term effect of raising soil organic matter levels.

One ecosystem level study of nutrient cycling which has been documented is the communal area farming system (CAFS) in Zimbabwe which is a low input agro-pastoral system confined to the peasant farming sector. Swift *et al.* (1989). gave a description of CAFS as interaction between the grazing and arable sub-systems centered on the role of cattle to transfer nutrients from the grazing lands to the arable fields in the form of manure. Detailed nutrient transfers for the CAFS model are shown in Figure 7.1. Other inputs and flows, which contribute to soil fertility, are termitaria soil, leaf litter and household compost (Nyathi, 1997). Little, if any, of the crop residues produced are incorporated directly into soil. The greatest potential for losses of nutrients in the CAFS is in the arable fields (6 - 42 kg N ha^{-1}), through leaching, and N volatilisation from stored manure (1 - 6% of total N), (Figure 7.2, Murwira *et al.* 1995). The manures from these farming systems have been noted to be of poor quality and mineralize little nitrogen in the short term, but the potential is higher if residual effects are considered (Murwira and Kirchmann, 1993).

Figure 7.1. Utilization of locally derived fertilizers by farm households in Mutoko Communal Area, Zimbabwe. Data are amounts in kg ha^{-1} transferred between different sources and links for clarity some minor transfers have been omitted,thus numbers may not seem to add up

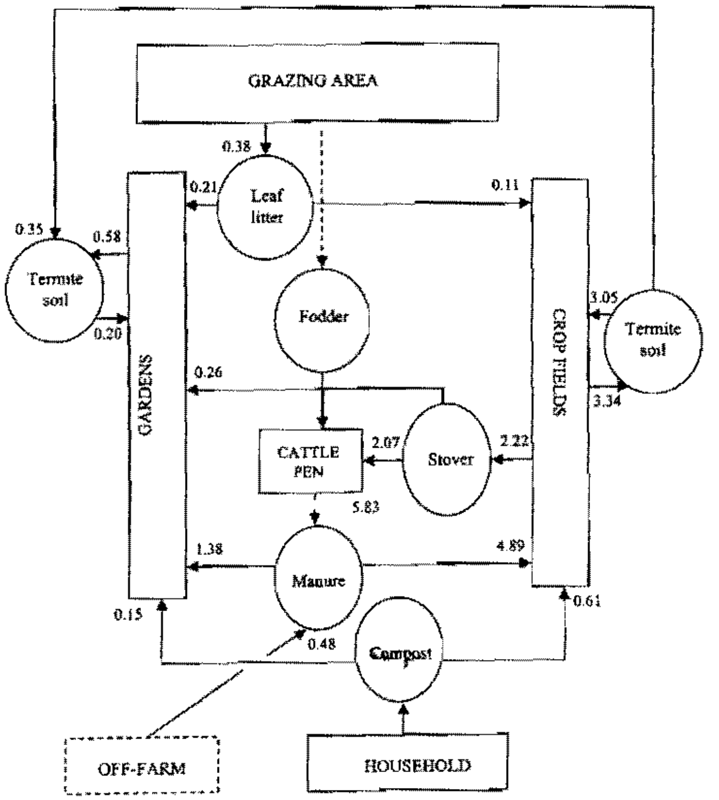
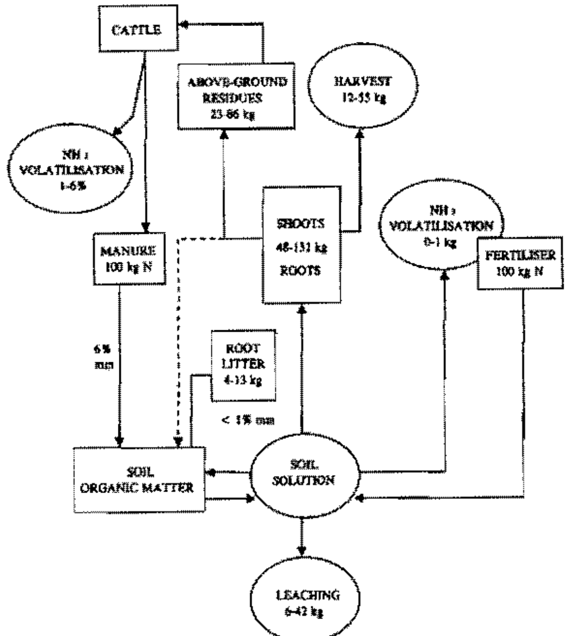


Figure 7.2. Nitrogen fluxes in an animal-plant-soil system of a communal area farm in Zimbabwe. The data are ranges of measured variables detected in applications of zero to 100 kg N of fertilizer as manure, inorganic N or as a mixture. Min indicates N mineralization



Source (Murwira *et al.*, 1995)

Manure is generally a scarce commodity on most farms. The amounts of manure available to a farmer is dependent on several factors such as herd size, its management system, ownership patterns, and for farmers with no livestock in semi-arid areas, the existence of manuring contracts. Manure production is also dependent upon seasonal differences and rainfall conditions, which determine availability of fodder. Manure production especially from unimproved livestock breeds in free-range grazing, open systems is generally low although highly variable. Production levels of 1 ton ha^{-1} yr^{-1} per animal for unimproved local breeds in a maize-livestock system have been reported for semi-arid parts of Eastern Kenya and Southern Zimbabwe (Scoones, 1990; Probert *et al.*, 1992). For the same regions of Kenya, Ockwell *et al.*, (1991), estimated manure levels as high as 2.5 tons ha^{-1} yr^{-1}. Livestock in this system graze in crop fields once harvested and in designated grazing areas.

Despite the low levels of manure produced from farms, recommended manure input levels are often between 10 to 15 t ha^{-1} yr^{-1} in semi-arid areas and appear to be lowered as rainfall conditions improve (Table 7.3). Actual application rates by farmers are far much lower. The manure used in trial recommendations often emanates from feedlots and ranches with higher feed quality and supply than communal areas. The quality of pen manure from livestock in communal areas is highly variable, with N levels as % of DM ranging from 0.46 to 1.98% (Mugwira and Mukurumbira, 1985; Tanner and Mugwira, 1984; Mureithi *et al.*, 1994; Lekasi *et al.*, 2001). Such levels are far lower than N contents found in manures derived from feedlot cattle or from ranch cattle with supplements. In addition, much of the communal area cattle manure contains high fractions of sand (Khombe *et al.*, 1992). N levels also vary between seasons as a consequence of changes in the quality and availability of fodder, this being a function of season feed quality.

Table 7.4. Recommended rates of manure application for field crops on sandy soils of Zimbabwe

Source	Area and Type of Soil	AEZ	Recommendation
Grant (1981)	Alvord (Makoholi) granite sandveld	IV	40 t ha^{-1} of manure every 4 years
Cackett (1960)	Matopos granite sandveld	IV	15-20 t ha^{-1} manure per year
Grant (1976; 1981)	Kwekwe Communal Area granite sandveld	III	10 t ha^{-1} manure + 120 kg N ha^{-1}
Johnson (1962)	Chiweshe Communal Area granite sandveld	II	5 t ha-1 manure + 191 kg ha^{-1} urea at 6 weeks after planting
Rodel *et al.* (1980)	Henderson Research Station granite sandveld	I	4.5 t ha^{-1} manure + 70 kg ha^{-1} P205 + 60 kg ha^{-1} K20

Adapted from Mugwira and Murwira, 1997.
All sites are on granitic sandy soils: Sites in Masvingo are on abandoned or fallowed sands.
AEZ = Agroecological zone according to annual rainfall as follows: AEZ I = >1000 mm; AEZ II = 800 to 1000 mm; AEZ III = 650 to 800 mm; AEZ IV = 450 to 650 mm per annum

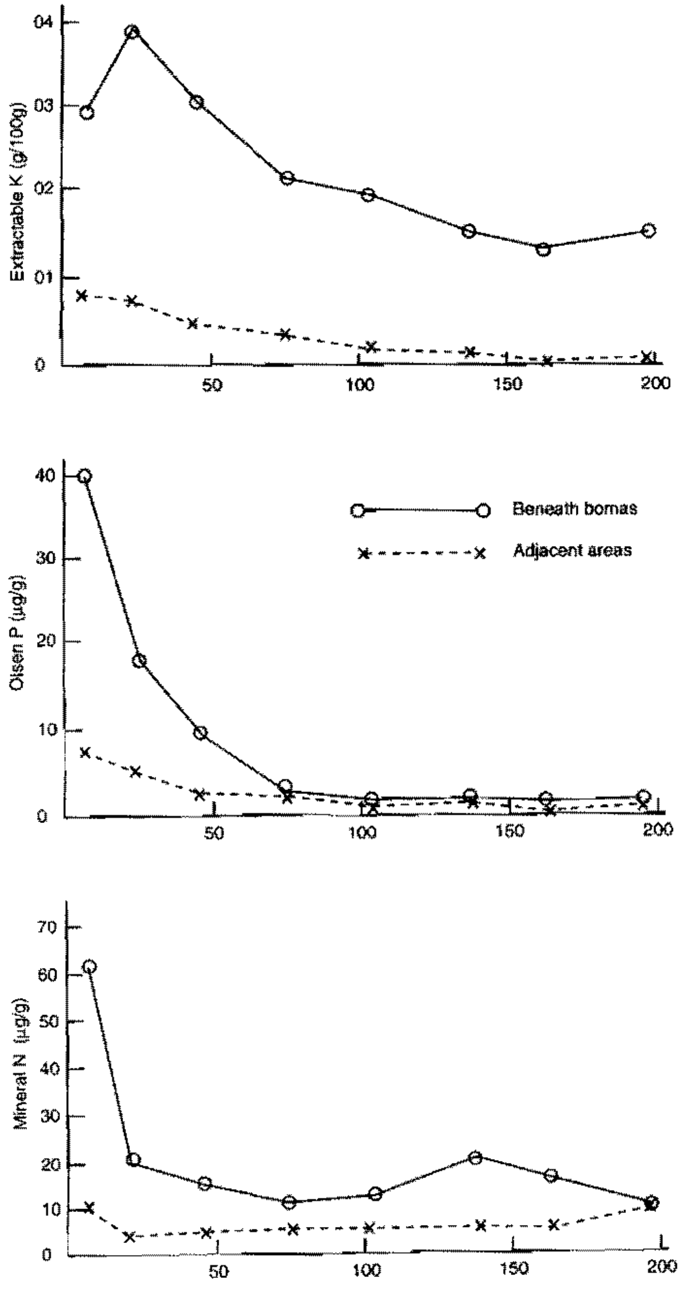
Inadequate feed is a major constraint to most farmers especially those with stall-fed animals. The planting of fodder species particularly Napier grass *(Pennisetum purpureum)* is, therefore, a recommended practice on farms with zero-grazed dairy production systems. The production of fodder can be enhanced by the use of fertilizers. Bayer (1990), showed that with the application of fertilizer at 100 kg N plus 20 kg P ha^{-1}, Napier grass can yield 25 t ha^{-1} dry matter with 1.5% N and 0.30% P content. Typical yield of Napier grass without fertilization is less than 10 t ha^{-1}. The use of fertilizers is crucial in increasing feed supply and its quality. Mineral fertilizers, however, continue to be costly and unavailable to most farmers. The small amounts of these fertilizers that are available need to be used judiciously, by combining them with organic sources of nutrients such as N-fixing legumes, crop residues and manures.

One way to improve manure quality (i.e., nutrient content) is to supplement livestock feed with nutrient rich concentrates and fodder (Lekasi *et al.*, 2001). Many trees and shrubs used in agroforestry systems can provide fodder that can improve the quality of manure. For example, Delve *et al.*, (1998) showed that N content in manure can be raised from 0.9 to 1.7% if the grass fed to zero-grazed dairy cows were supplemented with fresh leaves of *Calliandra calothrysus*, a leguminous shrub with fodder value, at 15% of the total dry matter offered to the animal. While this improvement in manure quality through fodder supplementation is possible in feedlot systems, it is more difficult to quantify under grazing systems in rangelands common in semi-arid regions.

The challenge in any production system whether it involves livestock or not, is how to minimize nutrient losses and improve the efficiency of nutrient cycling. In systems involving livestock, nutrients can be lost via several avenues. An important one in traditional livestock enclosures (bomas) is the leaching and loss of nutrients from the surface soil as shown by the profiles of N, P and K of soil under 'bomas' from studies in semi-arid Eastern Kenya (Figure 7.4). For both mineral N and K, the enrichment extended to the full sampling depth of 2 m, but for P the effect was restricted to the surface layers as expected from its low mobility (Probert *et al.*, 1992). This leaching of nutrients from 'poor' storage shows an accumulation of nutrients beneath the 'bomas', which act as sinks for nutrients that have been removed from farm soils or croplands and are no longer accessible unless mined.

The rate of mineralization of N is faster, and losses from volatilization are greater from animal excreta than from plant litter. This makes ammonia volatilization a major loss of N from manure. Vertregt and Rutgers (1988) estimated that ammonia losses accounted for four times as much of the N excreted from animals compared with N losses from decaying herbage from pasture. Other avenues of loss are in use of manure as fuel wood especially in the densely populated areas (e.g., highlands of Ethiopia) and as material for plastering of houses (for example Kenya, Zimbabwe, South Africa and Zambia). Data on losses of nutrients during manure management in smallholder farming systems is generally lacking. Recent estimates, however, suggest that up to 60% N and 10% of P can be lost through poor manure management (Shepherd *et al.*, 1995). Although there are uncertainties in these estimates, accurate measurement particularly in the context of intensive dairy farming with high manure fluxes are still required and the need to device appropriate management practices that minimize losses remains unfulfilled. Since 40 to 60% of the N excreted by livestock (ruminants) is in the form of urine, the potential for nutrient loss can be greater under stall-feeding than field grazing extensive systems since only manure is captured and applied to crop fields (Powell and Williams, 1995). More intensive stall-feeding systems of livestock could, therefore,

Figure 7.4. The accumulation of nitrogen, phosphorus and potassium beneath bomas



(Data plotted are means for seven bomas sampled from Mwala Division, Machakos District, Kenya
Adapted from Probert *et al.* (1992)

increase nutrient losses and jeopardize long-term soil productivity if technologies are not available that capture and recycle the nutrients voided by the animals.

The nutrient flows and leakages of livestock-crop-based systems are little understood. Ransom *et al.*, (1995) observed that 72% of all maize stover produced in the maize-coffee-livestock based system in Embu (Central Kenya) was fed to livestock. Nitrogen and phosphorus removal through grain from this system averaged 50.7 kg ha^{-1} and 8.5 kg ha^{-1}, respectively, and 4.9 kg ha^{-1} and 1.2 kg ha^{-1}, respectively through stover. Nutrients contained in crop residues (e.g. maize stover) may not be lost from the system if fed to livestock or used as bedding materials in livestock pens which will allow its recycling with manure. The success of this would, however, be dependent on the other demands for crop residues such as use as fodder, for fencing, roofing or fuel.

Loss of nutrients through off-farm sale of manure can be a major avenue for losses of nutrients (Shepherd *et al.*, 1995). The net effect on soil fertility is a negative nutrient balance at the farm level. This can only be made positive where nutrients imported in feed concentrates or harvested off-farm by grazing animals outweigh nutrients exported in the sale of livestock and its products. In zero-grazing systems, the use of nutrient-rich feed concentrates can balance nutrient losses.

In farming communities where some farmers keep livestock and others do not, grazing of livestock or sale of grass and crop residues from those without to those with livestock can result in overall nutrient imbalances at the community level in favor of those with livestock. This is demonstrated by Reynolds and de Leeuw (1995), in livestock-mixed farming systems in the Kaloleni area of the sub-humid coastal belt of Kenya. Farms with grazing cattle showed a net positive N balance at the expense of non-cattle owning farms in the area, provided there was unrestricted access to all on-farm feed resources. As a consequence, Reynolds and de Leeuw (1995), estimate that farms with access are able to provide a net input of 25 kg ha^{-1} for soil fertility and plant growth which is sufficient to maintain maize grain of 1.8 t ha^{-1}. A slightly lower net input of N ha^{-1} can be achieved in the semiarid zone given that it is slightly more arid than the subhumid zone and the two zones are sometimes difficult to separate.

Socio-economic factors that affect the use of manure

Most research on nutrient cycling to date has focused on its biological dimensions. Scoones and Toulmin (1985), pointed out that social and economic processes mediate the volume, pattern and distribution of different nutrient flows. Access to manure will be affected by a range of factors such as size of the herd and access to manure exchange contracts. The quantity of manure will depend on availability of fodder resources and access to grazing land, which in turn is affected by tenure rights. Manure quality will depend on the type of fodder resource, seasonal rainfall and feeding management.

The application of manure to arable areas will depend on availability of labor and transport (from livestock pens to the field), or the existence of arrangements whereby herders pen their livestock on farmer's fields. Availability of transport depends on access to carts and draught animals (Nyathi, 1997). Access to manure from livestock owners will be dependent on established mutually acceptable exchange relationships between crop and livestock farmers. The effective use of available nutrients for crop growth will be dependent on careful management and timing of manuring in relation to sowing and weeding the crop. The nutrient pools and flows of agro pastoral systems such as the ones presented in Figure 7.2 become much more complex once these issues are taken into account. Issues of resource quality and access affect the nutrient stocks within any one of the nutrient pools identified, while issues of labor availability, management skill, access to cash and availability of transportation influence the flows between nutrient pools.

In summary, the overall use of manure as a source of nutrients for crops is dependent on a range of socio-economic factors that are likely to vary from place to place in Eastern and Southern Africa but, which in general, are little understood when compared to ecological conditions.

References

Abel, N.J.O., Drinkwater, M.J., Ingram, J., Okafor, J. and Prinsley, R. (1989) *Agroforestry for Shurugwi, Zimbabwe: a report of an appraisal exercise for agroforestry research and extension.* Technical paper 277. Commonwealth science council, London 229 pp.

Allan, W. (1965) *The African husbandman.* Oliver and Boyd, Edinburgh, UK. 485 pp.

Anderson, I.P., Brinn, P.J., Moyo, M. and Nyamwanza, B. (1993) *Physical Resource Inventory of the Communal Lands of Zimbabwe- An Overview.* Bulletin 60, Natural Resources Institute, Chatham, United Kingdom.

Arnon, I (1972) *Crop production in dry regions.* Leonard Hill, London.

Badaruddin, M. and Meyer, D.W. (1989) Water use by legumes and its effect on soil water stress. *Crop Science.* **29:** 1212-1216.

Banks, P.F. (1982) The potential of agroforestry on forest land in the Sebungwe region. *Zimbabwe Agricultural Journal.* **79:** 161-163.

Barnes, D.L. (1979) Cattle ranching in the semiarid savannas of east and central Africa. In: Walker, B.H. (ed.). *Management of Semi-Arid Ecosystems,* pp 9-54. Elsevier Publications, Amsterdam.

Bayer, W. (1990) Napier grass - a promising fodder for smallholder livestock production in the tropics. *Plant Res. Dev.* **31:** 103-111.

Beukes, D.J. (1997) *Perspective on the soil acidity problem in South Africa.* Proceedings of the Soil Acidity Initiative, Ermelo, Mpumalanga RSA (in press).

Birch, H.F. (1958) The effect of soil drying on humus decomposition and nitrogen availability. *Plant and Soil.* **10:** 9-31.

Brady, N.C. (1990) *The Nature and Properties of Soil.* Macmillan Publishing Company, New York.

CABI (1994) Soil fertility Research in East Africa. An annotated bibliography. *CAB Abstracts.* Wallingford, CAB International.

Campbell, B.M, Clarke, J.M. and Gumbo, D.J. (1991a) Traditional agroforestry practices in Zimbabwe. *Agroforestry Systems.* **14:** 99-111.

Campbell, B.M., Swift, M.J., Hatton, J.C. and Frost, P.G.H. (1988) Small scale vegetation pattern and nutrient cycling in Miombo woodland. In: Verhoeven, J.T.A., Heil, G.W. and Werger, M.J.A. (Eds.) *Vegetation Structure in Relation to Carbon and Nutrient Economy,* pp 69-85. SPB Academic Publishing, The Hague, The Netherlands.

Campbell, B.M., Vermeulen, S.J. and Lynam, T. (1991b) *Value of trees in the smallscale farming sector of Zimbabwe.* IDRC Publications, Ottawa.

Campbell, B.M., Frost, P.G.H., Kirchman, H. and Swift, M.J. (1997) Nitrogen cycling and management of soil fertility in small-scale farming systems in North-Eastern Zimbabwe. *Journal of Sustainable Agriculture* (in press).

Carter, S. (1992) *Soil fertility management in Mutoko communal area, Zimbabwe.* Tropical Soil Biology and Fertility Programme, UNESCO Nairobi, Kenya. 78 pp.

Coe, R. (1994) Through the looking glass: Ten common problems in alley cropping research. *Agroforestry Today.* 6: 9-11.

Davidson, N. and Galloway, R. (eds.). (1993) Productive use of saline land. Proceedings of a workshop held at Perth, Western Australia, 10-14 May, 1991. ACIAR Proceeding number 42. 124 pp.

Delve, RJ, Tanner, JC, Kimani, S.K, Giller, K.E., Cadisch, G. and Thorne, P.J. (1998) Effects ofdietary nitrogen source fed to steers on faecal nitrogen, its mineralisation, and the vegetative responses in maize to the incorporation of the faeces in soil. 1999. In: CIMMYT and EARO 1999. *Maize production Technologies for the future: Challenges and Opportunities.* Proceedings of the 6th Regional maize conference for Eastern and Southern Africa. Addis Ababa, Ethiopia September 21-25, 1998 . pp. 282-285.

Dhliwayo, D.K.C., Sithole, T. and Nemasasi, H. (1998) Soil acidity - Is it a problem in maize-based production systems of the communal areas of Zimbabwe. pp 217-221. In: Waddington, S.R., Murwira, H.K., Kumwenda, D.T., Hikwa, D. and Tagwira, F. (eds.). *Soil Fertility Research for Maize-Based Farming Systems in Malawi and Zimbabwe.* Proceedings of the Soil Fert Net Results and Planning Workshop held from 7 to 11 July 1997 at Africa University, Mutare, Zimbabwe and CIMMYT-Zimbabwe, Harare. 312pp.

du Preez, D.R., Gunton, C. and Bate, G.C. (1983) The distribution of macronutrients in a broad leaf woody savannah. *South African Journal of Botany.* **2:** 236-242.

Edje, O.T. (1979) Cropping systems for small farmers. *Bunda College of Agriculture Bulletin.* **10:** 10-13.

Elwell, H.A. and Stocking, M.A. (1988) Loss of nutrients by sheet erosion is a major farming cost. *Zimbabwe Science News.* **22:** 83-85.

English, J., Tiffen, M. and Mortimore, M. (1994) Land Resource Management in Machakos District, Kenya, 1930-1990. *World Bank Environment Paper No. 5*. Washington DC.

FAO. (1986) African Agriculture. The next 25 years. The land resource base. Annex II: pp 116. FAO, Rome, Italy.

FAO. (1971) Improving Soil Fertility in Africa. *FAO Soils Bulletin number 14*. Food and Agriculture Organisation of the United Nations, Rome, Italy.

Farina, M.P.W. (1997) *Subsoil acidity and its management in South Africa*. Proceedings of the Soil Acidity Initiative, Ermelo, Mpumalanga RSA (in press).

Fisher, N.M. (1977) Experiments with maize-bean and maize-potato mixed crops in an area with two short rainy seasons in the highlands of Kenya. In : Keswani, C.L. and Ndunguru, B.J. (Eds). *Intercropping in Semi-arid Areas*. Report of a symposium held at Morogoro, Tanzania, 10-12 May 1976.

Foy, C.D. (1988) Plant adaptation to acid aluminium toxic soils. *Comm. Soil Sci. & Plant Analysis*. **19:** 959-987.

Francis, C.A. and Sanders, J.H. (1978) Economic analysis of bean and maize systems: monoculture versus associated cropping. *Field Crops Research*. **1:** 319-335.

FSRU (Farming Systems Research Unit). (1993) Soil fertility management by small holder farmers. A participatory rapid appraisal in Chivi and Mangwende areas, Zimbabwe. FSRU, DR and SS (Department of Research and Specialist Services), Harare, Zimbabwe.

Georgiadis, N.J. (1989) Microhabitat variation in an African savannah: effects of woody cover and herbivores in Kenya. *Journal of Tropical Ecology*. **5:** 93-108.

Giller, K.E. and Wilson, K.J. (1991) *Nitrogen fixation in tropical cropping systems*. CAB International, Wallingford, Oxon OX10 8DE, UK. p313.

Grant P.M. (1967) The fertility of sandveld soil under continuous cultivation. I. The effect of manure and nitrogen on the nitrogen status of soil. *Rhodesia Zambia Malawi Journal of Agricultural Research*. **5:** 117-128.

Grant, P.M. (1970) Restoration of productivity of depleted sands. *Rhodesia Agricultural Journal*. **67:** 34-37.

Grant, P.M. 1971. Lime as a factor in maize production. *Rhodesia Agricultural Journal*. **68:** 34-39.

Grant, P.M. (1976) Peasant farming on infertile sands. *The Rhodesia Science News*. **10:** 252-254.

Grant, P.M. (1981) The fertilization of sandy soils in peasant agriculture. *Zimbabwe Agricultural Journal*. **78:** 169-175.

Guar, A.C., Neelakanan, S. and Dargan, K.S. (1984) *Organic manure*. Indian Council of Agriculture Research, New Delhi, India.

Guttierez, V., M. Infante and A. Pinchinot. (1975) *Situacion del cultivo de frijol en America Latin*. C.I.A.T. Cali, Colombia.

Haque, I. (1993) Nutrient management and feed improvement in crop livestock systems of Sub-Saharan Africa: present status and future outlook. ILCA Environmental Sciences Division Working Document No. 28. ILCA (International Livestock Centre for Africa), Addis Ababa, Ethiopia.

Hesterman, O.B., Griffin, T.S., Williams, G.H., Harris, I. and Christenson, D.R. (1992) Forage legume-small grain intercrops: Nitrogen production and response of subsequent corn. *Journal of Production Agriculture*. **5:** 340-348.

Hikwa, D., Murata, M., Tagwira, F., Chiduza, C., Murwira, H. Muza, L. and Waddington, S.R. (1998) Performance of green manure legumes on exhausted soils in northern Zimbabwe: A Soil Fertility Network Trial. pp 81-84. In: Waddington, S.R., Murwira, H.K., Kumwenda, D.T., Hikwa, D. and Tagwira, F. (eds.). *Soil Fertility Research for Maize-Based Farming Systems in Malawi and Zimbabwe.* Proceedings of the Soil Fert Net Results and Planning Workshop held from 7 to 11 July 1997 at Africa University, Mutare, Zimbabwe and CIMMYT-Zimbabwe, Harare. 312pp.

Ingram, J. (1990) The role of trees in maintaining and improving soil productivity, a review of the literature. In: *Production: Economic Implications*, pp 243-303. Commonwealth Science Council, London.

Jama, B.A, Swinkels, R.A. and Buresh R.J. (1997) Agronomic and economic evaluation of organic and inorganic sources of phosphorus in western Kenya. *Agronomy Journal*. **89:** 597-604.

Jeranyama, P., Hesterman, B. and Waddington, S.R. (1998). The impact of legumes relay intercropped into maize at Domboshawa, Zimbabwe. pp 31-34. In: Waddington, S.R., Murwira, H.K.

Kang, B.T., Wilson, G.F. and Sipkens, L. (1981) Alley cropping maize (*Zea mays* L.) and Leucaena (*Leucaena leucocephala* LAM) in southern Nigeria. *Plant and Soil*. **63:** 165-179.

Karanja, N.K. and Wood, M. (1988) Selecting *Rhizobium phaseoli* strains for use with beans (*Phaseolus vulgaris* L.) in Kenya: tolerance of high temperature and antibiotic resistance. *Plant Soil*. **112:** 15-22.

Keating, B.A., Siambi, M.N. and Wafula, B.M. (1992) The impact of climatic variability on cropping research in semiarid Kenya between 1955 and 1985. In: Probert, M.E. (ed.) *Sustainable Dryland Cropping*. ACIAR Proceedings No. 41, Canberra, Australia, 16-25.

Kellman, M. (1979) Soil enrichment by neotropical savannah trees. *Journal of Ecology*. **67:** 565-577.

Kelly, R.D. (1973) A comparative study of primary productivity under different kinds of land use in southern Rhodesia. Ph D Thesis, University of London, London, UK.

Kelly, R.D. and Walker, B.H. (1976) The effects of different forms of land use on the ecology of a semi-arid region in South-Eastern Rhodesia. *Journal of Ecology*. **64:** 553-576.

Khombe, C.T., Dube, I.A. and Nyathi, P. (1992) The effects of kraaling and stover supplementation during the dry season on body weights and manure production of mashons steers in Zimbabwe. *African Livestock Research*. **1:** 18-23.

Kimani, S.K. (1994) Studies on maize-bean mixtures in a semi arid area of eastern Kenya. PhD Thesis. University College Dublin, Ireland.

Kimani, S.K., Mangale, N., Lekasi, J.K., Wamuongo, J.W., Gichuru, M. and Palm, C. (1999) Nitrogen and carbon mineralisation of some manures produced under different management systems in central Kenya. *E. Afr. Agric. For. J.* **65(1):** 1-5.

Kilewe, A.M. (1987) Prediction of erosion rates and the effects of topsoil thickness on soil productivity. Ph D Thesis, University of Nairobi, Nairobi, Kenya.

Knoop, W.T. and Waker, B.H. (1985) Interactions of woody and herbaceous vegetation in a Southern African savannah. *Journal of Ecology*. **73:** 235-253.

Lekasi, J.K., Tanner, J.C., Kimani, S.K. and Harris P.J.C. (1998) *Manure management in the Kenya highlands: Practices and Potential.* Emmerson Press, Kenilworth, UK.

Lekasi, J.K., Tanner, J.C., Kimani, S.K. and Harris P.J.C. (2001) *Managing manure to sustain smallholder livelihoods in the East African Highlands.* Emmerson Press, Kenilworth, UK.

Lugo, A.E. and Brown, S. (1993) Management of tropical soils and sinks of atmospheric carbon. *Plant and Soil.* **149:** 27-41.

Malcolm, C. (1992) Use of halophyte forages for rehabilitation of degraded lands. pp 1-21. In: *International workshop on halophytes for reclamation of saline wastelands and as a resource for livestock: problems and prospects.* UNEP (Nairobi)/The University of Adelaide, south Australia, 22-27 November, 1992, Nairobi, Kenya.

Mashali, A.M. (1997) Land degradation with focus on salinization and its management in Africa. Paper Presented at the Workshop on Expert Consultation on Integrated Soil Management for Sustainable Agriculture and Food security in southern and east Africa, Harare, Zimbabwe, 8-12 December 1997.

Marimi, A.M. (1975) *The effect of fertilizer nitrogen and phosphorus on maize yields in a marginal potential zone of Eastern Kenya.* Research report, Dryland Farming Research Station, Machakos, Kenya.

McCown, R.L. and Jones, R.K. (1992) Agriculture of semiarid eastern Kenya: problems and possibilities. In: Probert, M.E. (ed.) *Sustainable Dryland Cropping.* ACIAR Proceedings No. 41. Canberra, Australia, 8-14.

Mead, R. and Willey, R.W. (1980) The concept of a land equivalent ratio and advantages in yield from intercropping. *Experimental Agriculture.* **16:** 217-228.

Mugwira, L.M. and Mukurumbira, L.M. (1984) Comparative effectiveness of manures from the communal areas and commercial feedlots as plant nutrient sources. *Zimbabwe Agricultural Journal.* **81:** 241-250.

Mugwira, L. and Mukurumbira, L. (1985) Nutrient supplying power of different groups of manure from communal areas and their effect on plant growth and maize grain yields. *Zimbabwe Agricultural Journal.* **83:** 25-29.

Mugwira, L and Murwira, H.K. (1997) The use of cattle manure to improve soil fertility in Zimbabwe: past, current and future research needs. 33pp. *Soil Fertility Network Research Results Paper Number 2.* CIMMYT, Harare, Zimbabwe.

Mukurumbira, L. and Nemasasi, H. (1998) Micronutrients in the maize-based system of the communal areas of Zimbabwe. pp 229-232. In: Waddington, S.R., Murwira, H.K., Kumwenda, D.T., Hikwa, D. and Tagwira, F. (eds.). *Soil Fertility Research for Maize-Based Farming Systems in Malawi and Zimbabwe.* Proceedings of the Soil Fert Net Results and Planning Workshop held from 7 to 11 July 1997 at Africa University, Mutare, Zimbabwe and CIMMYT-Zimbabwe, Harare. 312pp.

Muller-Samann, K.M. and Kotschi, J. (1994) *Sustaining Growth: Soil Fertility Management in Tropical Smallholdings.* Margraf, Verlag, Weikershein, Germany.

Mureithi, J.G., Taylor, RS and Thorpe, W. (1994) The effects of alley cropping with *Leucaena leucocephala* and of different management practices on the productivity of maize and soil chemical properties in lowland coastal Kenya. *Agroforestry Systems.* **27:** 31-51.

Murwira, H.K., Swift, M.J. and Frost, P.G.H. (1995) Manure as a key resource in sustainable agriculture. p. 131-148. *In* Powell, L.M., Fernandez-Rivera, S., Williams, O.T., and Renard, C. (eds) *Livestock and sustainable nutrient cycling in mixed farming systems of sub-Saharan Africa.* Volume II. Technical papers. Proceeding of an International Conference held in Addis Ababa, Ethiopia, 22-26 Nov. 1993. International Livestock Centre for Africa, Addis Ababa, Ethiopia.

Murwira, H.K and Kirchmann, H. (1993) Nitrogen dynamics and maize growth in a Zimbabwean soil under manure fertilization. *Communications in Soil and Plant Analysis.* **22:** 1924-1938.

Murwira, H.K. (1993) Nitrogen Dynamics in a Zimbabwean Granite Derived Sandy Soil under Manure Fertilization. Ph.D. Thesis, 1993. University of Zimbabwe, Harare, Zimbabwe.

Mushambi, C.F., Nehanda, G., Mugwira, L.M. and Nzuma, J.K. (1997) Integrated soil management for sustainable agriculture and food security in Zimbabwe. In: Paper presented at the Workshop on Expert Consultation on Integrated Soil Management for Sustainable Agriculture and Food security in southern and east Africa, Harare, Zimbabwe, 8-12 December 1997.

Myers, R.J.K., Palm, C.A., Cuevas, E., Gunatilleke, I.U.N. and Brossard, M. (1994) The synchronization of nutrient mineralization and plant nutrient demand. In: Woomer, P.L. and Swift, M.J. (eds.) *The Biological Management of Tropical Soil Fertility.* John Wiley and Sons, Chichester, UK.

Nabhan, H. (1997) Land degradation and its impact on food security, with focus on fertility decline and its management. In: Paper presented at the Workshop on Expert Consultation on Integrated Soil Management for Sustainable Agriculture and Food security in Southern and East Africa, Harare, Zimbabwe, 8-12 December 1997.

Nadar, H.M. (1980) Intercropping under marginal rainfall conditions in Kenya. In: Keswani, C.L.and Ndunguru, B.J. (eds.) *Intercropping.* IDRC, 186e, Ottawa, Ontario, Canada, pp 50-55.

Nadar, H.M. and Faught, W.A. (1984a) Maize yield response to different levels of nitrogen and phosphorus fertilizer application. *East African Agriculture and Forestry Journal.* **44:** 147-156.

——(1984b) Effect of legumes on maize yield of associated and subsequent maize in intercropping and rotation systems without nitrogen fertilizer. *East African Agriculture and Forestry Journal.* **44:** 127-136.

Natarajan, M. (1989) Spatial arrangement of the component crops in developing intercropping systems: Some Concepts and Methodologies. In: Waddington, S.R., Palmer, A.F.E. and Edje, O.T. (eds.) *Research methods for cereal/legume intercropping: Proceedings of a workshop on research methods for cereal/legume intercropping in Eastern and Southern Africa.* CIMMYT Eastern and Southern Africa On-farm Research Network Report No. 17, sponsored by CMMYT, CIAT and Government of Malawi. Harare, Zimbabwe.

Natarajan, M. and Willey, R.W. (1985) Effect of row arrangement on light interception and yield in sorghum-pigeon pea intercropping. *Journal of Agricultural Science,* Cambridge. **104:** 263-270.

Natarajan, M. and Willey, R.W. (1986) The effects of water stress on yield advantages of intercropping systems. *Field Crops Research.* **13:** 117-131.

Natarajan, M. (1990) Spatial arrangement of the component crops in developing intercropping systems: Some concepts and methodologies. In: Waddington, S.R., Palmer, A.F.E. and Edje, O.T. (eds.) *Research methods for cereal/legume intercropping:* Proceedings of a workshop on research methods for cereal/legume intercropping in eastern and southern Africa. CIMMYT Eastern and Southern Africa On-farm Research Network Report No. 17, sponsored by CMMYT, CIAT and Government of Malawi. Harare, Zimbabwe.

Ngugi, D. (1988) *Agroforestry research project for the maize-livestock system in the unimodal upland plateau (Chipata and Kakete) in Eastern Province of Zambia.* AFRENA Report number 10, ICRAF, Nairobi, Kenya, 80 pp.

Nyathi, P. and Campbell, B.M. (1995) Interaction effect of tree leaf litter, manure and inorganic fertilizer on the performance of maize in Zimbabwe. *African Crop Science Journal.* **3(4):** 451-456.

Nyathi, P. (1997) Tree Leaf Quality Characteristics, Decomposition Patterns and the Effects of Leaf Litter on Sandy Soil Fertility and Maize Production in the Masvingo Province of Zimbabwe. Ph.D. Thesis, 1997. University of Zimbabwe, Harare, Zimbabwe.

Ockwell, A.P., Muhammad, L., Nguluu, S., Parton, K.A., Jones, R.K. and McCown, R.L. (1991) Characteristics of improved technologies that affect their adoption in the semiarid tropics of eastern Kenya. *Journal for Farming Systems Research-Extension.* **2:** 29-46.

Okalebo, J.R. (1987) A Study of the Effect of Phosphate Fertilizers on Maize and Sorghum Production in Some East African Soils. Ph. D. Thesis, University of Nairobi, Kenya.

Okigbo, B.N. (1978) *Cropping systems and related research in Africa.* AAASA Occasional Publication Series OT-1, 81 pp. Addis Ababa, Ethiopia.

Ong, C. (1994) Alley cropping - ecological pie in the sky. *Agroforestry Today.* **6:** 8-10.

Palm, C.A., Myers, R.J. and Nandwa, S.M. (1997) Combined use of organic and inorganic nutrient resources for soil fertility maintenance and replenishment. In: Buresh, R.J., Sanchez, P.A. and Calhoun, F. (eds.) *Replenishing Soil Fertility in Africa.* SSSA Special Publication number 51. SSSA, Madison, Wisconsin, USA.

Pereira, H.C., McCulloch, J.G., Dagg, M. and Kerfoot, O. (1962) Hydrological effects of changes in land use of some east African catchment areas. *East African Agriculture and Forestry Journal* 27 (Special issue).

Postgate, J. (1987) New studies in Biology. Nitrogen Fixation. 2nd edition. Edward Arnold. 73pp.

Powell, J.M. (1986) Manure for cropping. A case study from central Nigeria. *Experimental Agriculture.* **22:** 15-24.

Powell, J.M.. and Williams, T.O. (1995) An overview of mixed farming systems in sub-Saharan Africa. pp. 21-36. In: Powell, L.M., Fernandez-Rivera, S., Williams, O.T. and Renard, C. (eds) I. Volume II. Technical papers. Proceeding of an International Conference held in Addis Ababa, Ethiopia, 22-26 Nov. 1993. International Livestock Centre for Africa, Addis Ababa, Ethiopia.

Probert, M.E. and Okalebo, J.R. (1992) Effects of phosphorus on the growth and development of maize. In: Probert, M.E. (ed.) *Sustainable Dryland Cropping.* ACIAR Proceedings No. 41. Canberra, Australia, 55-62.

Probert, M.E.. Okalebo, J.R. and Jones, R.K. (1995) The use of manure on smallholders' farm in semiarid Eastern Kenya. *Experimental Agriculture.* **31:** 371-381.

Probert, M.E., Okalebo, J.R., Simpson, J.R. and Jones, R.K. (1992) The role of boma manure for improving soil fertility. In: Probert, M.E. (ed.) *Sustainable Dryland Cropping*. ACIAR Proceedings No. 41. Canberra, Australia, 63-70.

Ransom, J.K, Ojiem, J. and Kanampiu, F.K. (1995) Nutrient flux between maize and livestock in a maize-coffee-livestock system in Central Kenya. p. 411-419. In: Powell, L.M., Fernandez-Rivera, S., Williams, O.T. and Renard C. (eds.) *Livestock and sustainable nutrient cycling in mixed farming systems of sub-Saharan Africa*. Volume II. Technical papers. Proceeding of an International Conference held in Addis Ababa, Ethiopia, 22-26 Nov. 1993. International Livestock Centre for Africa, Addis Ababa, Ethiopia.

Rao, M.R., Ong, C.K. and Sharma, M.M. (1991) Productivity of annual cropping and agroforestry systems on a shallow Alfisol in semiarid India. *Agroforestry Systems*. **15**: 51-63.

Raven, J.A. (1985) Regulation of Ph and generation of osmolarity in vascular plants: A cost-benefit analysis in relation to efficiency of use of energy, nitrogen and water. *New Phytologist*. **101**: 25-77.

Reynolds, L. and P.N. de Leeuw. (1995) Myth and manure in nitrogen cycling: a case study of Kaloleni Division in Coast Province, Kenya. 509-521. In: J.M. Powell S. Fernandez-Rivera, T.O. Williams and C. Renard. (eds.) *Livestock and sustainable nutrient cycling in mixed farming systems of sub-Saharan Africa*. Vol. 2: technical papers. Proc. of an International Conference held in Addis Ababa, Ethiopia, 22-26 Nov. 1993. ILCA (International Livestock Centre for Africa). Addis Ababa, Ethiopia. 568 pp.

Rodel, M.G.W.; Hopley, J.D.H. and Boultwood, J.N. (1980) Effects of applied nitrogen, kraal compost and maize stover on the yields of maize grown on a poor granite soil. *Zimbabwe Agricultural Journal*. **77**: 229-232.

Russell, E.W. (1973) *Soil Conditions and Plant Growth*. 10th Edition. pp 284-326. Longman Group Ltd. London and New York.

SACCAR. (1997) Regional Research Priorities for Crop and Livestock Production. (Goldsworthy, P.R, Doto, A., de Jager, J., Nyathi, P. and Shumba, E. (eds.) *A Consultancy Report*, SACCAR (Southern Africa Centre for Co-operation in Agricultural Research), Gaborone, Botswana, January, 1997.

Salisbury, F.B. and Ross, C.W. (1992) *Plant Physiology*. Wadsworth, Belmont, California, USA.

Sanchez, P.A. (1976) *Properties and management of soils in the tropics*. A Wiley-Interscience publication.

Sanchez, P.A. and Salinas, J.G. (1981) Low input technology for managing Oxisols and Ultisols in tropical America. *Adv. Agron*. **34**: 280-406.

Sanchez, P.A. and Nicholaides, J.J. (1982) *Plant nutrition in relation to soil constraints in developing world*. Consultants Report, TAC Secretariate, FAO, Rome, Italy.

Sanchez, P.A. and Logan, J.J. (1992) *Myths and Science about the chemistry and fertility of soils in the tropics*. SSSA Special Publication number 29. Madison, Wisconsin, USA.

Sanchez, P.A., Shepherd, K.D., Soule, M.J., Place, F.M., Buresh, R.J., Izac, A.M.N., Mokwunye, A.U., Kwesiga, F., Ndiritu, C.G. and Woomer, P.L. (1997) Soil fertility replenishment in Africa: An investment in natural resource capital. In: Buresh, R.J., Sanchez, P. A. and Calhoun, F. (eds.) *Replenishing*

Soil Fertility in Africa. SSSA Special Publication Number 51. SSSA and ASA. Madison, Wisconsin, USA.

Sanders, D.W. (1991) International activities in assessing and monitoring soil degradation. Paper presented to the International workshop on assessment and monitoring of soil quality. Rodale Research Center, Emmaus, Pennsylvania, USA, 11-13 July 1991.

Schleich. K. (1986) *The use of cattle dung in agriculture*. Natural Resources and Resource Development. **23:** 53-87.

Scoones, I. and Toulmin, C. (1985) Socio-economic dimensions in nutrient cycling in agro pastoral systems in dryland Africa. In: Powell, J.M., Fernandez-Rivera, S., Williams, T.O. and Renard, C. (eds.) *Livestock and sustainable nutrient cycling in mixed farming systems of sub-Saharan Africa*. Vol. 2: technical papers. Proc. of an International Conference held in Addis Ababa, Ethiopia, 22-26 Nov. 1993. ILCA (International Livestock Centre for Africa). Addis Ababa, Ethiopia. 568 pp.

Scoones, I. (1990) Livestock Populations and the Household Economy: a case study from southern Zimbabwe. Ph D Thesis, University of London, London, U.K.

Shepherd, K.D, Ohlsson, E, Okalebo, J.R., Ndufa, J.K and S. David. (1995) A static model of nutrient flow on mixed farms in the highlands of western Kenya to explore possible impact of improved management. In: Powell, J.M, Fernandez-Rivera, S, Williams, T.O and Renard, C (eds.) *Livestock and sustainable nutrient cycling in mixed farming systems of sub-Saharan Africa*. Vol II: Technical papers. Proceedings of an international conference held in Addis Ababa, Ethiopia, 22-26 November 1993, ILCA, p 523-538.

Shepherd, K.D. and Soule, M.J. (1998) An assessment of the economic and ecological impacts of agroforestry and other soil management options on Western Kenyan farms using a dynamic simulation model. Agriculture Ecosystems and Environment (in Press).

Siderius, W. and Muchena, F.N. (1977) Soils and environmental conditions of agricultural research stations in Kenya. *Misc. Soil Paper* Number M5. Ministry of Agriculture, NAL, Nairobi, Kenya.

Simpson, J.R., Karanja, D.R., Ikombo, B.M. and Keating, B.A. (1992) Effects of legumes in a cropping rotation on an infertile soil in Machakos District, Kenya. In: Probert, M.E. (ed.) *Sustainable Dryland Cropping*. ACIAR Proceedings No. 41. Canberra, Australia, 44-49.

Simpson, J.R., Okalebo, J.R. and Lubulwa, G. (1996) *The Problem of Maintaining Soil Fertility in Eastern Kenya: A Review of Relevant Research*. ACIAR, Canberra, Australia, 3-60.

Smaling, E.M.A., Nandwa, S.M and Janssen, B.H. (1997) Soil fertility in Africa is at stake. In: Buresh, R.J., Sanchez, P.A. and Calhoun, F. (eds.) *Replenishing Soil Fertility in Africa*, SSSA Special Publication Number 51. SSSA, Madison, Wisconsin, USA.

Sprent, J.I. (1994) Nitrogen acquisition systems in the Leguminosae. In: Sprent, J.I. and Mckey, D. (eds.) *The nitrogen factor: Advances in Legume Systematics* 5: 1-16. Royal Botanic Gardens, Kew, UK.

Stewart, J.I. and Faught, W.A. (1984) Response farming of maize and beans at Katumani, Machakos District, Kenya: recommendations yield expectations and economic benefits. *East African Agricultural and Forestry Journal*. **44:** 29-51

Stocking, M. (1984) *Erosion and Soil Productivity: A review.* Soil Conservation Programme, Land and Water Development Division, UN Food and Agriculture Organization, Rome, Italy. 102 pp.

Stocking, M. (1986) *The impact of soil erosion in Southern Africa.* A research design for assessing physical and economic losses in soil productivity. Report number 2, SADC Soil and Water Conservation and Land Utilization Programme, Maseru, Lesotho.

Swift, M.J., Heal, O.W., and Anderson. (1979) Decomposition in terrestrial ecosystems. *Studies in Ecology* Vol. 5. Blackwell Scientific Publications, Oxford, UK.

Swift, M.J., Frost P., Campbell, B., Hatton, J. and Wilson, K. (1989) Nitrogen cycling in farming systems derived from savanna: perspective and challenges. In: Clarholm, M. and Berstran, L. (eds.) *Ecology of arable land Kluwer*, Amsterdam The Netherlands. pp. 63-76.

Swift, M.J., Bohren, L., Carter, S.E., Izac, A.M. and Woomer, P.L. (1994) Biological management of tropical soils: Integrating process research and farm practice. In: Woomer P.L. and Swift M.J. (eds.) *The Biological Management of Tropical Soil Fertility.* Chichester, UK, Wiley-Sayce, 209-227.

Swift, M.J, Frost, P.G.H., Campbell, B.M., Hatton, J.C. and Wilson, K.B. (1989) Nitrogen cycling in farming systems derived from savanna. In M. Clarholm and L. Bergstrom (eds.) Ecology of arable land. *Development in Plant and Soil sciences.* **39:** 63-67. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Szabolcs, C. (1992) *Salt affected soils.* Proceedings of an international symposium on Strategies for utilizing salt affected lands. 17-25 February 1992. Bangkok, Thailand.

Tanner, P.D. (1973) A relation between zinc deficiency and pellucid spot in maize. *Rhodesian Journal of Agricultural Research.* **11:** 83-85.

Tanner, P.D. and Grant, P.M. (1974) The effectiveness of NPK fertilizer and lime as carriers of zinc for maize under field conditions. *Rhodesian Journal of Agricultural Research.* **12:** 163-176.

Tanner, P.D. and Mugwira, L.M. (1984) Effectiveness of communal area manures as sources of nutrients for young maize plants. *Zimbabwe Agricultural Journal.* **81:** 31-35.

Tanner, P.D., Cooper, G.R.C., Madziva, T.J.T. and Vere, I. (1981) Copper deficiency. Probable cause of the purpling symptom in irrigated winter wheat. *Zimbabwe Agricultural Journal.* **78:** 185-187.

Tiffen, M., Mortimore, M. and Gichuki, F.N. (1993) *More people - less erosion: Environmental recovery in Kenya.* London, Wylie.

Tisdale, S.L. and Nelson, W.L. (1993) *Soil Fertility and Fertilizers.* pp 44-49; 128-168. Macmillan Publishing Company, New York.

TSBF Report (1992) The biology and fertility of tropical soils. In: Seward, P.D. and Woomer, P.L. (eds.) *Report of the Tropical Soil Biology and Fertility Programme,* 1992. TSBF, UNESCO-ROSTA, Nairobi, Kenya.

Thatcher, L.E. (1925) The soybean in Ohio. *Ohio Agr. Exp. Sta. Bull.* 384.

Trenbath, B.R. (1976) Plant interactions in mixed crop communities. In: Multiple Cropping, ASA Publication Number 27, Wisconsin, USA: American Society of Agronomy. pp 129-171.

UNESCO (United Nations Educational, Scientific and Cultural Organization). (1979) *Tropical grazing lands ecosystems.* UNESCO, Paris, France. 655 pp.

Vandermeer, J. (1990) *The Ecology of Intercropping*. Cambridge University Press, Cambridge, UK. 237 pp.

Vertregt, N. and Rutgers, B. (1988) Ammonia volatilization from grazed pasture. *Centre for Agrobiological Research Report 84*. Centre for Agrobiological Research, Wageningen, The Netherlands. 37 pp.

Whitlow, R. (1988) *Land degradation in Zimbabwe*. A geographical study. Geography Department, University of Zimbabwe. Published by the Natural Resources Board, Harare, Zimbabwe.

Willey, R.W. (1979) Intercropping, its importance and research needs. Part 2. Agronomy and research approaches. *Field Crop Abstracts*. **32:** 73-95.

Willey, R.W. and Rao, M.R. (1981) A systematic design to examine plant population and spatial arrangements in intercropping illustrated by an experiment on chickpea/safflower. *Experimental Agriculture*. **17:** 63-73.

Wilson, G.F., Kang, B.T. and Mulongoy, K. 1986. Alley cropping: trees as sources of green manure and mulch in the tropics. *Biology, Agriculture and Horticulture*. **3:** 251-267.

Wilson, G.F. (1989) Trees in fields in southern Zimbabwe. *Journal of Southern African Studies*. **15:** 369-383.

Woomer, P.L. and Swift, M.J. (1994) *The Biological Management of Tropical Soil Fertility*. John Wiley and Sons, Chichester, West Sussex United Kingdom.

Woomer, P.L., Martin, A., Albrecht, A., Resck, D.V.S. and Scharpenseel, H.W. (1994) The importance and management of soil organic matter in the tropics. In: Woomer, P.L. and Swift, M.J. (eds.) *The Biological Management of Tropical Soil Fertility*. John Wiley and Sons, Chichester, UK

Yamoah, C.F., Agboola, A.A. and Mulongoy, K. (1986) Decomposition, nitrogen release and weed control by prunings of selected alley cropping shrubs. *Agroforestry Systems* 4: 239-246

Yates, R.A. and Kiss, A. (1992) Using and sustaining Africa's soils. *Agriculture and Rural Development Series 6*. World Bank, Washington DC.

Young, A. (1989) *Agroforestry for Soil Conservation*. C.A.B. International, Wallingford, Oxon, UK.

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Soil Fertility Management for Sustainable Land Use in the West African Sudano-Sahelian Zone*

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Introduction

The Sudano-Sahelian zone of West Africa (SSZWA) is the home of the world poorest people, 90% of whom live in villages and gain their livelihood from subsistence agriculture. Per capita food production has declined significantly over the past three decades. According to FAO, total food production in Sahelian countries grew by an impressive 70% from 1961 to 1996, but it lagged behind the population which doubled, causing food production per capita to decline approximately by 30% over the same period. Low, erratic rainfall and high soil temperature, soil of poor native fertility, surface crusting and low water and nutrient holding capacity, and recurrent droughts are the main abiotic constraints to crop production in this environment.

Data on economic and human development characteristics of West African countries (Table 8.1) indicates that except for Senegal, Côte d'Ivoire, Mauritania and Ghana where the percentage of undernourished people is less than 19%, most countries have between 20 to 34% of undernourished people and countries like Niger have more than 35% of their population undernourished. Sahelian countries produce 80% of their total cereal production under very difficult conditions. The ability to obtain the remaining 20% of required food is limited by low income and underdeveloped marketing channels. Gross domestic product per capita, for example, ranged from US$177 in Chad to US$575 in Senegal and have stagnated in real terms over the past decade. From the United Nations Development Programme's Human Development index, which ranks countries in terms of life expectancy, education and income, Sahelian countries fall in the bottom 15% of the 174 countries ranked, the lowest being Niger.

In extensive agricultural systems, when crop yields decline to unacceptable levels, the land is left fallow to build up soil fertility, and new areas are then cultivated. Increasing population pressure has decreased the availability of land and resulted in reduced duration of fallow and increased the duration of cropping periods. Shifting cultivation is losing effectiveness and soil fertility is globally declining in many areas. The present farming systems are therefore unsustainable, low in productivity and destructive to the environment. Plant nutrient balances are negative (Stoorvogel and Smaling, 1990). The increasing need for cropland has prompted farmers to cultivate more and more marginal lands which are prone to erosion.

Agricultural output should expand by at least 4% annually by the year 2000 in order to ensure food security. Previous studies have clearly shown that the expansion of new farms cannot increase output by over 1% without accelerating environmental degradation. Consequently, productivity of land currently under cultivation should increase by at least 3% per annum. Presently, over a quarter of West African sub-region's population of two hundred million inhabitants is threatened by food insecurity. Any program aimed at reverting the declining trend in agricultural productivity and preserving the environment for present and future generations in West Africa must begin with soil fertility restoration and maintenance (Bationo *et al.*, 1996).

In this chapter, after a brief presentation of the crop production environment, we will present the state of the art of nitrogen, phosphorus and organic matter management for sustainable land use in the Sudano-Sahelian zone. Before presenting the new opportunities for future research for soil fertility restoration in this zone, we will discuss the effect of different cropping systems on soil fertility and also the main research achievements of the on-farm evaluation of soil fertility restoration technologies.

Crop Production Environments

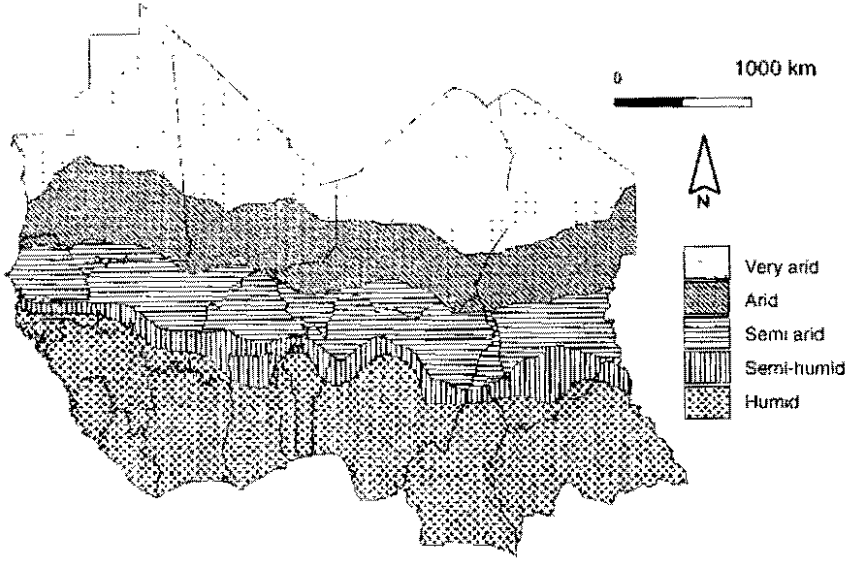
Climate

The rainfall in West Africa shows a significant north-south gradient because of the inter-seasonal movement of the intertropical convergence zone, north and south of the equator. The rainfall is low, variable and undependable. The north-south rainfall gradient is very steep. The further one goes from the Sahara margins, the greater is the rainfall by approximately 1 mm km^{-1}. The isohyets run parallel (Toupet 1965).

Sivakumar (1986) proposed a soil climatic zonation scheme for West Africa that is calculated from rainfall and potential evapo-transpiration. In this scheme a growing period of 60–100 days was used for defining the Sahelian zone. The geographical extent of the Sudanian zone has an average growing period of 100–150 days. The extent of the Sudano-Sahelian zone of West Africa (SSZWA) is represented by the Semi-Arid zone in Figure 8.1. The average annual rainfall of the cultivated zones varies from 300 to 900 mm and the ratio of annual rainfall to annual potential evapo-transpiration from 0.20 to 0.65. High soil temperature, sometimes exceeding 40°C, can prevent crop establishment. Sand blasting and burial of the seedlings caused by wind erosion adds to this problem.

Time dependent variations in rainfall are quite common in the region with coefficient of variation of annual rainfall ranges between 15-30%, and rainfall in some years can be 50% below or above the long-term average. For instance, Nicholson (1981) showed that in 1950 rainfall all over West Africa was above normal, at some location even 250% above normal. However, in 1970 rainfall was below normal throughout the region.

Figure 8.1. Agro-ecological zones of West Africa



It is well documented that precipitation determines the potential distribution of terrestrial vegetation and extended drought have initiated or exacerbated desertification. In the past 25 years, the SSZWA has experienced the most substantial decline in rainfall (Hulme and Kelly, 1997; Hulme 1992; Nicholson and Palao, 1993) and the downward trend is persistent since 1951 with more areas experiencing more higher rainfall variability. As a result of the decrease in rainfall there will be a decrease in the vegetation cover of the land and a reduction in the vegetation cover logically leads to reduce precipitation (Charney, 1975; Cunnington and Rowntree 1986; Xue *et al.* 1990). The other non-climatic forces of desertification includes unsustainable agricultural practices, overgrazing and deforestation.

With the reduction of the vegetation cover, the soil is left bare and therefore directly exposed to wind and water erosion. The effect of these changes on wind and water erosion are aggravated by the sandy nature of the soils of SSZWA, which are frequently poorly aggregated, offering little resistance to the erosive forces. The Global Assessment of Soil Degradation (GLASOD) project estimates that 65% of the African agricultural land, 31% of permanent pasture land, and 19% of forest and woodland has already been degraded. Three hundred and thirty two million hectares of African drylands are subjected to soil degradation. This represents one third of the entire area of dryland soil degradation in the world.

Land degradation is one of the most serious threats to food production and soil lost through erosion is about 10 times greater than the rate of natural soil formation while deforestation is 30 times greater than of planned reforestation. Buerkert *et al.* (1996a) measured absolute soil lost of 190 t ha^{-1} in one year on bare plots, as opposed to soil deposition of 270 t ha^{-1} on plot with 2 t ha^{-1} millet stover mulch. Sterk *et al.* (1996) reported a total loss of 45.9 t ha^{-1} of soil during four consecutive storms. Buerkert *et al.* (1996b) reported that in unprotected plot up to 7 kg of available P and 180 kg ha^{-1} of organic carbon are lost from the soil profile within one year. Wind erosion will decrease also the exchangeable base and increase soil acidification. Wind erosion constitutes one of the major causes of land degradation. This results from the low vegetation cover at the time when the most erosive winds are blowing in combination with sandy and easy erodable soils. Wind erosion induced damage includes direct damage to crops through sand blasting, burial of seedling under sand deposits and loss of top soils (Fryar 1971). The loss of the top soil which can contain 10 times more nutrients than the sub-soil is particularly worrying, since it potentially affects crop productivity on the long-term basis by removing the soil that is inherently rich in organic matter.

Soils

Entisols and Alfisols occupy most of the landscape in the SSZWA. Entisols are mainly composed of quartz sand, with low water and nutrient holding capacity. Alfisols have a clay accumulation horizon and a high base saturation because of lower rainfall and leaching but they have poor structural stability, poor water and nutrient holding capacity and lower organic matter than the ultisols and oxisols in the sub-humid areas.

The data in Table 8.1 shows physical and chemical properties of soils in the SSZWA. Most of the soils are sandy. One striking feature of these soils is their inherent low fertility which, is expressed in low levels of organic carbon (generally less than 0.3%), low total and available phosphorus and nitrogen and low Effective Cation Exchange Capacity (ECEC). The ECEC is attributed to low clay content and the kaolinitic mineralogy of the soils. Bationo and Mokwunye (1991) found that the ECEC is more related to the organic matter than to the clay content, indicating that a decrease in organic matter will decrease the ECEC and then the nutrient holding capacities of those soils. De Ridder and Van Keulen (1990) reported that a difference of 0.1% in organic C content results in a difference of 4.3 Cmol kg^{-1} in ECEC.

Table 8.1. Mean and standard deviation of physical and chemical properties of selected West African soils, 0-15 cm

Parameters	Mean	Standard deviation
pH H_2O (2:1 water: soil)	6.17	0.66
pH KC1 (2:1 KC1: soil)	5.05	0.77
Clay (%)	3.9	2.67
Sand (%)	88	8
Organic matter (%)	1.4	1.09
Total nitrogen (mg kg^{-1})	446	455
Exchangeable bases (cmol kg^{-1})		
Ca	2.16	3.01
Mg	0.59	0.55
K	0.20	0.22
Na	0.04	0.01
Exchangeable acidity (cmol kg^{-1})	0.24	0.80
Effective cation exchange	3.43	3.801
Capacity (ECEC; cmol kg^{-1})	88	17
Base saturation (%)	3	8

Source: Bationo *et al.*, 1996

Soil nutrient depletion is a major bottleneck to increased land productivity in the region and has largely contributed to poverty and food insecurity. Soil nutrient depletion occurs when nutrient inflows are less than outflows. Nutrient balances are negative for many cropping systems indicating that farmers are mining their soils. Table 8.2 shows the aggregated nutrient budgets for some West African countries. In Burkina Faso, current estimates indicate that in 1983, for a total of 6.7 million hectares of land cultivated, soil nutrient mining amounted to a total loss of 95000 tons of N, 28000 tons of P2O5 and 79000 tons of K2O, equivalent to US$159 million of N, P and K fertilizers. In Mali, Van der Pol and Van der Geest (1993) reported that farmers extract, on average, 40% of their agricultural revenue from the soil mining. The significance of these figures is alarming when it is realized that productivity of these soils in their native state is already low because of low inherent levels of plant nutrients. The countries of the SSZWA consume less than 5 $kg.ha^{-1}$ of plant nutrients and in addition there is intense pressure on the governments to remove subsidies on fertilizers without alternative policies to sustain even the current low levels of use of plant nutrients.

Table 8.2. Nutrient losses for some West African countries

Country	Area (1000 ha)	Nutrient losses (1000 tons)		
		N	P_2O_5	K_2O
Benin	2972	41.4	10.4	32.5
Burkina Faso	6691	95.4	27.8	78.8
Ghana	4505	137.1	32.3	90.5
Mali	8015	61.7	17.9	66.7
Niger	10985	176.1	55.3	146.6
Nigeria	32813	110.7	316.7	946.2

Source: Stoorvogel and Smaling, 1990

The data in Table 8.3 indicates that continuous cultivation of the weakly buffered soils of northern Nigeria will result in a rapid decline of exchangeable cations and soil acidification in the Sudanian zone of Northern Nigeria. Soil calcium will decrease by 21% and pH by 4% after 50 years of continuous cultivation in farmers' fields.

Rains in West Africa frequently occurs in short and intense storms and pose special problems in term of soil conservation (Kowal and Kassam 1978). Charreau (1974) reported on rainfall intensities between 27 to 62 mm h^{-1}. In Northern Nigeria, Kowal (1970) reported rainfall intensities over 250 mm h^{-1} for a short period. Hoogmoed reported a pick intensity of 300 mm h- in Niono, Mali and a pick of 386 mm h^{-1} for Niamey, Niger (Hoomoed 1986). Land degradation due to water erosion is more severe in the Sudanian zone than in the Sahelian zone. On the bare, weakly crusted surface of the sandy Sahelian soil, infiltration rate of up to 100 mm h^{-1} have been reported (ICRISAT 1985). For the Alfisols with indurate crust, infiltration rates of 10.8 mm h^{-1} in Central Burkina Faso have been reported. As a result of the high rainfall intensities and low infiltration rates, runoff and soil loss are common in the region. The data in Table 8.4 indicate runoff and soil loss will depend on soil types and erodibility, land form and management system (Lal 1980). Whereas Sefa in Senegal with a slope of 1.2% on a bare soil a total runoff of 39.5% was recorded resulting in soil loss of 21 t ha^{-1} Yr^{-1}, in Burkina Faso with a slope of 1.20% only 7.5% of runoff was recorded with soil loss of 6.4 t yr^{-1} on pearl millet field.

Table 8.3. %age of soil fertility over 50 years in farmers' fields under continuous cultivation in the savanna zones of Nigeria

Zone	Exchangeable cations			
	Ca	Mg	K	pH
Sudan	21	32.0	25.0	4.0
Northern Guinea	18.6	26.8	33.0	3.8
Southern Guinea	46.0	50.6	50.0	10.0

Source: Adapted from Balasubramanian *et al.* (1984).

Table 8.4. Runoff and soil loss data for selected locations in west Africa

Country	Location	Mean annual rainfall (mm)	Slope %	Treatments	Runoff annual %	Soil loss (tons ha^{-1} $year^{-1}$)
Benin	Boukombe	875	3.7	Millet conventional	11.7	1
Niger	Allokoto	452	3	Village	16.3	8
Nigeria	Samaru	1062	0.3	Sorghum, cotton	25.2	3
	Ibadan	1197	15	Bare soil	41.9	229
				Bare soil	13.5	40
				Maize-maize	2.6	0
				Maize-cowpea	1.7	4
Senegal	Sefa	1300	1.2	Cowpea-maize	39.5	21
		1241	1.2	Bare soil	22.8	69
		1113	1.2	Groundnut	34.1	83
Burkina Faso	Ougadougou	850	0.5	Sorghum	40.6	10.2
				Bare soil	2.32	0.6
			.	Crop	2.5	0.1
Côte d' Ivoire	Bouake	1200	0.3	Forest	15.3	18.3
	Abidjan	2100	7.0	Bare soil	38.0	108.2
Mali	Niono		1.3	Bare soil	25.0	NA
Niger	Sadore	560		Millet	1.5	NA
				Millet	0.2	NA
Sierra Leone	Mebai	2000		Bare soil	11	NA
Sierra Leone	Mabai	2000		Unfertilized maize	8	NA

Source: Bationo *et al.* (1996)
Na=not available

Management of Nitrogen, Phosphorus and Organic Matter

Nitrogen

For many years, several scientists in the Sudano-Sahelian zones initiated research to

(i) Assess the performance of the different sources of N fertilizers

(ii) To assess the efficiency of different methods of N placement

(iii) To calculate 15N balances in order to determine N uptake and losses and

iv) To determine efficiency of N under different management systems and the effect of the different soil and agro climatic factors on the performance of N fertilizers (Mughogho *et al.* (1986), Bationo *et al.* (1989), Christianson and Vlek (1991), Ganry *et al.* (1973), Gigou *et al.* (1984).

Soil N is derived from air and dust, biological N fixation, organic sources, and fertilizers. About 98% of the soil N is stabilized in the organic matter. Thus the total nitrogen in the soil and the amount of nitrogen released for plant nutrients uptake will depend on organic matter content.

Efficiency of N Fertilizers as Affected by N Sources, Methods of Placement and Time of Application

Christianson and Vlek (1991) used data from long-term experiment from the Sudano-Sahelian Zone to develop response function to N by pearl millet and sorghum and found that the optimum rate is 50 kg N/ha for sorghum and 30 kg N/ha for pearl millet. At these N rates the returns were 20 kg grain per kg N for sorghum and 9 kg grain per kg N for pearl millet.

The use of 15N in order to calculate N balances and to determine fertilizers N uptake and losses provide an important tool for nitrogen management. Results with 15N research in early years are reported in Mughogho *et al.* from which the following conclusion can be made.

- Apparent uptake of fertilizer N exceeds measured uptake using 15N.
- Uptake of 15N labelled fertilizer and apparent recovery of unlabelled N decreases with increasing rates of application.
- Loss of 15N labelled fertilizer to the atmosphere and recovery of 15N in the soil increases with increasing rates of fertilizer application.
- Estimated losses of N are high regardless of N sources.

The urea and calcium ammonium nitrate (CAN) are the most common sources of N in the region. Trials were undertaken to evaluate these two sources of nitrogen with basal or split application, banded, broadcast or applied point placed as urea supergranule (USG) or CAN point placed. 15N was applied in microplot in order to construct N balances and to determine N uptake and losses from the different sources of N, methods of application and timing of application.

From the data in table 8.5, 8.6 and 8.7 the following conclusion can be made:

(i) Fertilizer N recovery by plant was very low, averaging 25 – 30% over all years.

(ii) There is a higher loss of N with the point placement of urea (USG) (> 50%) and the mechanism of N loss is believed to have been ammonia volatilization.

(iii) For all years losses of N from CAN were less than from urea because one-half of the N in CAN is in the non-volatile nitrate form.

(iv) Although CAN has a lower N content than urea, it is attractive as an N source because of its low potential for N loss via volatilization, and its point placement will improve its spatial availability. The data in Figure 8.2 clearly indicates that CAN point placed outperformed urea point placed or broadcast and 15^N similar trials indicate that 15^N uptake by plants was almost three times higher from CAN than that of urea applied in the same manner.

Table 8.5. Recovery of 15^N in the millet plant and soil at harvest, Sadore, Niger 1982

Treatment	Grain yield[a] (kg ha)	N recovery (%) Grain	Plant[b]	Soil	Loss
Check	590	-	-	-	-
CAN split band	970	20.8	36.8	38.2	25.0
Urea split band	1.070	19.0	31.0	37.3	31.7
Urea split broadcast	1.070	17.0	31.3	41.0	27.7
Urea basal broadcast	1.010	16.9	26.7	41.6	31.7
USG basal	960	16.2	27.5	39.3	33.2
USG split	1.070	14.3	26.5	33.2	40.3
LSD (0.01)	167	4.6	6.0	6.0	9.8

[a] Average yield for all N rates for each source

[b] Sum of grain and stover 15^N

CAN: Calcium ammonium nitrate

USG: Urea super granule

Source: Christianson *et al.* 1990

Table 8.6. Yield and recovery of ^{15}N in the millet plant and soil at harvest (1983-85), Sadore, Niger

Year	Treatment	Grain yield[a] (kg ha^{-1})	Stover yield (kg ha^{-1})	Grain	^{15}N recovery (%) Plant[b]	Soil	Loss
1983	Check	660	-	-	-	-	-
	CAN split band	940	-	13.0	28.8	34.2	37.0
	Urea split band	1.040	-	9.8	22.8	39.2	38.0
	USG split	990	-	8.0	22.0	25.3	52.7
	LSD (0.01)	110	-	1.6	3.2	3.4	2.2
1984	Check	460	1.570	-	-	-	-
	CAN split band	480	1.850	9.9	36.8	37.1	26.1
	Urea split band	470	1.930	5.5	20.0	40.1	39.9
	USG split	490	1.780	8.1	21.6	24.8	53.6
	LSD (0.01)	30	220	1.6	3.8	4.2	4.4
1985	Check	900	2.315	-	-	-	-
	CAN split band	1.320	2.910	-	-	-	-
	Urea split band	1.225	3.020	-	-	-	-
	USG split	1.350	3.000	-	-	-	-
	LSD (0.05)	175	386	-	-	-	-

^{15}N was not used in 1985

[a] Average yield for all N rates for each source
[b] Sum of grain and stover 15N
CAN: Calcium ammonium nitrate
USG: Urea super granule

Source: Christianson *et al.* 1990

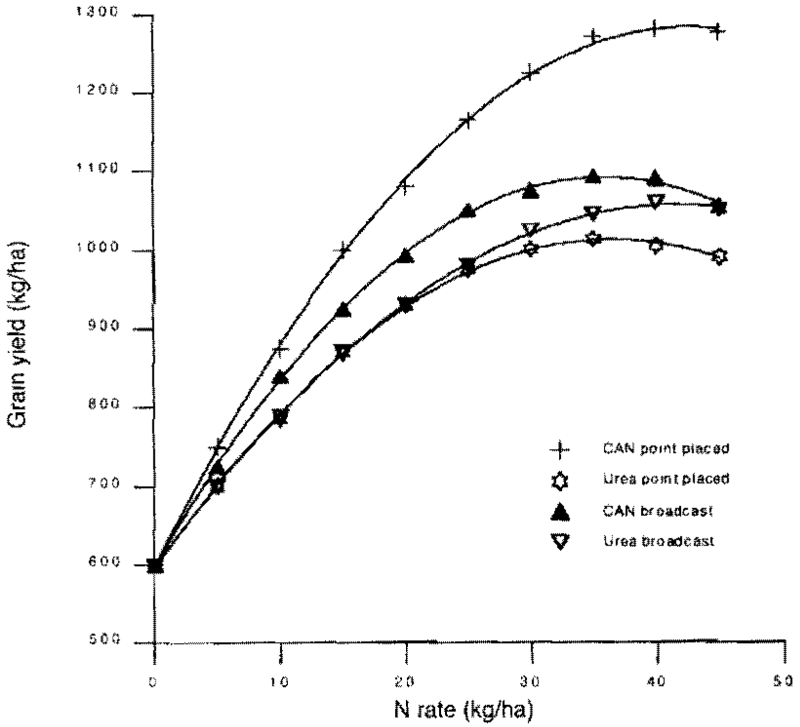
Table 8.7. Recovery 15N fertilizer by millet applied at Sadore, Niger, 1985

N source	Application method	^{15}N Recovery Grain	Stover	Soil	Total
		%			
CAN	Point incorporated	21.3	16.8	30.0	68.1
CAN	Broadcast incorporated	10.9	10.9	42.9	64.7
Urea	Point incorporated	5.0	6.5	22.0	33.5
Urea	Broadcast incorporated	8.9	6.8	33.2	48.9
Urea	Point surface	5.3	8.6	18.0	31.9
SE		1.2	2.0	1.9	2.4

CAN: Calcium ammonium nitrate

Source: Christianson and Vlek, 1991

Figure 8.2. Effects of urea and calcium amonium nitrate application on grain yield, Goberi, Niger



Source: Christianson and Vlek, 1991

Efficiency of N Fertilizers as Affected by Soil and Crop Management and Rainfall

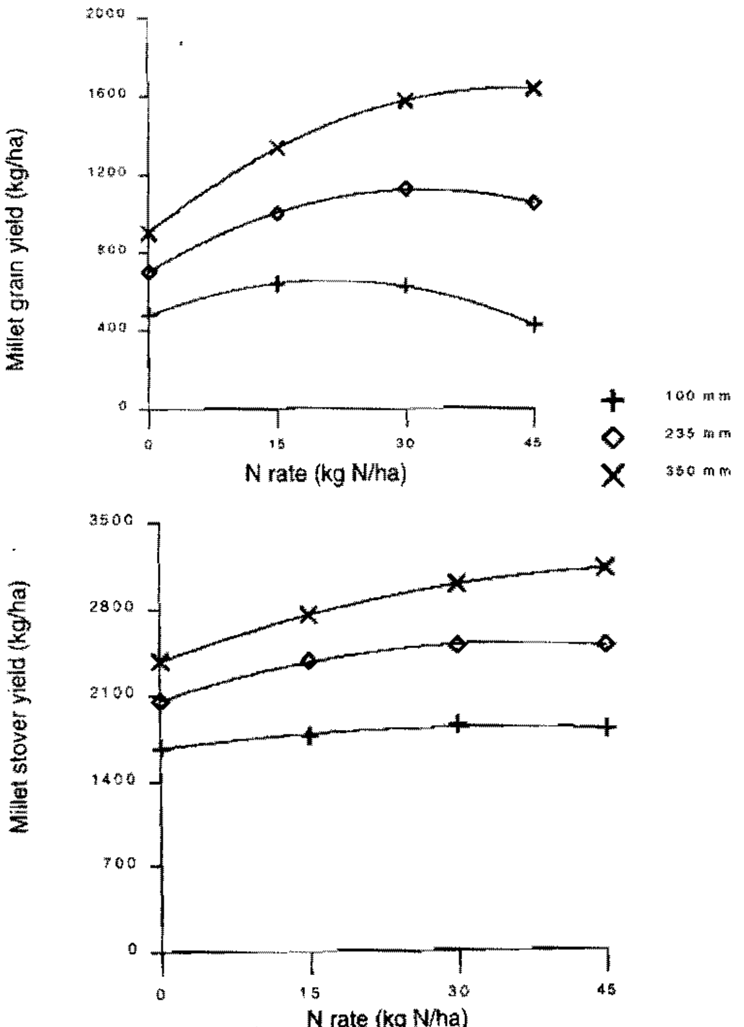
Mughogho *et al.* (1986) found significant relationships between crop yields and N recovery. N losses averaged 20% in the humid and sub-humid zones with maize and were significantly less than the average loss of 40% found over all treatments in the Sudano-Sahelian zone.

In the Sahelian zone, Bationo and Vlek (1998) reported N use efficiencies of 14% in plots without lime and phosphorus whereas this amount increased to 28% when P and lime were applied.

Rotation of cereals with legumes could be a way to increase N use efficiency. Bationo and Vlek 1998 reported a N use efficiency of 20% in the continuous cultivation of pearl millet but its value increased to 28% when pearl millet was rotated with cowpea.

Bationo *et al.* (1989) found a strong effect between planting density and response to N fertilizer. Christianson *et al.* (1990) developed a model on the effect of rainfall on N use for pearl millet production in the Sahel and found that the response to N was affected by rainfall over a 45 days yield-sensitive period which coincides with the culms elongation and anthesis growth stages for millet (Figure 8.3).

Figure 8.3. Grain and stover yields affected by N rate and midseason rainfall Sadore, Niger, 1982 to 1985



Millet stover yield (kg/ha)
Millet grain yield (kg/ha)

Source: Christianson *et al.*, 1990

Phosphorus Sources and Management

Among soil fertility factors, P deficiency is a major constraint to crop production in the Sudano-Sahelian zone. For many years, research has been undertaken to assess the extent of soil phosphorus deficiency, to estimate phosphorus requirement of major crops, and to evaluate the agronomic potential of various phosphate rock (PR) from local deposits (Goldsworthy, 1967; Pichot and Roche, 1972; Thibout *et al.* 1980; Bationo *et al.* 1987; Bationo *et al.* 1990; Hauck, 1966; Jones, 1973; Juo and Fox, 1977; Kang and Osiname, 1979; Boyer, 1954; Nalos *et al.* 1974; Juo and Kang, 1978; Mokwunye, 1979; Truong *et al.* 1978)

About 80% of the soils in sub-Saharan Africa are short of this critical nutrient element and without the use of P, other inputs and technologies are not effective. However, sub-Sahara Africa use 1.6 kg P/ha^{-1} of cultivated land as compared to 7.9 and 14.9 kg/ha respectively for Latin America and Asia respectively. It is now accepted that the replenishment of soil capital phosphorus is not only a crop production issue, but an environmental issue and P application is essential for the conservation of the natural resource base.

Availability and total P levels of soil are very low in the SSZWA as compared to the other soils in West Africa (Bache and Rogers, 1970; Mokwunye, 1974; Jones and Wild, 1975; Juo and Fox, 1977). For the sandy Sahelian soils total P values can be as low as 40 mg P kg^{-1} and the value of available P less than 2 mg P kg^{-1}. In a study of the fertility status of selected pearl millet producing soils of West Africa, Manu *et al.* 1991 found that the amount of total P in these soils ranged from 25 to 340mg kg^{-1} with a mean of 109mg kg^{-1}. The low content of both total and available P parameters may be related to several factors including

(i) Parent materials, which are mainly composed of eolian sands, contain low mineral reserves and lack primary minerals necessary for nutrient recharge.
(ii) A high proportion of total P in these soils is often in occluded form and is not available to crop (Charreau, 1974).
(iii) Low level of organic matter and the removal of crop residue from fields. Organic matter has a favourable effect on P dynamics of the soil; in addition to P release by mineralization, the competition of organic ligands for Fe and Al oxides surface can result in a decrease of P fixation of applied and native P.

The P sorption characteristics of different soil types has been investigated and compared to the soils of the more humid regions, indicating that the soils of the SSZWA have very low capacity to fix P (Sanchez and Uehara, 1980; Udo and Ogunwale, 1972; Fox and

Kamprah, 1970; Juo and Fox, 1977; Syers *et al.* 1971). For pearl millet producing soils, Manu *et al.* 1991 fitted the sorption data to Langmuir equation (Langmuir 1918) and P sorption maximum was determined using the method of Fox and Kamprath (1970). From these representative sites in the Sudano-Sahelian zone the values of maximum P sorbed ranged from 27 mg kg^{-1} to 253 mg kg^{-1} with a mean of 94 mg kg^{-1}.

P deficiency is a major constraint to crop production and response to it is substantial only when both moisture and phosphorus are not limiting. Field trials were established to determine the relative importance of N, P and K fertilizers. The data in Table 8.9 indicates that from 1982 to 1986 the average control plot gave 190 kg grain ha^{-1}. The sole addition of 30 kg P2O5ha^{-1} without N fertilizers increased the average yield to 714 kg ha^{-1}. The addition of only 60 kg N/ha did not increase the yield significantly over the control as the average grain yield obtained was 283 kg ha^{-1}. Those data clearly indicate that P is the most limiting factor in those sandy Sahelian soils and there is no significant response to N without correcting first for P deficiency. When P is applied the response to N can be substantial and with the application of 120 kg N ha^{-1} a pearly millet grain yield of 1173 kg ha^{-1} was obtained as compared to 714 kg ha^{-1} when only P fertilizers were applied. For all the years the addition of K did not increase significantly the yield of both grain and total dry matter of pearl millet.

Table 8.8. Effect of N, P, and K on pearl millet grain and total dry matter (kg/ha) at Sadoré and Gobery (Niger)

Treatments	1982		1983		1984		1985	1986	
	Sadoré		Sadoré	Gobery	Sadoré		Sadoré	Sadoré	
	Grain	TDM	Grain	Grain	Grain	TDM	Grain	Grain	TDM
N0P0K0	217	1595	146	264	173	1280	180	180	1300
N0P30K30	849	2865	608	964	713	2299	440	710	2300
N30P30K30	1119	3597	906	1211	892	3071	720	930	3000
N60P30K30	1155	3278	758	1224	838	3159	900	880	3200
N90P30K30	1244	3731	980	1323	859	3423	1320	900	3400
N120P30K30	1147	4184	1069	1364	1059	3293	1400	1000	3300
N60P0K30	274	2372	262	366	279	1434	290	230	1500
N60P15K30	816	2639	614	1100	918	3089	710	920	3100
N60P45K30	1135	3719	1073	1568	991	3481	1200	980	3500
N60P30K0	1010	3213	908	1281	923	3377	920	910	3400
S.E.	107	349	120	232	140	320	162	250	400
C.V(%).	24	22	26	30	24	22	28	32	25

N.B. Nutrient applied are N, P205 and K20 kg/ha
TDM= Total dry matter

The use of alternative locally available phosphate rock

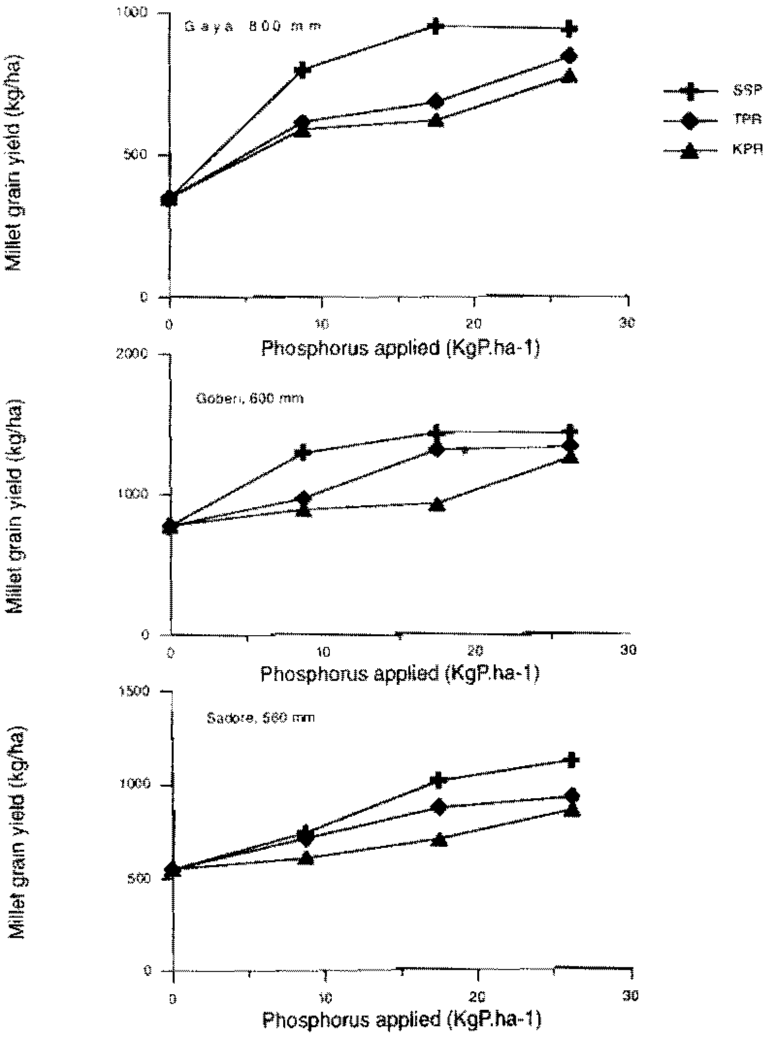
Despite the fact that deficiency of P is acute on the soils of West Africa, very little P fertilizers is used by local farmers, partially because of the high cost of the imported fertilizers. The use of locally available phosphate rock indigenous in the region could be an alternative to use of high cost imported P fertilizers. The effectiveness of phosphate rock (PR) depends on its chemical and mineralogical composition (Khasawneh and Doll, 1978, Lehr and McClellan, 1972, Chien and Hammond, 1978. The most important feature of the empirical formula of francolite is the ability of carbonate ions to substitute for phosphate in the apatite latice. Smith and Lehr (1966) concluded from their studies that the level of isomorphic substitution of carbonate for phosphate within the latice of the apatite crystal influences the solubility of the apatite in the rock and therefore controls the amount of P that is released when PR is applied to soil. The most reactive PR are those having a molar PO4/CO3 ratio less than 5. West African PR's are not very reactive. Chien (1977) found that the solubility of PR in neutral ammonium citrate (NAC) was directly related to the level of carbonate substitution. Diamond (1979) proposed a classification of phosphate rock for direct application based on citrate solubility as >5.4% high; 3.2–4.5% medium and <2.7% low. Based on this classification only Tilemsi PR has a medium reactivity.

Environmental conditions, crop types, and management practices control the P supply and hence the effectiveness of a given PR in a given crop management environment, (Mokwunye, 1995). The ability of the soil to provide H+, soil with low P and Ca, soil moisture, the acidification of the rhizosphere, plants with high root density and high Ca uptake play an important role in P availability from PR (Kasawneh and Doll, 1978; Chien, 1977; Mokwunye, 1995; Hammond *et al.* 1986; Kirk and Nye, 1986; Hedley *et al.* 1982; Sale and Mokwunye, 1993; Föhse *et al.* 1988).

Bationo *et al.* (1987) have shown that direct application of PR indigenous to the region may be an economical alternative to the use of more expensive imported water-soluble P fertilizers for certain crops and soils. Bationo *et al.* 1987 while evaluating Parc-W and Tahoua PR indigenous to Niger found that PR is only 48% as effective as single superphosphate (SSP), whereas the effectiveness of the more reactive Tahoua rock was as high as 76% of SSP. Further studies by Bationo *et al.* (1990) showed that Tahoua PR is suitable for direct application, but Parc-W has less potential for direct application. The data from a long-term benchmark experiment show that SSP outperformed the other sources and its superiority to sulphur-free Triple Superphosphate (TSP) indicates that with continuous cultivation, sulphur deficiency develops. For both pearl millet grain and total dry matter yields, the relative agronomic effectiveness was almost similar for TSP as compared to the partially acidulated Parc W phosphate rock (PAPR) with 50% acidulation (PAPR50) indicating that partial acidification of Parc-W PR can significantly increase its effectiveness (Bationo *et al.* 1996).

In trials conducted in the different agro-ecological zones of Niger it was found that Tahoua PR outperformed Kodjari PR (from Burkina Faso) (Figure 8.4). The results are in agreement with the fact that the molar PO4/CO3 ratio is 23 for Kodjari PR and 4.9 for Tahoua PR, and Tahoua PR has also a higher solubility in NAC.

Figure 8.4. Effects of different sources and rates of phosporus on pearl millet grain yield in agroecological zones of Niger, 1996 rainy season a) Gaya b) Goberi c) Sadore



Bationo *et al.* (1997) found that Tilemsi PR can result in net returns and value/cost ratios similar to recommended cotton or cereal complex imported fertilizers. There is ample evidence that indicates that market differences exist between species and genotype for P uptake (Föhse *et al.* 1988; Caradus, 1980; Nielsen and Schjorring, 1983; Spencer *et al.* 1980). Bationo (unpublished data) found that the PUE among nine pearl millet varieties varied from 25 kg grainkg^{-1}P for variety ICMVIS 85333 to 77 kg grainkg^{-1}P for Haini-Kirei cultivar.

The data on Table 8.10 clearly shows that hill placement of small quantities of P fertilizers will have a higher phosphorus use efficiency (PUE) as compared to the broadcasting of 13 kg Pha^{-1} as recommended by the extension services. Whereas in 1995 the PUE was 47 kg millet/kg/P with the broadcasting of 13 kg^{-1}P ha, a value of 111 kg millet/kg/P was obtained with the hill placement of 3 kg P^{-1}ha with the seed at sowing time. In on-farm researchers managed trials in the Sahelian zone, it was found that the efficiency of PR from Kodjari or Tahoua can be improved with the hill placement of 4 kg P^{-1}ha. Whereas the PUE of Kodjari PR applied alone was 14 kg millet/kg/P it increased to 31 kg millet/kg/P when additional P was hill placed at seedling time as 15-15-15 for pearl millet grain yield (Bationo, unpublished data).

In long-term soil management trials, application of N, crop residue and ridging and rotation of pearl millet with cowpea were evaluated to determine their effect on PUE. The results show that soil productivity of the sandy soils can dramatically increase with the adoption of improved crop and soil management technologies, whereas the absolute control recorded 33 kg ha^{-1} of pearl millet grain, 1829 kg ha^{-1} was obtained when P, N and crop residue was applied to the ridged and fallowed leguminous cowpea upon the previous season. Results for the grain yield indicate that PUE increases from 46 kg millet/kg/P with only P application to 133 when P is applied in combination with N, crop residue and the crop is planted on ridge in a rotation system (Table 8.11).

Organic Matter Management

Maintaining soil organic matter is a key to sustainable land use management. Organic matter acts as source and sink for plant nutrients. Other important benefits resulting from the maintenance of organic matter is low-input agro-systems include retention and storage of nutrients, increasing buffering capacity in low activity clay soils, and increasing water holding capacity. Nye and Greenland (1960)

Table 8.10. Effect of phosphorus placement on pearl millet total dry matter (TDM), grain yield, and phosphorus use efficiency (PUE), Niger, 1995-1996 cropping seasons

	1995				1996			
	TDM		Grain		TDM		Grain	
Treatments	Yield	PUE	Yield	PUE	Yield	PUE	Yield	PUE
(Kg/ha^{-1})	(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})	
0	1951		532		2413		641	
13 (broadcast)	4012	159	1138	47	4884	190	1240	46
3 (HP)	3157	402	864	111	3216	268	846	68
5 (HP)	3341	278	937	81	3847	287	996	71
7 (HP)	3498	221	1018	69	4041	233	1074	62
13 (broadcast) + 3 (HP)	4830	180	1382	53	5314	181	1279	40
13 (broadcast) + 5 (HP)	4713	153	1425	50	5180	154	1295	36
13 (broadcast) + 7 (HP)	4381	122	1287	38	4685	114	1131	35
SE	314		92		425		89	

HP Hill placed, TDM : Total dry matter; PUE = kg yield/kg P

Source: Muelhing-Versen *et al* 1997

Table 8.11. Effect of mineral fertilizers, crop residue (CR) and crop rotation on pearl millet yield wasts (kg/ha) and phosphorus use efficiency (PUE) Sadore, Niger, 1998 rainy season.

Treatment	Without CR, without N				Without CR, with N				With CR, without N				With CR, with N			
	TDM		Grain		TDM		Grain		TDM		Grain		TDM		Grain	
	Yield	PUE	Yield	PUE	Yield	PUE	Yield	PUE	Yield	PUE	Yield	PUE	Yield	PUE	Yield	PUE
Control	889		33		2037		58		995		61		1471		98	
13 kg P/ha	2704	140	633	46	4339	177	1030	75	4404	185	726	51	240	4594	1212	86
13 kg P/ha + ridge	2675	137	448	32	4057	155	946	68	3685	210	785	56	4530	235	1146	81
13 kg P/ha + rotation	5306	340	1255	94	6294	327	1441	106	5392	338	1475	109	6124	358	1675	121
13 kg P/ha + ridge + rotation	5223	333	1391	104	5818	291	1581	117	6249	404	1702	126	7551	468	1829	133
SE	407		407		407		407		407		407		407		407	

CR Crop Residue; N Nitrogen; TDM Total Dry Matter; PUE (kg grain/kgP);
TDM= Total dry matter

estimated that the annual increase in nitrogen under forest fallow was 30 kg N ha^{-1} in the soil and 60 kg N ha^{-1} in the vegetation. For the savanna ecosystems, the annual increase was 10 kg N ha^{-1} in the soil and 25 kg N ha^{-1} in leaves and vegetation. Bationo *et al.* 1995 reported that continuous cultivation in the Sahelian zone has led to drastic reduction in organic matter and a subsequent soil acidification. Bationo and Mokwunye (1991) reported that in the Sudano-Sahelian zone, the effective cation exchange capacity (ECEC) is more related to organic matter than to clay, indicating that a decrease in organic matter will decrease the ECEC and subsequently the nutrient holding capacity of these soils. In a study to quantify the effects of changes in organic carbon on cation exchange capacity (CEC) De Ridder and Van Keulen (1990) found that a difference of 1 g kg^{-1} in organic carbon results in a difference of 4.3 mol kg^{-1}. In many cropping systems few if any agricultural residues are returned to the soil. This leads to decline soil organic matter, which frequently results in lower crop yields or soil productivity.

The concentration of organic carbon in the top soil is reported to average 12 mg kg^{-1} for the forest zone, 7 mg kg^{-1} for the Guinean zone, 4 mg kg^{-1} in the Sudanian zone and 2 mg kg^{-1} for the Sahelian zone (Windmeijer and Andriesse, 1993). The soils of the Sudano-Sahelian zone are inherently low in organic carbon. This is due to the low root growth of crops and natural vegetation but also the rapid turnover rates of organic materials with high soil temperature and microfauna, particularly termites. In a survey of millet producing soils, Manu *et al.* (1991) found an average soil Corg content of 7.6 g kg^{-1} with a range from 0.8 to 29.4 g kg^{-1}. The data also showed that these Corg contents were highly correlated with total N ($R = 0.97$) which indicates that in the predominant agro-pastoral systems without the application of mineral N fertilizers, N nutrition of crops largely depend on the maintenance of soil Corg levels.

The importance of soil textural (clay and silt) properties for the Corg content of soil was stressed repeatedly as clay is an important component in the stabilization of organic molecules and mino-organisms (Amato and Ladd, 1992; Greenland and Nye, 1959; Feller *et al.* 1992). Thus Feller *et al.* (1992) reported that independently of climatic variations such as precipitation, temperature, and duration of the dry seasons Corg increased between 600 and 3000 mm annual rainfall with the clay and silt contents of low activity clay soils. Therefore small variations in topsoil texture at the field or watershed level could have large effects on Corg.

Effect of Soil Management Practices on Organic Carbon Contents

There is much evidence for rapid decline of Corg levels with continuous cultivation of crops in the SSZWA (Bationo *et al.* 1995). For the sandy soils, average annual losses in Corg often expressed by the K value (calculated as the %of organic carbon loss per year), may be as higher as 4.7%, whereas for the sandy loam soils, reported losses seem much lower, with an average of 2% (Pieri, 1989, Table 8.12). The data in Table 8.12 also clearly indicated that soil erosion can increase Corg losses from 2 to 6.3% and management practices such as crop rotation, following soil tillage, application of mineral fertilizers and mulching will have a significant effect on annual losses of Corg. The K-value in cotton cereal rotations were 2.8%, lower than in continuous cotton system. At Nioro-du-Rip in Senegal, soil tillage increased annual Corg losses from 3.8 to 5.2% and annual Corg losses declined from 5.2% without NPK to 3.9% with NPK application.

Table 8.12. Annual loss rates of soil organic carbon measured at selected research stations in the SSWA

Place and Source	Dominant cultural succession	Observations	Clay + Silt (%) (0-0.2 m)	Annual loss rates of soil organic carbon (k)	
				Number of years of measurement	k(%)
Burkina Faso		With tillage			
Saria,	Sorghum monoculture	Without fertiliser	12	10	1.5
INERA-IRAT	Sorghum monoculture	Low fertilizser	12	10	1.9
	Sorghum monoculture	High fertiliser	12	10	2.6
	Sorghum monoculture	Crop residues	12	10	2.2
CFJA,	Cotton-cereals	Eroded	19	15	6.3
INERA-IRCT		watershed			
Senegal		With tillage			
Bambey,	Millet-groundnut	Without fertiliser	3	5	7.0
ISRA-IRAT	Millet-groundnut	With fertiliser	3	5	4.3
	Millet-groundnut	Fertiliser + straw	3	5	6.0
Bambey,	Millet monoculture	with PK fertiliser	4	3	4.6
ISRA-IRAT		+ tillage			
Nioro-du-Rip,	Cereal-leguminous	F0T0	11	17	3.8
IRAT-ISRA	Cereal-leguminous	F0T2	11	17	5.2
	Cereal-leguminous	F2T0	11	17	3.2
	Cereal-leguminous	F2T2	11	17	3.9
	Cereal-leguminous	F1T1	11	17	4.7
Chad		With tillage, high fertility soil			
Bebedjia,	Cotton monoculture		11	20	2.8
IRCT-IRA	Cotton - cereals			20	2.4
	+ 2 years fallow			20	1.2
	+ 4 years fallow			20	0.5

F0 = no fertiliser, F1 = 200 kg ha^{-1} of NPK fertiliser, F2 = 400 kg ha^{-1} of NPK fertiliser + Taiba phosphate rock, T0 = manual tillage, T1 = light tillage, T2 = heavy tillage.
Source: Pieri, 1989

Effects of Crop Residues and Manure on Soil Productivity

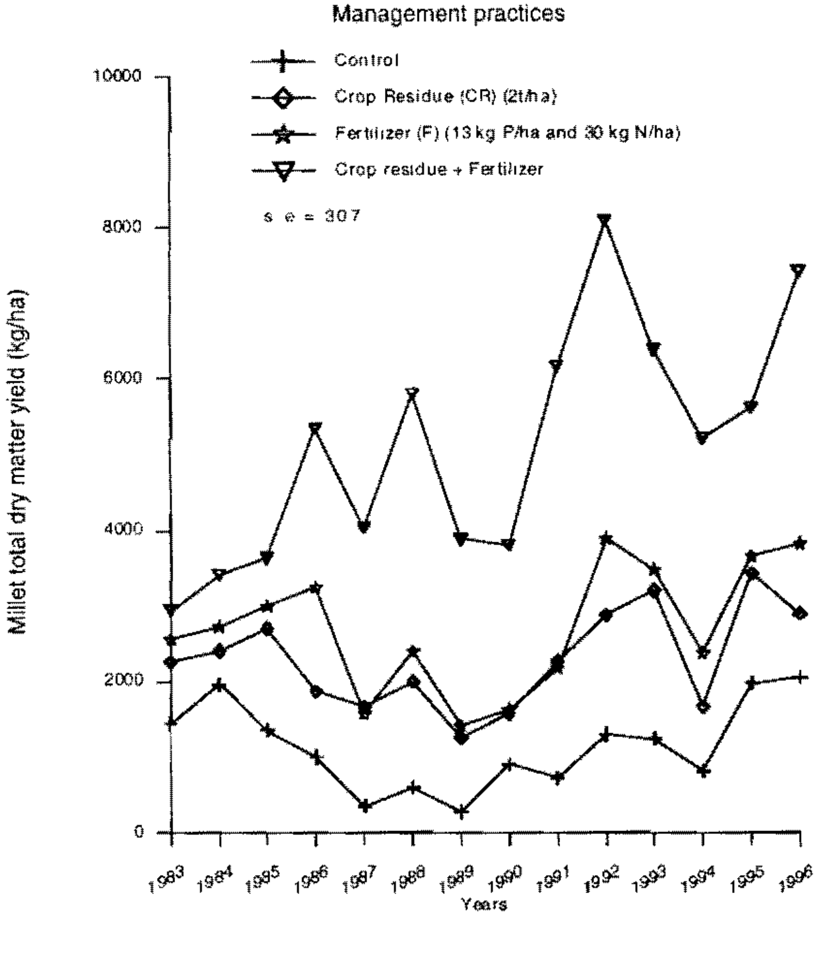
The Sahelian zone

In long-term crop residue and management trials, Bationo and Buerkert 2001 reported for the Sahelian zone a very significant effect between crop residue and mineral fertilizer (Figure 8.5). From the time this experiment started (since 1984), Bationo *et al.* (1993) reported that the grain yield declined to 160 kg ha^{-1} in unmulched and unfertilized plots. However, grain yield could be increased to 770 kg ha^{-1} with a mulch of 2 t crop residue per hectare and 1030 kg ha^{-1} with 13 kg P plus 30 kg N ha^{-1}. The combination of crop residue and mineral fertilizers resulted in grain yield of 1940 kg ha^{-1}. The application of 4 t of crop residue per hectare maintained soil organic carbon at the same level as that in an adjacent fallow field in the top soil but continuous cultivation without mulching resulted in drastic reduction of Corg (Figure 8.6). In the Sudanian zone, all available reports show a much smaller or even negative effect of crop residue use as soil amendment (Bationo *et al.* 1995; Sedogo, 1993). In the Sahelian zone the application of crop residue increased soil pH, and exchangeable bases and decreased the capacity of the soil to fix P.

On the nutrient poor West African soil, manure, the second farm-available soil amendment can substantially enhance crop yields. For Niger, McIntire *et al.* (1992) reported grain yield increased between 15 and 86 kg for millet and between 14 and 27 kg for groundnut per ton of applied manure. Similar manure effects have been reported from other Sahelian countries. However, given the large variation in the nutrient concentration of the manure types applied comparisons between results from different experiments should be reported with caution. Powell *et al.* (1998) reported a very significant effect of manure and urine application on pearl millet in the Sahelian zone.

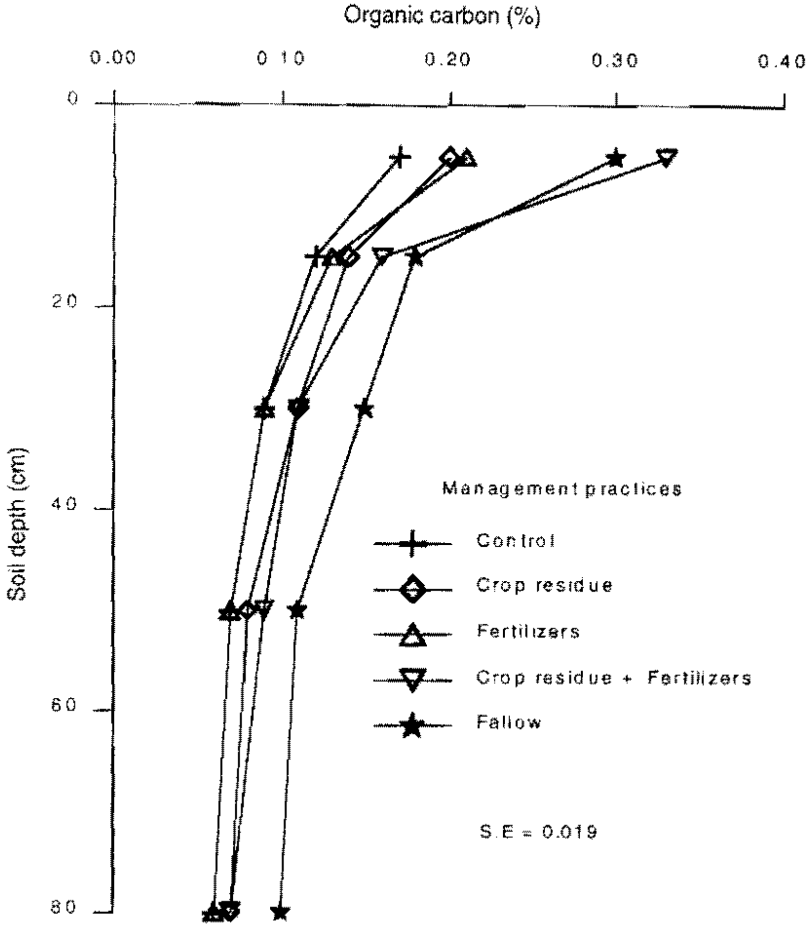
In the SSZWA crop residues use as surface mulch can play an important role in the maintenance of Corg levels and productivity of the prevailing acid soils through the recycling of mineral nutrients, increase in fertilizer use efficiency and a decrease in soil erosion effect. However, organic material available for surface mulching are scarce given the low overall production levels of biomass and their multiple competitive use as fodder, construction material and cooking fuel (Lamers and Feil, 1993). The crop residue quantities found on-farm at the beginning of the rainy season ranged from 0 to 500 kg ha^{-1}. McIntire and Fussel (1986) reported that on farmers' fields in the Sahel average grain yields were 236 kg ha^{-1} and mean crop residue yields barely reached 1300 kg ha^{-1}. Baidu-Forson (1995) reported on availability of 250 kg ha^{-1} of crop residue at the onset of the rains. Powell *et al.* (1987) showed that 50% of the disappearance rates of millet stover could be attributed to livestock grazing.

Figure 8.5. Effect of different management practices on pearl millet total dry matter yield over years, Sadore, Niger



Animal manure has a similar role as residue mulching for the maintenance of soil productivity but depending on rangeland productivity, it will require between 10 to 40 ha of dry season grazing land and 3 to 10 ha of rangeland of wet season grazing to maintain yields one one hectare of cropland (Fernandez-Rivera *et al.* 1995). The potential of manure to maintain soil Corg and sustain crop production is thus limited by the number of animals available and the size and quality of the rangeland.

Figure 8.6. Effect of different management practices on soil organic content, Sadore, rainy season 1997.



Soil depth (cm)

At the farm level, the maintenance of Corg levels in the soils of the region will largely depend on an increase in C fixation by plants. Given the strong limitation of plant growth by the low availability of mineral nutrients, a yield-effective application of mineral fertilizers is crucial. It would not only allow large increase in crop production and the amount of by-products but also to improve soil coverage by forage grass and weeds.

Relationships Between Cropping Systems and Fertility Management

The most common cropping system involves growing several crops in association as mixtures or intercrop. This practice provides the farmers with several options for returns from land and labor, often increases efficiency with scarce resources, and reduces dependence upon a single crop that is susceptible to environment and economic fluctuations. Steiner (1984) reported that traditional intercropping systems cover 75% of the cultivated land in the SSZWA. The principal reasons for farmers to intercrop are flexibility, profit and resource maximization, risk minimization, soil conservation and maintenance, weed control and nutritional advantages Swinton *et al.* 1974; Fusel and Serafini, 1985).

Cowpea (*Vigna unguiculata* (L.) Walp) and groundnut (*Arachis hypogea* L.) are two of the predominant grain legumes in the SSZWA. Groundnut occupies 2.7 million hectares of arable land and cowpea 6 million hectares. The two legumes are important components of the mixed cropping systems of the resource-poor farmers. The most important cereals are sorghum and pearl millet and the two legumes are often intercropped with these cereals. While considerable information is available on fertilizer requirements for sole cropping of various crops, little is known on fertilizer requirement in intercropping.

In the mixed cropping systems, legume yields are very low due to low soil fertility, low planting densities and pest and decrease (Ntare,1989; Reddy *et al.* 1992). The yield of cowpea grain varies between 50 and 300 kg ha^{-1} in farmers fields in marked contrast to yield over 2000 kg ha^{-1} obtainable on research station and by large scale commercial enterprises in pure cropping. Rotation of cereals with legumes has been extensively studied in recent years. The use of rotational systems involving legumes for harvesting nitrogen fixation is gaining importance throughout the region because of economic and sustainability considerations. The beneficial effect of legumes on succeeding crops is normally exclusively attributed to the increased soil N fertility as a result of N-fixation. The amount of N2 fixed by leguminous crops can be quite high but some workers have demonstrated also that legumes can deplete soil nitrogen (Rupela and Saxena, 1987; Blumenthal *et al.* 1982; Tanaka *et al.* 1983). Most data reported on the quantity of N fixed by the legume crops in the SSZWA concerned the above ground part of the legume and very little is known on the N fixed by roots where much of the legume bio-mass is returned to the soil as green manure a positive N balance is to be expected. However, this may not be true for grain legumes and fodder. Where the bulk of above legume material is removed from the system. Nevertheless, many other positive effects of grain legumes such as the improvement of soil biological and physical properties and the ability of some legumes bounded P by roots exudates (Gardner *et al.* 1991; Arihara and Okwaki, 1989).

Other advantages of crop rotations include soil conservation (Stoop and Staveren, 1981), organic matter restoration (Spurgeon and Grimson, 1965) and pest and disease control (Sunnadurai, 1973).

In the mixed crop-livestock systems of the SSZWA, increasing legume component in the farming systems is important in order to increase the availability of fodder as source of livestock feed while increasing soil fertility.

Intercropping

Fussel and Serafini (1985) reported yield advantages from 10-100% in millet cowpea systems. Yield stability has been proposed as a major advantage of intercropping (Wiley, 1979a, 1979b; Willey *et al.* 1985; Steiner, 1984) as farmers want to rely on management practices that increase yields, when this is possible, while improving the stability of the production in both good and poor rainfall years. Baker (1980) has compared relative stability of intercropping and cropping using stability analysis of Finlay and Wilkinson (1963) and found that in the groundnut or cereal systems in Northern Nigeria, intercropping systems were found to be more stable. Ntare (1989) reported yield advantages of 20-70% depending on the different combinations of pearl millet and cowpea cultivars. Although traditional intercropping cover over 75% of the cultivated area in the SSZWA, there is a scarcity of information on the efficiency of fertilizers under these systems. The number of days before planting the second crop will depend on the importance of the next rains after the first cereal crops have been planted. With a basal application of P fertilizers the cereal growth is rapid and can suppress completely the second crop if its planting occurs after three weeks after the cereal crops have been sown. In contrast if the legume crops is planted early it will compete more with the cereal crop for light, water and nutrients and can significantly reduce the yield of the cereal crop.

Relay and sequential cropping

In the Sudanian zone with longer growing season and higher rainfall there is greater opportunity than in the Sahelian zone to manipulate the systems with appropriate genotypes and management systems. Field trials have been conducted to examine the performance of the cultivars under relay and sequential systems. They revealed the potential of these alternative systems over traditional sole or mixed cropping (ICRISAT, 1984 and 1987).

In Mali, by introducing short season sorghum cultivars in relay cropping with other short duration cowpea and groundnut cultivars, substantial yields of legumes and sorghum were obtained as compared to traditional systems (IER, 1990; Sogodogo and Shetty, 1991).

In the Sahelian zone Sivakumar (1986) analysed the data of the onset and ending of the rains and the length of the growing period. He found that an early onset of the rains offers the probability of a longer growing period while delayed onset results in a considerable short term growing season. The above analysis suggests that even for the Sahelian zone, cropping management factors using relay cropping can increase soil productivity with an early onset of the rains.

Crop Rotation

Despite the recognised need to apply chemical fertilizers for high yields, the use of fertilizers in West Africa is limited by lack of capital, inefficient distribution systems, poor enabling policies and other socio-economic factors. Cheaper means of improving soil fertility and productivity are therefore necessary.

Cereals and legumes rotation effects on cereals yields have been reported by several scientists (Bationo *et al.* 1998; Klaij and Ntare, 1985; Stoop and Van Staven, 1981). Bationo and Vlek, 1998 data at Tara in the Sudanian zone clearly indicates that at all levels of N application the yield of pearl millet after cowpea outperformed the yield of millet in the continuous millet cultivation.

15N has been used to quantify the amounts of N fixed by cowpea and groundnut under different soil fertility levels. The N derived from the air (NDFA) varies from 65 to 88% for cowpea whereas the values varied from 20 to 75% for groundnut. In the complete treatment where all nutrients were applied cowpea stover fixed up to 89 kg N ha^{-1} whereas for same treatment groundnut fixed only 40 kg N ha^{-1} in this Sahelian environment (Bationo and Vlek 1998). In order to determine 15N recovery from different cropping systems, labelled nitrogen fertilizers were applied to microplots of pearl millet grown continuously, in rotation with cowpea, in rotation with groundnut, intercropped with cowpea, and intercropped with groundnut. The data indicates that nitrogen use efficiency increased from 20% in continuous pearl millet cultivation to 28% when pearl millet was rotated with cowpea (Bationo and Vlek, 1998). The same authors reported that in the Sudanian zone nitrogen derived from the soil increased from 39 kg N ha^{-1} in continuous pearl millet cultivation to 62 kg N/ha when pearl millet was rotated with groundnut. Those data clearly indicate that although all the above ground biomass of the legume will be used to feed livestock and not returned to the soil, rotation will increase not only the yields of succeeding cereal crop but also its nitrogen use efficiency.

Bayayoko *et al.* (2000) in studies of cereals legumes effects on cereal growth in the Sudano-Sahelian zone of West Africa reported that the rotation effect although significant in most of the cases varied with sites and years. At Sadore as an example, the millet rotated with cowpea yielded 1904 kg/ha whereas the continuous millet cultivation yielded 1557 kg ha^{-1}. Bayoyoko *et al.* 2000 reported higher levels of mineral N and native arbuscular mychorrhizae infection in the rotation systems as compared to the continuous cereal cultivation.

The different cropping systems have a significant effect on the soil organic carbon. The soil organic carbon levels was 0.22% in the continuous systems whereas it is increased to 0.27% in the rotation systems. As a result of this soil pH was higher in the rotation systems as compared to the continuous monoculture (Bationo, unpublished data).

Farmers Evaluation of Soil Fertility Restoration Technologies

A review of the state of the art of the agronomic research in soil fertility management showed that on-station research has developed a considerable amount of promising results but very few of these technologies have reached the small farmers. It is recognized that most of these technologies developed on-station, are not always built on indigenous practices, local socio-economic realities, farmers priorities and perceptions. Most often no account has been taken of enabling policy environment and indigenous knowledge. Therefore on-farm research should involve farmers, researchers, extension agents, non-governmental agencies at the design, implementation and evaluation stages. In this way, the technologies generated have a better chance of adoption by the land users. Promising technologies were identified to be tested on-farm under farmers managed trials knowing that a particular farm management practice is often less effective in the hand of the farmer, than it is on-station. There is need for experimental farm input packages to be tested under farmer's conditions to allow the scientists to observe the transfer of technologies to the farmers field and to determine associated management practices to be adopted by farmers in order to ensure good economic returns.

The objectives of on-farm research activities is:

(i) To assess farmers' perception of the different technologies proposed
(ii) To identify the farmers' management practices affecting the good performance of the different technologies
(iii) To evaluate the profitability of the different technologies tested

(iv) To identify the constraints to technology adoption and means to alleviate them and
(v) To assess the impact of technology adoption.

Effects of Soil Fertility Restoration Technologies on Land Productivity From Farmers Managed Trials in the SSZWA

In the Sahelian zone of Gobery in Western Niger, 20 farmers evaluated P and N fertilizers including partially acidulated phosphate rock (PAPR) from parc-W. The data in Table 8.13 indicate a strongly response to P with yield increase of 181% over control with the application of N and P. No significant difference was found between PAPR and SSP, nor was difference between broadcasting and hill placement of nitrogen. However, crop response to fertilizer use was strongly affected by the cropping density chosen by individual farmers (Bationo *et al.* 1992). Averaged over all fertilized treatments and all years, when farmers planted at less than 3500 pockets per hectare, yield was very low and no response was found to fertilizer use. However, each 1500 pocket ha^{-1} increases about 200 kg grain/ha.

Table 8.13. Millet grain yields by treatment (mean of 3 years), Goberi, Niger

Treatment	Yield (kg ha^{-1})
Control	261
SSP only	586
SSP + N hill placed	700
SSP + N broadcast	751
PAPR + N broadcast	752
$LSD_{0.05}$	84

Source: Bationo *et al.*, 1992

Bationo (unpublished data) reported the agro-economic evaluation of farmers managed trials on the evaluation of water soluble fertilizers, phosphate rock and rotation of cereals with legumes. The net grains, over three years, resulting from partial budgeting analysis show that farmers could make net financial gains with only the application of P fertilizer. The use of N in addition to P significantly improved net grains. Water soluble single superphosphate generated higher net gains than Tahoua phosphate rock. As a result of the higher cowpea price and is beneficial effect on the improvement of soil fertility, the rotation systems involving cowpea were more profitable than continuous pearl millet cultivation.

Bationo *et al.* 1997 reported the economic evaluation data of Tilemsi phosphate rock by farmers in three agro-ecological zones of Mali. The agro-ecological zones were; Tafla with an average rainfall of 600 mm, Sougoumba with 800 mm rainfall and Tinfounga with 1200 mm rainfall. The cropping systems used were rotation of pearl millet with groundnut in Tafla, sorghum with cotton in Sougoumba and maize with cotton in Tinfounga. The data indicate that the different sources of fertilizers have a significant effect on crop yields and there was no difference between Tilemsi phosphate rock and the recommended imported water soluble fertilizers. However, the economic analysis of the data indicate that at some sites the imported recommended water soluble P fertilizers are more profitable than the use of Tilemsi phosphate rock.

Bationo *et al.* 1998 undertook an agro-economic evaluation of a set of soil fertility restoration technologies and concluded that hill placement of small quantities of P fertilizers at planting time had higher returns than broadcasting 13 kg P/ha.

From 1988 to 2000 farmers-managed trials in the Sahelian zone at Karabedji (~550 mm of rainfall per year) and in the Sudanian zone at Gaya (~800 mm of rainfall per year), over an average of about 2800 field plots showed the agronomic potential of fertilizers (Table 8.14). The hill placement of 4 kg P/ha almost doubled crop yield. Integrated use of hill placement of water soluble fertilizers in addition to Tahoua phosphate rock broadcast and soil amendment with crop residue application as mulch gave the highest crop yield (Figure 8.7). The returns over variable cost of fertilizers presented clearly demonstrate the economic importance of soil fertility restoration in the SSZWA.

Table 8.14. Mean millet yield (kg ha^{-1}) as affected by fertilizer, phosphate rock and crop residue in Sudano-Sahelian zone, Niger, 1998-2000

*Treatment	Karabedji	Gaya
Farmer practice (FP)	210	505
P hill placement (HP)	470	990
HP + Phosphate rock (PR)	580	1150
HP+PR+Crop residue	835	1320

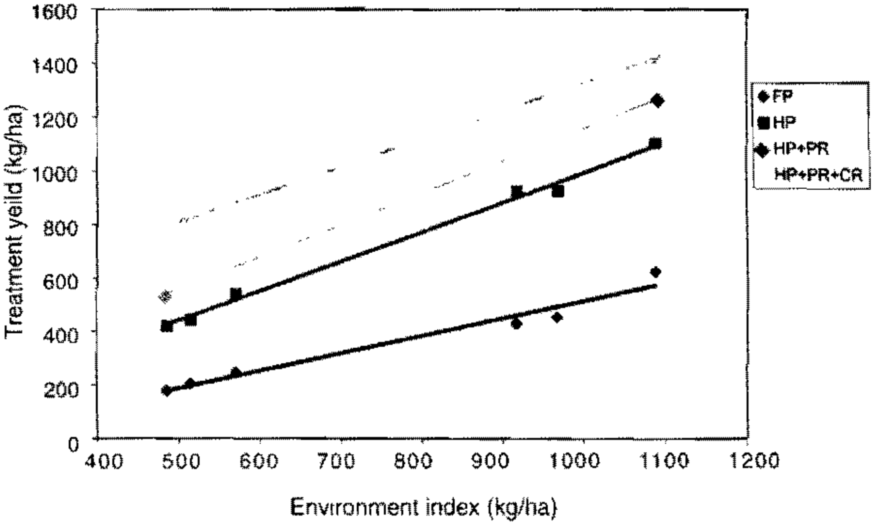
*Hill placed (HP): P applied at 4 kg ha^{-1} as 15-15-15.

Phosphate rock (PR): P broadcast and incorporated at 13 kg ha^{-1} as Tahoua PR

Crop residue (CR): millet stover applied as mulch at 2 t ha^{-1}

Average rainfall: 600 mm and 800 in Karabedji and Gaya

Figure 8.17. Relationship between environmental index and treatment yield of pearl millet in different agro-ecological zones of Niger



New Research Opportunities in the SSZWA

New strategies for integrated nutrient management

In the past, integrated nutrient management concentrated mainly on the utilization of available organic and inorganic sources of plant nutrients in a judicious and efficient way. Integrated nutrient management is recently perceived much more broadly as the judicious manipulation of all soil nutrient inputs and outputs and internal flows.

Future research needs to adopt this new holistic approach to integrated nutrient management. For a given cropping system or watershed, this will require the establishment of the nutrient balances. Interventions to limit nutrient losses through erosion can be in some cases as important as research on increasing the efficiency of organic and inorganic plant nutrients for a sustainable land use. This new approach will enhance more carbon sequestration and increase more bio-mass production on the farms for domestic use and there will be more bio-man available for livestock feeds and for soil mulching.

Integration of socio-economic and policy research with the technical solution

In the past several technical solutions to the problem of land degradation in the SSZWA have been researched and tested, and may have shown the potential for addressing the problem in some places. Unfortunately a review of the state of the art indicated that very few of these technologies have been adopted by the resource poor farmers. Therefore, future research should focus more on problems driven by socio-economic factors and enabling policy environment in order to enhance farmers' capacity to invest in soil fertility restoration. The adoption of the participatory approach will be essential. In this way, the technologies generated have a better chance of adoption by land users.

Combining rain water and nutrient management strategies to increase crop production and prevent land degradation

In the SSZWA high inter-annual variability and erratic rainfall distribution in space and time result in water-limiting conditions during the cropping season.

In areas with inadequate rainfall or in runoff-susceptible land, water conservation techniques and water harvesting techniques offer the potential to secure agricultural production and reduce the financial risks associated with the use of purchased fertilizers. Under the conditions of adequate water supply, the addition of organic and inorganic amendments is the single most effective means of increasing water use efficiency. Future research needs to focus on enhancing rainwater and nutrient use efficiencies and on capitalizing on their synergies for increasing crop production and preventing soil degradation.

Increasing the legume component for a better integration of crop-livestock production systems

The rotations of cereals with legumes have led to increased cereals yield at many locations in the SSZWA. Factors such as mineral nitrogen increase, enhancement of Vesicular-Azbuscular Mycorrhizal (VAM) for better P nutrition and a decrease in parasitic nematodes have been identified as mechanisms accelerating the enhanced yield of cereals in rotation with legumes. Most of the research attempt has focused on the quantification of the above-ground N fixed by different legumes cultivars, but very little is known on the below-ground N fixed.

There is need to increase the legume component in the mixed cropping systems for a better integration of crop-livestock. The increase of legume component in the present cropping system will not only improve the soil conditions for the succeeding cereal crop, but will provide good quality livestock feed, and the manure produced will be of better quality for soil amendment.

Exploiting genetic variation for nutrient use efficiency

Phosphorus is the most limiting plant nutrient for crop production in the SSZWA and there is ample evidence that indicates marked differences between crop genotypes for P uptake. A better understanding of the factors affecting P uptake such as the ability of plants to (i) solubilize soil P through acidification of the rhizosphere and the release of chelating agents and phosphate enzymes, (ii) explore a large volume of soil, and (iii) absorb P from low P solution would help screening for the genotypes the best appropriate for nutrient use efficiency.

Another important future research opportunity is the selection of genotypes that can efficiently associate with Vesicular-Azbuscular Mycorrhizal (VAM) for better utilization of P applied as indigenous phosphate rock.

Use of decision support systems modelling, and GIS for the extrapolation of research findings

Farmers production systems vary with respect to rainfall, soil types and socio-economic circumstances and therefore they are complex. Dealing with such complexity only by empirical research will be expensive and inefficient. Use of models and GIS will facilitate the transfer of workable technologies to similar agro-ecological zones. The use of DSSAT, APSIM and GIS will facilitate extrapolation of findings to other agro-ecozones similar of the benchmark sites chosen for testing technologies and will be cost effective.

References

Amato, M. and Ladd, J.N. (1992) Decomposition of ^{14}C Labelled Glucose and Legume Material in Soils: Properties influencing the accumulation of organic residue-C and microbial biomass-C. *Soil Biol Biochem*. **24:** 455-464.

Arhara, J. and Ohwaki, Y. (1989) Estimation of Available Phosphorus in Vertisol and Alfisol in View of Root Effects on Rhizosphere Soil. In XI Colloquium Wageningen, Holland.

Bache, B.W. and Rogers, N.E. (1970) Soil phosphate values in relation to phosphate supply to plants from some Nigerian soils. *J. Agric. Sci., Camb.* **74:** 383-390.

Baidu-Forson, J. (1995) Determinants of the Availability of Adequate Millet Stover for Mulching in the Sahel. *J. Sust. Agric.* **5:**101-116.

Bakayoko, M., Buerkert, A., Lung, A., Bationo, A. and Romheld, V. (2000) Cereal/ Legume Rotation Effects on Cereal Growth in Sudano-Sahelian West Africa: Soil Mineral Nitrogen, Mycorrhizae and Nematodes. *Plant and Soil.* **218:** 103-116.

Baker, E.F. I. (1980) Mixed Cropping in Northern Nigeria. IV. Extended trials with cereals and groundnuts. *Experimental Agriculture.* **16:**361-369.

Balasubramanian, V., Singh, V.L., Nnadi, L.A., Mokwunye, A.U., (1984) Fertility status of some upland savanna soils of Nigeria after fallow and cultivation. *Samaru J. Agric. Res.* **2:** 13-23.

Bationo, A., Christianson, C.B. and Mokwunye, A.U. (1987) Soil fertility management of the millet-producing sandy soils of Sahelian West Africa: The Niger experience. Paper presented at the Workshop on soil and crop management systems for rainfed agriculture in the Sudano-Sahelian zone, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Niamey, Niger.

Bationo, A., Christianson, C.B. and Baethgen, W.E. (1989) Plant density on plant millet production in a sandy soil of Niger. *Agronomy J.* **82:**290-295.

Bationo, A., Chien, S.H., Christianson, C.B., Henao, J. and Mokwunye, A.U. (1990) A three year evaluation of two unacidulated and partially acidulated phosphate rocks indigenous to Niger. *Soil Sci. Soc. Am. J.* **54:** 1772-1777

Bationo, A. and Mokwunye, A.U., 1991. Role of manures and crop residues in alleviating soil fertility constraints to crop production with special reference to the Sahelian zones of west Africa. *Fert. Res.* **29:** 125-177.

Bationo, A., Christianson, B.C., Baethgen, W.A. and Mokwunye, A.U. 1992. A Farm-level evaluation of nitrogen and phosphorus fertilizers use and planting density for pearl millet production in Niger. *Fert. Res.* **31:** 175-184.

Bationo A Christianson BC and Klaij MC (1993) The effect of crop residue and fertiliser use on pearl millet yields in Niger. *Fert Res.* **34:** 251-258.

Bationo A Buerkert A Sedogo MP Christianson BC and Mokwunye AU (1995) A critical review of crop residue use as soil amendment in the West African Semi-Arid Tropics. In: Powell, J.M., Fernandez-Rivera, S., Williams, T.O. and Renard, C. (eds.) *Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of Sub-Saharan Africa*, pp 305-322. Volume 2: Technical Papers. Proceedings of an International Conference, 22-26 November 1993. International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia.

Bationo, A., Rhodes, E., Smaling, E.M.A., Visker, C., (1996) Technologies for restoring soil fertility. In: Mokwunye, A.U., de Jager, A., Smaling, E.M.A. (eds.), *Restoring and Maintaining the Productivity of West African Soils: Key to Sustainable Development*. IFDC-Africa, LEI-DLO and SC-DLO, Miscellaneous Fertilizer Studies No. 14. International Fertilizer Development Center.

Bationo, A., Ayuk, E.D. Ballo and Kone, M. (1997) Agronomic and economic evaluation of Tilemsi phosphate rock in different agro-ecological zones of Mali. *Nutrient Cycling in Agroecosystems*. **48:** 179-189.

Bationo, A. and Vlek, P.L.G. (1998) The role of nitrogen fertilizers applied to food crops in the Sudano-Sahelian zone of West Africa. In: Renard, G., Neef, A, Becker, K. and von Oppen, M. (eds.). *Soil Fertility Management in West African Land Use Systems*. Margraf Verlag, Weikersheim, Germany. Pp 41-51.

Bationo, A., Lompo, F. and Koala, S. (1998) Research on nutrient flows and balances in West Africa: state-of-the-art. *Agric. Ecosyst. Environ.* **71:** 19 35

Bationo, A., J. Ndjeunga, C. Bielders, V.R. Prabhakar, A. Buerkert and S. Koala. (1998) Soil fertility restoration options to enhance pearl millet productivity on sandy sahelian soils in south-west Niger. In: Peter Lawrence, Geneviève Renard and Matthias von Oppen (eds.) *The Evaluation of Technical and Institutional Options for Small Farmers in West Africa.* Proceedings of an International Workshop held on April 21-22-1998 at the University of Hohenheim as part of the Special Research Programme 308. Adapted Farming in West Africa. Margraf Verlag, Weikersheim, Germany.

Blumenthal, M.J., Quach, V.P. and Searle, P.G.E. (1982) Effect of soybean population density on soybean yield, nitrogen accumulation and residual nitrogen. *Australian Journal of Experimental Agriculture.* **28:** 99-106.

Hulme, M. (1992) Rainfall changes in Africa (1931-1960 to 1961-1990). *International Journal of Climatology.* **12:** 658-690.

Hulme, M. and Kelly, M. (1997) Exploring the links between desertification and climate change. In: Owen, L. and Unwin, T.B.H. (eds.) *Environmental* management: Readings and case studies. Blackwell, Oxford, UK.

Annual report (1984) ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1985. Patancheru, A.P. 502 324, India: ICRISAT.

Annual Report, (1984 to 1988) ICRISAT, 1984-1988, Patancheru, A.P. 5023, India, ICRISAT.

IER, 1990. Institut d'Economie Rurale. Rapport Annuel et Commissions Techniques Production Vivrieres et Oleagineuses. Program cooperatif ICRISAT/Mali, IER, Bamako, Mali.

Jones, M.J. and Wild, A (1975) Soils of the West African savanna. *Commonw. Bur. Soils Tech. Comm.* No. 55, Harpenden, England.

Jones, M.J. (1973) A review of the use of rock phosphate as fertilizer in Francophone West Africa. *Samara misc paper* 43, Institute for Agricultural Research, P.M.B. 1044 Zaria.

Juo, A.S.R. and Fox, RL. (1977) Phosphate sorption characteristics of some benchmark.

Juo, A.S.R. and Kang, B.T. (1978) Availability and transformation of rock phosphates in three forest soils from southern Nigeria. *Comm Soil Sci and Plant Analysis.* **9:** 495-505.

Kang, B.T. and Osiname, A.O. (1979) Phosphorus response of maize grown on alfisols of Southern Nigeria. *Agron. J.* **71:** 873-877.

Khasawneh, F.E. and Doll, E.C. (1978) The use of phosphate rock for direct application to soils. *Adv. Agrono.* **30:**155-206.

Kirk, G.J.D. and Nye, P.H. (1986) A simple model for predicting the rate of dissolution of sparingly soluble calcium phosphate in soil. I. The basic model. *J. Soil Sci.* **37:**529-540.

Klaij, M.C. and Ntare, B.R. (1995) Rotation and tillage effects on yield of pearl millet (Pennisetum glaucum) and cowpea (Vigna unguiculata), and aspects of crop water balance and soil fertility in semi-arid tropical environment. *Journal of Agriculture Science*, Cambridge, **124:** 39-44.

Kowal, J.M. (1970) The hydrology of small catchment basin at Samaru, Nigeria. III. Assessment of surface runoff under varied land management and vegetation cover. *Nigerian Agricultural Journal.* **7:** 120-133.

Kowal, J.M. and Kassam, A.H. (1978) *Agricultural ecology of Savanna; a study of west Africa.* Oxford, UK: Clarendon Press. 403 pp.

Lal, R. (1980) Soil erosion as a constraint to crop production. Page 405-423. In: *Priorities for alleviating soil related constraints to food prodution in the tropics*, Los Baños, Laguna, Philippines: International Rice Research Institute.

Lamers, J.P.A. and Feil, P. (1993) The many uses of millet residues. ILEA Newsletter 9:15.

Langmuir, J. (1918) The adsorption of gases on plain surface of glass, mica, and platinum. *J. Amer. Chem. Soc.* **40:**1361-1403.

Lehr, J.R. and McClellan, G.H. (1972) *A revised laboratory reactivity scale for evaluating phosphate rocks for direct application*, Bulletin 43, Tennessee Valley Authority, Muscle Shoals, AL, U.S.A.

Manu, A., Bationo, A. and Geiger, S.C. (1991) Fertility status of selected millet producing soils of West Africa with emphasis on phosphorus. *Soil Sci.* **152:**315-320.

McIntire, J. and Fussel, L.K. (1986) On-farm experiments with millet in Niger. III. *Yields and econimic analyses*. ISC (ICRISAT Sahelian Center), Niamey, Niger.

McIntire, J., Bourzat, D. and Pingali, P. (1992) *Crop-livestock interactions in Sub-Saharan Africa*. Washington, DC: The World Bank.

Mokwunye, U. (1974) Some reflections on the problem of "available" phosphorus in soils of tropical Africa. *Samaru Conf. Pap.* **3:**1-11.

Mokwunye, U. (1979) Phosphorus fertilizers in Nigerian savanna soils. II. Evaluation of three phosphate sources applied to maize at Samaru. *Trop Agric.* (Trinidad). **56:** 65-68.

Mokwunye, A.U. (1995) Reactions in soils involving phosphate rocks. In: Henny G. and Mokwunye, A.U. (eds.) *Use of Phosphate Rocks for Sustainable Agriculture in West Africa*. IFDC-Africa.

Muelhig-Versen, B.A., Buerkert, A., Bationo, A. and Maschner, H. (1997) Crop residue and phosphorus management in millet based cropping systems on sandy soils of Sahel, p. 31-40. In: Renard, G., Neef, A., Becker, K. and von Oppen, M. (eds.) *Soil fertility management in West African land use systems*. Proceedings of a Regional Workshop, University of Hohenheim, ICRISAT, INRAN, Niamey, Niger, 4-8 March 1997. Margraf Verlag, Weikersheim, Germany

Mughogho, S.K., Bationo, A., Christianson, C.B. and Vlek, P.L.G. (1986) Management of nitrogen fertilizers for tropical African soils. In: Mokwunye, A.U. and Vlek, P.L.G. (eds) *Management of nitrogen and phosphorus fertilizers in sub-Saharan Africa*. Martinus Nijhoff, Dordrecht, The Netherlands.

Nabos, J., Charoy, J. and Pichot, S. (1974) Fertilization phosphates de sols du Niger, utilization des phosphates naturels de Tahoua. *Agron Trop.* **29:** 1140-1150.

Neef, K. Becker and von Oppen, M. (eds.) *Soil fertility management in West African land use system*. Proceedings of a Regional Workshop, University of Hohenheim, ICRISAT, INRAN, Niamey, Niger, 4-8 March 1997. Margraf Verlag, Weikersheim, Germany.

Nicholson, S.E. (1981) Rainfall and atmospheric circulation during drought and wetter periods in West Africa. *Monthly weather Review*. **109:** 2191-2208.

Nicholson, S.E. and Palao, I.M. (1993) A re-evaluation of rainfall variability in the Sahel. Part I. Characteristics of rainfall fluctuations. *International Journal of Climatology*. **13:** 371-389.

Nielsen, N.E. and Schjorring, J.K. (1983) Efficiency and kinetics of phosphorus uptake from soil by various barley genotypes. *Plant and Soil*. **72:**225-230.

Ntare, B.R. (1989) Intercropping morphologically different cowpea with pearl millet in a short season environment in the Sahel. *Experimental Agriculture*. **26:** 41-47.

Nye, P.H. and Greenland, D.J. (1960) *The soil under shifting cultivation*, CAB International, Wallingford, UK.

Pichot, J. and Roche, P. (1972) Le phosphore dans les sols tropicaux. *Agron Trop.* **27:** 939-965

Pieri, C. (1989) *Fertilité des terres de savane*. Bilan de trente ans de recherche et de développement agricoles au Sud du Sahara. Ministère de la Coopération. CIRAD. Paris, France. 444 pp.

Powell, J.M. and Mohamed S. (1987) Nitrogen and phosphorus transfers in a crop-livestock system in West Africa. *Agric. Syst.* **25:**261-277.

Powell, J.M., Ikpé, F.N., Somda, Z.C. and Fernandez-Rivera, S. (1998) Urine effects on soil chemical properties and the impact of urine and dung on pearl millet yield. *Expl. Agric.* **34:**259-276.

Reddy, K.C., Visser, P. and Buekner, P. (1992) Pearl millet and cowpea yields in sole and intercrop system, and their after-effects on soil and crop productivity. *Field crops Research.* **28:** 315-326

Rupela, O.P. and Saxena, M.C. (1987) Nodulation and nitrogen fixation in chickpea. Pages 191-206 In: Saxena, M.C. and Sigh, K.B. (eds.) *The chickpea.* Farnham Royal, UK: Commonwealth Agricultural Bureaux International and International Center for Agricultural Research in the Dry Areas.

Sale, P.W.G. and Mokwunye, A.U. (1993) Use of phosphate rock in the tropics. *Fert. Res.* 35:33-45.

Sanchez, P.A. and Uehara, G. (1980) Management considerations for acid soils with high phosphorus fixation capacity. In: Khasawneh, F.E. (ed.) The role of phosphorus in agriculture. *Am. Soc. Agron.*, Madison, WI, pp. 471-509.

Segodogo, D. and Shetty, S.V.R. (1991) Progres de la recherché vers une technologie ameliorее de production du sorgho en culture pluviale. Paper presented at the Inter-Network Conference in Food Grain Improvement, 7-14, March 1991, Niamey, Niger (proc. in Press).

Sedogo, M.P. (1993) Evolution des sols ferrugineux lessivés sous culture: influences des modes de gestion sur la fertilité. Thèse de Doctorat Es-Sciences, Abidjan, Université Nationale de Côte d'Ivoire.

Sinnadurai, S. (1973) Crop rotation to control nematodes in tomatoes. *Ghana Journal Agricultural Science.* **6:** 137-139.

Sivakumar, M.V.K. (1986) Soil climatic zonation for West African semiarid tropics: implications for millet improvement. Presented at the Regional Pearl millet workshop, 6-12 Sept. 1986, Niamey, Niger

Smith, J.P. and Lehr, J.R. (1966) An X-ray investigation of carbonate apatites. *J. Agric. Food Chem.* **14:**342-349.

——soils of West Africa. *Soil Sci.* **124:**370-376.

Spencer, K., Govaars, A.G. and Hely, F.W. (1980) Early phosphorus nutrition of eight forms of two clover species. *Trifolium ambiguam* and *T. Repens. New Zealand Journal of Agricultural Research.* **23:** 457-475.

Spurgeon, W.I. and Grissom, P.H. (1965) *Influence of cropping systems on soil properties and crop production.* Mississipi Agriculture Experiment Station Bulletin No. 710

Steiner, K.G. (1984) Intercropping in tropical smalholder agriculture with special reference to West Africa. Stein, West Germany, 304pp

Sterk, G., L. Herrmann and Bationo, A. (1996) Wind-blown nutrient transport and soil productivity changes in southwest Niger. *Land Degradation and Development.* **7:** 325-335.

Stoop, W.A. and Staveren, J.P.V. (1981) Effects of cowpea in cereal rotations on subsequent crop yields under semi-arid conditions in Upper-Volta. In: Graham, P.C. and Harris, S.C. (eds.) *Biological Nitrogen Fixation Technology for Tropical Agriculture* , Cali, Colombia: Centro International de Agricultura Tropical.

Stoorvogel, J.J., Smaling, E.M.A. (1990) *Assessment of soil nutrient depletion in sub-Saharan Africa: 1983-2000.* Volume 1. Main report. The Winand Staring Centre, Wageningen, The Netherlands.

Swinton, S.M., Numa, G. and Samba, L.A. (1984) *Les cultures associees en milieu paysan dans deux regions du Niger: Filingue et Madarounfa.* Pages 183-194 Proceedings of the Regional Workshop on Intercropping in the Sahelian and Sahelo-sudanian zones of West Africa, 7-10 Nov 1984, Niamey, Niger, Bamako, Mali: Institute du Sahel.

Syers, J.K., Evans, T.D., Williams, J.D.H. and Murdock, J.T. (1971) Phosphate sorption parameters of representative soils from Rio Grande du Sol, *Brazil. Soil Sci.* **112**:267-275.

Tanaka, N., Fujii, H. and Yoshida, A. (1983) Balance sheet of soybean nitrogen (in Ja) *Nogyo Gijutsu.* **38**:71-72.

Thibout, F., Traore, M.F., Pieri, C. and Pichot, J. (1980) L'utilisation agricole de phosphate naturels de Tilemsi (Mali): synthese de resultants de la recherché agronomique sur les cultures vivrieres et oleagineuses. *Agron Trop.* **35**: 240-249.

Toupet, C. (1965) Les elements annuels du climat. *International Atlas of West Africa.* Organization of African Unity/Scientific and Technical Research Commission. Dakar, Sénéegal: OAU/STRC.

Truong, B., Pichot, J. and Bennard, P. (1978) Caracterisation et comparaison des phosphates naturels tricalciques d'Afrique de l'ouest en vue de leur utilization directe en agriculture. *Agron Trop.* **33**: 136-145.

Udo, E.J. and Ogunwale, J.A. (1972) Characteristics of phosphorus adsorption by some Nigerian soils. *Soil Sci. Soc. Am. J.* **36**:879-883.

Van der Pol, F., and Van der Geest, N. (1993) "Economics of the nutrient balance." In: Hujsman and Van Tilburg (eds.) *Agriculture, economics, and sustainability in the Sahel.* Royal Tropical Agriculture, Amsterdam., The Netherlands.

Willey, R.W. (1979a) Intercropping – its importance and research neds. Part 1. Competition and yield advantages. *Field crop Abstracts.* **32**:1-10.

Willey, R.W. (1979b) Intercropping – its importance and research needs. Part 2. Agronomy and research approaches. *Field crop Abstracts.* **32**:733-85.

Willey, R.W., Natarajan, M., Reddy, M.S. and Rao, M.R. (1985) Intercropping to make use of limited moisture supply and to minimize the effects of drought. Pages 421:429. In: *La secheresse en zone intertropicale pour une lutte integree.* CIRAD Boudin Press, Paris 591pp.

Williams, T.O., Powell, J.M. and Fernandez-Rivera, S. (1995) Manure utilization, drought cycles and herd dynamics in the Sahel: Implications for crop productivity. In: Powell, J.M., Fernandez-Rivera, S., Williams, T.O. and Renard, C. (eds.) Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of Sub-Saharan Africa, pp 393-409. Volume 2: Technical Papers. Proceedings of an International Conference, 22-26 November 1993. International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia.

Windmeijer, P.N., Andriesse, W., 1993. Inland valleys in west Africa: an agro-ecological characterization of rice-growing environments. Publication 52, ILRI, International Institute for Land Reclamation and Improvement, Wageningen, Netherlands.

Xue, Y., K.-N. Liou, and A. Kasahara. 1990. Investigation of biogeophysical feedback on the African climate using a two-dimensional model. *Journal of Climate.* **3**: 337-352.

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Managing Africa's Soils: Approaches and Challenges

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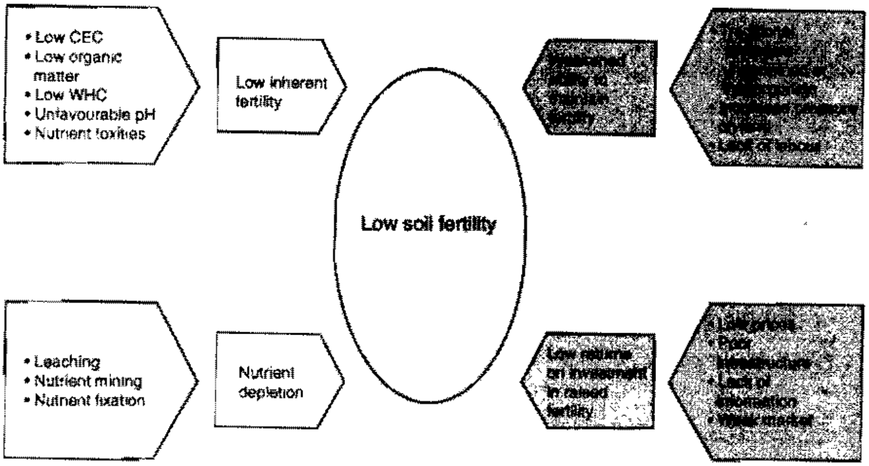
Introduction

The fore-going chapters have clearly shown the problems of soil fertility in sub-Saharan Africa and the various technologies, which have been developed and tested, in a wide range of environments to solve the problems of food insecurity. The low productivity of agriculture is strongly related to the low quality of the soil resource base (Part 1). Many of the soils are characterized by inherent or induced (see Fig. 9.1) deficiencies of the major nutrients N, P and to some extent low levels of K, and micronutrients. Low nutrient holding capacities, high acidity and low organic matter are also constraints to soil productivity. There are additional physical constraints, which include poor structure and low water-holding capacities. The inherent constraints in some soils have been exacerbated by over-exploitation. Perhaps more critically large areas of soil of high production potential in sub-Saharan Africa have been degraded due to continuous cropping without the replacement of nutrients taken up in harvests. Stoorvogel and Smaling (1990) estimated annual net depletion in excess of 30kg N and 20kg K per ha of arable land in Ethiopia, Kenya, Malawi, Nigeria, Rwanda and Zimbabwe (see Table 1.7, Part 1).

Figure 9.1: Some biophysco-chemical and socio-economic factors contributing to low soil fertility and poor productivity in Sub-Saharan Africa



The problem of low soil fertility is driven by a wide range of socio-economic factors, which diminish farmers' capacity to invest in soil fertility as well as the returns obtained from such investment where value cost ratios are often less than 2. Resource depletion by soil mining thus becomes an important part of the farmers' income-generating strategy.

Macro-economic policies play a pivotal role in influencing the accessibility, availability and the type of inputs a farmer can use. Unfavorable exchange rates, poor producer prices, high inflation, poor infrastructure and lack of markets all contribute to low fertilizer use by farmers. In many areas farmers are often almost entirely dependent on organic inputs as a result. Organic input availability on its turn is determined by negative nutrient balances and the downward spiral in soil fertility continues.

These multiple causes of soil fertility depletion are strongly inter-related including the interaction between biophysical and socio economic factors (Fig 9.1). A holistic approach is thus required to ameliorate the soil fertility constraints. Though soil productivity is constrained when biophysical conditions are limiting, socio-economic factors can act as important modifiers to enhance potential effects even under conditions of stress. Technical approaches alone are thus likely to be inadequate in addressing the problems, which are driven by farmers' circumstances and production goals that may have more to do with meeting basic food needs and other livelihood issues than with satisfying market demands. It is common sense that no farmer wants to be poor hence they will strive to utilize available resources and technologies available unless they are inappropriate.

Boyer, S. (1954) L'emploi des phosphates de thies dans l'agriculture Senegalaise, CR 2nd Conf Interafr de Sols. Leopoldvill, p 1395.

Buerkert, A., Lamers, J.P.A., Marschner, H. and Bationo, A. (1996a) Inputs of mineral nutrients and crop residue mulch reduce wind erosion effects on millet in the Sahel. In: Buerkert, B. Allison, B.E. and von Oppen, M. (eds.) *Wind Erosion in West Africa*. The problem and its control. Proc. Intern. Symp., Univ. Hohenheim, Stuttgart, Germany, 5-7 Dec. 1994. pp. 145-160.

Buerkert, A.K. Michels, J.P.A. Lamers, H. Marshner and Bationo, A. (1996b) Anti-erosive, soil physical, and nutritional effects of crop residues. In: Buerkert, B., Allison, B.E. and von Oppen, M. (eds.) *Wind Erosion in Niger*. Kluwer Academic Publishers in cooperation with the University of Hohenheim. Dordrecht, The Netherlands. p. 123-138.

Caradus, J.R. (1980) Distinguishing between grass and legume species for efficiency of phosphorus use. *New Zealand Journal of Agricultural Research.* **23:** 75-81.

Charney, J.G. (1975) Dynamics of deserts and drought in the Sahel. *Quarterly Journal of the Royal Meteorological Society.* **101:** 193-202.

Charreau, C. (1974) Soils of tropical dry and dry-wet climatic areas of west Africa and their use and management. A series of lectures. Agronomy Mimeo 74-26. Ithaca, New York, USA: Cornell University, Department of Agronomy, 434 p.

Chien, S.H. and Hammond, L L (1978) A simple chemical method for evaluating the agronomic potential of granulated phosphate rock. *Soil Sci. Soc. Am. J.* **42:** 615-617.

Chien, S.H. (1977) Thermodynamic considerations on the solubility of phosphate rock. *Soil Science.* **123:** 117-121.

Christianson, C.B. and Vlek, P.L.G. (1991) Alleviating soil fertility constraints to food production in West Africa: Efficiency of nitrogen fertilizers applied to food crops. In: Mokwunye, A.U. (ed). *Alleviating soil fertility constraints to increased crop production in West Africa.* Kluwer Academic Publishers, Dordrecht. The Netherlands

Christianson, C.B., Bationo, A., Henao, J. and Vlek, P.L.G. (1990) Fate and efficiency of N fertilizer applied to millet in Niger. *Plant and Soil.* **125:** 221-231.

Cunnington, W.M. and Rowntree, P.R. (1986) Simulations of the Saharan atmosphere-dependence on moisture and albedo. *Quarterly Journal of the Royal Meteorological Society.* **112:** 971-999.

De Ridder, N. and van Keulen, H. (1990) Some aspects of soil organic matter in sustainable intensified arable farming systems of West African semiarid tropics. *Fert. Res.* **26:** 299-310

Diamond, R.B. (1979) *Views on marketing of phosphate rock for direct application.* Halifa, Israel. March 20-23, 1978. pp. 448-463. Special publication. IFDC-S1, International Fertilizer Development Center, Muscle Shoals, Alabama, U.S.A.

Feller, C., Brossard, M. and Frossard, E. (1992) Caractérisation et dynamique de la matière organique dans quelques sols ferrugineux et ferrallitiques d'Afrique de l'Ouest. In: Tiessen, H. and Frossard, E. (eds), pp 94-107. Phosphorus Cycles in Terrestrial and Aquatic Ecosystems. Proceedings of a workshop arranged by the Scientific Committee on Problems of the

Environment (SCOPE) and the United Nations Environmental Programme (UNEP), 18-22, March 1991. Nairobi, Kenya.

Fernandez-Rivera, S. Williams, T.O. Hiernaux, P. and Powell, J.M. (1995) Livestock, feed, and manure availability for crop production in semi-arid West Africa. In: Powell, J.M. Fernandez-Rivera, S., Williams, T.O. and Renard, C. (eds.) *Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of Sub-Saharan Africa*, pp 149-170. Addis Ababa, Ethiopia: International Livestock Centre for Africa.

Finlay, K.W. and Wilkinson, G.N. (1963) The analysis of adaptation in a plant-breeding programme. *Australian Journal of Agricultural Research*. **14:** 742-54.

Föhse, D.N., Claasen, and Jungk, A. (1988) Phosphorus efficiency of plants. I. External and internal P requirement and P uptake efficiency of different plant species. *Plant and Soil*. **110:** 101-109.

Fox, R.L. and Kamprath, E.J. (1970) Phosphate sorption isotherms for evaluating the phosphate requirements of soils. *Soil Sci. Soc. Am. Proc.* **34:** 902-907.

Fryrear, D.W. (1971) Survival and growth of cotton plant damaged by wind-blown sand. *Agronomy Journal*. **63:** 638-642.

Fussell, L.K. and Serafini, P.G. (1985) Associations de cultures dans les zones tropicales semi-arides d'Afrique de l'Ouest: strategies de recherché anterieures et futures. In: Ohm, H.W. and Nagy, J.G. (eds.) Pages 254-278 in Technologies appropriees pour les paysans des zones semi-arides de l'Afrique de l'Ouest. West Lafayette, Indiano, USA: Purdue University.

Ganry, F., Rideau, J. and Nicoli, J. (1973) The effect of nitrogenous fertilizers and organic materials on yields and nutritional value of Souna III millet. Technical report - Institute for Agricultural Tropical Research in Senegal (Bambey, Senegal).

Gardner, M.K., Parbery, D.G. and Barker, D.A. (1981) Proteoid root morphology and function in legumes alnus. *Plant Soil*. **60:** 143-147.

Gigou, J., Ganry, F. and Pichot, J. (1984) The nitrogen balance in some tropical agrosystems. Paper presented at the International Symposium on Nitrogen Management in Farming Systems in the Tropics, Ibadan, Nigeria, October 1984.

Goldsworthy, P.R. (1967) Responses of cereals to fertilizers in northern Nigeria. II. *Maize Expl Agric.* **3:** 263-273

Goldsworthy PR 1967 Responses of cereals to fertilizers in Northern Nigeria. I. Sorghum. *Expl Agric.* **3:** 29-40.

Greenland, D.J. and Nye, P.H. (1959) Increases in the carbon and nitrogen contents of tropical soils under natural fallows. *J. Soil Sci.* **10:**284-299.

Hammond, L.L. Chien, S.H. and Mokwunye, A.U. (1986) Agronomic value of unacidulated and partially acidulated phosphate rocks indigenous to the tropics. *Adv. Agron.* **40:**89-140.

Hauck, F.W. (1966) *Fertilizer needs and effectiveness with tropical crops in West Africa*, FFHC Bulletin, Rome: FAO

Hedley, M.J., Nye, P.H. and White, R.E. (1982) Plant-induced changes in the rhizosphere of rape (Brassica napus var. Emerad) seedlings. II. Origin of the pH change. *New Phy.* **91:**31-44.

Hoogmoed, W.B. (1986) Analysis of rainfall characteristics relating to soil management from some selected locations in Niger and India. Report No 86-3. Wageningen The Netherlands: Wageningen Agricultural University.

The central issue of improving agriculture in Africa is how to build up and maintain soil fertility despite low incomes of farmers and the increasing land and labor constraints they face. One lesson to be drawn from this book is that soil fertility in Africa is more likely to be improved sustainably through relatively small incremental gains that build on what farmers are currently doing rather than on costly green revolution technologies. This calls for an evolutionary process rather than a revolution whose consequences may be less manageable and predictable. In this chapter we analyze the different strategies presented in the preceding papers in terms of how sustainable the current management systems are, whether farmers are willing to invest in soil fertility, and on how we can scale up from the plot to the landscape level and ensure that network results are widely implemented.

Options for Soil Fertility Improvement

There are a number of choices open to small-holder farmers to address the problem of declining soil fertility. The simplest but more costly is through increased application of inorganic inputs. There is no doubt that judicious application of inorganic inputs has been responsible for large increases in crop yields in commercial agriculture throughout Africa (Kenya and Zimbabwe for example) as well as the rest of the world. However there has been no corresponding sustained large increase in yield with use of inorganic fertilizer in the smallholder sector. Throughout most of East and Southern Africa there have been declines in crop yields following market liberalization and the removal of subsidies that permit fertilizer use. Declines in yield can also be attributed to low rates of application, lack of technical knowledge on fertilizer use, and other underlying structural causes such as poor producer prices, lack of credit support, withdrawal of marketing infrastructure and input delivery systems that continue to be largely unresponsive to smallholder needs.

Another approach is that which seeks to combine increased fertilizer use with optimization of locally available resources by integrating different farming system components (eg. crops and livestock) and by minimizing the use of external inputs to create an efficient nutrient cycle. Such integrated approaches incorporating a number of technical interventions are needed to improve soil productivity in Africa. Efficient nutrient cycles in farming systems consists of using balanced combinations of plant nutrients that are locally available or generated on farm and moderate amounts of externally derived nutrients, usually mineral fertilizers, to obtain optimum profitability and sustainability of the system.

The preceding chapters have detailed various case studies and technologies for improving soil fertility. Most of these technologies utilize organic inputs of one kind or another, either in combination with inorganic fertilizers, or without. Organic inputs do not just add nutrients but also build-up soil organic matter. Improved soil organic matter can increase nutrient availability and fertilizer use efficiency. The improvement of the soil organic matter status and the prudent use of mineral nutrient inputs have been demonstrated as effective ways for improving soil fertility in Africa in numerous trials (e.g. Bekunda, Bationo and Ssali, 1997). Synchronizing nutrient release from organic inputs with crop needs also increases nutrient use efficiency, and a high potential exists for optimizing the release pattern by adding materials of different quality (Myers et.al, 1994; Handayanto, Cadisch and Giller, 1997; Palm *et al.* 2001).

The prospects for large increases in productivity through use of organic resources alone are however limited by insufficient quantities and poor quality of the locally available resources (Palm *et al* 1997). However we would argue though that organic matter management forms the foundation for any sustainable increase in soil productivity. Indeed, as agreed above, a lot of farmers in Africa rely of necessity on organic resources, and these provide a substantial subsidy to the cropping systems. Therefore any strategies for soil fertility enhancement have to build on the existing indigenous technical interventions and to improve the management of nutrient flows within the farming systems.

The shift towards greater reliance by farmers on locally available organic resources means that research has to recognize these changes to achieve greater impact. The organic matter management practices are often labor intensive though this has to be analyzed in relation to the opportunity costs of alternative strategies and in the light of longer-term gains, which may be realized. A significant component of the benefits of such practices (e.g. increased SOM levels) may be deferred for several seasons and are also difficult to relate directly to crop yield changes (Swift, 1999). Detailed farm level economic analyses of different types of organic matter management strategies still remain to be carried out. Future research must also focus on establishing farmers' valuation criteria, as it is key to determining the pace of adoption of organic matter management technologies.

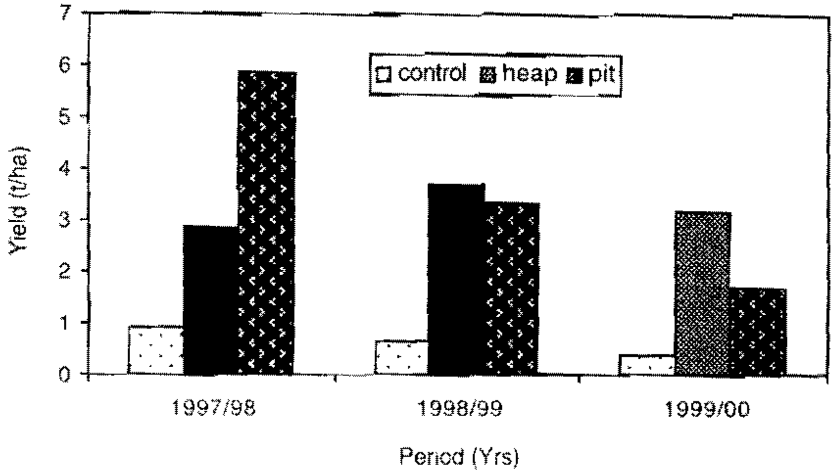
Also, and in particular, it requires the provision of means to increase the availability of plant biomass in agro-ecosystems. Legumes can help achieve increased productivity. However, under current mixed cropping systems, the small quantities of legume residues produced are almost invariably insufficient to meet crop N requirements. Hence organic matter technologies that enhance supply of high quality residues are required. Legume tree species have been introduced in the farming systems as multipurpose trees in agroforestry systems such as alley cropping, relay planting, biomass transfer, improved fallows, fuelwood and browse for livestock. Improved fallows with *Sesbania sesban*, green manuring with *Mucuna pruriens*, for example have shown potential in improving soil fertility in areas of high rainfall such as Eastern Zambia (Chapter 4), but land constraints can limit the success of these technologies. Green manure technologies are not viable where land sizes are small as it involves taking land out of production. Intercropping based on residue incorporation and increasing the legume density in cropping systems is a more sustainable option for soil fertility improvement where rainfall is not limiting (Kanyama-Phiri, Snaap and Minae, 1998). Above all, it is necessary to point out that legumes only supply N and are therefore suitable to N limiting situations. Where soils are overloaded with N, Liebig's law of the minimum will likely manifest itself through other nutrients such as P becoming limiting (OIV, 1995). A holistic nutrient management approach is therefore critical.

Replenishing soil P is often problematic as it has no biological origin and can be fixed in soils with high sorption capacity rendering it less available. There has been recent arguments and calls for use of large one-off applications of reactive rock phosphates in areas where it is readily available and less costly to transport. The cost effectiveness of this approach is yet to be determined though proponents argue that the African continent is in dire need of food hence there are grounds for public interventions to intensify investments in the agricultural sector (Sanchez, *et al.*, 1997).

A major focus of work in Southern Africa (Chapter 3 and 4) has been on the integrated use of manure and inorganic fertilizers, herbaceous legumes and leguminous shrubs. Other soil management options that should be tested include intensification of grain legumes in areas where they currently form a small component of the cropping system, cover crops, conservation tillage and the use of other organic resources with a potential to improve soil fertility. Screening of legumes suited to the region should be top priority. The integrated use of organic and inorganic nutrient sources should continue to be the main target in all cases.

An important issue in the research component is addressing both the within season and longer-term benefits. One of the most important results from the manure work in Zimbabwe is that benefit may be gained from either residual or immediate nutrient gains, from the use of different manure management practices (Figure 9.2). The higher yields in the season of application from anaerobic (pit) compared to aerobic (heaped) manure, which has larger residual effects, creates a range of options for farmers depending on their production objectives. Providing such flexible sets of options to the farmer is a far more valuable approach than being prescriptive and aiming for monolithic technological fixes.

Figure 9.2. Effects of different manure storage and methods on maize yield (J. Nzuma, Unpublished)



A Framework for Soils' Research

The magnitude of the problem of soil fertility degradation in sub-Saharan Africa has been well covered in present and past debates. A fundamental and cautionary principle in response is to avoid any so-called solutions based on low-input, low output systems that do not address poverty alleviation (The World Bank Soil Fertility Initiative; Sanchez *et al*, 1997). New initiatives have been drawn up that call on massive investments in agriculture by local governments and international donors (The World Bank Soil Fertility Initiative; Sanchez *et al*, 1997). The initiatives have all noted the need for increased use of inorganic fertilizers and this is a principle that can not be contradicted. Nonetheless, in the haste for solutions, caution is required to avoid being top heavy and, prescriptive in ways that do not recognize the perceptions and ambitions of local communities.

Extension in most of Africa has tended to be prescriptive and input-driven focussing primarily on promoting use of hybrid maize and fertilizer through blanket recommendations. There has been little success with this approach over attempts to help farmers to adopt other nutrient management practices. The result is that although farmers recognize soil fertility as a primary constraint to production, they often consider mineral fertilizers to be a substitute for, rather than a complement to, other land husbandry practices as the means of stabilizing and improving soil productivity. This threatens the long-term sustainability of their production systems.

It is clear from the preceding chapters that well validated technical solutions for nutrient recapitalisation exist; even in the dry areas of the Sudano-Sahelian zone (Chapter 8), what are lacking are the appropriate framework for their successful implementation. There is no single 'ideal' framework but a number of key elements can be identified which are discussed in the following sections following. The approach, described as integrated soil fertility management (ISFM), emphasizes context-specific and adaptive responses that are tailored to meet the farmer's circumstances, constraints and opportunities. Farmers' decision-making processes are central to this approach including the development of new skills, knowledge and partnerships between key stakeholders (farmers, researchers, policy makers and the private sector).

Improving soil fertility management is only one of the various pathways contributing to rural livelihoods. If this is the case then there is very strong argument to pursue a strategy aimed broadly at promoting sustainable rural livelihoods. The challenges and questions needing to be addressed vary according to circumstances, but general principles can be applied. These include analysis of trade-offs of different options available that contribute to the farmer's livelihood such as off-farm versus on-farm income. Critical questions for assessment include what are the impacts of soil nutrient depletion on livelihoods, where substitutes for natural soil capital exist? Where can alternative livelihoods be secured? Where can soils be mined now and losses made up later? Are farmers willing and able to make the necessary investments which will depend on the expected returns in relation to the other options available to them? It is obvious that the approaches advocated here require a change in the mind set and call for action research and support for networking between various institutions working on soil fertility and livelihood issues at both the macro and micro level. Of the greatest importance is a policy environment that ensures an enabling macro-level support that facilitates and does not engender failure of local initiatives.

Social and Economic Criteria for Sustainable Agriculture

The sections above have emphasized the importance of providing choices to farmers and empowering them to make decisions that will change the way they manage resources available to them. Decisions on change are likely to depend on perceptions of need, lack of other options, societal influences, pressures and ability to invest and the perceived returns to investments. The key components to successful interventions that will aid the process of change go beyond direct interventions aimed at increasing soil nutrients. This means recognizing that long-term soil fertility improvement requires an evolutionary process (section 9.1), and a participatory research and development focus which broadens the approach away from a purely technical focus. This is no doubt a knowledge intensive process. Empowering farmers through greater understanding and application of principles is paramount and requires us to understand the social and economic context in which investments in soil fertility are constructed and the pathways along which the goal of improved soil fertility management can be achieved at varying scales of analysis.

Intensification

With the exception of South Africa and commercial farmers in a few countries such as Zimbabwe and Kenya, most farmers in sub-Saharan Africa use low input /low output technology with extremely small applications of fertilizer (Chapter 1, Stoorvogel and Smaling, 1990) which average 15kg nutrients/ha, and many countries much lower than that against a world average of 87kg/ha. That means there is a lot of scope for raising output by improving technology in relatively simple ways. This could come about by more widely disseminating improved farming practices already in use, and through greater efforts to identify technology gaps that should be worked on as quickly as possible.

It is clear that the performance of the agricultural sector in Africa has been poor relative to the increasing demand for food. It is often noted that there are strong synergies and causality chains linking rapid population growth, degradation of the environmental resource base and poor agricultural performance (Cleaver and Schreider, 1994). What is required therefore is to remove sub-Saharan Africa from this quagmire. This requires not only an analysis of technical solutions but of how the major pressures that have affected soil fertility management (population, degradation etc; Fig.9.1) have driven farmers to adopt current strategies. Such an analysis will show whether strategies are leading to diversification, intensification or extensification of agricultural activities and land-use.

Farmers seek to maximise production per unit of land only when land becomes scarce relative to labor. A series of coping strategies have been developed to deal with this; most of them based on some form of niche management. This is probably now occurring in most parts of sub-Saharan Africa. The weakness of the traditional coping strategies however are often quantitatively insufficient and are not capable of adjusting quickly enough to prevent the serious negative impact of rapid population growth and increasing population pressure on soil fertility, farm size, land tenure systems etc. Because agricultural technology adapted to these environments is inadequate, sustainable management of soils is problematic (Cleaver and Schreider, 1994). However, there are reasons to believe that the future is not so bleak as shown by the example of Machakos, Kenya where productivity has reportedly gone up despite increasing population pressures (Tiffen, Moretimore, and Gichuki, 1994).

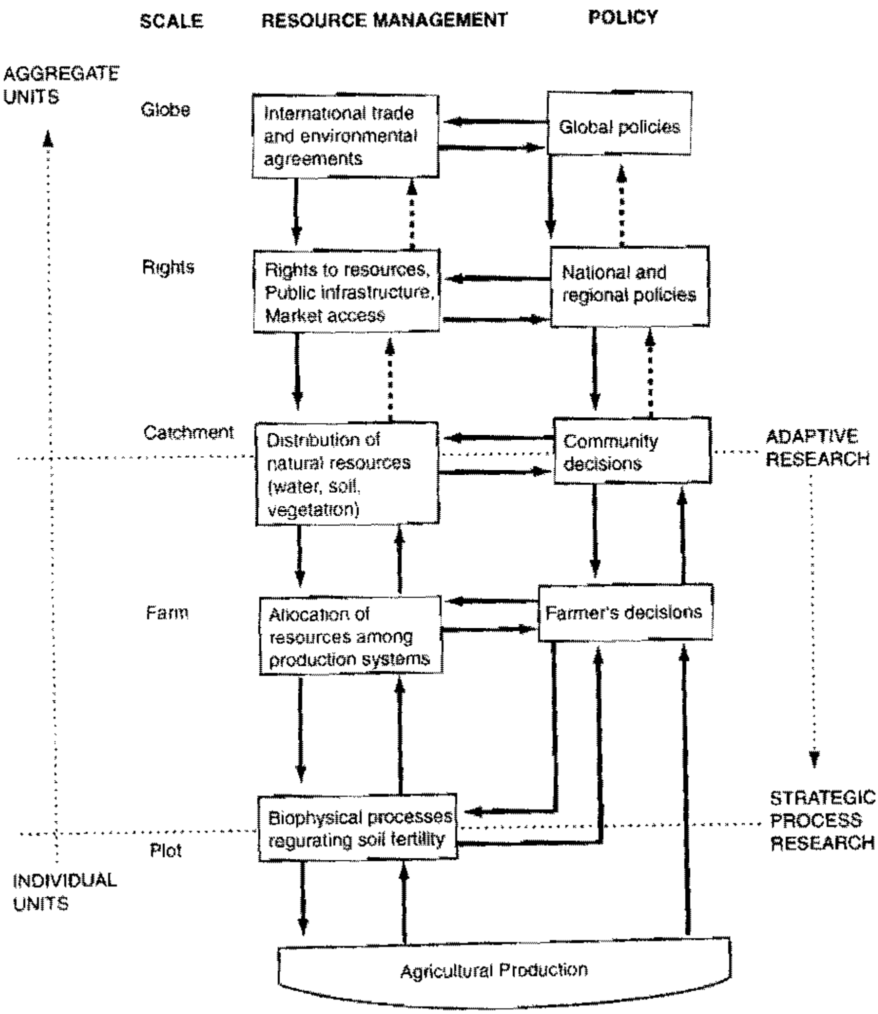
Analyzing the socio-economic system is critical in understanding the drive towards intensification. Differences in soil fertility management exist because of wealth differentiation between households. In cases such as in North-Eastern Zimbabwe, an area dominated by infertile sand soils (poor resource base) and where labor availability is high, extensification seems a rational option (Carter and Murwira, 1995). Farmers spend their labor cultivating more land even though returns per unit of land are low. This is one way of safeguarding a minimum level of productivity for their labor. However other farmers have intensified land use by optimizing use of labor in soil improvement through manuring, composting and limited use of inorganic fertilizers on selected niches (Carter and Murwira, 1995). In such cases the important issues of concern for research are increasing nutrient use efficiency and building soil productivity. Strengthening farmer knowledge of soil processes is an important feature for encouraging improvements in soil fertility management practices. This is unlikely to be successful however unless researchers and extension officers gain an equally informed understanding of the farmer's knowledge system and production goals.

Increasing Adoption and Scaling up of Results

There is no doubt that sustainable improvement of soil fertility has so far proved to be an intractable problem in Africa. Much has been and is being done in sub-Saharan Africa to address issues of declining soil fertility, but there is consensus that the results remain limited in relation to the scale of the problems and that widely replicable and sustainable approaches have yet to be identified. This situation is unlikely to change without integrated strategies that bring together technical and policy solutions that can encourage behavioral changes amongst all the stakeholders involved from farmers to decision makers at both national and global levels. Potential synergies can be exploited to address the problem of soil fertility through combining technical solutions with new approaches to farmer training and policy debate. The role that scientists can and should play in such behavioral change is a critical issue.

The scaling up of sustainable solutions is essential if we are to get the necessary wider impact with many farmers. The approaches detailed in the case studies in the antecedent chapters so far have focussed on the plot level and on generating detailed understanding of processes at. the micro level. As we aim for impact it becomes more important to look at the people-level impact, which measures the effects of the research output on the ultimate user. Scaling up requires us to look at impacts at the individual farm, target group, national as well as regional levels (Fig 9.3).

Figure 9.3. Relationship betwen decision-making (policy) and the management of natural resources at a range of different scales (Modified from Swift, 1999)



Dissemination of technology using participatory approaches is key to scaling up from the plot to farm level and beyond, and it requires that we investigate first what local communities know and have. This provides a productive context for activities designed to help the communities and for integration of indigenous knowledge into the development process as an exchange of information from one community to another, farmer group to another etc. The same process of knowledge transfer can be used for disseminating improved technologies from research. Participation of farmers and communities is therefore useful when scaling up and in promoting a wider and deeper ripple impact. It is important to note however that not all indigenous practices remain beneficial as pressures on agriculturally based livelihoods intensify. This creates the risk of undermining the relevance of some earlier agricultural practices (Murwira and Mukamuri, 1998). Typical examples are traditional shifting cultivation and slash and burn agriculture (Chapter 5, 6 and 7).

Significant gains have been made within TSBF-AfNet towards linking process research with farmers' knowledge and practice. The case study of banana based maize systems in East Africa (Chapter 6) is one example of gaining an understanding of farmers' management practices and using this to improve the capacity to develop recommendations for change that are relevant and realistic at the farm level. What is required is translating knowledge gains into increases in productivity.

There appear to be two approaches to this, which may be termed the mechanistic and humanistic. The mechanistic approach envisages the defining of recommendation domains in terms of extrapolation potential by combinations of biological, physical, social and economic conditions. This is usually done by some type of modeling approach. The results from the many trials that have been conducted across the various TSBF-AfFNet sites offer opportunities to use such approaches and define these conditions. The outputs can then be included in decision support systems, which can ultimately be developed to a more 'expert system' level. Nonetheless recommendation domains are difficult to define when conditions are heterogeneous and complex and alternative approaches are needed.

The second approach, which emerges from recent experiences in Zimbabwe, is to utilize farmers' experience as a guide to the dissemination of technology. This can be developed by building on the flexibility that farmers have, focusing on the enhancement of the best management practices that they currently employ. In other words we should seek to develop and test, through participatory approaches, more practical and flexible options that are suited to the varied socio-economic and biophysical conditions of farmers.

The challenges are great when scaling up, for example on-farm or farmer based experimentation can be specific to the individual farmer's situation. On-site experimentation is also hard to replicate at a large scale because of the uniqueness of farmers' complex, diverse and risk-prone conditions.

Of greater significance in scaling up is development of the appropriate institutional arrangements needed to ensure longer-term sustainability of the systems. There are several ways in which this can be done. The first is to strengthen and build on existing civil society institutions at the local level such as farmer training institutions, farmers' organizations, cooperatives and groups. The second approach requires more networking and development of multiple agency strategies for implementing integrated soil fertility management options. This involves more effective utilization of new information technology dissemination strategies such as websites, e-mail networks etc. Most often the problem is of not being able to integrate the information that is already available and of linking the appropriate people together.

At an intermediate level and perhaps more appropriate is to ask ourselves whether the tools and methods commonly used to support farmers' research are sufficient to address and influence the broader enabling conditions for wide scale adoption of technologies. Emphasis should not only be placed in developing farmer knowledge but in equipping researchers with the skills and appreciation that scaling up has multiple dimensions and contexts-institutional, spatial, economic, temporal and technological. There must always be a developmental context for scaling up, i.e. empowerment and social change though it has to be remembered that not all research will have this focus.

Scaling up requires us to take note of the trade-offs between adoption of technical recommendations and the need for increased scientific insight and technological application in different environments (Fig 9.3). Clearly, a balance needs to be struck between the two as has been demonstrated by the several case studies presented elsewhere in the book.

Implications for Research and Policy

There are a great variety of factors beyond soil fertility degradation that can hold back attainment of a higher level of productivity. Barriers to intensification often start with an indisposed research system that needs to be more innovative (Donovan, 1998). To be successful, innovations must reflect deep, intimate knowledge of the real conditions farmers face including their risks; must start by using available inputs and skills; must generate substantial surplus; must not be too demanding of cash or credit; and must also address soil fertility issues in an holistic fashion. Many farmers still find it hard to get inputs, as marketing channels have not been developed well enough.

There is need to create an environment to stimulate farmers to adopt technologies leading to improved soil fertility. This can be achieved at different levels of resolution.

1. Research: making integrated soil fertility management strategies more widely acceptable at both farm and decision making levels
2. Policy: Enabling macro-policies. Lack of incentives through low producer prices means farmers may not be willing to invest in soil fertility. Also, while useful phosphate rock and lime deposits exist in sub-Saharan Africa, their use has been hampered by high production costs which are often associated with lack of infrastructure, and other unfavorable policy interventions which often decrease profitability of investments at the farm and industry level. Another impediment to intensification is lack of access to credit, which limits the procurement of agricultural inputs and general investments in improved farming practices. With no effective credit institutions in place, many farmers are too poor to make outlays or investments that may take long to pay off.

An important lesson of the work in this book is the recognition of the need to identify with farmers the constraints and opportunities for modifying and changing current practices. In the dialogue with farmers little emphasis seems to be placed on sustainability issues. It is important therefore, to generate tools that can be used by farmers for assessing sustainability of options of using the different scarce resources for maintaining soil fertility and improving crop yields. There is an urgent need to link farmer practices and needs with current scientific information particularly on soil organic matter build-up and nutrient dynamics. Participatory research that incorporates farmer knowledge and information on testing, selecting and adapting soil management strategies with researcher information on biological processes, resource quality and subsequent nutrient availability is an essential component of this process.

Conclusions

The challenges raised in any survey of the current situation in Africa with respect to soil fertility degradation are daunting but not insurmountable. They require concerted efforts from all concerned, researchers, extensionists, policy makers, farmers and other stakeholders, to make things work and realize that the goal and challenges are collective. The results presented in the different chapters are testimony to the progress that has been made in soil biology and fertility in Africa. However, further research should not be to justify our disciplinary training but to show our willingness to contribute to human welfare in Africa and beyond.

References

Bekunda, M., Bationo, A. and Ssali, H. (1997) Soil fertility management in Africa: A review of selected research trials. Pp. 63-80. In: Replenishing soil fertility in Africa. Ed. R. Buresh, P. Sanchez, and F. Calhoun, SSSA Special Publication No. 51.

Carter, S.E. and Murwira, H.K. (1995) Spatial variability in soil fertility management and crop response in Mutoko communal area, Zimbabwe. *AMBIO*. **24**:77-84.

Cleaver, K.M and Schreider, G.A. (1994) Reversing the spiral. The population, agriculture and environment nexus in sub-Saharan Africa. Washington DC. The World Bank.

Donovan, W.G. (1998) Investing in rural development. pp 47-65. In: Agricultural intensification in sub-Saharan Africa. Ed. S. A. Breth. Center for Applied Studies in International Negotiations, Geneva.

Handayamoto, E., Cadisch, G. and Giller, K.E. (1997) Regulating N mineralization from plant residues by manipulation of quality. pp 175-186. In: Driven by nature: Plant litter quality and decomposition. Ed. G. Cadisch and K. E. Giller, CABI.

Kanyama-Phiri, G., Snaap, S. and Minae, S. (1998) Partnership with Malawian farmers to develop organic matter technologies. *Outlook on Agriculture*. **27(3)**: 167-175.

Myers, R.J.K., Palm, C. Cuevas, E. Gunatilleke, I. and Brossard, M. (1994) The synchronization of nutrient mineralization and plant nutrient demand. Pp 81-116. In:The biological management of tropical soil fertility, Ed. P. L. Woomer and M. J. Swift, John Wiley and Sons.

Murwira, H.K. and Mukamuri, B.B. (1998) Traditional views of soils and soil fertility in Zimbabwe. *Advances in GeoEcology*. **31**:1367-1373.

OIV (Operations Review Unit). (1995) Fertilizer aid. Evaluation of Netherlands fertilizer iad, 1975-1993, with special reference to Bangladesh, Mali and Zambia. Netherlands Development Cooperation, The Hague.

Palm, C., Myers, R. and Nandwa, S. (1997) Combined use of organic and inorganic nutrient sources for soil fertility mainetance and replenishment. pp 193-218. In: Replenishing soil fertility in Africa. Ed. R. Buresh. P. Sanchez, and F. Calhoun, SSSA Special Publication No. 51.

Sanchez, P. *et al.* (1997) Soil fertility replenishment in Africa: An investment in natural resource capital. pp 1-46. In: Replenishing soil fertility in Africa. Ed. R. Buresh, P. Sanchez, and F. Calhoun, SSSA Special Publication No. 51.

Stoorvogel, J.J and Smaling, E.M.A. (1990) Assessment of soil nutrient depletion in sub-Saharan Africa, 1983-2000. Report 28. DLO, Wageningen, The Netherlands.

Tiffen, M, Moretimore, M. and Gichuki, F. (1994) More people less erosion: Environmental recovery in Kenya. ACT press, Nairobi, Kenya.