MSU International Development Paper

Fertilizer Impacts on Soils and Crops of Sub-Saharan Africa

by

David Weight and Valerie Kelly

**MSU International
Development
Paper No. 21
1999**

**Department of Agricultural Economics
Department of Economics
MICHIGAN STATE UNIVERSITY
East Lansing, Michigan 48824**

**MSU Agricultural Economics Web Site: http://www.aec.msu.edu/agecon/
MSU Food Security II Web Site: http://www.aec.msu.edu/agecon/fs2/index.htm**

MSU INTERNATIONAL DEVELOPMENT PAPERS

Carl Liedholm and Michael T. Weber

Editors

The MSU International Development Paper series is designed to further the comparative analysis of international development activities in Africa, Latin America, Asia, and the Near East. The papers report research findings on historical, as well as contemporary, international development problems. The series includes papers on a wide range of topics, such as alternative rural development strategies; nonfarm employment and small scale industry; housing and construction; farming and marketing systems; food and nutrition policy analysis; economics of rice production in West Africa; technological change, employment, and income distribution; computer techniques for farm and marketing surveys; farming systems and food security research.

The papers are aimed at teachers, researchers, policy makers, donor agencies, and international development practitioners. Selected papers will be translated into French, Spanish, or other languages.

Individuals and institutions in Third World countries may receive single copies of papers published since 1993 free of charge. Requests for copies and for information on available papers may be sent to:

MSU Bulletin Office
10-B Agriculture Hall
Michigan State University
East Lansing, Michigan 48824-1039
U.S.A.

Information concerning how to purchase MSU International Development Papers is included in the back of this publication and requests should be sent to:

MSU Bulletin Office
10-B Agriculture Hall
Michigan State University
East Lansing, Michigan 48824-1039
U.S.A.

FERTILIZER IMPACTS ON SOILS AND CROPS OF SUB-SAHARAN AFRICA

by

David Weight and Valerie Kelly

September 1999

This paper is published by the Department of Agricultural Economics and the Department of Economics, Michigan State University (MSU). Funding for this research was provided by the Food Security II Cooperative Agreement (PCE-A-00-97-00044-00) between Michigan State University and the United States Agency for International Development, through the Africa Bureau's Office of Sustainable Development, Productive Sector Growth and Environment Division, Technology Development and Transfer Unit (AFR/SD/PAGE/TAT).

Weight is an independent soil scientist and Kelly a visiting associate professor, Department of Agricultural Economics, Michigan State University.

ISSN 0731-3438

Published by the Department of Agricultural Economics and the Department of Economics, Michigan State University, East Lansing, Michigan 48824-1039, U.S.A.

Acknowledgments

This paper began as an individual effort by the first author to inform social scientists about the basic debates concerning current soil fertility issues in Sub-Saharan Africa. Over time, Valerie Kelly's assistance in revising and expanding the paper led to a jointly authored document. I wish to acknowledge her efforts in seeing this paper to completion, especially her generosity in availing the principal author of her wise counsel and editing experience. I would also like to thank the other members of the Food Security staff who supported and provided assistance to the effort, including Eric Crawford, Julie Howard, Patricia Johannes, Josie Keel, and Michael Weber.

Special thanks are due to the following individuals who read through various drafts of the paper and supplied critical and sometimes extensive commentary: Henk Breman (IFDC, Togo); Eric Crawford (Michigan State University); Bruce James (University of Maryland); Mike McGahuey (USAID/Africa Bureau); Christian Pieri (The World Bank); and John Sanders (Purdue University). Thanks also to Richard Harwood and Michel Cavigelli of the Crop and Soils Department/Kellogg Biological Station, Michigan State University; Joost Brouwer, University of Wageningen (the Netherlands); and to colleagues, too numerous to list here, who have provided valuable insights and information. Every effort has been made to assure that they are cited in the text.

Sincere appreciation is extended to my wife, Linda, and children, Alex and Leah, for their patience and perseverence during the more intensive periods of writing and revisions and for their love and encouragement.

David Weight

The authors would appreciate receiving comments on the paper from readers. They can be sent via the following e-mail address:

David Weight: weight@msu.edu

EXECUTIVE SUMMARY

Background: Successful agricultural development has resulted in substantial alleviation of poverty and food security in Asia and Latin America since the 1960s. Much of this success can be attributed to the introduction of high-yielding varieties of crops, especially wheat and rice, which have addressed the constraints faced by farmers using traditional varieties. In Sub-Saharan Africa (SSA), however, productivity levels have remained stagnant despite the introduction of new crop germplasm. In recent years, scientists have recognized that low soil fertility is the primary constraint blocking agricultural development in SSA.

Soil fertility problems in SSA can be attributed to soil degradation due to soil mining (associated with long-term low-input agriculture), tillage, and accelerated erosion. Soil organic matter (SOM), soil organic carbon (SOC), and nutrients have become depleted in most soils. In the lower rainfall regions of the continent, the situation is analogous to the "Dust Bowl" era in US history when SOM levels reached their lowest point after years of agriculture-induced soil degradation. In these regions of SSA, wind and water erosion are depleting what little remains of the topsoil, leaving farmers with low-fertility subsoils or desertification, declining or stagnant yields, and long-term poverty. Fertilizers are considered by many to be critical tools for increasing crop yields and restoration of soil fertility in SSA. The purpose of this paper is to (1) evaluate the potential impacts of fertilizer, both positive and negative; (2) suggest ways in which positive impacts can be maximized and negative impacts minimized; and (3) identify national strategies that have the greatest potential to achieve positive impacts and address the constraints of farmers.

Positive Impacts of Fertilizer and Effective Strategies: The primary positive impact of fertilizers is to increase the biological base of the plant/soil system, measured as net primary productivity (NPP), resulting in increased crop yields and recapitalization of soils, if appropriate management systems are introduced. When fertilizers (or organic inputs) are applied, essential nutrients are supplied for the creation of plant biomass by means of photosynthesis. In the process, carbon dioxide (CO_2) is incorporated or fixed into the biomass from the atmosphere which is then referred to as organic carbon (C). However, the organic C and nutrients in the plant biomass can only recapitalize the soil if crop residues are allowed to remain on the soil surface where they decompose and are transformed into SOM.

In this paper, fertilizers are recommended as the primary nutrient input and organic materials are recommended as "amendments" to fertilizers. This recommendation is based on the fact that large quantities of organic material are required to deliver a nutrient load equivalent to fertilizers. Such large quantities are required due to the low concentrations of nutrients in organic matter. It is difficult for farmers to obtain such large quantities of organic materials due to competition from non-agricultural uses (fuel, fodder, construction, etc.). Also, there are declining rates of biological cover in SSA.

Historical research in the Great Plains (Dust Bowl) region of the US has indicated that the introduction of fertilizers and return of crop residues to the soil has been a successful strategy for increasing levels of SOC and SOM, effectively reversing declines. In the 1970s, conservation tillage (e.g., no-till) as well as use of cover crops, both of which included increased returns of residues to the soil, were introduced or expanded and also contributed to increases in SOC/SOM. In South America, no-till systems have been very successful in addressing constraints and increasing productivity. Besides application of fertilizers, these systems, based on "agro-ecological" principles, typically include no tillage, green manure cover crops, and rotations. Primary advantages of such systems are increased yields and profits, reduced costs and labor requirements, and increased fertilizer and water-use efficiency.

In conventional agricultural systems, especially in the tropics, fertilizer efficiency is typically very low with the result that the majority of available nutrients are not utilized by the crop (low "recuperation rates"). This is due primarily to accelerated rates of decomposition and mineralization which means that outflows of mineralized inorganic nutrients are too great for them to be utilized efficiently. This leaves them vulnerable to losses, especially leaching of nitrates in sandy soils. This is the primary reason for the inefficient rates of recuperation of nutrients by crops in SSA. Roughly twice as many nutrients are lost in SSA compared to other regions.

In integrated "agro-ecological" systems, however, fertilizer-use efficiency is high, primarily due to better soil structure and aggregation. Improved soil structure and aggregation are associated with higher levels of SOM in which soil microbes attack particulate organic matter from residues as sources of C and nutrients. In this process, soil aggregates are formed which have a high capacity for sequestering C and nutrients. If one observes fields under these systems, there is a much higher level of biological cover (larger crop canopies, cover crops, and trees) as well as residue cover compared to conventional fields, which are bare except for the primary monocrop. The high levels of residues result in high levels of SOM and associated improvements in soil structure and aggregation. The net result is increased nutrient use efficiency with an estimated potential for increases in nutrient uptake by the crop of at least two times current rates and parallel decreases in water pollution from losses to leaching and run off.

One of the most severe constraints in SSA for production as well as for fertilizer use is low availability of water (relative to other continents). "Agro-ecological" systems are associated with increased water-use efficiency with estimated increases in crop water uptake of three to five times current rates. Such efficiency can result in stable or increasing levels of crop yields, even during periods of drought stress.

Negative Impacts of Fertilizer: If fertilizer use in SSA is increased, the primary negative impacts that are expected are:

- Acidification of soils by ammonium-N fertilizers which can result in serious declines in yields and soil quality. This can be addressed by use of non-acidifying nitrate fertilizers and application of lime or lime plus manure.

- Negative impacts on traditional systems and environments, especially when extensive management systems are implemented that take over from appropriate traditional soil management practices. Management systems need to be sensitive to traditional values and knowledge systems.

- Non-point source pollution of water resources which is the result of excessive fertilizer use. This can be addressed by developing more efficient "agro-ecological" systems with minimal losses to leaching/ runoff and avoiding excessive use of fertilizers beyond crop nutrient requirements.

- Increased carbon dioxide emissions (greenhouse gasses) associated with fertilizer-based conventional agricultural systems. More efficient systems sequester increased quantities of C resulting in lower levels of SOC that are lost to CO_2 via decomposition.

Historical Evidence Concerning the Potential of Fertilizer-based Production in SSA: It is clear from the historical record that, under favorable climatic and soil conditions, farming has been productive and profitable in SSA, especially on commercial, large-scale farms. The critical factor for that success has been the implementation of fertilizer-based crop management systems, especially conventional and/or "green revolution" systems which have focused on improved cultivars, planting density, and pest/weed control. In many cases, farm management has been backed up by technological, institutional, and financial support such as research and input services, credit for fertilizers, and pre-set price levels for farmers.

In regions of lower rainfall, there is very little evidence of successful agriculture on a large scale. However, on-farm experiments have shown the technical potential for fertilizer-based production in these zones. Experimental findings suggest that the primary restrictions for use of fertilizers have been the expense and lack of availability of fertilizers, as well as lack of institutional support and knowledge about fertilizers and fertilizer-based management systems. Efforts to improve productivity, especially in the lower rainfall zones, will need to address these constraints.

While it is technically feasible to maintain productive systems, the overwhelming majority of farmers in SSA are smallholders with severe economic constraints. These farmers do not possess the financial or technical capacity to implement intensive conventional systems. Rather, strategies are being sought that take advantage of natural restorative processes and are, therefore, efficient in terms of fertilizer and water requirements as well as costs and labor.

National Strategies: Currently, there is a need for stronger collaboration between fertilizer-based "green revolution" programs in SSA, such as Sasakawa-Global 2000 which has been successful at increasing productivity in Ethiopia and other countries, and "agro-ecological" programs such as the "Soil Fertility Initiative" (SFI) or various non-governmental organization (NGO) efforts. This paper argues that the goal should be to combine fertilizer strategies with "agro-ecological" systems (no-till, cover crops, rotations, agroforestry). For this to happen, the two "camps" need to cooperate and develop an integrated strategy, especially in light of current funding constraints in SSA. Such a strategy would have the potential to build on successful fertilizer-based or ecologically based programs that are already in place, integrating the missing elements of the alternative approach, rather than trying to develop entirely new and separate national programs.

It is important to remember that there are alternative approaches that can be effective in adopting "agro-ecological" systems, as seen in South America. First, farmers can take the initiative in developing new strategies, especially through the leadership of active farmer organizations. In this case, researchers as well as development and extension workers will need to learn from and assist farmers in their efforts. Secondly, NGO's can play a critical role in introducing new technologies or systems on a national scale.

Conclusions: Major findings from this study may be summed up in five key points:

- Declining fertility and SOM in SSA are a result primarily of agriculture-induced degradative processes (especially soil mining, tillage, and accelerated erosion) that can be reversed using high levels of nutrient inputs as part of "agro-ecological" farming systems to recapitalize the soil.

- Fertilizer is recommended for recapitalization because nutrients available from organic sources in low-fertility African ecosystems are not adequate.

- The primary positive impact of fertilizers is to increase the biological base of the plant/soil system resulting in increased crop yields. If the system is properly managed, the outcome can be a fertile and efficient cycling system for nutrients and water due to improved soil structure associated with increased levels of SOM. Since there is competition for uses of crop residues (fuel, construction, animal feed), biomass production needs to increase and alternatives need to be found to satisfy other demands for crop residues.

- Fertilizers and organic matter are complements rather than substitutes – both are recommended to recapitalize SSA soils. Fertilizer can increase crop yields and residues, but maximum levels of residues (or equivalent manure) should be returned to the soil.

- Because of the very high quantities of residue or manure required to reverse declines in SOM and inadequate supplies of these materials, integrated "eco-intensive" systems are recommended to create an aggrading system, including mulch or conservation tillage and agroforestry/cover crops.

SSA has an historic opportunity to reverse the current trends of stagnant or declining productivity and soil fertility. The challenge is to begin the enormous process of moving SSA from the low point of the soil degradation curve to levels which are close to pre-disturbance (native) fertility. Effectively, this means that long-term fallows, which accomplished this task in the past, need to be replaced with (or adapted to) appropriate integrated systems that include fertilizers or other effective input sources, as well as no-till (or mulch tillage), cover crops, rotations, and/or agroforestry practices based on sound "agro-ecological" principles. That is, systems that take advantage of natural restorative processes and are, therefore, efficient in terms of fertilizer and water requirements as well as costs and labor. This is especially critical for smallholder farmers who make up the vast majority of agricultural producers in SSA and face severe economic and technical constraints. Once fertility and SOM levels are restored, ideally to pre-disturbance levels, the primary objective will be to maintain a "sustainable" balanced system with equivalent inputs/outputs of nutrients and C, as in a natural, undisturbed system.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS/ACRONYMS

A/CC	agroforestry/cover crops
AEUs	agro-ecological units
Al	aluminum
Al(OH)	complexed aluminum
C	carbon
C_3	three-carbon molecules
C_4	four-carbon molecules
Ca	calcium
$CaCO_3$	calcium carbonate
CARD	The Center for Agriculture and Rural Development
CDs	climate divisions
CEC	cation exchange capacity
CO_2	carbon dioxide
CR	crop residues
CT	conservation tillage
CTIC	Conservation Technology Information Center
Cu	copper
EARO	the national agricultural research organization of Ethiopia
ECEC	effective cation exchange capacity
FAO	Food and Agriculture Organization of the United Nations
Fe	iron
FURP	Fertilizer Use Recommendation Project
ICRAF	International Centre for Research in Agroforestry
ICRISAT	International Crops Research Institute for the Semi-arid Tropics
IFA	International Fertilizer Industry Association
IFDC	International Fertilizer Development Center
IFPRI	International Food Policy Research Institute
IITA	International Institute of Tropical Agriculture
K	potassium
kg ha^{-1}	kilograms per hectare
Mg	magnesium
Mn	manganese
N	nitrogen
NGO	non-governmental organization
NPP	net primary productivity
OM	organic matter
P	phosphorus
S	sulfur
SFI	Soil Fertility Initiative
SOC	soil organic carbon
SOM	soil organic matter
SSA	Sub-Saharan Africa
t ha^{-1}	tons per hectare

USAID	United States Agency for International Development
WASAT	West African semi-arid tropics
Zn	zinc

1. BACKGROUND, OBJECTIVES AND METHODS

1.1. Background

While recognizing the economic obstacles that currently block widespread use, many concerned with improving agricultural productivity and food security in Sub-Saharan Africa are focusing on fertilizer[1] as a remedy for declining soil quality and stagnant yields. Some have suggested that SSA needs to increase fertilizer use from 9 to 30 kilograms per hectare (kg ha $^{-1}$) during the next decade (Borlaug and Dowswell 1995). Others fear that increased use will have undesirable environmental impacts (soil acidification, water pollution) that could outweigh the benefits (Pretty 1995). Much of the SSA literature on agricultural productivity and soil quality presents extreme views for or against fertilizer; supporting arguments are often more ideological than technical. Both the technical and economic evidence underlying these arguments need to be understood by those designing policies to promote agricultural productivity and reverse declining trends in SSA soil quality. This paper focuses primarily on the technical/biophysical evidence, complementing other Michigan State University research that presents economic evidence (Yanggen et al. 1998; Weight and Kelly 1998).

1.2. Objectives and Methods

This study reviews agronomic studies from SSA and elsewhere that examine (1) environmental and agriculture-induced constraints to agricultural production and (2) fertilizer-based strategies that have the potential for increased productivity and sustainability in SSA that address these constraints. The following questions will be addressed:

What are the positive impacts of fertilizer?
What are the dangers or negative impacts of fertilizer?
How can the positive impacts be maximized and the negative impacts be reduced?
What national strategies have the greatest potential to achieve positive impacts and address constraints?

Soil recapitalization, as used in this paper, is the replenishment of SOM[2] and associated soil fertility as C and nutrients are added to the soil (inflows) to replace C and nutrients removed from the soil (outflows) by (i) decomposition and mineralization and (ii) harvests, erosion, runoff, leaching, nitrogen (N) volatilization, and denitrification.[3] Soil fertility is considered a form of

---

[1] In this document, “fertilizer” means “inorganic fertilizer.”

[2] Soil organic matter is defined, in this paper, as all living and dead biotic components of the soil including plant roots, residues, bacteria, fungi, earthworms, etc.

[3] The term recapitalization implies that one is aiming to return to a previous (higher) level of fertility and SOM. There is also the possibility of building SOM to levels beyond the native (pre-disturbance) level suggesting perhaps the terms capitalization or intensification. Since the focus of this paper is for SSA as a whole,

renewable natural capital with service flows (crop production, food security) that increase with recapitalization (inflows) and decrease with excessive outflows. The objective of recapitalization is not to build up maximum stocks of nutrient capital, but “appropriate” stocks of nutrient capital which can provide sustainable levels of nutrients to crops.

Excessive outflows result in declines in SOM and degradation of soil physical properties, especially aggregation of soil structure resulting in lower levels of efficiency for delivery of nutrients and water to crops. The primary vehicle for reversing such degradation of soil quality is by increasing levels of SOM.

In this paper, a combination of fertilizers, organic inputs, and beneficial agricultural practices are recommended which have the potential to recapitalize soils and provide an efficient soil physical environment for delivery of nutrients and water to crops. The ultimate goal is to return to a level of soil fertility across SSA that approximates pre-disturbance levels of fertility and results in increased yields, efficiency, and profitability.

---

the term recapitalization is used most extensively because the primary goal is to begin the task of returning to pre-disturbance levels, a very difficult task on such a large scale. On a local or farm level, other terms may be used.

2. REVIEW OF ENVIRONMENTAL FACTORS

The most critical environmental factors that determine a sustainable system are climate and soils. Systematic analysis of these factors can serve as a basis for the determination of guidelines and policies (Stewart et al. 1991). Most African soils have inherent difficulties for agriculture in terms of fertility, acidity, or drainage which, in many cases, can be overcome with proper management. A recent general classification of African soils provides data for distribution of soil types: "acid infertile soils" (Oxisols and Ultisols)[4] 21%, "very infertile sandy soils" (Psamments) 13% and "poorly drained soils" (Aquepts) 2%. On the other hand, "Moderately fertile, well-drained soils" (Alfisols,[5] Vertisols, Mollisols, Andepts, Tropepts and Fluvents), which account for 33% of Asian soils, represent only 19% of African soils (Brady 1990; Eswaran et al. 1997) (Figure 1).

Low soil nutrient reserves are common in tropical ecosystems: "About 36% of the tropics (1.7 billion ha) are dominated by soils with low nutrient reserves, defined as having <10% weatherable minerals in the sand-and-silt fraction. This constraint identifies highly weathered soils with limited capacity to supply C, phosphorus (P), potassium (K), magnesium (Mg), and sulfur (S). Soils with low nutrient reserves are more extensive in the humid tropics (66%) and in the acid savannas (55%) but are locally important in the Sahel. It is relevant to note that about two-thirds of the soils in the tropics (64%) do not suffer from low nutrient reserves." (Sanchez and Logan 1992, 37)

Because farmers universally seek out soils that are high-base-status, non-acidic soils,[6] the percentage of African cultivated soils that are moderately fertile is expected to be considerably higher than the above data suggest. Precise information for cultivated soils is not available due to the lack of a land use database classifying cultivated lands (Russell Almarez, NRCS World Soil Resources, personal communication).

It should be pointed out that certain tropical soils which are commonly categorized as "infertile" such as the Oxisols actually possess great potential for agricultural production if managed properly.

> The management of Oxisols presents both problems and opportunities. Most of them have not been cleared of their native forest vegetation or have been tilled using only primitive methods. The few instances where modern farming techniques have been used have met with mixed success. Heavy fertilization, especially with phosphorus-rich

---

[4] USDA soil classification system will be used in the paper.

[5] African Alfisols typically have considerable constraints including weak soil structure, vulnerability to erosion and lack of infiltration due to compaction (Lal 1997).

[6] Unless they are cultivating specific crops that prefer acid environments

Figure 1. Distribution of Soil Orders

(Figure 1. Removed to reduce download time. Please download separately.)

Source: Reproduced with permission from USDA/Natural Resources Conservation Service

> materials, is required. Deficiencies of micro nutrients are common. In some areas, torrential rainfall makes cultural practices that leave the soil bare extremely harmful....
>
> Research on crop production on Oxisols suggests that the potential of some of these soils for food and fiber production is far in excess of that currently being realized. In Brazil and central Africa, selected areas of these soils have been demonstrated to be high in productivity when they are properly managed. (Brady 1990, 73)

Organic matter levels, however, are not inherently lower in the tropics and Africa than in the temperate zones, despite early literature to the contrary. The "myth" of low organic matter levels in the tropics was initially based on misunderstandings of soils such as Oxisols that had red coloring rather than black/brown coloring associated with organic matter content. Later scientific studies in North America led to an apparent inverse relationship between annual temperature and organic matter content. Subsequent studies revealed that such findings could not be extrapolated to the tropics. When comparisons were made between soils of the same order in temperate and tropical ecosystems, it was found that organic matter levels were comparable (Greenland, Wild, and Adams 1992). It is the turnover rate of organic matter[7] in the tropics that is different. Research has shown that, in the humid tropics, decomposition losses[8] in natural systems are balanced by high biomass input, all of which are caused by high temperatures, high levels of available moisture, and a 12-month period for decomposition (vs. 8-9 months in temperate regions). For example, litter fall[9] and decomposition/turnover rates are approximately five times higher in tropical forest soils than in temperate forests (Parton et al. 1989). The critical problem is that when agriculture is introduced, there are increased losses of SOM due to accelerated decomposition rates.

In the Sahel, vegetative cover is very limited due to the extreme aridity of the dry season which severely limits perennial plant life compared with areas with the same total annual rainfall. Thus, levels of biomass input and SOM are lower under these conditions (Breman and Kessler 1995).[10] In this case, agricultural disturbance exacerbates an even more difficult fertility situation, depleting already low native levels of SOM. Also, the low levels of clay in Sahelian soils mean that SOM is minimally (physically) protected from accelerated decomposition.

A critical factor concerning tropical and African soils is their level of diversity or variability which is based on the high level of environmental diversity in tropical ecosystems. "In view of the immense environmental diversity encountered in the tropics, often over short distances, the

---

[7] The rate at which organic matter is decomposed.

[8] Atmospheric CO_2, water and inorganic ions.

[9] Litterfall is the annual transfer of living plant material to non-living forms of organic matter, from both above-ground (leaves, grasses, etc.) and belowground (roots) sources.

[10] The contribution of perennials to vegetative biomass production increases with rainfall and with the transition from one to two rainy seasons (Breman and Kessler 1995).

complexity and variability of the resultant soils patterns should come as no surprise. The small island of Puerto Rico may serve as an example: in an area of <9000 km^2, soils representing 10 of the 11 orders currently recognized in *Soil Taxonomy* have been identified." (Eswaran et al. 1992, 3)

Large-area reconnaissance maps of African soils were made after World War II and were based primarily on surveys by a few individuals. Understanding and appreciation of the diversity of these soils has only come about in recent years with the advent of more detailed soil surveys using modern scientific methods including the Food and Agriculture Organization of the United Nations (FAO) Soil Map of the World using a scale of 1:5,000,000 which was published in the 1970s (Eswaran et al. 1992).

Research indicates that water is less available in Africa than elsewhere. African levels of available water from rainfall, measured as precipitation minus evaporation (cm $year^{-1}$) are low relative to other continents. One survey of data (Brady 1990 citing Mather 1984) found African levels at 12.7 cm $year^{-1}$ vs. North America at 25.8 and South America at 64.8 with a world average of 24.9. Water is absolutely critical for fertilizers to be effective. Besides the fact that water is a requirement for plant growth, fertilizers are distributed to and within the rooting zones of crops in soil solution.

To compound matters, low soil quality results in low water use efficiency in many regions of SSA. For example, in the Sahel, it is common for plants to utilize only 10 to 15% of rain water (Penning de Vries and Djiteye 1991). This is a serious constraint considering that rainfall in the region is so limited in the first place. Also, variability of rainfall is a critical factor affecting fertilizer efficiency and in determining risk-aversion strategies for farmers in SSA (Bationo 1998; Brouwer and Bouma 1997).

The high intensity of storms is the primary cause of high levels of soil erosion in the tropics when compared with erosion levels of temperate regions. "Rains in the tropics, particularly those caused by thunderstorms, have sharp, high-intensity peaks. Because tropical rains are caused by convection, they are generally accompanied by lightning and thunder, are localized, and are intense.... The result is intense downpours, high rates of rainfall per unit time, and relatively high drop size.... Both the amount and the rate of rainfall, or its intensity, affect soil erosion. The same amount of rain falling over a short time causes more erosion than when it is distributed over a relatively long time and falls as a gentle rain of low intensity." (Lal 1990, 29-32) Likewise, the high intensity of wind in tropical storms is responsible for severe wind erosion in the semi-arid regions of SSA, especially in the Sahel. Vulnerability of the soil to wind and water erosion in the region is exacerbated by the extremely limited vegetative cover.

Soil compaction is another serious constraint of some African soils. Coarse-textured soils with low activity clays, such as West African Alfisols, are especially prone to compaction. This results in soils with high bulk density and low total porosity with impaired seedling establishment, inhibited root development, and low fertilizer and water-use efficiency since it is difficult for water to infiltrate into the soil. In contrast, soils with a higher sand/clay ratio are more likely to be limited by low nutrient content (Lal 1987).

Finally, drought stress is a major constraint in many regions of SSA. "The term 'drought stress' implies crop response to the integrated effects of low available water-holding capacity, high evaporative demand, and high soil and ambient temperatures. Compaction and high water run off cause severe and frequent drought stress even in regions of high annual rainfall.... Crops susceptible to drought do not respond to fertilizers and other chemical amendments." (Lal 1987, 693-4)

3. FERTILIZER-BASED STRATEGIES THAT ADDRESS CONSTRAINTS

3.1. Agriculture-Induced Constraints

Scientists agree that the introduction of agriculture has caused significant declines of SOM and associated soil quality relative to the undisturbed system (Woomer et al. 1994). Effects include decreased aggregation, water-holding capacity, nutrient-holding capacity, soil macro-structure and infiltration. Studies have been carried out that trace the long-term evolution of SOM under various cultivation scenarios. Woomer et al. (1994) have reviewed a study by Resck et al. (1991) showing trends in loss of SOM in disturbed systems in South America. Annual decline in SOM is generally in the 1-2% range. One example is from the Cerrados region of Brazil. Under 2 years of upland rice cultivation, SOM increased. The authors surmise that this is due to the decomposition of root residue from the native vegetation. Rice was followed by soybean cultivation. After 11 years of total cultivation, SOM and soil quality, especially aggregation, declined at about 2% per year, consistent with declines in other studies.

Cultivation with low-input methods (no fertilizer) in the humid savanna zones of SSA can induce a 30% loss of SOM after 12 years and 66% after 46 years, with rainfed rice yields declining from 1 ton/ha to only 300 kg ha $^{-1}$ at the end of the period (Pieri 1992, citing Siband 1974).

Beyond natural constraints, the following factors are considered to be responsible for such declines.

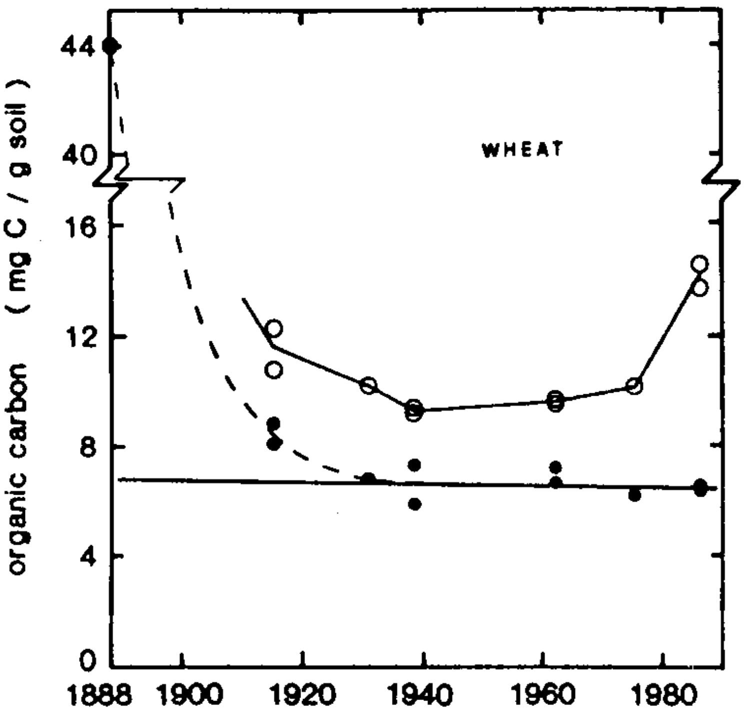
3.1.1. Soil Mining

Soil mining is the process by which farming removes more nutrients (and C) from the system than are replaced. It is associated with low input agriculture in which low-nutrient value organic amendments are used which are insufficient to replace nutrients extracted by crop harvests, resulting in a negative balance of nutrient elements. Estimation of nutrient balances (inflows minus outflows) is a common method used to evaluate soil mining. Estimates for 38 countries in SSA suggest that annual loss of nutrients per hectare during the 1980s was 22 kg of N, 2.5 kg of P, and 15 kg of K (Smaling 1993b).

A historical U.S. study shows that rapid loss of SOC – approximately 70% over a period of 35 years or 2% annually – occurs on virgin Kansas prairie when native vegetation is replaced with annual wheat crops (Figure 2). Crop residues returned to the soil are not sufficient to offset the annual removal of nutrients and C by crops and increasing erosion. Thus, inflows are not sufficient to offset outflows and there is a negative balance in the system ("mining") (Brady 1990; Balesdent, Wagner, and Mariotti 1988). In a comparison with timothy grass plots, it is shown that decline is greater under wheat because of the negative effects of wheat tillage on SOC and that clay is the most important soil fraction for protection of C. "... the loss of soil C was clearly greater under cultivation of wheat than under timothy grass, supporting the idea that the annual tillage exposes physically protected organic materials to degradation by soil biota. Under both cultures, C associated with clay was the most persistent."[11] (Balesdent, Wagner, and Mariotti 1988, 122)

While most texts attribute declines in SOM and SOC[12] primarily to tillage, some authors consider mining, especially of C, to be more important. "The loss of SOC upon conversion to arable agriculture is traditionally attributed to the physical effect of tillage, which can disrupt soil aggregates and expose previously inaccessible materials to rapid decomposition. Although this

Figure 2. Changes in Soil Organic Carbon



Changes in amount and origin of soil organic C accompanying the long-term cultivation of wheat on formerly virgin prairie soil. Open circles denote total C, and solid circles represent C of prairie origin with upper and lower points at different dates for the 0- to 10- and 10- to 20-cm depth samples, respectively. The straight, solid line shows the level of stable C.

Source: Reproduced with permission from Balesdent, Wagner, and Mariotti (1988, 121).

---

[11] Clay is known to physically protect soil C from decomposition loss to CO_2.

[12] As the primary building block of SOM, SOC is the most commonly used indicator for SOM. SOM values (%) can be estimated by multiplying SOC values (%) by a factor of 1.7.

process is undoubtedly a factor, the SOC loss upon cultivation reflects multiple effects. Indeed, the primary reason for C loss may be the enhanced removal of C from agroecosystems; since the intent of agriculture is to trap C in a marketable form, C inputs in agricultural systems are usually lower than those in native systems (e.g., Voroney et al. 1981)." (Janzen et al. 1997, 61-2)

The Role of Soil Nutrient Budgets in Assessing Nutrient Balances: If sufficient nutrients and carbon are supplied by fertilizer and residue, the potential is created to recapitalize SOM so that it has the physical capacity to maximize retention and minimize losses of nutrients. Smaling (1993a) has written extensively on the subject of soil nutrient budgets and developed the following system of inflows and outflows for N, P and K. Inflows are fertilizers, organic matter, wet and dry deposition (from the atmosphere). Outflows are harvested product, crop residue (accounting for the fraction removed), leaching, gaseous losses (e.g. denitrification) and erosion. In commercial agriculture, the point is to maximize the first outflow, harvested product. Minimizing all other outflows has the effect of channeling NPK to the harvested product.

In a study of one district in Kenya, the two strongest outflows were harvested product (a positive outflow-from the point of view of the farmer) and erosion (a negative outflow). Kissii is a highland district with high rainfall resulting in runoff on sloping clay soils. A management system that is responsive to these factors would be comprised of first, inflow management with sufficient fertilizer to support crop growth and second, outflow management that promotes high yield (harvested product), high levels of residue return and minimal erosion. The optimal combination of inflow/outflow management would result in high profits that were sustained over time.

In an undisturbed system, a balanced equilibrium exits where inflows and outflows are balanced. In a degrading system, as seen in the early years of the Kansas example, there are high outflows relative to inflows. Under recapitalization, we seek ways to have high inflows relative to outflows with the goal of increasing SOM and, thus, reaching a “fertile” level of nutrient capital in which sustainable levels of nutrients are supplied to crops. When this occurs, higher levels of nutrients can be stored in organic forms and released over time. Traditionally, when fertilizers are applied, high levels of N can be lost by leaching, particularly in sandy soils. High levels of P can be chemically bonded so that the P is unavailable to crops grown in clay soils. Storage of nutrients in organic forms (in SOM) can minimize these problems, increasing fertilizer efficiency and providing sustainable nutrient capital. If nutrient release is synchronized with the crop growth cycle, nutrients become available at the time of greatest need.

Nutrient budgets can provide a valuable tool for measurement of nutrient flows. There are serious flaws, however, in the current methodologies that are being used as a basis for budget estimates, especially for soil erosion. Typically, controlled soil erosion experiments are carried out on bounded small plots which produce highly inflated erosion rates, not taking into account deposition of soil that occurs on an actual slope. These exaggerated rates have been used to support the idea that soil erosion is severe throughout SSA (Stocking 1996; Sanchez 1998). More recently, scientists H. Breman and N. de Ridder, working in West Africa, have developed a method to translate data from small plots into an estimate of run-off on large plots (Hank Breman, Director, International Fertilizer Development Center-Africa, (IFDC) personal communication). More precise analyses suggest that while erosion is often severe in SSA, there is a great deal of variability in the level of vulnerability of soils to erosion.

3.1.2. Tillage

Soil tillage has been used since the dawn of agriculture to alter the physical condition of the soil and to prepare the seedbed for cultivation. Often its benefits, such as breaking down of clods and increasing infiltration, have been found to be short-lived with the result that it is necessary to repeat the operations regularly. Conventional tillage has been found to have significant destructive influences on soils, especially in the case of intensive and mechanical tillage. In some cases, the constraints for which tillage is used (e.g. bulk density, infiltration) are actually made worse by tillage (see northern Nigeria experiment below). Cavigelli (1998, 26) lists the following negative impacts associated with conventional tillage:

- erosion (both wind and water)
- burying residues so that they are not able to protect the surface from erosion and are exposed to greater microbial activity
- exposing SOM to oxygen (aeration) and increasing soil temperature both resulting in increased decomposition
- physically breaking up soil aggregates and exposing the internal SOM to microbial activity.

Reviewing the above points, erosion can result in the loss of the fine particles of the surface soil which are associated with organic and nutrient content with the result that soils can become completely denuded of organic material and vegetation. Secondly, residues are a critical factor in protecting the surface from erosion and will decompose more rapidly when buried and exposed to soil microbes. Thirdly, research in SSA has indicated that clay fractions in soils physically protect SOM and organic N from aeration and high temperatures associated with increased decomposition. If the soil is torn open by tillage with exposure of SOM, increased decomposition will result. Finally, aggregation is perhaps the most important factor in building a well-structured soil and may be described as the “glue” that holds the soil matrix together. Continuous conventional tillage results in the destruction of this fragile component of the soil matrix. The primary cumulative impact of tillage, based on these factors, is increased decomposition of soil organic matter in which organic C is lost to the atmosphere as CO_2 and SOM declines. Since rates of decomposition are higher in the tropics due to increased temperatures, the impacts of tillage are more severe with greater declines in SOM over time.[13]

Tillage is also associated with decreases in soil quality, due to SOM losses. Four-year experiments at Zaria in semi-arid northern Nigeria concluded "that soil bulk density measured 7 weeks after planting increased with increasing intensity of mechanical tillage. Accordingly, the percentage of water stable aggregates was more in untilled and less intensively tilled than in tilled

---

[13] Biomass inputs to tropical systems are higher compared to temperate systems, again due to temperature. This balances the high rates of loss due to decomposition of SOM in the natural system. Agriculture disrupts this equilibrium by increasing decomposition rates beyond equilibrium levels.

treatments." (Lal 1987, 578, citing Dunham and Aremu 1979, Aremu 1980, and Dunham 1982) In another Nigerian experiment at Ife, scientists also observed higher bulk density as well as lower porosity in tilled plots. Compaction and crusting were most severe on plots which had received the most intensive tillage treatments (Lal 1987, citing Aina 1979). While these are the most typical results, there are also contradictory findings at a number of sites.

3.1.3. Accelerated Erosion

"Soil erosion began with the dawn of agriculture, when people began using the land for settled and intensive agriculture. In fact, soil erosion has been a quiet crisis and has plagued the land since people began practicing agriculture by removing the protective vegetation cover and growing food crops on disturbed soil surface.... Soil erosion is severe in all regions, temperate and tropical, wherever the land is used beyond its capability by crop and soil management systems that are ecologically incompatible." (Lal 1990, 10-12)

Long-term studies on agricultural plots in North America have quantified the impacts of cultivation on erosion. Specific practices are associated with greater levels of erosion, even on slight slopes (Paustian et al. 1997, 27) provide the following examples: "For the Sanborn plots [Missouri], Gantzer et al. calculated that topsoil thickness had been reduced by 56% under continuous corn and by 30% under corn rotated with oats, wheat, and perennial crops, compared with permanent timothy grass. In long-term plots at Wooster, Ohio, Dick et al. estimated that conventionally tilled plots lost about 3.7 cm more soil than no-tilled plots over 18 years, an amount equivalent to about 500 g C m^{-2}...."[14]

Lal has summarized regional erosion trends in SSA as follows: "The Sahel suffers from severe wind erosion during the dry season and accelerated gully erosion during the much-awaited rains. (FAO 1979) reported that in Africa, north of the equator, 11.6 % of the total land area is affected by water erosion. High erosion rates are especially prevalent in the coastal regions of northwest Africa. Soil erosion is equally serious in eastern Africa and is particularly menacing in the Ethiopian highlands. The Ethiopian highlands are believed to lose over 1 billion t/yr of topsoil (Brown 1981). Gully erosion is catastrophic in some parts of southeastern Nigeria. Soil erosion is also severe in southern Africa whenever large-scale farming is practiced without appropriate conservation measures." (Lal 1990, 15)

3.1.4. The Process of Decline in Soil Organic Matter in SSA

Woomer et al. (1997, 154) have described the process of decline in SOM in smallholder farms of SSA as follows:

---

[14] Lower erosion rates on no-till plots supports the relationship, described previously, that tillage is associated with accelerated erosion.

> System carbon dynamics within small hold agriculture may be viewed as a three-step process. The first two steps are essentially the same as the well-documented case of shifting agriculture (Nye and Greenland 1960; Sanchez and van Houten 1994). Initially, carbon and nutrient stocks which have accumulated within natural vegetation are mobilized through land conversion. Felling large volumes of vegetation often necessitates burning simply to obtain access to the land for cultivation and as a result much of the above-ground biomass carbon is lost to the atmosphere.... Next, the soil resource base is exploited through productive cropping for several years while nutrient-rich, mineralizable organic matter and root residues decompose. Reduced yields are often associated with declining soil organic matter levels. At this point traditional shifting agriculture abandons land to fallow allowing for re-accumulation of carbon and nutrients in vegetation and soils. This is also the point of departure of smallholder systems in Africa, where population pressure has decreased farm size to the point where natural fallows are precluded.[15] Thus the third step in carbon dynamics in small hold farms, where the most labile soil organic matter fractions have become mineralized at a lower-level equilibrium of soil organic matter is approached. Continued productivity becomes dependent upon the application of external inputs or the development of indigenous solutions which make better use of locally available and under-utilized organic resources (Swift et al. 1994). Typical responses by African farmers to reduced fallow have been crop rotations, manuring, and composting (Binns 1992).

While the three-step process for carbon dynamics in SSA is different from processes in temperate ecosystems, the outcome is similar; a significantly lower level of SOM (lower level of equilibrium vs original pre-disturbance levels). In the earlier Kansas example, only 30% of original SOM remained at the lower equilibrium level (see Section 3.1.1.). In a national survey in Kenya, only 28 to 33% of SOM remained at the lower level, depending on soil type. While the levels are similar, the amount of time required to reach these levels was very different. In the Kansas example, the degraded level was arrived at after 35 years. In the Kenya example, the equivalent degraded level was achieved in only 24 years.[16] This is not surprising considering the increased rates of decomposition of tropical SOM.

3.2. Geographical Estimates of Constraints and Potentialities of African Soils

3.2.1. Distribution of Soil Types

---

[15] In humid savanna zones of SSA there is no soil quality improvement for a fallow of less than 10 years; in many cases fallows of 15 to 30 years are required to recapitalize soils adequately (Pieri 1992, citing Charreau and Nicou 1971).

[16] Based on data from the Kenya Fertilizer Use Recommendation Project (FURP 1994) in Woomer et al. 1997.

The African landscape has been mapped by Eswaran et al. (1997) based on estimates of its potential for sustainable development (Figure 3). Such maps provide an estimate of the types of soil constraints that need to be addressed in intensification efforts. Broad categories of lands are as follows.

<u>Prime land</u> contains highly buffered soils with high levels of SOM and good water retention.[17] Soils are deep, with excellent tilth, and have few impermeable layers. They comprise approximately 10% of the African land surface and exhibit little to no decline in SOM or fertility under various soil management systems. As a result, they have the greatest potential for agricultural production.

<u>High potential land</u> is similar to prime land with some limitations such as "extended period of moisture stress, sandy or gravelly materials, or with root restricting layers in the soil." (Eswaran et al. 1997, 16) These soils (7% of land) are vulnerable to declines in SOM and fertility under low-input agriculture but they have good potential for recapitalization. However, if they are mismanaged with continuous mining, they may become degraded with low soil fertility and quality.

<u>Medium to low potential land</u>. These soils (28% of land) have significant constraints and are very vulnerable to declines in SOM when cultivated with low-input techniques. Risks of crop failure can be very high unless proper management techniques are applied. "The constraints include adverse soil physical properties including surface soil crusting, impermeable layers, soil acidity and specifically subsoil acidity, salinity and alkalinity, and high risks of wind and water erosion." (Eswaran et al. 1997, 16) Many areas of the southern Sahel region are classified under this category as low potential lands.

Humid tropical forest soils, especially Oxisols, found in Central and West Africa, are also considered to be medium potential soils. Constraints are primarily acidity and significant fixation of phosphorus. As described earlier, farmers may only achieve good yields if proper management practices are followed. Otherwise, crops will fail and soils will be degraded.

<u>Marginally sustainable and unsustainable land</u> (57% of African total) has poorly buffered soils with very low SOM and very poor water retention. A large share is not arable (e.g., the Sahara Desert). The arable portions are on the fringes of deserts where both water availability and nutrients are limiting. These lands "are considered to be fragile, easily degraded through management, and in general are not productive or do not respond well to management. They are generally highly erodible and generally require very high investments for any kind of

---

[17] The buffering capacity of a soil is a measure of its ability to resist changes in pH; highly buffered soils are more resistant to acidification, which inhibits crop growth, than poorly buffered soils.

Figure 3. Potential for Sustainable Development

(Figure 3. Removed to reduce download time. Please download separately.)

Source: Reproduced with permission from USDA/Natural Resources Conservation Service agriculture." (Eswaran et al. 1997, 15) The process of intensification for soils in this classification is not fully understood, but there is some evidence that it is possible.

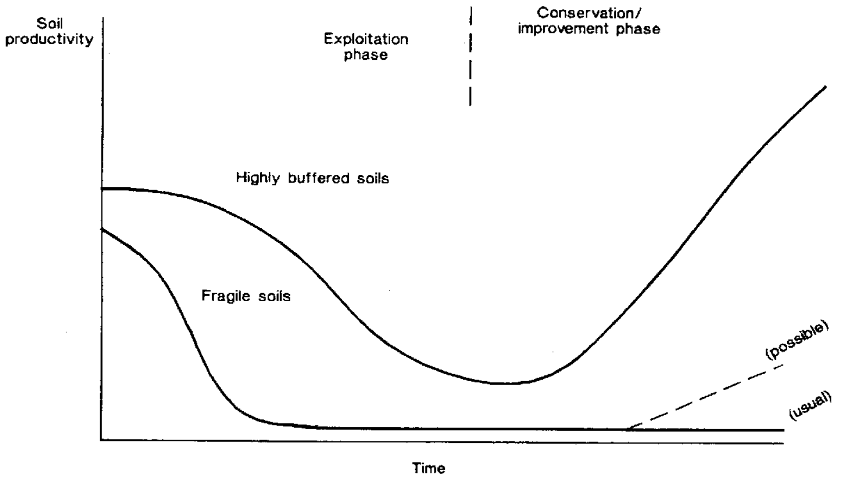
3.2.2. Addressing the Constraints of Marginally Sustainable ("Marginal") Soils

There is a concern by some scientists that "marginal" (or "fragile") soils, with low native levels of SOM and cation exchange capacity (CEC) which have been further degraded by agricultural activities may not have the potential to regain their fertility or productivity.

Figure 4 represents two hypothetical recapitalization scenarios – one for "highly-buffered soils," as found in the Kansas prairie, and another for "fragile soils"commonly found in semi-arid regions of SSA. The lower "fragile" curve suggest that there is a point-of-no-return at which SOM is so depleted that soil productivity may not recover after the introduction of soil conservation practices (Anderson and Thampapillai 1990, citing Ragland and Boonpuckdee, forthcoming).

This concept of "fragile" soils or lands is based on the idea that marginal poorly-buffered soils with low CEC and SOM can reach a point where they are permanently "damaged" and may not recover their fertility or productivity. According to Pieri (1992, 180): "... experiments on less fertile soils which occur more frequently, showed that there is a critical level for soil organic

Figure 4. Contrasting Profiles of Soil Productivity



Source: Reprinted with permission from Anderson, J., and J. Thampapillai. 1990. *Soil Conservation in Developing Countries: Project and Policy Intervention,* p. 9. Washington, DC.: The World Bank.

matter at or above which yields are maintained.[18] While there is no need to keep organic matter levels greatly above that level, and it would not be practically possible to do so, to maintain the critical level is not impossible and it is essential to do so. Once organic matter impoverishment passes below the barrier, yields decrease catastrophically."

Some soil scientists have estimated that soils below a critical level of 0.6% organic matter suffer damage to soil structure resulting in irreversible erosion that precludes the possibility of recapitalization (van der Pol 1992). "... There is no smooth relationship between the decline in soil properties, organic matter, and nutrients and especially structural organization of the soil profile and yield. Yields decline seriously only when soil properties fall below a critical level." (Pieri 1992, 113)

In this paper, the term "marginal" is used rather than "fragile" because the term "fragile" implies permanent damage and the evidence for such a permanent effect is inconsistent. First, there are research results on marginal soils which show that yields can be increased significantly using fertilizers with crop residues or other organic amendments. For example, one three-year study on *sols fatigues* ("tired soils") at Sadore, Niger, showed a fifteen-fold increase in millet yield when fertilizer and residues were added (Bationo and Mokwunye 1991).[19] Soil organic matter levels increased from a low 0.24% (well below the 0.6% "critical" level) to 0.33% in these treatments, showing the potential for some level of recapitalization over time (Bationo, Christianson, and Mokwunye 1989).[20]

Bationo and Mokwunye (1991, 221) also discuss another study from Niger by Geiger, Manu, and Bationo (1988) in which SOM does **not** increase after long-term additions of residues: "after 5 years of the addition of crop residue, the levels of calcium (Ca), Mg, and K had increased significantly in the top soil (0-20 cm).... It was also found that the organic matter levels in the soil did not increase significantly after 5 years with the addition of crop residue."

Based on SOM studies including simulation and validation models, Breman and Sissoko (1998) conclude that it is technically feasible to restore soils that are below the "critical" level of SOM to higher levels of fertility but such restoration will require intensive management (see below).

Organic matter is vulnerable to leaching in "marginal" sandy soils. While the rate of leaching of organic matter is less than that of inorganic nitrate, it can still be significant. In one experiment on sandy soil in Niger: "Calculations showed that within 1 year after the application of 10 tons per

---

[18] This critical level of SOM formulated by Pieri is based on particle size distribution. It is a function of the level of clay and silt particles: (SOM_{crit} in g kg^{-1}) = 0.05 x (%clay + %silt). Groot et al. (1998), citing Pieri (1989).

[19] Similar increases in SOM were also found with addition of manure, also in Niger (Bationo and Mokwunye 1991).

[20] One important finding from the study was the strong decrease in percent Al + H saturation with addition of residues. The decrease was from 48% to 20% saturation with residue alone; it changed to 16% with residue and fertilizer. This suggests that a key factor linking residues with increases in crop yield is suppression of Al toxicity in soils.

hectare (t ha $^{-1}$) of cattle manure (a rate that does occur in farmers' fields), soil nutrient store ... had increased by 91 kg ha $^{-1}$ of N, 19 kg ha $^{-1}$ of P, and 1070 kg ha $^{-1}$ of organic C." (Brouwer and Bouma 1997, 23, citing a study by Brouwer and Powell 1995) Unfortunately, these levels were stored at a depth of 1.5 to 2.0 meters! The authors suggest that similar levels of nutrients and organic C were also stored below the 2.0 m depth. Such severe leaching, in this region, is associated with torrential rainstorms and specific micro-topography variables. Thus, it is possible that leaching could be responsible for the lack of success in recapitalization of these soils; the build-up could be occurring in the subsoil rather than the surface soil where it is needed. There are plant root systems in semi-arid soils of the Sahel which extend to a 1.5 to 2 m depth which have the capacity to access subsoil nutrients (Penning de Vries and Djiteye 1991; Breman and Kessler 1995).[21]

Numerous studies have been conducted which show the potential afforded by significant organic inputs for the restoration of degraded soils including the improvement of soil structure and fertility. Among these, there are several which address the potential to restore soils to a higher level of fertility/SOM than native levels. For example, Padwardhan et al. (1997), citing Johnson (1995) have developed a hypothetical model in which SOM reaccumulates under "new management" (after significant losses with agricultural disturbance) at a higher (new) steady-state than the native, pre-disturbance steady state. Breman (1998) actively supports efforts of "eco-intensification" to achieve such new/higher steady-state levels of soil fertility for soils in SSA. However, it is difficult to increase SOM levels in some regions, especially in the Sahel, due to the length and severity of the dry period which is long enough to decompose most biomass. It is estimated that it takes between 10-30 years of intensification to build up SOM in this region, depending on soil type, quantity, and quality of inputs. Breman (personal communication) suggests that soil fertility initiatives with fertilizer use should begin in regions with higher potential than marginal regions (both agroecological and socio-economic) to create fertilizer demand and input market development, both of which are required for addressing the constraints of marginal areas.

3.3. Fertilizers, Organic Matter and the Carbon Cycle

When combined with recycling of organic materials, the primary positive impact of fertilizers is to increase the biological base of the plant/soil system resulting in increased crop yields and recapitalization of soils. When fertilizers or organic inputs are applied, essential nutrients are supplied for the creation of plant biomass by means of photosynthesis. In the process, CO_2 is incorporated or fixed into the biomass from the atmosphere which is then referred to as organic C. "Ecologists call the production of plant biomass from sunlight, water, atmospheric CO_2 and nutrients primary production. Primary production is based on photosynthesis and is the basis for the global food chain. During photosynthesis, energy from sunlight is stored in the chemical bonds holding carbon atoms together." (Robertson 1998, 6) When fertilizers are applied, the

---

[21] For example, millet is used in Northern Australia in rotation with sorghum to bring "lost" nutrients back to the surface (Breman, personal communication).

increased availability of nutrients to the plant creates an increased capacity for absorption of the above “ingredients,” thereby increasing the biology and productivity of the soil system.

The biological health and sustainability of an ecosystem is typically assessed by its NPP which is “the amount of plant biomass produced during a given time period within a particular ecosystem. Ecosystem NPP depends on the plants’ photosynthetic efficiency, leaf area, leaf duration and on water and nutrient availability.” (Robertson 1998, 7) Again, the Sahel provides an example of environmental limitations of agroecosystems in SSA. The region has severely limited NPP due to "sub-optimal" conditions which result in limited biomass, SOM, nutrients and water levels. Rates of growth of plants and crops are three to five times less than the maximum "production potential" which could be achieved if nutrients and water were not limited. NPP is also limited due to the short season of rapid growth (Penning de Vries and Djiteye 1991).

Plants are typically 40-45 % C on a dry-weight basis (Cavigelli 1998). When the plant is harvested, approximately 50 % of the above-ground biomass is removed as grain in North American ecosystems (Robertson 1998). However, in SSA, this "harvest index" is much lower, averaging 15-30 % (Breman, personal communication). For example, a local millet variety in Niger has a harvest index of approximately 20%. That which remains, including below-ground root biomass, is considered plant residue, a primary precursor to SOM.

Residue organic matter (OM) serves as a critical nutrient source for crops. Over 95% of N and S of surface soils are found in SOM as well as 20-75% of P (Duxbury et al. 1989). Residue micro nutrients that the crop has taken up from the soil are also recycled back into the soil as SOM. These micro and macro-nutrients in SOM may be considered as a source of nutrient capital which is mineralized and becomes available to crops over the long term.[22]

Second, carbon in the residue OM becomes a food/energy source for soil microorganisms including fungi, bacteria and nematodes. Five to fifteen percent of residue C is incorporated into microbial biomass in this way (Cavigelli 1998).

> Although the microbial biomass carbon pool generally represents less than five percent of the total soil organic carbon pool, it is fundamental to the functioning of any ecosystem and is crucial in developing SOM. As a result of *microbial activity*, carbon undergoes many complex chemical transformations that are collectively known as *decomposition.* Decomposition rates are influenced by factors that influence microbial activity: temperature, moisture, aeration, pH, amount and quality of residue, residue particle size and degree of burial in soil....
>
> A certain portion of the carbon in residues and manure is readily decomposed and is thus called *short-term SOM.* Short-term SOM provides some benefits to soil physical condition, but it is mostly important as a short duration (one to three years) source of plant nutrients (primarily nitrogen, phosphorus, and sulphur). Manipulating this portion in

---

[22] Mineralization is the conversion of an element from an organic to an inorganic form by microbial decomposition. Plants require mineralized, inorganic nutrient elements for growth.

> seasonal patterns is absolutely essential to nutrient use efficiency and preventing nutrient loss to the environment. (Cavigelli 1998, 21)

Remaining portions of decomposed C from crop residues (10-35%) are incorporated into *long-term SOM* or *humus*. This more recalcitrant matter includes lignin and hemicellulose and has a turnover rate in the 100s to 1000s of years. Although scientists have traditionally associated aggregation and its structural benefits with humus, more recent research points to intensive decomposition of residues in short-term SOM for this benefit . "Recently incorporated particulate organic matter was shown to initiate aggregation by acting as a substrate for the fungi and bacteria which aggregate soil particles through their associated mucilages or physical enmeshment.... Golchin et al. (1994) proposed a model of micro aggregate (20-250 *u*m) formation around plant residues. They suggested that particulate SOM entering the soil is rapidly colonized by a microbial population. The micro flora and its by-products have strong adhesive properties, and mineral particles adhere to them.... The plant fragments are thereby rapidly encrusted by mineral particles and become the center of water-stable aggregates." (Angers and Chenu 1997, 201)

This explains the direct relationship that has been observed between crop residues and aggregation and associated physical benefits including moisture infiltration and retention (water-holding capacity), reduced erosion, and nutrient sorption (retention) or base saturation. Thus, residues and other particulate organic matter increase SOM levels and aggregation/improvement of soil physical structure simultaneously. Manure also has high potential for build-up of SOM and aggregation. In this case, the processes involved may be more related to long-term humus due to higher levels of recalcitrant products in manure, especially lignin.

Research has indicated that organic materials have the ability to reduce the P sorption (retention) capacity of soil and thus increase P availability to crops. Addition of organic inputs can be especially useful on certain soils, such as Oxisols, that are known to have low availability of P due to P sorption despite the presence of medium to high levels of P in the soil. A variety of complex organic reactions are responsible for this effect (Palm, Myers, and Nandwa 1997). Also, organic inputs have been associated with increased root-length density resulting in increased uptake of P. This is an important benefit since P is immobile and the plant depends on the root system to scarf P (as opposed to N which is mobile in soil solution). Bationo et al. (1993, 318) write: "Hafner et al. (1993) ... reported an increase of root-length density with [crop residue] CR application which led to an increase in total P uptake from 3.4 to 10.6 kg P/ha."

Bationo and Mokwunye (1991, 218), citing work by Charreau and Nicou (1971) and Poulain (1980), listed the primary benefits of OM in the West African semi-arid tropics (WASAT)[23] as:

- Improvement of soil macro-structure.
- Increased water-holding capacity of the soil.

---

[23] This does not imply that these factors are not important in other regions as well.

- Improved infiltration and erosion control.
- Prevention of soil hardening.
- Improved soil cation exchange capacity. This is of particular importance for the sandy soils of the WASAT. For example, for the millet-producing soils of West Africa effective cation exchange capacity (ECEC) is more correlated with the organic matter content of the soil than with the clay content.
- Increased supply of slowly released inorganic nutrients ... ensures a steady release of nitrogen at a time when the established crop can use it. This minimizes losses of readily available nitrate-nitrogen through leaching.
- Development of a favorable environment for microbial activity in the soil.
- Prevention of phosphate fixation by iron and aluminum oxides.
- Certain substances like quinones and benzo-quinones which appear in the course of transformation of organic matter may play a specific physiological role and might increase the absorption capacity and length of roots.
- Increase in the resistance of roots to some diseases.

In the WASAT, residues on the surface of the soil are also critical for protection of the soil from the desiccation and high temperatures of the dry season and the potentially severe wind and water erosion of the rainy season (Mokwunye, Uzo and Hammond 1992).

Large quantities of crop residues are required to be effective in recapitalization of soils and promoting the above factors. This is due to the fact that 60-75% of original residue C is respired by soil organisms back into the atmosphere as CO_2 (Cavigelli 1998). "Because a large proportion of added residues and a portion of already existing SOM is converted to CO_2 during microbial decomposition, large amounts of residue are required to maintain or increase SOM levels." (Cavigelli 1998, 23) Even higher levels of residue are required in SSA due to more rapid decomposition (turnover) rates that are associated with higher temperatures and 12 month periods of decomposition.

To build a sustainable soil base, it is critical that appropriate contributions are made to SOM.[24] Certain crops are especially efficient at building up long-term SOM by providing high levels of carbon from photosynthetic C. "Some plants (notably corn), warm-season grasses and common

---

[24] It should be pointed out that there are management systems, especially in the West, which do not depend to a great degree on the soil for macronutrients or water but rather on reliable, very high inputs of fertilizers with irrigation. In SSA, where such resources are not commonly available, it is necessary to rely on the soil for nutrient and water storage and delivery for sustainability, especially for those years when fertilizers are not readily available and rainfall is limited.

weeds have a photosynthetic pathway dominated by four-carbon (C_4) molecules. At high temperatures these C_4 plants can photosynthesize at much higher rates than their three-carbon molecules (C_3) counterparts such as wheat, soybeans and cool-season grasses." (Robertson 1998, 7) C_4 maximum rates of photosynthesis are estimated to be about 50% higher than C_3 rates (Penning de Vries and Djiteye 1991).

This higher level of C fixation into the plant biomass in C_4 plants results in higher levels of NPP. Not surprisingly, the quantity of residues is also higher. Thus, higher levels of associated energy and nutrients are incorporated into the soil system. As a C_4 plant, maize/corn produces one of the best crop residues (of primary crops) for build-up of SOM, exhibiting a high carbon content. Contrary to traditional research findings, rotation with annual leguminous crops, such as soybeans, results in lower levels of SOM, organic C and N (Omay et al. 1997). However, rotations remain important for achieving agronomic goals, especially control of plant disease and erosion.

As in the case of C, researchers have "concluded that the major contribution of N in crop residues, particularly low-quality [i.e., high C/N ratio] gramineous residues [such as maize], is through the soil organic matter [SOM]."[25] (Myers et al. 1994, 92) Nitrogen in maize residue is sequestered primarily in long-term SOM. Feller and colleagues found that 25% of N^{15} added as maize stover residue to a sandy soil in Senegal was found in the new plant biomass with the remaining 75% in the soil with no losses to leaching or runoff. Most of the remaining N was located in the larger, more recalcitrant >50 *u*m particle size fraction of SOM associated with long-term SOM (Myers et al. 1994, citing Feller, Chopart, and Dancette 1987).[26] The remaining N is cycled relatively rapidly through the microbial biomass of the short term SOM. First, it is tied up or immobilized into the microbial biomass. After a typical period of 1-3 years, it is released or mineralized as inorganic N in soil solution as a crop nutrient.[27]

There is an inverse relationship between biomass production and "quality" (nutrient content and digestibility by animals and microorganisms). For example, C_4 plants such as maize have high levels of production (with high carbon levels) but very low quality (low N levels) (Penning de Vries and Djiteye 1991). Maize has a high C/N ration of 60:1. As a result, maize residues often result in significant N limitations during the immobilization phase because soil microbes need all of the available N in order to utilize C. "Decomposition of materials [such as maize] with N concentrations of less than 2% (or C/N >25) lead initially to immobilization of mineral N, whereas materials with higher than 2% N (or C/N <25) release mineral N." (Myers et al. 1994, 91). Thus, N becomes less available to the crop and crop growth is limited during the length of the

---

[25] Different portions of the plant residue have different C/N ratios and , thus, different "quality." Therefore, certain portions of the plant residue are recommended as forage for livestock. In this paper, the "quality" of specific crop residues is based on the average C/N ratio of the crop residue and not that of a particular plant part.

[26] *u*m denotes a micrometer or micron which equals 1 millionth of a meter.

[27] Immobilization is the microbial conversion of an element from the inorganic to the organic form.

immobilization phase. Soybean is an example of a low productivity/high quality plant with a C/N ration of 30:1.

The negative impact of cereal residues, such as maize, on crop growth has been shown to be consistent in agronomic trials. In one study, addition of 2.5 to 5.0 t ha^{-1} of maize stover resulted in a 30 to 60% decline in available N (Palm, Myers, and Nandwa 1997, citing Ishuza 1987). Losses of nitrate are most common and the length of the “nitrate depression period” can range from several weeks to the entire length of the growing season depending on the quality of the residue (Brady 1990). Since the addition of low-quality residues is common in SSA without complementary N inputs, it is likely that long nitrate depression periods are a significant contributor to low crop yields on the continent. Research has shown that the immobilization effect can be offset by the addition of N fertilizer and/or high-quality organic inputs (Palm, Myers, and Nandwa 1997).[28]

The IFDC-Africa Division, based in Togo, has been working with other international research centers to learn which combinations of fertilizer with various organic inputs (residues, manure, cover crops, green manure) from a variety of quality classes result in a beneficial "nutrient equivalency value." This value is based on those soil fertility factors described earlier which provide water and nutrient use efficiency and other benefits. It is considered to be more critical than nutrient content alone (Breman, personal communication).

3.4. Fertilizer-Based Strategies that Address Constraints

Management systems or strategies for SSA will be most effective when they respond successfully to site-specific environmental and agriculture-induced constraints outlined above and restore depleted soil fertility and SOM. This approach is suggested because soil and water constraints are frequently severe and have resulted in declines in productivity and sustainability in SSA. Lal et al. (1997) list the following four "Site Specific Soil Management Options for C Sequestration:"

1. Soil Fertility and Nutrient Management (Macro nutrient [N, P, K], Micro nutrient [S, zinc (Zn), copper (Cu)], Strengthening nutrient cycling mechanisms to minimize losses)

2. Tillage Methods and Residue Management (conservation tillage, cover crops, mulch farming)

3. Water Management (supplementary irrigation, surface and subsoil drainage, soil-water management, water harvesting)

4. Erosion Control (runoff management, vegetative barriers, soil surface management and mulch farming).

---

[28] This immobilization effect will vary according to plant species.

In SSA, it is not unusual that intensified management systems have focused primarily on nutrient management and improved cultivars, similar to "green revolution" strategies in Asia. However, because they have not addressed the other constraints via appropriate management systems, they have proved to be unsustainable. Stewart et al. (1991, 142), citing El-Swaify et al. (1985) provide the following example pertaining to Alfisols of West Africa:

> The most abundant soils in the semiarid tropics are Alfisols, and these soils are extremely vulnerable to erosion, crusting, compaction, drought, and limited rooting depth. Alfisols contain predominantly low-activity clays and have low plant-available water reserves. Improved management systems for conventional cropping of Alfisols have succeeded in increasing yields of conventional crops, largely due to improved cultivars and use of fertilizers. Effective practices for improving soil and water conservation, however, have not been developed. This is primarily because of the extreme structural instability of these soils.... Alfisols are inherently low in soil organic matter, even under native vegetation, and once they are tilled, the organic matter becomes critically low.

The authors continue (p. 136) citing Hartmans (1983):

> 'Why do most tropical soils become unproductive and useless after only a few years, and what can be done to arrest this deterioration?' He stated that results of 15 years of research at the International Institute of Tropical Agriculture (IITA) at Ibadan, Nigeria, in pursuit of these questions are quite clear. Chemically, the land becomes more acid very rapidly. Physically, the soil seems to collapse on itself. It becomes more dense, and erosive forces often cause the finer particles to disappear, leaving a sandy or gravelly material. The soil loses its capacity to form stable aggregates because the binding material, the soil organic matter, is gone. The result is a rapid downward spiral of soil productivity.

This illustrates the direct relationship between loss of SOM (the primary determinant of fertility) and soil structure with resulting declines in productivity.

3.4.1. Nutrient Management for Soil Fertility: Combining Fertilizers with Organic Inputs/Systems

Since this is a paper about fertilizer use and impacts, the primary management system being addressed is nutrient management and soil fertility. However, this system cannot function sustainably, especially in SSA, without close complementarity with the other three systems: tillage methods and residue management, water management, and erosion control. These systems and associated benefits will also be addressed.

Recent research and writings support the use of fertilizers in combination with organic inputs as part of intensification strategies to drive sustainable growth in agricultural production in SSA and end the long cycle of agricultural and economic stagnation (Bationo and Mokwunye 1991; Bekunda, Bationo, and Ssali 1997; Breman and Sissoko 1998; Pieri 1992; Quinones, Borlaug, and Dowswell 1997; Reardon 1997; Swift 1996; Wallace 1997; Yanggen et al.1998). There is a consistent perspective, in these works, that neither input strategy, on its own, is capable of achieving production goals. Quinones, Borlaug, and Dowswell (1997, 83) point out that

> Increased fertilizer use in Africa can create a win-win situation, by promoting more efficient crop production and reducing soil degradation. Mineral fertilizers should be at the core of strategies to restore soil fertility and raise crop productivity, although their use should be part of integrated systems of nutrient management in which organic fertilizer sources are included. Organic sources of nutrients, however, will be complementary to the use of mineral fertilizers, and not the other way around. Exclusive use of organic fertilizers will increase food production at best by 2% yr^{-1} (Hiyami and Ruttan 1985), well below the population growth rate, and not even close to the 5 to 6% required to reduce poverty and assure food security.

The Kansas prairie study, (comparable to "high potential SSA land" described previously) provides an example of how increased nutrient input via a combination of fertilizers and crop residues can result in increased yields and C sequestration to SOC/SOM over time. In the study, as in most of North America, fertilizer use increased dramatically in the 1950's, increasing crop yields and the amount of unharvested crop residue that was returned to the soil (Figure 2) (Brady 1990, citing Balesdent, Wagner, and Mariotti 1988). As a result, SOC/SOM increased at an annual rate similar to the decline noted in section 3.1.1. (1-2% per yr).[29] The prairie soil is an Alfisol which, by definition, includes a base saturation > 35% (in non-frigid climates) which indicates that it is a well-buffered soil. Such U.S. prairie soils have been used as models to show how soils can be improved with both fertilizer and residue input.[30]

Janzen et al. (1997, 71-2) have reviewed crop nutrient/ litter input/SOC/SOM relationships for Canadian agroecosystems:

> The rate of plant litter input in agroecosystems is closely related to crop yield. Numerous studies have shown strong correlations between crop residue inputs and SOC contents (e.g., Campbell and Zentner 1993; Biederbeck et al. 1994; Nyborg et al. 1995; Gregorich et al. 1996). Many of the SOC gains in response to improved management practices can be directly linked to higher yields arising from better crop nutrition, more efficient nutrient and water utilization, and higher yielding crops. In part, the variable response of SOC to a given management change depends on whether the new practice elicits a yield response. For example, under semiarid conditions of western Canada, adoption of no-tillage [with

---

[29] When possible, efforts should be made by researchers using labeled carbon to determine if apparent increases in fertility are simply internal SOM transfers from long-term SOM to shorter-term biomass SOM or are from sequestered C inputs. Brady (1990) notes that 60 years after the initiation of wheat farming, most of the organic matter that remains (after soil mining) is the original native prairie organic matter which is a very "stable" long-term form of SOM. After the initiation of recapitalization in 1950, an increasing portion of SOM can be estimated to be derived from wheat residue rather than from long-term SOM since long-term levels remain relatively constant.

[30] U.S. Alfisols do not have the severe structural instability of many African Alfisols.

> high inputs of crop residues] can maintain or enhance crop yields (Lafond et al. 1992) because of greater moisture retention, thereby favoring higher SOC (Campbell et al. 1995). Under humid conditions like those in eastern Canada, however, reduced tillage may have little yield advantage and therefore elicit only limited gains in SOC (Angers et al. 1995; Angers and Carter 1996).[31]

Research trials by the IFDC have shown the impact of increased nutrient use efficiency (from soil improvement) to increased yields. "IFDC showed on its research fields in Togo that the efficiency of the "national recommended package of fertiliser" increased 2 to 3 times through soil improvement. At the start, on relatively good soils (> 10 year fallow), the nutrient recovery was only about 30%, leading to an increase of maize yield with 900 kg. After 4-7 years of soil improvement, the nutrient use efficiency increased 2-3 times, and maximum yield increases of 2000 to 3000 kg/ha have been measured with the same fertiliser package." (Hank Breman, personal communication) He suggests that the principal cause for the increase is not simply supply of nutrients but, more importantly, the improvement of soil structure with increased SOM levels resulting in increased efficiency of nutrient and water supplies to crops, increased infiltration rates, decreased erosion and improved plant rooting. Without such improvement, crops in the Sahel region, for example, have "recuperation rates"[32] on average of only 35% for N and 15% for P which are approximately half of typical rates elsewhere. Due to low efficiency and high losses, the amounts of fertilizers required are too great to interest farmers in most cases (Breman 1998, 6). With improved fertility and efficiency, there is a realistic potential to increase these rates to 50% and 30% respectively (Groot et al. 1998).[33]

Lessons from Long-Term Experiments in SSA: Bekunda, Bationo, and Ssali (1997) reviewed findings from long-term experiments (7-27 years) in SSA which compared fertilizer with organic inputs and liming – both alone and in various combinations (Table 1). Countries represented were Kenya, Nigeria, Uganda, Zambia, Tanzania, Chad, Burkina Faso, Senegal, and Cote d'Ivoire. Use of **fertilizer alone** resulted in "measurable yield declines" in 9 of 13 cases. According to the authors (p. 71), "Such declines [for fertilizer alone] might result from (i) soil acidification by the fertilizers, (ii) mining of nutrients as higher grain and straw yields remove more nutrients than were added (Scaife 1971), (iii) increased loss of nutrients through leaching as a result of the downward flux of nitrate when fertilizer N is added, and (iv) decline of SOM." According to the extensive research of Pieri (1992), the first negative impact (soil acidification), especially from N fertilizers, is the primary impact of fertilizers used alone (see below).

---

[31] Success of no-till in humid regions of the U.S. suggests that its effectiveness is not limited to low rainfall areas.

[32] The percent of the total amount of an applied nutrient which is recuperated or extracted by the crop from the soil.

[33] It should be noted that not all nutrients are cycled to crops but are stored in SOM to improve the C/N, C/P, and C/S ratio.

Table 1. Impact of Soil Management Treatments on Crop Yield Trends in Selected Long-term Experiments from Sub-Saharan Africa

					Treatment†				
Number	Site	Soil description	Experiment duration	Test crops	Mineral fertilizers (A)	Animal manures (B)	Crop residues (C)	A + B or A + C	Liming or A + Liming
1‡	Côte								
	D'Ivoire	Ferralitic§	1969 to 1990	Cotton	++S		+S	++S	
	Bouake	Ferralitic	1969 to 1990	Cotton	+D				+S
	Korhogo								
2	Senegal								
	Darou	Ferruginous	1957 to 1974	Groundnut	+D				
	Bambey	Ferruginous	1957 to 1974	Groundnut	+D	+S	+D		+D
3	Burkina Faso								
	Niangoloko	Ferruginous	1962 to 1984	Groundnut, millet		+S			
	Saria	Ferruginous	1960 to 1983	Groundnut, millet	+D	+D	+DD	+S	+S
4	Chad								
	Bebeda				+S				
5	Tanzania	Ferralsol	1981 to 1988	Maize	+D				
		Luvisol	1981 to 1988	Maize	+D				
6	Zambia								
	Misamfu	Oxisol	1966 to 1981	Maize, groundnut	+DD				+S
	Magoye	Luvisol	1966 to 1981	Maize, groundnut	+S				
	Katito	Ultisol	1966 to 1981	Maize, groundnut					+S
7	Uganda								
	Serere	Ferralsol	1937 to 1964	Cotton, millet, sorghum, groundnut	+D			+S	
8	Nigeria								
	Samaru	Ferruginous	1964 to 1975	Cotton, millet, sorghum, groundnut	+S				
9	Kenya								
	Kabete	Nitisol	1976 to 1996	Maize, bean	+D	+S	+D	++S	

---

† +, yield higher than control; ++, yield relatively higher than + within the row; S, stable yield trend; D, measurable yield decline; DD, sharp yield decline.

‡ Sources: 1, Traore & Harris (1995); 2, 3, 4, Pieri (1995); Laryea et al. (1995); 5, 6, Singh & Goma (1995); 7, Research Reports, Serere Experiment Station; J.B. Byalebeka (1996, personal communication); McWalter and Wimble, (1976); 8, Singh and Balasubramanian (1997); 9 = Swift et al. (1994) and S. Nandwa (1996, personal communication).

§ Approximate USDA Soil Taxonomy equivalents: Ferralitic, Oxisol; Ferruginous, Alfisol; and Luvisol, Alfisol.

Source: Reproduced from Bekunda, Bationo, and Ssali (1997, 72) with permission from The American Society of Agronomy and Soil Science Society of America.

One of the four experiments where there was no significant yield loss from fertilizer use alone was Bebedjia, Chad. Crop yields were stable over time. According to Pieri (1992), the soils at this site are unusually fertile and well-buffered with no erosion or deep leaching which may explain their lack of vulnerability to these inputs. Presumably, these soils may be categorized as "prime land" since they are not vulnerable to degradation.

Experiments which were "successful" in all cases were **fertilizer combined with manure or residue**.[34] As described previously, fertilizer, particularly when used on fertilizer-responsive crops with high biomass production, "primes the photo synthetic pump," helping the plant use more of the available CO^2 and water; resulting in more biomass production. When crop residue is recycled, increased biomass nutrients and C (from the plant CO^2) are captured into SOM, creating a sustainable system for delivery and storage of plant nutrients and water.

Liming or fertilizer with liming was successful in maintaining stable yields in 4 of 5 experiments which indicates the importance of pH in maintaining soil fertility for sustainable crop management. Results for **residue alone** and **manure alone** were mixed. Manure alone resulted in stable yields in 3 of 4 trials. Residue alone, however, led to a decline in yield in 3 of the 4 trials.[35] The authors suggest that these declines may have been caused by residues with high C/N rations (typically from the primary crop, e.g. maize) leading to short-term N deficiencies due to N immobilization.[36]

There are experiments in SSA indicating that residue alone can be moderately successful in increasing yields and, again, that fertilizer plus residue is a superior combination, even on "marginal" lands. "In 1983, at the [International Crops Research Institute for the Semi-Arid Tropics] ICRISAT Sahelian Center at Sadore, Niger, a trial was set up to study the effect of crop residue and fertilizer on pearl millet production. Crop residue (4 tons ha^{-1} pearl millet stover) was added to the soil surface in the first year to prescribed plots. In subsequent years the residues produced were simply placed on the plot surface. After 3 years, addition of crop residue alone had resulted in statistically the same amount of millet grains as plots to which fertilizers had been applied." (Bationo and Mokwunye 1991, 221) Specifically, residue alone raised yields from about 200 to 750 kg ha^{-1}; fertilizer alone raised yields to about 900 kg ha^{-1} and; crop residue plus fertilizer increased yields to about 1700 kg ha^{-1} (Figure 5) (Bationo and Mokwunye 1991).

---

[34] The experiments were considered "successful" from the perspective of stable yield trends. They do not include soil recapitalization parameters, however, for measurement of success. Thus, it is not possible to know if the use of residues and manure are having the effect of building up SOM and nutrient storage.

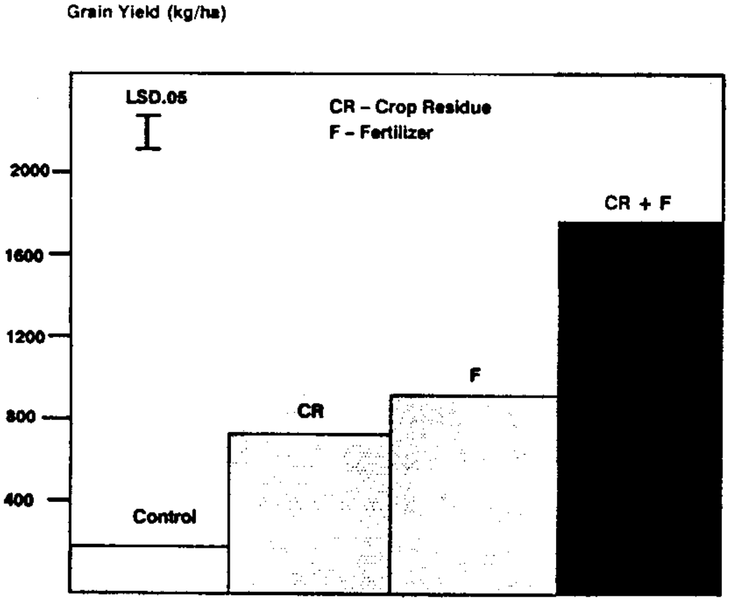
[35] As Bekunda et al. is a broad review of experiments across SSA, experimental details indicating types, levels and timing of organic inputs are not included.

[36] It is also possible that residues in the experiments were not protected from (uncontrolled) grazing or other exports. Such lack of protection of residues in SSA experiments is not unusual.

It should be pointed out that research station results may more accurately reflect the reality of production on medium to large scale western farms with access to investment capital, advanced education and sources of information rather than actual conditions in SSA.

> Despite the low average crop yields obtained under smallholder farm conditions, large yield levels are achieved under research station conditions. What is common in ... all Sub-Saharan African countries is a huge yield gap between on-station results compared with those obtained under smallholder farmers' fields. This huge yield gap can mainly be attributed to the problems of managing soil fertility faced by smallholder farmers who are constrained by cash to purchase farm inputs. Poor crop husbandry practices, which also directly impinge on soil fertility, contribute greatly to the observed low crop yields. It is also being recognized that technological innovations currently recommended to smallholder farmers have not been fully adopted by this target group. The recommended packages have failed to take into account the resource constraints and limitations of the smallholder farmers, hence the low rate of technology adoption....
>
> ... smallholder farmers [in Malawi] who cultivate small land holdings of between one and two ha per farm family of five people, are constrained by lack of cash to purchase mineral fertilizers, and have limited access to credit facilities (Saka, Green, and Ng'ong'ola 1995, 1-2).

Figure 5. Millet Grain Yield Response to Fertilizer and Crop Residue Application



Source: Reprinted from Bationo, A., and A.U. Mokwunye. 1991. Role of Manures and Crop Residues in Alleviating Soil Fertility Constraints to Crop Production: With Special Reference to the Sahelian and Sudanian Zones of West Africa. In *Alleviating Soil Fertility Constraints to Increased Crop Production in West Africa,* ed. A.U. Mokwunye, Fig. 5, p. 222. With kind permission from Kluwer Academic Publishers..

Besides these factors, adoption of recapitalization is also dependent on farmers' perceptions and understanding of the technical potential of residue recycling. Farmers may not accurately value the nutrient content of crop residues. For example, the straw produced on one hectare of millet yielding 1.2 tons of grain contains 74 kg of K that could be recycled as residue. The harvested (exported) grain actually contains only 6 kg of K (Bationo and Mokwunye 1991). As yield and total biomass increase, crop residue availability also increases. In much of SSA, farmers use crop residues as animal feed, fuel, or construction materials; this severely diminishes the role that increased biomass associated with fertilizer use can play in recapitalizing SOM. A partial solution to this problem is to target fertilizer to cropping situations where the increased production of biomass will be the greatest, thereby providing farmers with biomass production to meet both traditional and recapitalization needs. A more sustainable system is to develop alternative sources for fuel, construction and forage so that all crop residues are available to soils and crops.

Comparisons of Organic Inputs and Fertilizers: As illustrated in the previous section, there is a growing consensus regarding the complementarity of fertilizer and organic amendments. Fertilizer and organic matter each contain nutrients required by plants to create biomass via photosynthesis, but sustainable intensification of SSA soils can be achieved by a combination of both types of inputs. Fertilizer makes very little (if any) direct contribution to soil macro-structure, increased water-holding capacity, improved infiltration and erosion control, prevention of soil hardening, or improved nutrient holding capacity. But organic matter and fertilizer combined have the capacity to make positive contributions to all of these factors.

There are limitations on the amounts of organic matter that are available as agricultural inputs in SSA. Giller et al. (1997, 170), citing work by several other researchers, provide the following example of the large area of grazing land that is required in West Africa to provide sufficient manure to produce a significant maize crop. "Sandford (1989) estimated that 16 to 47 ha of grazing land were required to produce sufficient manure for sustained maize production of 1 to 3 t ha $^{-1}$ in a semiarid environment in West Africa. It is clear that there is insufficient manure to sustain even such moderate yields in many parts of West Africa (Fernandez-Rivera et al. 1995; Williams et al. 1995). There is also a danger of long-term degradation of grazing lands, as there is substantial nutrient removal over prolonged periods."

In many regions of SSA, significant quantities of manure go to non-agricultural uses which limits their availability for agriculture. In Ethiopia, where livestock numbers are high, manure is used primarily as a cooking fuel and rarely to improve soil fertility (Quinones, Borlaug, and Dowswell 1997, citing Giller et al. 1997). As described in a previous section, crop residues are often exported for non-agricultural purposes as well. Breman (personal communication) estimates that the organic matter that is available in the high potential cotton zone of Mali is only one-third of the amount required to maintain crop production. He concludes that organic matter should not be considered primarily as a nutrient source (since it is so limited in availability) but rather as a complement to fertilizers (i.e., "organic amendment" rather than "organic fertilizer") which can improve nutrient use efficiency and other beneficial properties of the soil.

Aside from high decomposition rates of residues, the reason that such large quantities of organic materials are required for crops is the low concentration of these materials, especially when compared with fertilizers. "Animal manures and plant material contain from 1 to 4% N (10-40 g N kg $^{-1}$) on a dry weight basis, while inorganic fertilizers contain from 20 to 46% N (200-460 g N kg $^{-1}$) and are already dry. To haul the 100 kg N generally needed for a 4 t ha $^{-1}$ maize crop, it would take 217 kg of urea or 20 t of leaf biomass with 80% moisture and a 2.5% (25 g N kg $^{-1}$) N concentration on a dry weight basis. Furthermore, organic inputs are very low suppliers of P because of their low concentrations." (Sanchez et al. 1997, 8-9, citing Palm 1995 and Palm et al. 1997)

It is obvious from the figures in the previous paragraph that it is technically possible for a farmer to use only organic inputs and have sufficient nutrients for yield goals and there are sufficient examples of such practices in SSA in the literature. However, it would be imprudent for a national government to recommend such a strategy when there are insufficient organic resources available on a national or regional scale. Secondly, it is more difficult for African organic farmers to achieve satisfactory yields because they are usually dealing with depleted soils and can not count on the soil for significant nutrient inputs. Finally, most African farmers need to recapitalize their soils for long-term sustainability. If one were to calculate the amount of organic inputs (manure or plant material) that are required to satisfy both crop demands and recapitalization requirements, the total amount would be enormous. Fertilizers provide a concentrated response to this demand.

There are two principal reasons for the emphasis in this paper on crop residues as organic inputs. First, residues are typically provided internally by the crop providing a direct and, therefore, efficient source of organic inputs. That is, they are not imported from elsewhere thus requiring an investment by the farmer as well as depleting the soil of OM in another location. Ideally, all residues should be left on the ground because the quantity required for recapitalization is so high. To the extent that livestock are raised and residues used as forage, all subsequent manure should be returned to the soil. While there is some efficiency lost in the process, the quality of manure as an amendment makes up for it due its high lignin content. Second, manure does not provide vegetative cover for the soil (vs. residues which do), especially for erosion control. Therefore, in a livestock/crop system using manure inputs, other management practices need to be implemented such as low-lying cover crops to provide this function.

Fertilizer and Organic Matter Practices in SSA: Residue use as a soil amendment is common in SSA compared to fertilizer use which is encouraging for the development of residue-based strategies outlined in previous sections. Bationo and Mokwunye (1991, 217, citing Poulain 1980) state that "the amounts of the nutrients in crop residue of developing countries are seven to eight times higher than the quantities of these nutrients applied as fertilizers in these countries." Segda (1991) cited in Bationo et al. (1993, 307-8) reviewed crop residue availability in the Sudanian zone of central Burkina Faso concluding "that the production of cereal straw can meet the currently recommended optimum level of 5 t/ha every two years. However, the competition with other uses was not accounted for in this study."

Bationo et al. (1993, 307-8) write: "At the onset of the rains the residual stover on-farm was only between 21 and 39% of the mean stover production at harvest time ... cattle grazing is likely to be responsible for most of the disappearance of the crop residues. Similar losses were reported by Powell (1985) who found that up to 49% of sorghum and 57% of millet stover disappearance in the subhumid zone of Nigeria was due to livestock grazing." Typically, in the WASAT "grazing animals remove more biomass and nutrients from cropland than they return in the form of manure, an exception being reported from Burkina Faso."

“Traditionally, many farmers burn whatever is left of their CR once their needs for fuel, animal feed, or housing and fencing material have been fulfilled. Economic data collected recently show the rationality of this strategy as mulched millet stalks increase weed growth and subsequently labor requirements at weeding (Lamers, unpublished data). However, the same farmers may conscientiously apply CR at a rate of up to 6 t/ha to counteract erosion and build up soil fertility on selected spots of poor millet growth (Lamers and Feil 1993).”

In regions where livestock are an important component of the agro-ecological system, innovative approaches need to be found by which crops, soils and livestock can be sustained. For example, “intensive rotational grazing” incorporates perennial crops, such as alfalfa, into rotation with a primary crop, such as maize (Cavigelli 1998) in areas of higher rainfall. Some fields may be under maize while others are being grazed. Livestock are carefully controlled by portable fences. The system has the advantage of building up SOM via perennial residues without the usual export losses of residue for livestock fodder.[37] In areas of lower rainfall, the system could be adapted to include local grass species that are appropriate to the ecosystem.

There are regions in SSA, however, where use of fertilizers as well as residues and manure are high. For example, in Central Kenya, 83% of farmers use fertilizers, 98% use crop residues and manure; In Mutoko district of Zimbabwe, 98% use fertilizer, 77% use crop residues and 86% use manure (Palm, Myers, and Nandwa 1997). Despite these pockets of high fertilizer use, in most of SSA it is the adoption of fertilizers that is the greater obstacle to recapitalization efforts.
The Role of Fertilizers in Maximizing Water Use Efficiency: As stated in the first section, SSA has less available water than most other continents. For this reason, there are those who state that there can never be a truly productive agricultural sector in SSA. On the other hand, there is convincing historical evidence that successful agricultural production is possible on the continent, despite these limitations (see Section 5). There will need to be an in-depth analysis of water use issues and the development of appropriate practices that can maximize water use efficiency if SSA is to be successful in developing a successful and sustainable agricultural base.

The traditional point-of-view on water use is that fertilizers simply require more water than organic sources to be effective and create a water deficit relative to organic inputs. Research results, however, suggest that the reverse is true: fertilizer actually promotes water use efficiency and conservation. By increasing plant biomass, canopy, leaf area, and root development, the plant develops increased capacity for capturing and retaining water from rainfall (a process that may be observed more dramatically in tropical rain forests). For example, field experiments were conducted in Pakistan comparing two levels of NPK fertilizer treatment over three rainfall

---

[37] Other than a few comments, such as the preceding, this paper does not attempt to address the complex issues of integrated livestock/crop systems. Sources/researchers that do address this issue are: McIntire, J., D. Bourzat, and P. Pingali 1992. *Crop-livestock Interactions in Sub-Saharan Africa.* Washington, D.C.: World Bank; as well as the works of Salvador Fernandez-Rivera, Pierre Hiernaux, J. Mark Powell, Matthew Turner, and Timothy Williams.

regimes: 360, 398, and 462 mm. "The results show a gradual but marked reduction in grain yield with decreasing water supply, both at high and low soil-fertility levels. The yield obtained with optimum fertilizer application (34-84-168 kg/ha) at the lowest level of water supply (360 mm) exceeded the yield of wheat at the highest water supply level (462 mm) with low and unbalanced fertilizer (0-28-56 kg/ha)." (FAO 1987, 46-7, citing Saleem 1983)

From this perspective, nutrients are the primary limiting factor in SSA. "On soils with natural fertility in the southern Sahel, the water use efficiency is so low by lack of nutrients (N and P) that only 10 to 15% of the rain water (300 to 500 mm annual rainfall) is used by the plants. Correction of N and P deficiency leads to a 3 to 5 times higher biomass production and water use at the same rainfall!" (Hank Breman, personal communication; Breman 1998) Multi-location water balance studies conducted in Niger have also indicated that a critical consequence of fertilizer use is increased water use efficiency (Bationo 1998).

Land preparation technologies in areas with limited rainfall have been shown to have potential for containing run-off, thereby increasing water retention. Strategies such as tied ridges, contour dikes and *zai* holes that are used for containing and concentrating runoff of water and nutrients are only appropriate on loamy or clay soils and are generally unsuccessful on sandy soils.[38] In countries that adopt these technologies, it is important that national policies and strategies are developed based on soil classification parameters (John Sanders, Professor of Agricultural Economics, Purdue University, personal communication).

Dryland conservation technologies are specific conservation tillage practices that have been developed in the U.S. in low rainfall regions and have been effective for water retention and conservation, water use efficiency, and increased productivity, especially in the Great Plain states. For example, "Water use efficiency[39] in dryland cropping systems can be doubled if producers adopt dryland conservation technologies. Instead of producing 2500 pounds of grain per 20 inches of plant available water, 5000 pounds of grain could be produced with the same amount of water." (Cooperative Extension Service, Kansas State University 1995, 2-3)

3.4.2. Conservation or Mulch Tillage as a Complementary System

Conservation or mulch tillage has the potential to complement the benefits of fertilizer-based nutrient management with controls on environmental and agriculture-induced constraints, especially tillage, erosion, and compaction in semi-arid regions. It also complements fertilizer-based soil fertility by cycling crop C and nutrients back into the soil. Thus, it can be utilized for all four of the management objectives proposed by Lal et al. (1997) (see Section 3.4). In most developed countries, conservation tillage (no-till, mulch-till, and ridge-till) has increasingly

---

[38] See Section 5 for a description of these technologies.

[39] Expressed as pounds of grain produced per inch of soil water used by the crop.

replaced conventional tillage. In conservation tillage, also called mulch tillage (the term used most frequently in this paper), 30% or more of the preceding crop residue covers the soil after planting and plowing is limited or avoided altogether (no-till) thus limiting or avoiding negative impacts of tillage. "A tillage system that ensures a maximum retention of crop residue on the soil surface is called *mulch tillage* or *stubble mulch farming.* It is defined as preparation of the soil in such a way that plant residue or other mulching materials are specifically left on or near the surface." (Lal 1990, 357) Rather than opening the soil via plowing to plant seeds, "direct seeding" drills or other devices plant the seeds with minimum disturbance of the soil.

In the U.S., conservation tillage has gone from being an alternative technique to being a major tillage/residue management technique, accounting for 37% of annually planted acres. “Among states with 1 million to 13 million or more acres of total cropland,... conservation tillage systems are now the conventional way of farming (used on more than 50% of total cropland acres) in Iowa, Nebraska, Missouri, Kentucky, Tennessee and Maryland.” (Conservation Technology Information Center 1997, 1)

There are two primary reasons for the success of conservation tillage and its impact on such a large area of the U.S. First, it is profitable. This is due primarily to the fact that:

- it is based on “efficient” residue-based agro-ecological principles, enumerated in previous sections, which positively impact SOM, soil fertility, water retention, and productivity by controlling SOM, water, and nutrient losses from erosion, runoff, and leaching, and

- it is cost and labor-efficient with reduced labor requirements, time savings, and fuel savings.

Second, it is a management system that farmers can implement independently without involvement in government programs.[40] In recent years, however, adoption of conservation tillage practices in the U.S. has plateaued at 37% and not increased, suggesting that there are significant constraints for some farmers. Evidence indicates that farmers with cold and wet soil conditions, especially corn farmers, are reverting to conventional tillage. No-till practices for soybeans, however, continue to be popular (Dan Towery, Natural Resources Specialist, Conservation Technology Information Center (CTIC), personal communication).

Mulch tillage, especially no-till, has the potential to be successful throughout SSA, especially in semi-arid and arid regions of the Sahel. Clay soils in these regions have been especially difficult to manage due to severe erosion runoff during rainfall events and have required special land preparation efforts (contour dikes, tied ridges, *zai* holes) to capture run-off of water and

---

[40] Nyle Brady recently commented that no-till has been the most effective practice in fighting erosion in the history of the U.S., including the results of the government soil conservation programs. An important factor in the success of no-till is that no involvement in government programs is required. Independent farmers, not tied to government programs, make up the vast majority of farmers. Brady suggests that this factor be taken into account in determination of agricultural policy in the developing world (Comments at the World Bank Symposium for Sustainable Agriculture, Baltimore, 1998).

nutrients. No-till has the potential to replace these labor intensive methods by providing equivalent water retention benefits with the critical advantage that it improves soil quality and limits the negative impacts of conventional tillage (see Section 3.1.2.). One reason for the effectiveness of this approach is that residues increase termite activity which in turn increases soil porosity.[41] In the case of crusted soils, termites break up crusts, assuming that residues are left on the surface. Research by Kleij in Niger and Hulugalle in Burkina Faso has indicated that when residues are protected, no-till methods are effective, especially for comminution (breaking down into smaller particles) of crusts and prevention of crusting and erosion in semi-arid regions (Rattan Lal, Professor of Soil Science, Ohio State University, personal communication). There are cultural practices in SSA that are indigenous no-till technologies such as the use of planting sticks in the Sahel region. However, the residues in these regions are typically communal property and utilized for livestock grazing after the growing season.

In terms of water and nutrient retention on such soils, residues have the capacity to (i) capture water and nutrients which would normally be lost to run-off on clayey or crusted soils, (ii) increase infiltration of water and nutrients by soil faunal activity (such as termites), and (iii) increase the water and nutrient-holding capacity of the soil by increasing SOM levels via C sequestration from the residues. Water retention is a primary factor in minimizing the potential for drought stress, especially in lower rainfall regions (Lal 1987; Lal 1990).

Of no less importance, residues protect the soil from wind and water erosion by providing a vegetative cover close to the surface which minimizes separation of fine soil particles (especially clay, silt, and organic matter) by intense winds and splashing from raindrops, respectively. They also protect the soil from temperature extremes, especially from the intense heat that impedes seed germination (Lal 1987; Lal 1990).

It is instructive to learn what conservation tillage practices have been successful in different regions of the world under specific soil and climate conditions for possible adoption in SSA. Since tillage practices in SSA are typically less intensive than in the West due to a general lack of mechanical equipment, the primary advantage of conservation tillage practices is in the adoption of residue-based strategies (using fertilizers). In the developing world, Brazil and other South American countries have made successful large-scale adoption of conservation tillage practices in the 90s, especially no-till (Pieri 1998). From a bio-physical perspective, South America is especially instructive for comparison with SSA due its tropical climate systems and soil types (e.g. Oxisols). Soils of the two continents are derived from parent material belonging to the same landmass that predated continental drift. Presentations by South American no-till farmers and scientists at the 10th International Soil Conservation Organization Conference and No-Till Workshop (May 22-27, 1999) provided a wide range of insights on the topic of no-till and its relevance for SSA.[42]

---

[41] From a plant pest perspective, however, termites are a problem.

[42] The following discussion of presentations at the no-till workshop is drawn from an unpublished report on the conference (Weight 1999).

The countries that have had the most success with no-till over large areas of South America have been Brazil, Argentina, Chile, and Paraguay. The primary explanation for the success and profitability of the no-till system is that it is based upon fundamental principles of nature and soils, especially carbon and nutrient cycling. Understanding of these principles and appropriate application of the complete system is considered to be critical for success. No-till farmers in these countries report that they have been able to reverse the severe impacts of accelerated erosion, nutrient mining, and accelerated decomposition from tillage (associated with the tropics and sub-tropics) with increased levels of crop yields and profits. Farmers reported increased yields over time even during periods of limited rainfall. Argentinian farmer/scientist Roberto Peiretti showed a graph from his farm in which rainfall and yield levels were "parallel" for the first 5-6 years while the no-till system was being established but after that period, no-till yields increased steadily regardless of rainfall declines. Farmers also reported that increasing soil fertility and SOM levels resulted in decreasing fertilizer requirements over time, including the termination of P fertilizer application in some cases.

However, it takes time and determination to succeed, according to the farmers. Increases in yields and SOM beyond conventional levels are typically not achieved until after 5-6 years and it is necessary to adapt the system when failures occur – which are inevitable. Thus, it is understood to be a long-term strategy for sustainability.

The other critical factor described by the South American group was that the no-till movement has been farmer-developed and driven. There were a number of pioneer farmers, especially in Brazil, who were given technical assistance by no-till experts from U.S. universities. In the initial stages, it took time to develop successful strategies but once yields, profits and soil fertility increased at consistent levels, other farmers noticed and the technology spread rapidly. According to the farmers, researchers and extension workers also became increasingly involved as they perceived the level of increasing success. Farmers' associations have grown which support farmers' efforts, including bulk purchases of inputs and grants or credit for specialized equipment.

According to the statistics presented, 96% of cultivated acres under no-till are in South and North America, 2% are in Australia, and the other 2% "elsewhere." To appraise the potential of no-till for SSA, it will be most important to follow the growth of adoption and economic success for small farmers in South America. While large-scale farmers have been the primary practitioners of no-till in the region, increasing numbers of small farmers have been adopting it in Brazil and Paraguay using a variety of adapted technologies, especially animal or human-drawn small direct seeding equipment, as well as hand planters and pointed sticks. Low-cost alternatives to herbicides are also being developed which can be used by small farmers.

At a presentation by Brazilian farmer/scientist, John Landers, benefits for large-scale farmers were attributed in large part to savings in equipment, fuel, time, and inputs (over time). Benefits for small farmers have been primarily: reductions in labor and time that had been spent on plowing, increased yields (50-60%) and profits, erosion control (described as critical under tropical conditions), diversification of enterprises, time, and improved future for children (and community) with the possibility of staying on the land rather than being forced to migrate to cities.

The two countries where outside agencies have been instrumental in adopting no-till technology have been Paraguay and Brazil. In Paraguay, approximately 55-60% of cultivated land is currently under no-till; 72% of mechanized farm land is under no-till. This accelerated rate of adoption of the no-till system is attributed primarily to the efforts of the German development agency, GTZ, under the direction of Rolf Derpsch. After years of witnessing the accelerated erosion, soil degradation and loss of SOM resulting from conventional agriculture and associated negative economic impacts, Mr. Derpsch became convinced that it was the only system that works in the tropics. He said that the primary components of the no-till system in Paraguay are (i) no tillage (i.e., no plowing), (ii) use of green manure cover crops, and (iii) rotations. He provided figures for changes in net income for three small farms using no-till in Paraguay with increases of 62%, 35% and 99% per farm. GTZ is now making plans to work with this technology in SSA.

In Brazil, approximately 20-22% of cultivated land is under no-till.[43] Osmar Muzilli, soil scientist with the Agronomic Institute of Parana, IAPAR, reviewed the success of the World Bank-supported."Parana Rural Program" in southern Brazil in which 90,000 farmers (including 3,000 small farmers) have adopted no-till on 3.2 million hectares. As in Paraguay, alternative technologies are being used which are appropriate to socio-economic conditions. He said that after 16 years, yields in the project zone for soybeans have increased by approximately 33% and corn by 27%. Farmers from Brazil and other countries in South America repeatedly commented that they are required to consider the whole farm system when making decisions and that scientists need to do the same rather than taking the usual reductionist approach. As a result, the Parana project has implemented pilot projects which take a farming systems research approach.

Based on the success of conservation tillage in the Americas, logic would suggest that adoption of conservation tillage or mulch farming adaptations of these systems in SSA would be sufficient to reverse the decline in African productivity and soil degradation when combined with fertilizer-based nutrient management.

Adoption and research of mulch tillage and no-till has been limited in SSA. One study by Lal (1997) compared declines in SOC content of 0-5 cm depths for an Alfisol of western Nigeria over six years. In no-till plots, SOC declined from 2.07 to 1.07% vs. plow till which declined from 1.32 to 0.54%.[44] A 17-year study in the same region showed similar results with consistently higher levels of SOC/SOM in no-till plots (Lal 1997). It is important to point out that these were studies comparing tillage practices only, and not larger systems. These results suggest that no-till is associated with more favorable soil conditions (i.e., higher levels of SOC) when compared with conventional tillage but not to a sufficient degree to result in an aggrading system; that is, where SOC and its benefits actually increase over time.

---

[43] Other figures are Argentina: 32% and USA: 16%.

[44] Results for no-till in the 5-10 cm depth were more similar to plow-till which is consistent with other literature. Alfisols are the predominant soil of the dry tropical rainforest regions of West Africa.

Lal (1997) advises that restoration of soil fertility and SOM requires more than adoption of a single practice such as no-till which is shown to be insufficient. Similar to the no-till farmers of South America, he proposes the adoption of complementary systems which provide multiple benefits. According to Lal (1997, 123-4), in the case of tropical rainforest soils, "appropriate land use and management strategies that enhance SOC content are: (i) tree crops and plantations, (ii) deep-rooted grasses and improved pastures, (iii) cover crops, (iv) mulch farming, (v) conservation tillage, and (vi) judicious inputs of inorganic fertilizers and organic amendments. These practices decrease the decomposition constant K, improve soil structure and aggregation, decrease soil degradative processes (e.g., erosion and leaching), and increase nutrient cycling and other ecosystem restorative mechanisms."

The following section examines complementary systems, other than conservation tillage, which are especially relevant for agriculture in SSA.

*3.4.3. Cover Crops, Rotations, and Agroforestry as Complementary System*s

Mulch tillage, cover crops, rotations, and agroforestry are each effective systems – on their own – for controlling erosion or tillage. As described in the above paragraphs, research suggests that mulch tillage has significant but limited potential for building SOM and associated benefits (water and nutrient-use efficiency, etc.) and will require complementary systems to result in an aggrading system.

Cover Crops and Rotations: Mutch and Martin (1998, 45-8) describe cover crops as follows:

> A cover crop is a crop that is not harvested but is grown to benefit the soil and/or other crops in a number of ways. Cover crop benefits include: reduced soil erosion; improved soil quality; reduced weed pressure; and reduced insect, nematode and other pest problems. Cover crops are grown during or between primary cropping seasons... Legume cover crops fix atmospheric nitrogen into a form plants and microorganisms can use....
>
> Timing is very important to successfully establishing a cover crop.... It is extremely important to seed when there is enough light to germinate and establish the cover crop, yet late enough so it will not compete with the corn [or other] crop for water nutrients or light.

Mutch and Martin (1998, 46-7) also describe rotations: "Rotating crops is an important practice that has repeatedly proven to be an excellent pest management tool. Rotation also provides an opportunity for seeding cover crops." A typical crop rotation is a four-year rotation of corn-corn-soybeans-wheat. Cover crops can be integrated with any primary crop. For example, multiple varieties of clover, annual ryegrass, and hairy vetch can be seeded into a corn crop.

Rotation is also an important tool for controlling soil erosion throughout the world. Lal (1990) sites evidence from India and other Asian countries regarding the positive impacts of rotations with the appropriate mix of crops on lowering rates of soil erosion.

Stewart et al. (1991,136-7) propose the following: "Ecological limits of application of no-till farming can be increased by developing appropriate cropping/farming systems based on cover crops, cropping sequence [e.g., rotations], agroforestry techniques, etc...to provide a stabilizing perennial element of vegetation to the agroecosystem." Cover crops typically take advantage of the deep-rooted permanent root systems of perennial grasses to achieve SOM-related benefits (see below).

While there are numerous studies of no-till or cover crops alone, there are a limited number of studies examining impacts of both no-till and cover crops on agroecosystems. One such study is by Donigian et al. (1997) who reviewed predictive model data for the Midwest U.S. to estimate the C sequestration potential of agricultural production systems to increase SOC to levels approaching pre-disturbance levels by the year 2030 (Figure 6).[45]

The model estimates confirm the critical role that residues have played in reversing SOM/SOC loss trends in the U.S. "Historical practices, as represented by the model assumptions ..., have led to decreases in SOC until about the 1940s and 1950s. Since that time period, the model predictions of SOC are increasing for most crop production systems that leave significant amounts of crop residue on the field." (Donigian et al. 1997, 508)

The agricultural management practices which showed the greatest potential for C sequestration were primarily conservation tillage and secondarily cover crops, both of which depend on the return of crop residues to the soil.

Figure 6 shows the estimated impact of conservation tillage (reduced and no-till) using data from 1990 figures (27% and 3% of the study area under reduced and no-till respectively vs. 70% under conventional tillage) for future projections. Under conservation tillage, "SOC increased 10% to 15% for reduced till and up to 50% for no-till" with much lower changes for other tillage methods. Results were "highly variable throughout the study region." (Donigian et al. 1997, 516)

Figure 6 also shows projections for the impact of annual yield increases (1.5, 1.0 and 0.5% yield increases) which are attributable to both fertilizer inputs and complementary system impacts (conservation tillage and cover crops). "If this general pattern is accurate, agricultural SOC within the study region is making a comeback from a low of about 50% of original (i.e., native vegetation) levels in 1950-70, to about 60% of these levels in 1990. Continuing the increase would lead to 2030 total SOC levels that approach 75% to 90% of the original SOC prior to the onset of agricultural production (circa 1900)." (Donigian et al. 1997, 514)[46] Highest estimated SOC levels in 2030 of 90% are associated with highest yield increases of 1.5% per year.

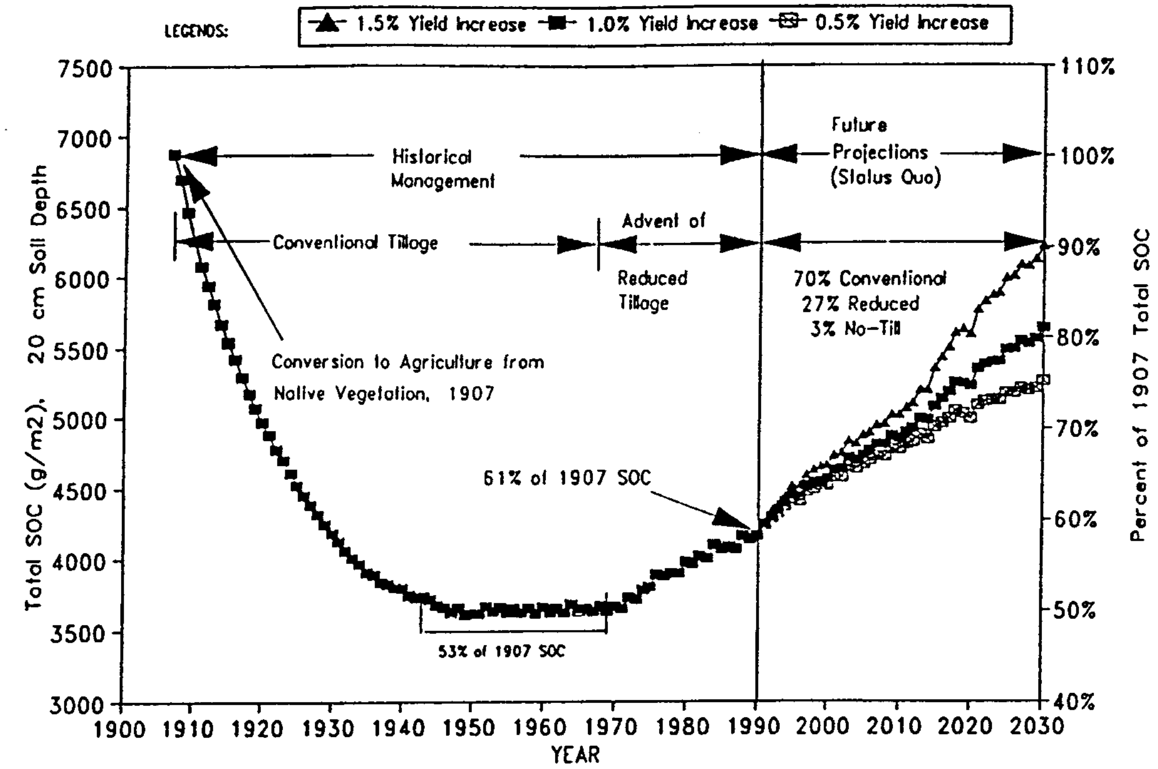
---

[45] Citations for the models and database can be found in Donigan et al. (1997).

[46] See Figure 2 for a parallel approach based on a study site in Kansas (in the same region) which focused on the adoption of high input fertilizers via crop residues to build SOM starting in the 1950s. While Figures 2 and 6 focus on different impacts (fertilizers for the former, conservation tillage and cover crops for the latter), effectively they are the same process; that is, building SOM/SOC by means of fertilizer-based increases in yield and crop biomass which is returned to the soil as crop residues (including residues of cover crops).

"Cover crops can lead to significant increases in soil carbon in crop, soil and climate regions where they are feasible and appropriate. Although only 12% of the study region cropland included cover crops ..., this increased soil carbon by 140 Mt through 2030.... Among the

Figure 6: Simulated Total Soil Carbon Levels



Source: Reprinted with permission from Donigian, A.S., Jr., A.S. Patwardhan, R.V. Chinnaswamy, and T.O. Barnwell. 1997. Modeling Soil Carbon and Agricultural Practices in the Central U.S.: An Update of Preliminary Study Results. In *Soil Processes and the Carbon Cycle*, ed. Rattan Lal, John M. Kimble, Ronald F. Follett, and Bobby A. Stewart. Copyright CRC Press, Boca Raton, Florida.

[climate divisions] CDs with cover crops, the average SOC increase over the status quo was 14% with a range of 0% to 132%." (Donigian et al. 1997, 516) Best results for cover crops were obtained in the southern and eastern regions which have the highest temperature and rainfall levels in the study area. Thus, highest vegetative growth and biomass contribution to SOM could be expected.

The enormous challenge in SSA is to accomplish what is currently being accomplished in the Americas; that is to move SSA from the low point of the degradation curve (see Figures 2 and 6) to levels that are close to pre-disturbance (native) fertility. Effectively, this means that long-term fallows which accomplished this task in the past need to be replaced with alternative SOM-building land use systems such as conservation or mulch tillage and other beneficial systems (e.g. cover crops, agroforestry).

Research in SSA has shown consistent benefits from "improved" planted "short-term fallows" using grasses and legumes as cover crops to restore soils. "In western Nigeria, Lal et al. (1978, 1979) used a range of grass and leguminous cover crops to restore physical properties of an eroded, compacted and degraded Alfisol. In comparison with the natural fallow and ambient soil conditions, fallowing for 2 years with grass and legume covers improved soil moisture retention capacity.... Also improved were the organic matter content, cation exchange capacity, infiltration rate and the field moisture capacity.... In another study, Hulugalle et al. (1985) observed that the deleterious effects of land clearing by heavy machines were alleviated by fallowing with *Mucuna utilis* grown for about 1 year immediately after the land clearing. These authors observed significant improvements in infiltration rate and in cumulative infiltration of the plots growing mucuna in comparison with those sown to maize." (Lal 1987, 665)

As described previously, cover crops are sometimes referred to as "green manure cover crops." This title refers to their effectiveness as soil amendments for building soil fertility and SOM including significant supplies of nutrients and C. There is a great deal of variability among cover crops in terms of their impact on soils. First, as with primary crops such as maize, C/N ratios of the plant residues vary with corresponding impacts on SOM. Legumes, the principal component of most cover crop systems, typically have high quality (i.e., low C/N ratios) with limited impacts on C sequestration and aggregation.[47] However, they are very effective at supplying N to the succeeding crop via SOM (see Ibewiro below). Second, amounts of root biomass and type of root system vary according to species which will vary the level of impact on sequestration and aggregation.

Recent research suggests that addition of cover crops or crop rotations can serve as effective complements with maize or other primary crops. If timed or “synchronized” correctly, such additions can play a critical role in manipulating short-term SOM to provide crop nutrients. In the case of maize, they can provide higher quality inputs that provide N during periods of nitrate depression, especially leguminous annuals such as Mucuna or perennials such as alfalfa. Timing of cover crops or rotations is adapted to pulses of the microbial ecosystem of the short-term SOM; that is, in response to microbial demand, for maximum efficiency, productivity, profitability and environmental protection (Myers et al. 1994). If successful, N from the added crop is mineralized during periods of crop growth and nitrate depression and immobilized at other times.

Ibewiro et al. (1998) carried out research at IITA, Ibadan, Nigeria in which mulch tillage and (leguminous) cover crops systems were combined. Herbaceous legumes were grown in succession with maize in an annual maize-bean cropping system with the objective of providing an alternative to commercial N fertilizers via legumes in a low-external N cropping system. One of the legumes was velvetbean, *Mucuna pruriens,* which has been successful in other tropical

---

[47] There are also legumes with high C/N ration such as Stylothanthes which are highly productive (i.e., low quality).

regions.[48] The authors describe the general characteristics of the system they were studying as follows (Ibewiro et al. 1998, 124):

> Farming systems that center around the use of herbaceous legumes are known as cover cropping.[49] This is generally superimposed on minimum tillage practices to provide organic inputs, nutrients, especially nitrogen (N), improvement in soil physical properties and soil erosion/run-off control. The mulch layer formed by the residues suppresses weeds and controls plant diseases and pests (Lal et al. 1979; Wilson et al. 1982). This system, which provides good soil cover for soil conservation, also has the potential for steady addition of organic inputs (above- and below-ground) and for better soil fertility maintenance even under continuous cropping in the tropics.... The contributions of legume residues to soil improvement and crop production are known to depend largely on the biomass production (Sanginga et al. 1996) and the chemical composition of the biomass (Oglesby and Fownes 1992; Palm and Sanchez 1991).

The experiment was conducted with a low level of fertilization (10 kg ha $^{-1}$ N/S fertilizer). Residues (whole residues including shoots and roots) increased maize yield by 156% for velvetbean vs. 16% and 37% for the two other legume species and 25% for maize residues. This increase was attributed to high levels of fixation of atmospheric N by the cover crop and subsequent contribution of fixed N by cover crop residues, especially from roots, to the succeeding maize crop.

In low-input systems such as those used in the experiments described by Ibewiro et al, this approach can be very effective but it may not be advantageous under an intensive system with high N fertilization rates since legumes typically respond to N fertilization with decreased fixation of N. N fertilizer input levels could be decreased significantly due to "credits" for N fixation with an expected decrease in cost to the farmer.[50]

While the combination of mulch tillage and leguminous cover crops does provide the general benefits described above (cover from erosion, improved soil fertility providing high levels of N to the maize crop), velvetbean (and the other legumes examined) produces a high quality, low productivity residue with a low C/N ratio (<14) and low lignin content. Like soybean, the residue cannot be expected to be a primary contributor of biomass C. Rather, its primary contribution is to soil N fertility status with carryover to the maize crop. Secondly, *Mucuna*

---

[48] According to Pieri (1998), the velvetbean-maize cropping system ("abonera" or "fertilized field" in Spanish) has had remarkable success in Central America. Use of the system by hillside farmers in Honduras spread from 5% to 70% over approximately 10 years due to the high yields and profitability of the system. He suggests that it is especially useful for the needs and constraints of smallholder farmers.

[49] As seen here, the definition of cover crop, by some, assumes the use of legumes.

[50] Other nutrient requirements would presumably remain at the same level unless there was compelling evidence of increased availability, especially P.

*prurien*s produces a "relatively small amount of root biomass."[51] (Ibewiro et al. 1998, 128) which also would be expected to limit its impact on C sequestration and aggregation.

Maize has the potential to make up for the low C input of the legume. As discussed previously, maize, as a low quality, high productivity plant, has the capacity to transfer high levels of biomass C into the soil. The two species, thus, are logical complements, each one providing strength where the other is limited.[52] Perennial cover crops and rotations can provide additional benefits to the system. In comparison to annuals such as Mucuna and even maize, cover crops and rotations with perennials are associated with greater sequestration of C and improved soil aggregation "...incorporating perennial crops increase[s] SOM levels more than continuous corn or any other rotation. Compared to continuous corn,... perennial crops result in increased SOM levels.... The positive influence of perennial crop rotations [or cover crops] is due to both the year round presence of roots in the soil and reduced tillage activities...." (Cavigelli 1998, 23) According to Breman (personal communication), primary contributions of perennials are due to improved internal and external nutrient cycling, resulting in an exponential increase in above-ground biomass and SOM over time.

Since perennials' primary contribution to SOM is through the impact of roots, it is important to understand how roots carry out this benefit including the critical role of physical aggregation of the soil. Jastrow and Miller (1997; 211, 219) have conducted research into the importance of roots and associated mycorrhizal hyphae to aggregation of soils. Citing the work of others, they note:

> The lengths of roots and mycorrhizal hyphae are often directly related to the percentage of soil in water-stable macro aggregates, particularly in aggrading systems (Tisdall and Oades 1980; Miller and Jastrow 1992). The direct effects of living roots and hyphae may be conceptualized by viewing the three-dimensional network of roots and hyphae as a "sticky string bag" that physically entangles or enmeshes smaller aggregates and particles, creating rather stable macro aggregates (Oades and Waters 1991). Not only do roots and hyphae form a network that can serve as a framework for macro aggregate formation, but extracellular mucilage coatings on root and hyphal surfaces can strongly sorb to inorganic materials, helping to stabilize aggregates (Tisdall and Oades 1979; Gupta and Germida 1988; Tisdall 1991; Dorioz et al. 1993). Furthermore, encrustation of roots and hyphae with inorganics is believed to physically slow decomposition, thereby preserving the enmeshing framework for a time even after the roots and hyphae senesce (Oades and Waters 1991)....
>
> ... relatively stable macro aggregates can be formed rapidly in response to the proliferation of roots and hyphae associated with grassland vegetation....

---

[51] There is no information given regarding type of root system (fine, tap, etc.). Also, the article does not discuss SOM aggregation/build-up issues but focuses on providing nutrients for increased yields.

[52] Research on leguminous cover crops is being carried out primarily by IITA (Nigeria and Benin), International Centre for Research in Agroforestry (ICRAF) (Southern Africa), and IFDC (Benin and Togo) (Henk Breman, personal communication).

Among root systems, fine root systems were most highly correlated with aggregation. Also, it would be expected that higher amounts of root biomass in the soil would result in increased soil aggregation and build-up of SOM.

While research trials provide critical biophysical information, Swift et al. (1994) suggest that they often do not reflect the reality faced by farmers. Most smallholder farmers in SSA typically cannot afford to go without the income of the primary crop during rotations or short-term fallows. Rather, they prefer traditional intercropping practices in which the cover crop is seeded along with the primary crop to grow at the same time so that the primary crop is not a "succeeding crop" grown after the legume. Use of cover crops or intercrops will only be used by farmers if they do not increase overall costs for the farmer so that fertility and related benefits are not a burden. Studies (such as Ibewiro et al.) suggest that costs can be lowered for fertilizers, especially when legumes are included as cover crops. "The long-term economic benefits of cover crops have not yet been calculated, but the value of increased soil biotic diversity, soil quality, soil organic matter, soil erosion control, insect and nematode biodiversity, soil water-holding capacity, aeration and water percolation is certainly important." (Mutch and Martin 1998, 52)

Agroforestry: There is also the potential of having trees fulfill the role of cover crops or complement cover crops in combination with mulch tillage. Their benefits are based on the biodynamics of traditional bush fallow systems:

> Declining soil fertility under arable farming has been known for time immemorial. The traditional smallholder farmer recognized this and responded by shifting and/or bush fallow systems of cultivation. These systems of cultivation are characterized by long fallow periods (>15 years) and relatively low human population densities (<10 persons per square kilometre).
>
> Fallowing restores soil fertility and reduces the incidence of noxious weeds, pests and diseases. The restorative capacity of the bush fallow is linked to the plant succession of deep-rooted trees and shrubs which are more effective than grasses in recycling nutrients and increasing soil organic matter. Fallow plant cover and litter also protect soil from erosion, increases water infiltration, and reduces surface run-off.[53] (Saka, Green, and Ng'ong'ola 1995, 48)

With increased population pressure, bush fallow systems are no longer common or feasible in most of SSA. As a result, researchers in agroforestry have been conducting trials to incorporate the advantages of trees into agricultural systems with particular attention to species which are most efficient at accessing sub-soil nutrients. Recent studies in western Kenya have shown evidence that fast-growing species of trees, especially Calliandra and Sesbania, are capable of accessing and recycling N by means of deep root systems which access deep soil horizons (Giller et al. 1997, citing Mekonnen et al. 1997; Jama et al. 1998 [in press]; and Hartemink et al. 1996).

---

[53] There are research results indicating that grasses are more effective, especially for increasing SOM.

In the case of agroforestry studies that include profitability analyses, research findings are mixed. In a cost-benefit analysis of four agroforestry practices conducted by ICRAF in southern Africa, for example, few of the practices showed clear benefits (as net present value/ha or returns to labor day) despite the fact that the trials were almost entirely on-station or were researcher managed on-farm trials. Continuous maize with fertilizer, however, showed consistent benefits in most cases. Other practices included improved fallows, relay cropping, hedgerow intercropping, and biomass transfer (Place 1995).[54]

The biophysical value that trees add to crops in resource-poor environments such as the Sahel is based on an understanding that trees are "fertility islands" which increase crop yields in their immediate vicinity due primarily to an enhanced SOM/ soil biological environment. As in the prior examples of organic inputs, the primary advantage of trees is SOM improvement leading to higher nutrient and water use efficiency (Breman and Kessler 1995). This situation may not pertain, however, under intensification combined with agroforestry and conservation practices. "In the process of agricultural intensification, where cropping systems include the use of fertilizers and make proper use of crop residues and soil conservation measures to maintain SOM contents, woody plants lose their additional value.... In a general sense, woody plants lose their value as 'fertility islands' in resource-rich environments. Also, as crop yields increase, the absolute yield losses due to shading by woody plants increase." (Breman and Kessler 1995, 305)

On the other hand, ICRAF results in Kenya suggest that strategies focused on crop yields and productivity may be misleading and that the value provided by trees to small holders is much greater than that which is typically calculated by agronomic and economic researchers. Trees planted in Kenyan agroforestry systems are becoming increasingly common across the landscape of that country since they provide critical resources that were formerly provided by forests such as fuel, construction materials, and in some cases, fodder (Pedro Sanchez, Director of ICRAF, presentation at World Bank Symposium on Sustainable Agriculture, Baltimore, 1998). As an important by-product, trees have the potential to relieve the burden placed on crop residues for such non-agricultural needs. As mentioned previously, they also are very effective in erosion control both as vegetative cover and as a stabilizing influence on the soil via root systems, especially on steep slopes (e.g. banana and coffee trees in Rwanda).

One of the most thorough research works in SSA which has been written on trees and their relationships with soil and climatic factors is *Woody Plants in Agro-Ecosystems of Semi-Arid Regions* by Breman and Kessler (1995). One of the myths that is dispelled by the book is that semi-arid tree species typically have deep roots with few branch roots or shallow lateral roots. While some trees do have this type of root system, recent research evidence consistently shows that the majority of trees in these regions have either deep roots with many superficial branch roots or shallow and extending roots which can extend well beyond the canopy of the tree. These superficial and extending roots can contain a high level of fine root biomass, especially directly under the canopy. As described earlier, a fine root system is one of the primary vehicles

---

[54] Likewise, in the case of cover crops, economics research needs to focus on whether the benefits of recapitalization of the soil by means of these complex systems is profitable over the long term.

for soil aggregation which protects SOM from decomposition losses and results in beneficial soil structure. Finally, there is the fact that trees are perennials and, thus, provide permanent positive impacts by roots.

In general, trees are known to significantly increase SOM levels, especially within the soil root zone. Again, the primary initial step in SOM accumulation is the transformation of plant biomass litter/residues into soil particulate organic matter which, as a C substrate, is then subject to microbial attack (Breman and Kessler 1995).[55] In the case of trees, the high quantities of plant biomass and residue result in high quantities of soil particulate organic matter. One of the primary reasons for the large biomass input from trees is the large surface area available for photosynthesis by which increased levels of CO_2 are captured from the atmosphere. Also, there is an internal cycling loop by which nutrients and water are increased by the C input and SOM and, at the same time, promote growth of the tree (Breman and Kessler 1995).

"Under woody canopies SOM content is almost always higher than in open areas." (Breman and Kessler 1995, 200) It is not surprising then that soil moisture and nutrient availability are usually higher under tree canopies when compared with open fields. Adjacent crops in an intercrop system can benefit from this increase so that there is a positive relationship (vis-a-vis water and nutrients) rather than competition.

Given the characteristics of trees described in the previous paragraphs, it is expected that trees would provide high input of C and build-up of SOM in agroecosystems, providing the multiple benefits that are required for efficient nutrient and water cycling. While there is an increasing body of research on agroforestry, research comparing integrated systems (e.g. combining mulch tillage/cover crops/agroforestry) such as proposed in this paper, is rare – especially including relevant carbon sequestration and economic data. One example of this kind of research is a paper written by Woomer, Palm, Qureshi, and Kotto-Same (1997) entitled *Carbon Sequestration and Organic Resource Management in African Smallholder Agriculture*. The authors present findings from the 18 year old Kabete experiment in Kenya in which various factorial combinations of fertilizer, stover (residue), and manure inputs for a maize/bean system are compared both for C sequestration potential as well as their profitability (return/cost ratio).[56] Interestingly, among all the treatments, the only one that appeared to be profitable was manure alone with a return ratio of 4.1.[57] All other combinations had return ratios of < 1.8![58] Not surprisingly, the highest improvement in soil C was attributed to fertilizer + stover + manure. The least improvement was from fertilizer + stover which may have been due to suppressed crop yields from N immobilization (see Section 3.3).

---

[55] Wood and leaf litter above-ground and root debris below-ground.

[56] The soil is a Kikuyu Red Clay Loam (an Alfisol).

[57] The profitability of manure use in Kenya helps explain the importance of dairy cattle farming in the country.

[58] Figures are for standard economic returns on the maize/bean system and not based on C sequestration factors.

It is apparent that any of the input combinations, while decreasing the severity of SOM/SOC decline, did not result in an aggrading system or even one in equilibrium. The authors (Woomer et al. 1997, 162) describe the situation as follows:

> One observation of concern is that all land managements resulted in a net loss of soil organic matter over 18 years. The soil contained 36.5 t C/ha at the onset of the experiment and 32.6 and 26.8 t C/ha after 18 years in the best and worst conserved treatments, or an annual loss of 0.22 and 0.54 t C/ha/yr, respectively. A crude extrapolation from these data based on soil organic matter changes resulting from different input levels, suggests that it would require 35 tons livestock manure/ha/yr alone to maintain the soil organic C at its initial level, and 17 t manure and 16 t stover/ha/yr to do so when fertilizers are applied. The calculated manure rate for soil C equilibrium is in general agreement with the 25-30 t/ha identified by Graham (1945) as necessary to restore degraded lands and maintain continuous cropping.

Economic analyses by the authors, based on these factors, indicates that any of these input levels would be unprofitable and unrealistic. "In summary, stabilization of C in agricultural soils within smallholder cropping systems is technically feasible given their present resource base, but economically non-viable, because investments equal to 40% of additional field crop revenues are necessary to offset soil carbon losses." (Woomer et al. 1997, 165)

The authors suggest that complementary systems be integrated with the main cropping system, especially agroforestry systems based on the advantages of trees for C assimilation and sequestration. The more eco-intensive new system has a larger carbon pool with higher primary productivity which translates into higher SOM and associated benefits (Figure 7). The expanded system includes the cover crop (the maize/bean rotation), an orchard, boundary tree plantings (80 trees/ha) as well as grass contour strips for erosion.[59] The net increase in C stocks is estimated to be 3.3 t C/ha/yr with 73% of the gains due to sequestration in orchard and boundary trees assuming they are not utilized as firewood.[60]

This example (Figure 7) is used to illustrate the potential of trees and herbaceous plants to sequester C and recapitalize an agroforestry system. Woomer et al. state that the main vehicle for C sequestration into soils in the model is through the return of residues and stubble (or indirectly via manure). They also indicate that C increases from the annual crop (maize) are "slight" (<2% of total increases) due to export of the harvested crop resulting in no "carry over effect." Presumably, this system constraint could be offset if a no-till system were applied thus increasing quantities of sequestered C.

> The organic resource management of smallholder agriculturalists in the Central Highlands of Kenya suggests that farmers are in the process of developing integrated soil management strategies and that these strategies favor improvement of the soil organic

---

[59] Besides erosion benefits, the grass is used as forage for livestock and returned to the soil as manure – thus maintaining a closed system.

[60] A "difficult" assumption from the point of view of supplying farmer needs.

> carbon status of soil. Yet in many ways, the farmers in Kenya are themselves a "best-case scenario" because they have greater access to markets and external nutrient inputs and practice more integrated nutrient management than farmers elsewhere in Africa..... We conclude that net C sequestration among small holdings in the Central Kenyan Highlands requires that additional mechanisms other than soil storage, particularly increased biomass of perennial plants, be explored. Given the integrated approaches to land management by smallholder farmers, additional C sequestration in the Kenyan Central Highlands appears to be an obtainable objective. (Woomer et al. 1997, 169)
> This Kenya study can serve as a research model since it integrates appropriate complementary systems as well as critical research variables, especially biophysical data (including soil C as well as yield values) and economic data based on long-term experimental plot data.[61] The authors also expanded their analysis by including research on real farm practices in the region. Subjective non-economic benefits for farmers, such as use of trees for construction and firewood, should also be included and evaluated.

To summarize, fertilizer and organic inputs, conservation tillage, cover crops, rotations, and/or agroforestry, when integrated into an appropriate system,[62] address specific constraints to production in SSA, especially (i) soil mining due to low input agriculture, (ii) low rainfall levels,[63] (iii) poor soil structural stability resulting in very low water and nutrient-use efficiency as well as crusting and sealing, (iv) accelerated rates of decomposition due to tillage, and (v) lack of vegetative cover with increased erosion and soil temperatures. Such integrated systems address these constraints in the following ways: Providing ecologically based recapitalization strategies with long-term build-up and stabilization of SOM[64] addresses constraints (i), (ii), and (iii); minimum tillage addresses constraint (iv); and providing vegetative cover near the soil surface addresses constraint (v). The most critical factor for the implementation of these practices will be that these systems provide economic and other critical benefits to farmers.

In order to adopt such integrated farming systems, the following management steps are advised. First, the system must be appropriate to plant, climatic and soil conditions. For example, cover crops are more appropriate under humid conditions vs. low rainfall conditions. Second, the level of intensity of the system(s) will depend on the quality/potential of the soil. For example, "prime lands" may require minimal management, perhaps reduced tillage (only). Whereas a "low potential land" (or a marginal land) would require a more intense level of management. Finally, specific management skills need to be learned for the systems being used, such as fertilizer application with no-till. While these systems are typically cost and labor-efficient, they are not "easier" than conventional systems. Rather they require careful attention/ understanding of

---

[61] It is difficult to extrapolate results for SOM fluxes from short-term studies.

[62] Appropriate to environmental (plant, soil, climatic) and socio-economic conditions.

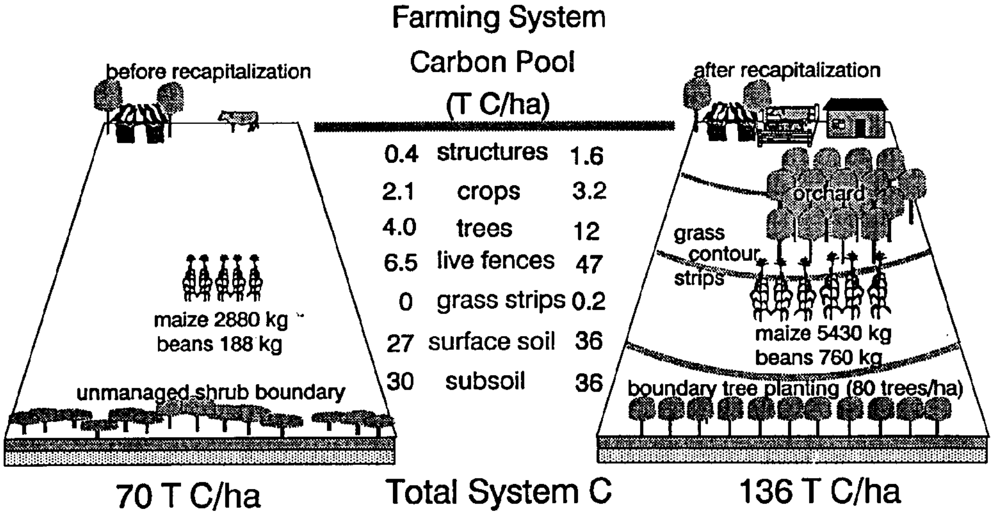
[63] Relative to other continents.

[64] Resulting in increased soil structural stability and increased water and nutrient use efficiency and infiltration rates.

nature and working with natural cycles. Fortunately, these are traditional skills/sensitivities that African farmers have depended on throughout history.

It is important to realize that there are "natural farming" systems which predate recent conservation and no-till systems with significant differences and similarities. Japanese farmer/philosopher Masanobu Fukuoka has written extensively about his experiences and findings. In his book, *The One-Straw Revolution: An Introduction to Natural Farming,* he explains his own system which is based on the following four principles: no tillage ("no cultivation"), "no chemical fertilizer or prepared compost," "no weeding by tillage or herbicides," and "no dependence on chemicals" of any kind (Fukuoaka 1978, 33-34). According to the author, nature has a remarkable regenerative capacity, as seen in fallows, which can provide whatever is required without imported fertilizers, herbicides, or pesticides. As in other no-till systems, careful attention and understanding of nature are required. Rather than a traditional African system in which fallows regenerate the natural system and agriculture degrades it, natural farming is a continually improving natural system, like a fallow with the critical difference that crops are grown within the system.[65]

Figure 7. A Scenario of Carbon Sequestration over 20 Years Resultant from Nutrient Recapitalization in the East African Highlands



Source: Reprinted from Woomer, Paul L., Cheryl A. Palm, Javaid N. Qureshi, and Jean Kotto-Same. 1997. Carbon Sequestration and Organic Resource Management in African Smallholder Agriculture. In *Management of Carbon Sequestration in Soil*. ed. Rattan Lal, John M. Kimble, Ronald F. Follett, and Bobby A. Stewart. Copyright CRC Press, Boca Raton, Florida.

---

[65] Fallows (in SSA) are, by definition, systems in which crops are not grown and the system is allowed to regenerate. With reduced time for fallows, "improved" shorter-term fallows are being implemented in SSA in which beneficial grasses and legumes are planted to intensify rates of regeneration (see previous section).

According to Mr. Fukuoka, by using this approach to agriculture, he has been able to achieve consistently high yields which are equivalent to the highest yields under conventional agriculture in his region of Japan. In his experience, when fertilizers or other inputs are added to the system, a new imbalance is also added, which then needs to be corrected. For example, fertilizers, by increasing soil fertility abruptly, result in high weed infestation during the growing period- which typically results in the farmer applying herbicides.[66] The author has found that low levels of manure are sufficient for his purposes and that high levels of any inputs are counter-productive.

Extrapolating from Mr. Fukuoka's writings, it is likely that he would find the quantitative approach to determining input levels (see previous sections) to be narrow-minded and based on conventional determinations of crop/soil requirements rather than a broad understanding of the potential of the whole system to provide nutrients and C. It is also likely that he would find no-till and other "agro-ecological" systems to be improvements over conventional agriculture but missing the point in some respects, especially in terms of fertilizer and herbicide use. Finally, the author explains that "natural farming" requires a certain reverence and awe of the natural world to be able to understand, work with, and depend totally on nature. Also, strategies will vary from farmer to farmer depending on what is learned over time.

Unfortunately, there is little research or other material available on theses strategies, making it difficult to evaluate their effectiveness. Also, the systems are idiosyncratic by nature, requiring a certain philosophical approach by the farmer. For these reasons, it would be inappropriate to promote them on a national or large-scale basis. However, if found to be effective, they should be encouraged as alternative systems due to their potential to restore agro-ecosystems and avoid pollution.

---

[66] Contrary to common opinion, the author believes that tillage actually increases weed infestation and that no-till is an effective tool for controlling weeds - if fertilizers or high levels of organic inputs are not applied.

4. NEGATIVE IMPACTS OF FERTILIZER

With current levels of SSA fertilizer use at about 9 kg ha $^{-1}$ (down from 11 a few years ago), the potential for fertilizer to have positive impacts on productivity and environmental quality, including soil quality, is much greater than the potential for it to cause environmental damage. Nevertheless, inappropriate use can lead to productivity declines and environmental problems in SSA. It is essential that SSA countries promoting increased fertilizer use be aware of the potential for negative impacts once use becomes widespread so that appropriate agricultural management strategies, monitoring systems, and policies can be put in place to limit these impacts.

The primary negative impact of high input fertilizer applications (used without complementary liming and/or organic amendments) is loss of productivity due to acidification. Potential negative impacts on traditional systems and on environmental quality are also discussed.

4.1. Acidification

Acidification or lowering of soil pH has negative impacts on most crop growth and occurs as a direct result of application of specific types of fertilizers. The most serious negative impact associated with acidication is aluminum (Al) toxicity. At acidic (low) pH values, complexed aluminum, Al(OH), which is common in soils, is converted to ionic form (Al^{3+}/ “exchangeable aluminum”). Crop growth is severely affected by high levels of Al saturation which cause direct injury to the plant root system.[67]

According to Sanchez (1976; 227, 230), “Poor crop growth in acid soils can be directly correlated with aluminum saturation.... Concentrations of soil solution aluminum above 1 part per million often cause direct yield reduction.” Certain soils, especially the majority of Oxisols common to SSA, have higher levels of Al than others, making them more vulnerable to Al toxicity problems.

The other most serious negative impact of acidification in SSA is increased limitation on the availability of P, already the most common limiting factor in SSA soils. At low pH levels, common in African soils, P is complexed with hydrous oxides of iron (Fe) and Al or reacts with silicate minerals. P is most available at neutral pH levels (6-7) (Sanchez 1976).[68]

---

[67] The percentage of CEC consisting of exchangeable aluminum is called “aluminum saturation.” As pH is lowered (acidification), exchangeable aluminum replaces other exchangeable cations in the soil, thus increasing Al saturation.

[68] Other negative impacts of acidification are micronutrient Ca and Mg deficiencies and manganese (Mn) toxicity, depending on soil type.

In his compendium of long-term West African research experiments, *Fertility of Soils,* Pieri (1992)[69] made comparisons of fertilizers alone (with no complementary organic inputs) and organic inputs, paying particular attention to acidification and associated Al toxicity. His findings indicated that N fertilizers are strongly associated with acidification in the region with an average annual increase in Al saturation of 10%, arriving at critical Al toxicity levels of 30% after only a few years of cropping. Sharp declines in crop yields occur in direct proportion to Al toxicity increases. Negative impacts were even higher when N fertilizers were used without complementary organic amendments, especially manure. Crop yields and Al toxicity were "normalized" with sufficient application of lime.

It should be explained that acidification is a product of the application not only of N fertilizers but of agriculture in general. When crops, and in some cases residues, are removed (soil mining), this creates a deficit in soil organic matter and a parallel decrease in levels of base nutrients and CEC and, therefore, acidification. This process is gradual in comparison to acidification by N fertilizers which can be quite rapid with the potential of decimating crop yields in a period of three years.

4.1.1. Comparison by Fertilizer Type

Ammonium nitrogen fertilizers are associated with acidification caused by increases in levels of ammonium ions which are derived from the fertilizers. When ammonium ions are added to soil, the chemical reaction with oxygen creates nitrate + water + 2 H^+ ions, associated with acidification (lowering) of pH, for every ammonium ion added. This microbially-mediated reaction is known as nitrification. Urea fertilizers also have significant impact since, after hydrolysis, urea is converted into ammonium.[70] Nitrate fertilizers are alternative sources of N which do not have the same acidification impact including sodium nitrate, calcium nitrate and potassium nitrate. There are also ammonium fertilizers which include lime to offset the acidification effect of ammonium such as ammonium nitrate of lime (Follett et al. 1981).

Schwab, Owensby, and Kulyingyong (1990, 35-6) studied these reactions on a Kansas silt loam Argiustoll with the primary objective being the quantification of "the effects of 40 years of fertilization with ammonium nitrate and superphosphate..." on brome grass using soil test and crop response values. "Soil pH values were observed to decrease when N applications exceeded plant requirements."

---

[69] An English translation of *Fertilite des terres de savanes* Pieri (1989).

[70] Urea is a synthetic fertilizer containing a relatively high 45% N. It is not technically an ammonium fertilizer but is an ammonium-forming fertilizer since hydrolysis converts urea to ammonium ions. Worldwide, it is the most commonly used N fertilizer. One constraint, relative to nitrate fertilizers, is that the ammonium from urea is subject to "volatilization", in which N gasses are released to the atmosphere. Consequently, it is preferable to incorporate urea in the soil rather than leaving it on the surface (Brady 1990). In no-till systems, other N fertilizers or appropriate urea incorporation methods are recommended to avoid unnecessary disturbance of the soil. Research has indicated that volatilization losses from urea in SSA can be substantial, resulting in negative N balances in some cases (Pieri 1992).

Ammonium-N fertilizer application at all levels contributed to acidification but the impacts were "significant" at "excessive" rates of application (above 67 kg N ha^{-1}). P fertilization had no acidification effect. Thus, "organic matter was found to be unaffected by P fertilization, but increased with increasing N rate." (Schwab, Owensby, and Kulyingyong 1990, 35) Plots were split after 20 years with half of the plots discontinuing fertilization. Results showed that acidification was reversed in these plots by natural processes. The study also showed that micro nutrients responded to acidification trends as predicted by established relationships between micro nutrients and pH. Levels of iron and manganese in solution increased with lower pH. Zinc increased with higher pH.

Ammonium fertilizers in order of their acid-forming capability are (Level I) ammonium sulfate and diammonium phosphate, (Level II) monoammonium phosphate, and (Level III) anhydrous ammonia, urea, and ammonium nitrate (Brady 1990).[71] It should be understood that all of the above ammonium fertilizers have significant acidification impact and that the classification levels give relative impacts. For example, the N fertilizer examined by Schwab et al. (1990) was ammonium nitrate, which resulted in significant acidification despite the fact that it is classified at the lowest level (Level III).

4.1.2. Comparison by Fertilizer Level

From a chemical perspective, it is expected that increased addition of ammonium ions will result in more precipitous declines in pH (acidification), increased Al saturation and, as a result, more precipitous declines in yield. Simply put, higher (ammonium) fertilizer rates result in more intense acidification (Pieri 1992). A long-term experiment at Saria in Burkina Faso examined NPK fertilizer inputs for responses of monocropped sorghum yields (Figures 8 and 9).[72] The primary soil type at the site is an Alfisol which is common in humid and sub-humid West Africa and East Africa. Yields for fields with the highest level of fertilizer alone (88 kg N ha^{-1}) dropped from a high of approximately 2000 to near 0 kg ha^{-1} over a period of 8 years (> 12% annual yield decline).[73] This was accompanied by an increase in percent Al saturation to 36% vs. a control of 9% in 1978 (after 8 years) (Pieri 1992). An Al saturation percentage of 30% is considered to be the critical value for Al toxicity to plant growth (Sanchez 1976).

Impacts at lower levels of fertilizer application were also profound but less precipitous. Yields at Saria with a lower level of fertilizer alone (41 kg N ha^{-1}) dropped from a high of approximately

---

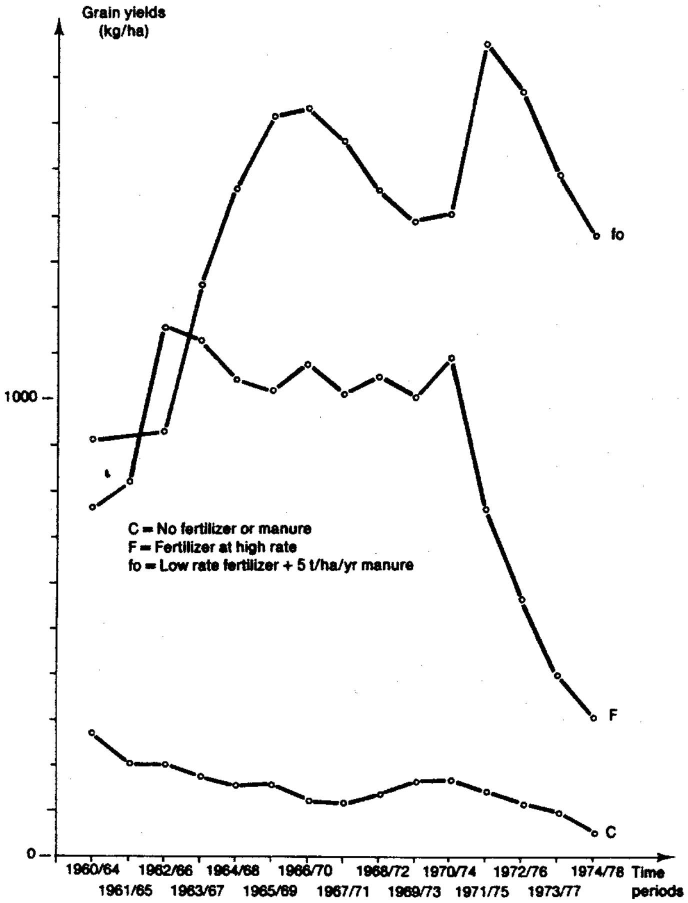
[71] Acid-forming capability of each N fertilizer is based upon the number of kilograms of calcium carbonate ($CaCO_3$)(liming) required to neutralize the acidity produced by the fertilizer (Brady 1990).

[72] It is assumed from the strong acidification reaction that the fertilizer is an ammonium-N or urea type of fertilizer. The fertilizer type is not given in the text.

[73] Historical fertilizer levels for these sites were 88 kg ha^{-1} for period 1971-1978 and 50 kg ha^{-1} for period 1963-1970.

1500 to 0 kg ha^{-1}, also over a period of 8 years.[74] This was accompanied by a somewhat less intense increase in percent Al saturation to 29% (Pieri 1992). Crops which had received treatments of manure with a high level of fertilizer also suffered severe declines but did not go below 500 kg ha^{-1} (FMO, Figure 9). Presumably, the organic amendments moderated the decline in yield.[75]

Figure 8. Yield of Sorghum Grain - 5 year Moving Averages, Saria, Burkina Faso



---

[74] Historical fertilizer levels for these sites were 41 kg ha^{-1} for period 1971-1978 and 19 kg ha^{-1} for period 1963-1970.

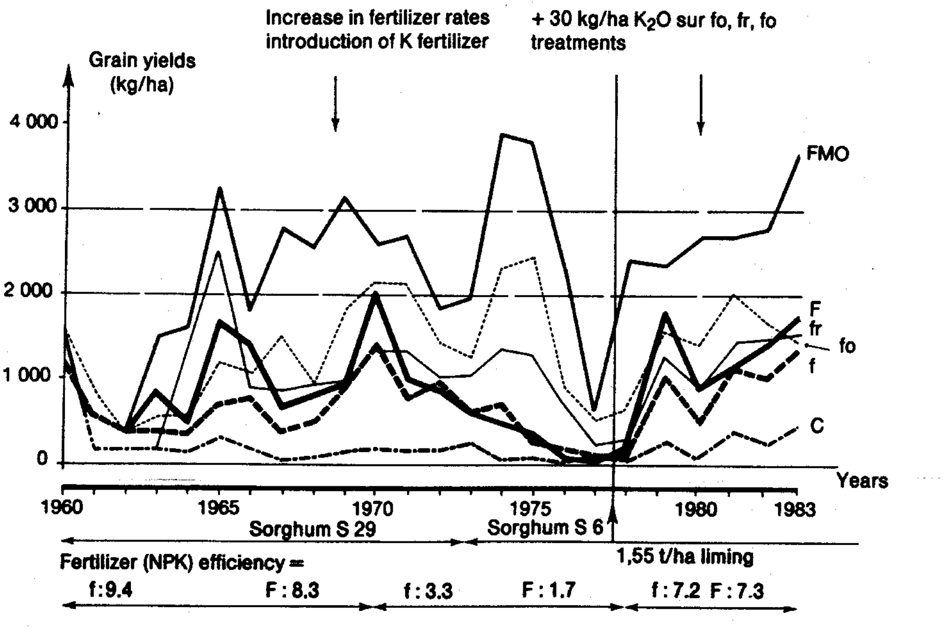
[75] Comparisons of treatments are made with the assumption that all other factors are equal with the understanding that soil and rainfall micro-variability within a given field are inevitable.

Source: Reproduced from Annexe to Part III in Pieri (1992, 184) with kind permission from Springer Verlag Publishers.

In 1978, lime was applied to all treatments. The application of lime over the next 5 years completely reversed declines in crop yields with return to original sorghum yields for all treatments (Figure 9). The impact of lime on all treatments indicates that the problems were pH-related.

A major finding of Pieri (1992, 173) is that all but one of the West African sites that received fertilizer inputs with no complementary application of manure "are distinguished by a fall in pH, in calcium and magnesium, and the accumulation of exchangeable aluminum (Al^{3+}). The more sandy the soils and the higher the rates of fertilizer, the more marked are these effects." Sandy soils are characterized by lower OM and clay + silt percentages which result in lower levels of base nutrients and CEC. Sandy soils are common in semi-arid and sub-humid regions of West Africa.[76] Thus, they are poorly buffered against acidification. Liming treatments and results vary considerably across experiments. There is no reason to believe that these problems are limited to West Africa since other regions of SSA have parallel climates and soil types.

Figure 9. Yields of Monocropped Sorghum at Saria, Burkina Faso



Source: Reproduced from the Annexe to Part III, Pieri (1992, 184) with kind permission from Springer Verlag Publishers. See key to Figure 8 for C, F, and fo definitions. In addition, FMO = F + 40 t/ha manure, f = fertilizer at low rate, fr = f + ploughed in sorghum straw.

---

[76] The local variability of clay levels is high (Penning de Vries and Djiteye 1991).

4.1.3. Comparison by Crop Species

Yield declines under acid conditions vary according to crop species. Crops originally grown in calcareous soils, such as cotton, sorghum, and alfalfa, are quite vulnerable at low levels of 10 to 20 % aluminum saturation. Corn is less susceptible at higher levels of 20 to 60 % saturation. Other crops such as rice, coffee, and cowpeas are more tolerant (Sanchez 1976). The prior example from Saria, Burkina Faso is an example of the dramatic impacts which may occur when inappropriate N fertilizers are applied to an Al sensitive crop, in this case sorghum.

New varieties of sorghum that are more tolerant of Al toxicity have been developed by researchers. Liming is the most commonly recommended practice for reversing acidification. Effectiveness of liming, however, will depend upon the sensitivity of the crop species to Al toxicity, as described in the previous paragraph. Liming with traditional varieties of sorghum, for example, will not be effective until Al saturation levels under 10% are achieved.

4.1.4. Comparison by Soil Type

Base saturation is inversely proportional to Al saturation. Soil types with high levels of SOM and fine particles (clay and silt) will have higher base saturation, CEC, water content and resultant buffer capacity which mitigate against acidification.

The one long-term experiment in Pieri (1992) that did not result in acidification was conducted in Bebedjia, Chad. The “experiment showed that on a better structured soil with a good level of organic matter, and where there was no erosion and not too sharp drainage, very satisfactory results were obtained from fertilizer alone. Yields were high and there was no acidification, though the initial organic matter level was not maintained. This case was exceptional and such soils are very rare.” (Pieri 1992, 180)[77] Pieri concludes that the lack of vulnerability to acidification was a result of a high buffer capacity associated with high organic matter, clay/silt content, rainfall, and a favorable equilibrium between upward and downward movement of water in the soil.

4.1.5. Yield Losses from Acidification Over Time

In his review of West African experiments, Pieri (1992, 173) found that Al saturation increased by around 10% year. “Acidification is always a risk and is a principal source of soil degradation in this area with low annual rainfall and a wet season which is interrupted by frequent dry periods. Unless lime is applied, it is common to obtain more than 30% saturation of the CEC by Al^{3+} after a few years cropping (3 years in Korhogo [Cote d’Ivoire]). This value is critical and

---

[77] Again, information on the type of N fertilizer was not included. Soil classification information was also not included.

only too easily achieved when the CEC is low. In Bambey (Senegal) soils, the CEC is around 1 mEq/100 g and Al saturation reaches 40% after 5 years under crop."

The following scenarios provide an estimate of the range of possibilities of yield loss due to acidification.

Worst-case scenario: The Saria study from Burkina Faso with monocropped sorghum (see Section 4.1.2.) is an example of a disastrous scenario in which:

- the crop is especially sensitive to Al toxicity,
- an (apparently) acidifying type of N fertilizer was applied at high levels,
- the soil is acidic and relatively infertile with low buffer capacity (typical for the region), and
- there was a significant decline in rainfall.

As described in Section 4.1.2., "fertilizer alone" treatments showed an annual decline in yield of > 12% with a complete loss of yield over 8 years. Over 20 or more years under this scenario, no recuperation of yield is expected unless specific measures are taken to reverse the acidification process.

Best-case scenario: In rare situations, such as the Bebidjia, Chad example, with well buffered soils, there is virtually no acidification effect – since the soil is buffered against changes in acidity. As a result, there is no decline in crop yields over >10 years, rather there is a slow increase! Over 20 or more years, there is no expectation that this would have changed if practices were continued. In this case, it is irrelevant whether crops are Al sensitive or not.

Between these two extremes, it is expected that there will be different degrees of decline depending primarily on the degree of soil buffering capacity. Presumably, a soil with moderate buffering capacity and pH would have a moderate decline. A theoretical hypothesis would be to take typical figures for CEC of the two scenarios and calculate a half-way point to serve as a "moderate" example.[78] At the estimated mid-point level of CEC, there is a moderate level of buffering capacity expected.

In the Saria, Burkina Faso example, there was a steep decline in sorghum yield over 8 years from 2000 to about 0 kg ha $^{-1}$ (Pieri 1992). Extrapolating from this example, a theoretical "moderate" curve may be drawn which drops from 2000 to only 1000 kg ha $^{-1}$ over the same period for soils with the estimated moderate CEC value of 4 meq/100g. At this rate, it would take 16 years, half the rate of decline of the Burkina example, to reach a level of 0 kg ha $^{-1}$ yield. Since the Burkina

---

[78] An estimated CEC value (Ca + Mg) would be 4 meq/100g which is approximately half-way between 1.5 (Burkina) and > 6 (Chad) meq/100g (Chad).

[Note: meq/100g is milliequivalents per 100 g of soil. The "equivalent weight" of a cation or anion is its atomic weight divided by its charge. Meq = 10 $^{-3}$ equivalents] scenario is under low rainfall conditions during the period of decline, this figure should be adjusted above 16 to perhaps 20 years or < 1 % yield loss per year. For more tolerant crops, such as maize, the decline in yield should be even more gradual, taking, perhaps, >25-30 years or more.

Yield would not be expected to recuperate after that unless specific measures are taken to reverse acidification. Application of lime or discontinuing ammonium-N fertilization is successful in achieving yield responses due to acidification in most situations. Also, organic inputs including manure, compost and residue have been shown to be effective (e.g. Diatta and Siband 1998 based on research on red ferrallitic soils in Senegal)

To summarize, fertilizers in combination with organic inputs (residue or manure) have the greatest potential for achieving long-term build-up of SOM and sustainable production if the following precautions are taken: (i) "balanced" nitrate-NPK fertilizers are used or lime applied in sufficient amounts to minimize acidification, (ii) conservation tillage,[79] agroforestry and/or cover crops are used to recapitalize SOM/soil fertility (such organic practices also reduce acidification), and (iii) sufficiently high levels of nitrate-N fertilizer or "high quality" (low C/N ratio) cover crops residues (especially legumes) are incorporated to supply N to the primary crop on a sustainable basis and timed to offset temporary N shortages due to immobilization if the (primary) crop residue has a high C/N ratio (e.g. maize).[80]

4.2. Negative Impacts on Traditional Systems and Environments

While it is important for the farmer to make an informed decision in selection of crop species and fertilizer appropriate to soil type, perhaps more critical is the overall production system. Traditional African management strategies have been adapted, over long periods of time, to location-specific soil, climatic and crop constraints. A primary concern is whether "modern" recommendations will be harmful to beneficial traditional practices or environments.

As stated previously, it is logical to assume that fertilizers will increase the overall fertility of the soil resulting in higher growth rates for all plants including weeds.[81] According to Fukuoka (1997), the abrupt increase of fertility caused by fertilizer during the growing season results in high levels of infestation of weeds. As a result, farmers are required to introduce new strategies to control the weed populations. These strategies are typically either chemical (herbicide) or

---

[79] In semi-arid regions with marginal soils, it is especially important to keep residues on the surface of the soil to protect the soil from the severe wind and water erosion of the region, to enhance water retention, and to break up and prevent soil crusting via increased termite activity.

[80] It is important to remember that high productivity (high C/N ratio) crops such as maize are ideal for building SOM and should not be avoided due to the potential for N-immobilization. Rather the immobilization problem should be addressed as suggested.

[81] However, since fertilizers are "placed" to achieve greatest availability for crops, the highest levels of fertility are expected to be in the micro-environment of the crop rooting zone.

labor-intensive. In the view of the author, high levels of inputs (fertilizer or organic) upset the delicate natural balance of the plant/soil environment.

According to Pieri (1992, 115), in many areas which have adopted fertilizers for cash-crop cotton production in West Africa:

> The farmers have modified their rotations by shortening the fallows, by planting more tolerant crops like cassava which are less demanding of labor. They have adopted mechanical methods for clearing and have lengthened the time for which a field remains under crops. This has had the effect of upsetting the system of animal husbandry (suppression of common grazing, reduced forage production), increasing the risks of erosion, and leaching of nutrients. Soil degradation appears to be the result of using inappropriate cultivation methods and a shortage of labor.
>
> However, its should be pointed out that in northern Togo, which is thickly populated and has an abundant supply of labor and a stable traditional social structure, the cotton crop has not been "added" as an extra, but has been integrated into the existing farming system. This has led to a permanent improvement of the land.

Also, in most areas, cotton was introduced by clearing more land ("extensive" system) but in northern Togo, it was rotated into cropping systems without expanding farm size ("intensive" system).

Figure 10 shows the multiple negative impacts that cotton production can have on soil quality in West African cotton zones using an example from eastern Senegal (Pieri 1992, citing Ange 1984). Before cotton, production systems were frequently based on cereals and pulses with fallows and pasture areas for cattle and goats. Cooperative farming was common and individually managed fields were rare. As Figure 10 illustrates, the introduction of cotton often led to extensive farming and individualization of production that ultimately led to negative impacts on soil quality.

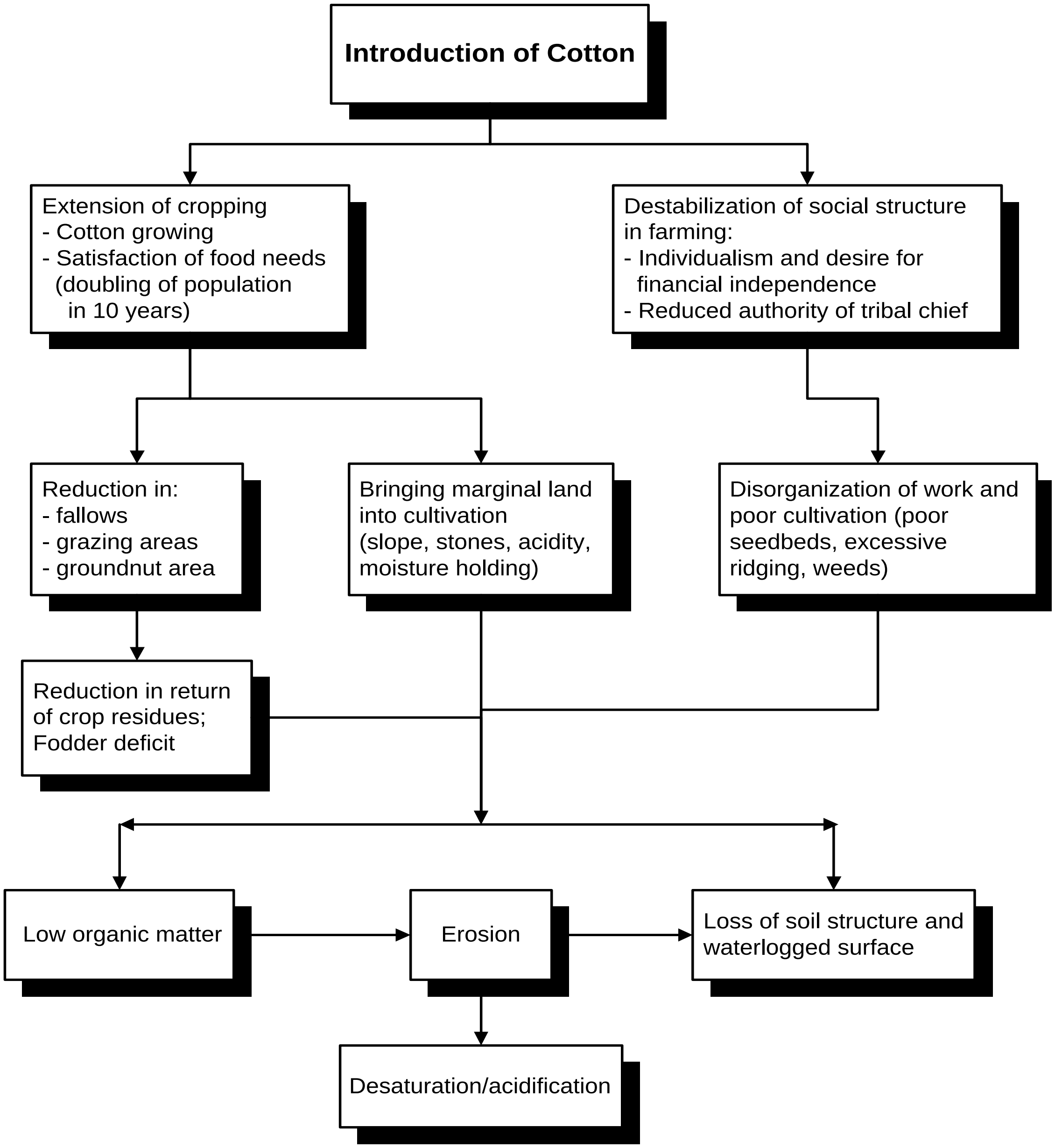
As Pieri states in his northern Togo example, it is possible to maintain traditional practices and integrate intensive production into the traditional system without replacing it. Traditional systems and indigenous knowledge typically provide significant benefits to farmers. For example, traditional intercropping with leguminous *Acacia Albida* trees in the Sahel has been shown to double traditional, low input crop yields (typically 300-400 kg/ha without Acacia) making it a "fertility island" in a nutrient-poor environment. Part of its success is attributed to its soil-building capability which is partially based on dropping its leaves (which contain significant N) at the start of the growing season. It is important that scientists pay close attention to these traditional soil management practices that are based on a detailed knowledge of the soils and the agro-ecological environment.[82] "Looking closely at traditional soil management techniques as well as the soils themselves and evaluating them in light of Western

---

[82] One of the best scientific sources of this nature is Breman and Sissoko (1998).

scientific understanding may yield valuable insights for scientists addressing conservation and sustainability." (Pawluk, Sandor, and Tabor 1992, 301-2)

Figure 10. Diagrammatic Representation of the Effects of the Introduction of Cotton on Soil Development in East Senegal



Source: Adapted with permission from Pieri (1992, 109) (citing Angé 1984).

4.3. Environmental Quality

4.3.1. Historical Environmental Degradation

Environmental degradation has been a fact of life in the last half century in SSA, particularly the Sahelian zone, as illustrated by the following interview with a Peulh, Hama Allahamdou, of rural Burkina Faso.

> My parents' fields stretched out so far you could not see the end of them. The seasons were good and the harvests abundant. The environment was benevolent and everyone knew they could savour the fruits of a few months' work in the fields.
>
> ... My father used to gather in a huge millet harvest. He had three granaries: each year he would fill them all....
>
> As the years went by, our luck began to turn. The rains became rare and inconsistent, the ponds dried up, and the trees died. Suddenly, our environment was a scene of desolation.... The ground was so poor that it produced nothing....
>
> The region used to be full of wild and ferocious animals, such as lions, panthers, buffaloes, hyenas and jackals – and less aggressive animals, such as does and gazelles. We were graced with almost every species of bird on the planet including wild ducks, ostriches, bustards and the crowned crane. Now these times have become something of a legend and the animals have disappeared as if under a spell. (Cross and Barker 1991, 124-5)

One hears these “legends” from people throughout the Sahel who were alive when there was still a fertile environment. An important factor of this environmental decline has been the cutting or burning of trees to clear land for agriculture and for firewood. Trees are typically the “anchor” of primary productivity in undisturbed ecosystems and their removal has been disastrous to the sustainability of these systems. When droughts occur, the water efficiency of the canopy and leaf systems are no longer there to provide valuable pathways. The soil then becomes more vulnerable to direct wind and rainfall impacts.

A major problem is that the environment is so vulnerable to human activities, especially agriculture. "The low overall natural resource quality explains why overpopulation (and resulting over-exploitation of natural resources) is reached at a very low absolute population density and why the efficiency of external inputs (required to solve the problem of over-exploitation) is so low." (Breman, personal communication) It is also difficult to separate out the role of drought from degradation by man. Nicholson (1996) has compiled historical evidence showing that droughts as serious as the recent Sahelian droughts have been constant factors throughout African history. In earlier centuries, the environment was able to return to fertile conditions with the return of increased rainfall. However, the impacts of agriculture (tree-clearing, soil degradation, etc.) and discontinuation of long-term fallows now precludes a return to fertile conditions after periods of drought. It is to be hoped that fertile conditions will return again if effective restorative measures are taken.

4.3.2. Non-point Source Pollution

Although there is not yet evidence of large-scale non-point source water pollution from fertilizers in SSA, a strategy to recapitalize soil by substantially increasing fertilizer use would be expected to result in N and P pollution of surface and groundwater with potentially serious impacts on the quality of drinking water. Impacts are also serious in terms of overall water quality, especially eutrophication (over fertilization) which results in low oxygen levels and resultant losses of fish and other aquatic life. In the West, N fertilizers are the most common sources of such pollution – especially in the form of nitrates. N fertilizers are notoriously inefficient; whatever is not used in plant uptake becomes a potential source of pollution. Most unused N, including N in crop residues, does not become directly available to pollution losses. Rather, it is cycled into SOM as organic N which partially accounts for the fact that over 95% of N in surface soils is found in SOM as organic N. After organic N in SOM is mineralized, it is released as inorganic N ions.[83] Myers et al. (1994, 100-1, citing Myers 1987 and Chotte et al. 1990) estimated the following fertilizer uptake values for tropical environments: "There are many examples of N being used inefficiently in the humid tropics. In a summary of a number of studies, uptake of fertiliser N in the humid tropics was frequently less than 25% of the applied N, whereas in the semi-arid subtropics it was often 30-60%, although some examples of less than 25% were also cited. Over a range of soil types in the tropics, uptake of fertiliser N ranged between 12 and 45%."

Historical levels of N water pollution, especially groundwater pollution, are directly correlated to increased levels of N inputs, regardless of whether ammonium or nitrate fertilizers are used. Thus, losses to the environment can be enormous as has been the experience with high fertilizer use in the West. The problem is especially acute in higher rainfall zones or with sandy soils. It should be noted that high inputs of organic sources also cause pollution including N pollution of water, particularly since the bulk amount of material required is so high. For example, in traditional Amish regions of the Chesapeake Bay Watershed, some estimates suggest that half of applied manure is lost as run-off to adjacent surface water, resulting in increased levels of water-born pathogens. P pollution is usually associated with run-off from clay soil to surface waters.

Since a majority of populations in developing countries obtain their water directly from rivers and streams, it is expected that public health problems would be profoundly impacted if high levels of N pollution occur (Anderson and Thampapillai 1990). Industrial and agriculture success in China and other countries in Asia has been achieved at the expense of environmental pollution for which future generations must pay (Kristof 1997). SSA needs to learn from the Asian experience and institute appropriate monitoring systems and safeguards as it increases fertilizer use. Sustainable management practices can be critical for minimizing or eliminating environmental pollution. For example, cover crops combined with timing or "synchrony"

---

[83] Initially ammonium ions are released. Then, in appropriate pH and oxygen conditions, they are microbially converted to nitrate ions (the process of "nitrification" described previously). Nitrate pollution is the most common form of N water pollution since (i) nitrates are the most common inorganic N ions in the soil and (ii) nitrate ions are easily leached because they are negatively charged and are not attracted to soil surfaces which are also normally negatively charged. Ammonium ions, however, are positively charged and are attracted to soil surfaces, especially clays and organic matter. This pattern will change in the case of variable-charge soils.

strategies can “tie up” N into microbial biomass at critical points in the crop growth cycle, thus maximizing efficiency of fertilizers and minimizing losses of polluting nutrients. Certain crops such as wheat and rye are especially efficient at absorbing high levels of nutrients from the soil via extensive fibrous root systems. These systems, however, require intense management and a considerable level of knowledge. As a result, it is expected that increased fertilizer use in SSA will have similar effects as in Asia with increased production and pollution unless or until farmers learn to adapt such systems.

4.3.3. Carbon Sequestration for Reduction of Greenhouse Gasses

The clearing of land for agriculture has resulted in the burning or cutting down of much forest land in SSA, particularly in the case of “extensive” production systems such as cotton in West Africa. Agricultural intensification provides the potential for farmers to produce more on currently cultivated land; an appropriate scenario on a continent of primarily small-scale farmers. This has a beneficial effect on the environment to the extent that uncleared forests provide a primary contribution to carbon sequestration for reduction of greenhouse gasses. There are counter-arguments, however, that if capital and labor shift toward more intensive agricultural, agroforestry, or livestock systems (such as cattle grazing in the Amazon), there will be increased deforestation (Sanchez 1998).

Increased carbon dioxide emissions (the primary greenhouse gas) due to tillage are associated with fertilizer-based conventional agricultural systems. "Agro-ecological" systems, such as conservation tillage, however, are associated with increased C sequestration and decreased emissions of carbon dioxide. “The Center for Agriculture and Rural Development (CARD 1997) carefully monitored the soil organic carbon gained between 1992 and 1997 by cropland from the “corn belt,” the [Great] Lake States and the Northern Plains of the United States, which eventually amounted to over 1 million tons as a result of a shift towards conservation tillage during this period.” (Pieri 1998, 10) Agricultural systems that integrate conservation tillage, cover crops, rotations, and agroforestry practices have the greatest potential for limiting conversion of CO_2 to greenhouse gasses and sequestration of C from greenhouse gasses. As a result, such systems are increasingly seen as a strategy which can provide a significant level of mitigation to global warming until higher-potential industrial-based strategies (automotive, power plants, etc.) can be adopted (Weight 1999).

5. HISTORICAL EVIDENCE CONCERNING THE POTENTIAL OF FERTILIZER-BASED PRODUCTION IN SSA

In Section 3 we reviewed long-term experiments that illustrated the potential of fertilizer-based production in SSA. There is also considerable evidence that SSA farming has been successful in non-experimental situations, especially on large-scale farms under favorable climatic conditions: "... this potential is recognized by large-scale farmers, who have been able to sustain relatively high yields of maize (Kenya, Zambia, and Zimbabwe), tobacco (*Nicotiana tabacum* L.; Malawi and Zimbabwe) and coffee (*Coffee arabica* L.; Kenya) for periods of up to 30 yr." (Bekunda, Bationo, and Ssali 1997, 71)

In this section, the historical potential for fertilizer-based productivity, especially by large-scale farm operations, is examined for lower rainfall zones of SSA where sustainability is more difficult to achieve. A review of this historical potential helps one arrive at an estimate of the geographical/environmental limits of sustainable production. Historical evidence for significant cotton and maize production in the sub-humid zone of West Africa has been found by Sanders, Shapiro, and Ramaswamy (1996). Critical issues highlighted by the authors are the means of intensification used in these agricultural management systems and how they are influenced and determined by environmental factors and constraints, especially climate and soil quality/fertility (see Figure 11 for agroecological zones of the region).

5.1. **The Sub-Humid Zone** (180-269 plant growth days)

Sanders, Shapiro, and Ramaswamy (1996, 53-5) note the following historical developments in the sub-humid tropics:

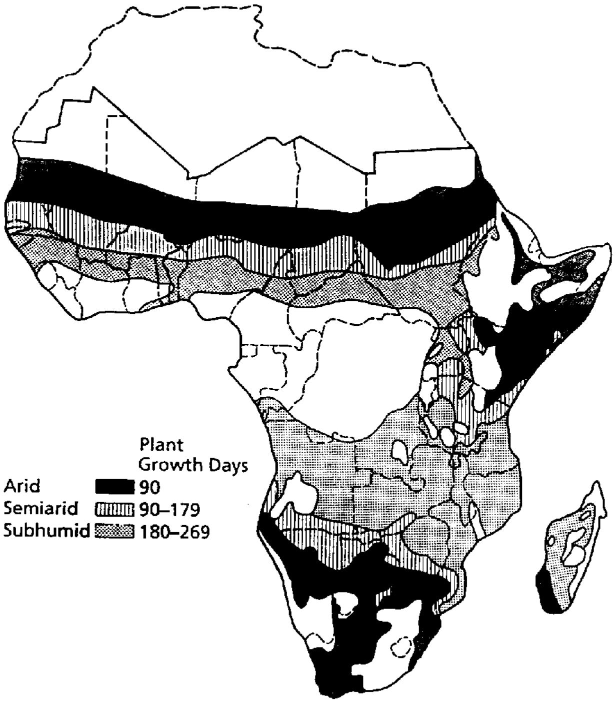
> New cultivar introductions of cotton and maize were very successful and were combined with crop management improvements, including increases in fertilization, density, and pest control, in each country. These regions have become surplus grain producers and exporters to the lower-rainfall regions in all three countries. With the higher rainfall in the Sudano-Guinean zone [800-1,100 mm], there is more agricultural potential than in the dry savanna regions....
>
> The quantity of compound fertilizer, consumed principally by cotton and maize producers in the Sudano-Guinean regions of Burkina, increased from 3,000 tons in 1977 to 16,000 tons in 1986. On cotton, average NPK fertilizer use in southwestern Burkina in the mid-1980s ranged from 131 to 148 kilograms per hectare (Savodogo 1990).... These are still only moderate levels of inorganic nutrients compared with use in developed countries.

Analysis of yields over this period shows a steady parallel increase from about 600 kg ha $^{-1}$ to a high of 1,400 kg ha $^{-1}$ in 1986. "Without inorganic fertilizer and pesticides, cotton yields remain in the 250-350 kilogram per hectare range. In those countries where farmers use inorganic fertilizers, however, yields are over 1 metric ton per hectare." (Sanders, Shapiro, and

Ramaswamy 1996, 55-6) Fertilizer inputs and associated yield increases dropped somewhat in the late 1980's due to elimination of subsidies.

The success of cotton in Francophone Africa has been the result of management by a French cotton corporation (CFDT) in joint ventures with West African companies and/or governments. Sanders, Shapiro, and Ramaswamy (1996, 56) note that: "The essential components of the CFDT success have been providing farmers with fertilizer on credit, timely payment of a product price known before planting, and support of an excellent research and input services system (Lele, van de Walle, and Gbetibuou 1989). This combination of technological and institutional support in cotton production is a significant model of development. Based on the substantially higher yields, the output in the former French colonies grew 740 % from 1960 to 1985. In contrast, the extensive, low-yielding production system in the Anglophone countries resulted in an increased production of only 60 % over that period."

Figure 11. Agroecological Zones in Semiarid and Subhumid Sub-Saharan Africa



Source: Reprinted from Winrock International, 1992, with permission.

A similar success story is reported for maize in the sub-humid cotton zone. "Maize yield increases in [cotton zones of] Mali were greater than those of cotton in the seventies and eighties from 600 kilograms per hectare in the early seventies to 1.75 metric tons per hectare in the late eighties." (Sanders, Shapiro, and Ramaswamy 1996, 58, citing Girdis 1993)

Traditional maize has been considered to be more sensitive to water availability than millet or sorghum and associated with high risk in regions of high rainfall variability. New maize cultivars have been developed to address this problem. "These new early cultivars increase the ability of maize to compete with the drought tolerance of sorghum and millet through drought escape. Earliness also enables maize to be planted early and then harvested in the *soudure* , or hungry season, before the principal cereals of sorghum and millet." (Sanders, Shapiro, and Ramaswamy 1996, 58)

These cultivars are more responsive to higher soil fertility conditions and fertilizers than traditional cultivars. Adoption of new cultivars (alone) without fertilizers is insufficient. Sanders, Shapiro, and Ramaswamy (1996, 58-9), citing work of others, note that:

> The most rapid introduction of maize technology occurred in the Sudano-Guinean zone where there was sufficient rainfall that inorganic fertilization was less risky and more profitable than in the dry savanna (Smith et al. 1994; Dakrurah et al. 1992; Marfo and Tripp 1992). In the wet savanna, the new maize cultivars are generally combined with inorganic fertilizers. For example, a case study for the wet savanna of northern Nigeria (average rainfall of 900 to 1,200 millimeters) showed a complete replacement of local cultivars with an improved maize cultivar, with most farmers also using inorganic fertilizer. Since the mid-seventies, this maize technology introduction has resulted in a rapid increase in maize consumption, replacing the traditional food staples of millet and sorghum. The use of inorganic fertilizer in northern Nigeria has spread to other crops, especially sorghum (Smith et al. 1994).

Fertilizer use in Nigeria, which occurred primarily in the sub-humid zone, was facilitated by direct fertilizer subsidies that were higher and lasted longer than was the case in other West African countries (Yanggen et al. 1998).

The historical evidence suggests that commercial agriculture has played a critical role in the development of fertilizer-based agricultural systems. In the sub-humid zone of West Africa, where sufficient rainfall and soil fertility levels co-exist, large-scale commercial production systems for maize and cotton, have been developed by corporations dating from the colonial period. A primary factor in their ability to increase production over time has been the development of a multi-faceted management system, including technological, institutional, and financial support such as research and input services, credit for fertilizers and pre-set price levels for farmers.

Likewise, in other parts of Africa with sufficient rainfall and soil fertility, large-scale commercial agriculture, with its roots in the colonial past, has played a critical role in the development of fertilizer-based agriculture, from both a technological and economics perspective. "Three of the top fertilizer consuming countries (Zimbabwe, Kenya, and Zambia) benefitted from the establishment of large-scale commercial farms by European settlers.[84] These farms have provided a minimum level of stable fertilizer demand that helps promote economies of scale and lower fertilizer prices." (Yanggen et al. 1998, 64) Lower costs, as well as increased availability of fertilizers, can be of enormous importance for small-scale farmers wishing to implement fertilizer applications.

On those commercial farms that have been applying fertilizers at relatively high rates over time, a reasonable level of soil fertility and SOM is to be expected. On the vast majority of smaller farms, however, low input agriculture has resulted in long-term soil mining. These farmers need to recapitalize their soils to increase crop yields on a sustainable basis. Cultural practices were suggested in previous sections that can accomplish this goal, particularly residue-based strategies that combine fertilizers with cover crops, rotations, and conservation tillage practices. As in the case of commercial farms, smallholder farmers also need the benefit of some level of technological, institutional, and financial support to be successful in implementing new production systems. Educational support will be especially critical in this regard. At the same time, farmers need to be able to maintain their independence and control of their own resources (i.e., land tenure rights) if they are to enjoy the fruits of their own labor. Without independence and control of resources, most farmers will be unlikely to assume the risks associated with moving to a more input intensive type of agriculture.

5.2. The Semi-Arid to Arid Zone (90-179 plant growth days)

The history of the semi-arid and arid zones is entirely different. Due to rainfall and soil fertility constraints, there is virtually no long-term history of commercial agriculture or any significant fertilizer-based agriculture. Presumably, European settlers were not interested in taking the increased risk of agricultural development in these zones. Sanders, Shapiro, and Ramaswamy (1996) write that in the semi-arid and arid zones of the Sahel, beginning with the Sudanian zone (600-800 mm), little to no fertilizer is used due to the increased risk associated with high rainfall variability and low soil fertility. As a result, crop yields are low despite the existence of new drought-tolerant cultivars of maize and other crops.

In these regions, scientists have debated whether water is more of a limiting factor for agriculture than nutrients. A more useful approach has been developed by Brouwer and Bouma (1997, 17) based on observation of farmers' practices and parallel analysis of agricultural parameters, particularly of soils.

> In fact, water and nutrients alternate in limiting crop production. Within a field, they can alternate not only from year to year (good rainy season vs poor rainy season), but also from week to week and even from day to day (before and after a rainstorm following a dry period) (Brouwer 1996). In fact, water may be limiting in some parts of a field (where the crop is already wilting), while nutrients may be limiting in other parts (where there is still some water stored in the soil).

---

[84] Not coincidentally, these are three of the four countries listed in Section 5 that have sustained relatively high yields of crops for up to 30 years (Bekunda, Bationo, and Ssali 1997).

> ... Because higher soil fertility generally means more rapid development, a crop will develop unevenly where there is significant micro variability. This means that the whole crop will not be equally sensitive to the same environmental factors at the same time: drought around flowering time is less likely to wilt all the florets on all the inflorescences, and the occurrence of a particular pest or disease may not wipe out the whole harvest (Brouwer et al. 1993b). Risk reduction through diversity is an ecological principle that is also relevant in agricultural environments.

To deal with these factors, farmers have handed down risk-aversion strategies such as the following observation from a farmer in Diakindi, Niger: "Under older trees of *F. albida,* millet grows much thicker and darker than in the open field. The farmer explained that this well-known "albida effect" is due largely to the manure and urine left by livestock that come to rest in the shade or to feed on fallen or lopped-off fruit and branches. Because these trees lose their leaves at the beginning of the rainy season, they do not compete with the growing millet for light. The albida effect is not evident under young trees, which are too small to produce much fodder." (Brouwer and Bouma 1997, 12) N contributions to the soil from leaves and are also an important component of the albida effect.

Such a release of N to the soil is especially important in the extremely N-limited Sahelian environment. According to Breman (1998, 6-7): "The relative importance of N over P deficiency ... increases gradually from the rainforest to the Sahel. At least in semi-arid and subhumid West Africa, N is often more limiting than P (Penning de Vries and Djiteye 1982)." This is logical since N status is a direct function of biological status and vegetative biomass decreases from the rainforest to the Sahel.

The farmer cited above also described variability associated with a total of eight tree species. Other farmers describe variability related to crop position on a toposequence, movement of sand related to topography, the sensitivity of the crop to drought, and numerous other topics. Farmers in these regions became experts in site-specific management practices long before the field was founded in the West. This development occurred due to the understanding that, in their environment, it was the only ecologically and economically-sound practice (Brouwer and Bouma 1997).

In regard to the use of fertilizer, Brouwer (1997, 1) writes: "... [M]any dryland farmers in the Sahel, and in other semi-arid areas of Africa, cannot afford to buy external inputs, and will not be able to do so for the foreseeable future. There is also no large market for their millet or sorghum at prices that make it attractive to use mineral fertiliser or other external inputs. And even if farmers can afford to buy such inputs, they are often hesitant to do so because of the risk involved in using them in areas where rainfall is less than reliable."

Results of a study by the IFDC in collaboration with ICRISAT in Niger indicate that farmers will adopt fertilizer use when the economic risk factor is removed and intensive institutional efforts are made to promote fertilizer availability and use with appropriate management practices. After extensive trials were carried out by ICRISAT on the effect of P and N fertilizer applications on crop yields, a farmer outreach program was carried out in Gobery, a village located 100 km southeast of Niamey. Mokwunye and Hammond (1992, 131-2) describe what happened as follows:

> In 1986, 20 farmers were randomly selected to validate the information that had been obtained by the researcher in both the research station trials and the on-farm trial conducted in the village. Very few of the farmers in Gobery had used fertilizers before and their knowledge of fertilizer use was limited. During a series of meetings, farmers' opinions were elicited to develop a suitable package of fertilizers, seeds, and management practices. For these trials, farmers were provided with free fertilizers and seeds and given assistance in laying out the experimental plots. All other operations from planting to harvesting were carried out by the farmers themselves. These farmer-managed trials were repeated in 1987.
>
> Over these 2 years, millet yields in the farmers' fields where fertilizers were applied increased by an average of 250% (IFDC 1986, 1987, and 1988). Fertilizers improved crop establishment, crop density, and subsequent grain yield. The improved dry matter meant more crop residue for domestic use while up to 2 t ha^{-1} remained in the fields. This protected the soil from the effects of both the harsh dry season and the extremely severe storms that accompany the onset of the rains.
>
> Although IFDC worked with only 20 of the 150 farm families in the village, a survey undertaken by ICRISAT showed that more than 98% of the farms in Gobery were fertilized in 1987.... [F]ertilizer consumption in the village increased from about 2 t of single super-phosphate (SSP) in 1982 to 115 t of SSP, urea, and compound N-P-K in 1987. Results of the baseline survey had indicated that availability and high cost of fertilizers were the major constraints to its use. The farmers organized themselves into a cooperative so they could buy fertilizers in bulk for the village and overcome the problem of fertilizer supply. This resulted in the phenomenal increase in the use of fertilizers [to 115 t] ... without any changes in the government's procurement or pricing policies. The yield increases meant increased food security.

The results of this study indicate that, even in this difficult region, fertilizer availability and use with strong institutional support can overcome biophysical risk factors and result in strong yield responses. Once fertilizers were made available at no cost, the farmers were able to achieve an average millet yield increase of 250%. This suggests that it was, in fact, the high cost and lack of availability of fertilizers that were the primary obstacles to fertilizer use by farmers in the region, as indicated in the baseline survey. Also, it suggests that most farmers were not familiar with fertilizers at the outset and came to realize the potential of fertilizer technologies as a result of their on-farm trial experience with IFDC/ ICRISAT researchers.

It can be expected that costs will be reduced as farmers gain experience with combined inputs, as higher efficiency fertilizers are introduced and made available, and as new cultivars that are more responsive to fertilizers are introduced (John Sanders, personal communication). Also, continued experimentation and trials by farmers and researchers can determine if the application of recommended cultural practices, such as conservation tillage, cover crops, or agroforestry, have the expected potential to recapitalize soils and increase nutrient efficiency permitting the gradual reduction of fertilizer inputs over time.

In areas with clay soils, especially when the soil surface is crusted, water erosion is a severe problem with significant runoff of water, nutrients, and fine-textured nutrient-rich soil particles. Research has been conducted in SSA on water-retention technologies to increase water availability in the arid and semi-arid zones including building of earth or stone contour dikes which impede runoff of water and surface nutrients, tied ridges which consist of perpendicular ridges with a depression in the center serving as a water catchment and crops grown on the ridges, and *zai* holes which consist of digging a planting hole and adding manure or other organic matter at planting time.

Sanders, Shapiro, and Ramaswamy (1996) reviewed on-farm trials conducted by researchers in the Central Plateau of Burkina Faso. Research findings suggested that there are potential benefits for water retention technology with increased yields and profits, despite labor requirements and costs for fertilizers. On-farm trials in the region during the years 1983 and 1984 indicated that sorghum yields increased by 50 % with tied ridges or fertilization alone. Combined tied ridging and fertilization increased yields by 100 %. On poorer "bush land" with millet, yield increases were calculated at 50 %.

The study also illuminates points that are often missed by researchers, especially on experimental stations. One important point is that farmers usually cannot afford to adopt new technologies, whether fertilizer, tied ridges or other examples, over all their land. Use tends to be on higher quality land, usually near the compound or village where fertility is higher, with higher valued crops such as sorghum or maize (vs. millet). As profitable results are obtained on better land by the introduction of these technologies, especially in combination, their use tends to be expanded to less-valued lands. The potential outcome of such expansion will be for increased fertility and profitability on these lands.

Despite the research evidence for the potential profitability of water retention technologies, actual adoption of these practices has been sparse throughout the Sahel. This is probably due to a lack of willingness to make the labor intensive investment that is required prior to the growing season.

Mulch farming or conservation tillage practices may provide an effective tool for combating the negative effects of conventional tillage, erosion, and soil mining on these soils. Also, dryland conservation technologies are available that are conservation tillage practices specifically adapted to limited rainfall regions with the goal of increasing available water and water use efficiency. These technologies appear to be more efficient than current water retention technologies since they provide multiple benefits, beyond containing run-off. The most critical benefits in this environment are (i) the physical improvement of the soil via SOM build-up as well as soil faunal activity, especially by termites, with increased water retention capacity via increased soil porosity, and (ii) the fact that they are integral cultural practices within the growing season which are reasonably labor-saving. Further research comparing biophysical effects of fertilizer applications with dryland conservation technologies vs. water retention technologies in the low rainfall zones of SSA is warranted. If there is strong evidence that dryland technologies can accomplish their intended goals, extensive on-farm trials could be conducted with selected farmers, as in the Gobery, Niger example.

In some regions of SSA with high water tables (mainly river valleys and wetland depressions), adoption of irrigation technology is possible. In Niger and Sudan, both countries which have major arid zones (<90 plant growth days), government-developed and controlled irrigation has been successful in lowland river valleys for production of rice in Niger and cotton and wheat in Sudan. Use of fertilizer has been an integral component of these systems. In Sudan, such use has expanded beyond the state-run cropping system to adoption of a new hybrid sorghum cultivar by farmers on their own irrigated lands.

> In the Gezira [Sudan] there was a tradition of using inorganic fertilizer on cotton and wheat. There were organized channels for obtaining fertilizer and seeds. It was not difficult for Gezira farmers to convince irrigation-scheme officials that they wanted hybrid seeds and inorganic fertilizer for their own crop, sorghum. When water availability is assured, as in these irrigation schemes, there is a larger response and less risk from fertilization than in the dryland regions. Farmers in the Gezira adopted HD-1 [a new sorghum cultivar] with low levels of inorganic fertilizer and then increased fertilization over time (Ahmed and Sanders 1992). Without fertilizer, even with assured water in the Gezira, there was no advantage to HD-1, according to the farmer interviews. The Gezira had all these favorable conditions of a substantial, stable response to inorganic fertilizer and a history of access to this input. The economic returns to the investment in research on HD-1 have been high for the Gezira (Sanders, Shapiro, and Ramaswamy 1996, 131).

As long as there are limited economic resources in the countries of SSA, irrigation will be limited to these zones where water is readily available (high water tables). The vast majority of lands do not have access to this resource and require alternative strategies.

5.3. Summary

It is clear from the historical record that, under favorable environmental conditions (i.e., higher rainfall zones with higher quality soils), farming has been productive and profitable in SSA, especially on large-scale farms. The critical factor for that success has been the implementation of fertilizer-based crop management systems, especially systems based on "green revolution strategies" which have focused on improved cultivars, planting density, and pest/weed control. In many cases, farm management was backed up by technological, institutional, and financial support such as research and input services, credit for fertilizers and pre-set price levels for farmers.

In regions of lower rainfall, there is very little evidence of successful agriculture on a large scale. However, the success of the IFDC/ICRISAT program at Gobery and other recent experiences have shown the technical potential for fertilizer-based agriculture in these zones. The evidence suggests that the primary restrictions for use of fertilizers have been the expense, lack of availability, and poor institutional support -- particularly a lack of good extension programs to promote knowledge about fertilizers and fertilizer-based management systems. Efforts to improve productivity, especially in the lower rainfall zones, will need to address these constraints.

Unfortunately, there was very little discussion concerning sustainability in the historical literature cited in this chapter. Over the periods examined (typically two decades), yields in the higher rainfall zones increased over time. However, in conventional systems with no return of residues to the soil, fertilizers can provide sufficient nutrient inputs for crop yields to increase yet allow declines in soil fertility. With the limited information provided by the studies reviewed in this section (primarily yield changes, with little attention to scientific measures of changes in soil quality), it is not possible to determine if there has been a change (either positive or negative) in fertility and SOM levels associated with the increased use of fertilizers.

While it is technically feasible to maintain productive systems using conventional methods of intensification, the overwhelming majority of farmers in SSA are smallholders with severe economic constraints who do not possess the financial or technical capacity to implement intensive conventional systems. Rather, strategies are being sought that take advantage of natural restorative processes and are, therefore, efficient in terms of fertilizer and water requirements as well as costs and labor. Once fertility and SOM levels are restored, ideally to a pre-disturbance level, the primary objective will be to maintain a "sustainable" system. Lal has defined a sustainable agro-ecosystem as being a "balanced" system with equivalent inputs/outputs of nutrients and C, as in a natural, undisturbed system.[85]

---

[85] Based on a plenary presentation by Rattan Lal at the 10th International Soil Conservation Organization Convention, Purdue University, May 22-27, 1999.

6. DEVELOPING EFFECTIVE STRATEGIES

Due to increased population and food requirements, there has been an increasing “land hunger”in SSA which has resulted in larger portions of forests and marginal lands being taken over for agriculture. The very large challenge for donors and governments in the region is to create productive and efficient agricultural strategies that can effectively reverse these patterns of low-input, extensive agriculture and associated soil mining and degradation. Van Keulen and Breman (1990, 194) have summarized critical points that need to be integrated into agricultural programs to meet this challenge, recognizing that low-input organic inputs at typical levels are only capable of lessening the rates of soil degradation but not of reversing them:

> ... [T]he only real cure against “land hunger” is increased productivity of the land, both in animal husbandry and in arable farming, requiring at least the import of phosphorus (fertilizer) from outside the system, because recycling of crop residues, manure and household waste, regeneration of degraded rangeland, anti-erosion measures, etc., may at best prevent further deterioration of the land resource, but are insufficient to lead to improvements. A real solution requires a “green revolution,” resulting in an annual yield increase that exceeds population growth (de Wit and van Heemst 1976 and de Wit 1986).... That means that at the present yield level of ~ 500 kg ha $^{-1}$ for cereals, increases of at least 15 kg ha $^{-1}$ year $^{-1}$ are necessary to keep up with the population growth of 3% per annum. This seems a feasible proposition on the basis of the technical know-how available (de Wit 1986). The economic environment, however, leaves hardly any other option than aiming at maximizing the efficiency of water and nutrient utilization, either from natural sources or from external sources. In practice, this means that the measures discussed earlier, i.e., judicious resource management, regeneration of degraded resources, erosion control, etc., are a “conditio sine qua non” for viable intensification policies and vice versa.

What is called for is the generation of sustainable agro-ecosystems in which recapitalization of nutrient and C capital in SOM results in sustainable nutrient flows to crops with the potential of increased yields, profitability, and sustainability. It is not enough to select a single strategy such as erosion control or fertilizer recommendations; rather a comprehensive, integrated strategy is required, as suggested by Van Keulen and Breman and described previously in this paper.

6.1. Using Fertilizers to Increase the Biological Base of the Plant/Soil System while Avoiding Negative Impacts

The goal of this paper has been to review and analyze the positive and negative impacts of fertilizers. When combined with recycling of organic materials (residues and/or manure), the primary positive impact of fertilizers is to increase the biological base of the plant/soil system resulting in increased yields and improvements in agriculture-induced soil degradation. Previously, it was stated that the purpose of soil recapitalization is not to build up maximum stocks of nutrient capital but “appropriate” stocks of nutrient capital which can provide sustainable levels of nutrients to crops. To accomplish this goal, the system needs to be extremely efficient, delivering required inputs at appropriate times and levels.

An illustrative example is the more efficient and profitable production system now used by most U.S. auto makers. Formerly, part supplies were delivered in large quantities to car plants and stored at the plant with a limited number of deliveries per year. At times, parts would run out when the assembly required them since the periodic supplies were based on large, rough estimates. At other times, there would be large overflows of stocks when figures were under-estimated. Under the new system, parts are delivered on a regular basis, closely adjusted to the changing needs of the assembly line. Managers are in close contact with suppliers to inform them of new supply level requirements. Supplier trucks roll into the plant day and night to feed the system. Thus, supply of inputs is determined in close correlation to changing times and levels of need.

Efficient agricultural systems deliver nutrient inputs to crops according to times and levels of need.[86] While it is difficult to determine such needs on a regular basis in an agricultural system, there are cultural practices and management systems that have been shown to be effective. When these practices and systems are functioning at maximum efficiency, nutrients are supplied at appropriate times and levels for crop needs directly from fertilizers (via soil solution) as well as from short-term SOM.

The most common problem of inefficiency in tropical soils is the accelerated rates of decomposition and mineralization which means that outflows of mineralized inorganic nutrients are too great for them too be utilized efficiently. This leaves them vulnerable to losses, especially leaching of nitrates in sandy soils. This is one of the primary reasons for the very inefficient rates of recuperation of nutrients by crops in SSA. Returning to the auto plant analogy, this is equivalent to having the production line work at maximum rates when there is an insufficient immediate need for them (crop requirements). So they pile up at the end of the assembly line and disappear to places unknown! In this manner the majority of nutrients mineralized in SSA agricultural systems are not recuperated by crops. Compared to other regions, (approximately) twice as many are lost in SSA, (i.e., low recuperation rates).

If the system is functioning properly, its productive capacity, measured as NPP, will increase over time. That is, fertilizer inputs drive increased crop uptake of C from the atmosphere as CO_2. Their combined effect is to increase NPP. This also contributes to increased water uptake by increased canopy size. When residues (of any kind) are recycled, a significant percentage of the NPP is “captured” back into the system as SOM rather than being exported and lost to the system (e.g. by cattle that don't return manure to the field or for non-agricultural purposes). This creates a positive feedback loop that is continually reinforced by increased inputs of nutrients and C. When cover crops or trees are added to the system, the process is amplified further with

---

[86] Nutrients are also required by SOM, especially long-term SOM (humus) for structural purposes with specific ratios required for each nutrient. If sufficient nutrients levels are not achieved, decomposition/ mineralization rates are increased with accelerated output of carbon dioxide to the atmosphere and inorganic nutrients to the soil solution (Himes 1997).

increased storage and productivity due (again) to increased canopy size and biomass inputs of particulate organic matter to SOM.

Increased SOM results in improved soil structure which, in turn, results in increased nutrient and water use efficiency with an estimated potential for increases in nutrient uptake (crop recuperation rates) of at least two times current rates and for water uptake of three to five times current rates (Breman 1998).[87] In a manner similar to the auto plant using on-time input delivery, the cropping system increases productive capacity, structural integrity, and efficiency. The principal requirement is to truly increase SOM levels[88] across SSA, as has been occurring in North America since the 1950s, rather than simply decrease the rate of loss of SOM. If this is accomplished over the long term (arguably 50-100 years), the continent will have met one of its greatest challenges.

6.2. Developing Effective Fertilizer-Based Programs

It is important that the schools of high input agriculture and ecological farming work together rather than fight each other because each, on its own, does not have the capacity to achieve these objectives on a large-scale in SSA (Breman, personal communication). One example from the high input agriculture side of the spectrum is the Sasakawa-Global 2000 (SG 2000) program which focuses primarily on adoption of fertilizers and new crop cultivars; taking lessons learned from the "green revolution" in countries such as India which undertook an ambitious national program and achieved self-sufficiency in food. This section will examine the strengths and weaknesses of the SG 2000 approach to gain a better idea of how it could increase the capacity for intensification in SSA.

Quinones, Borlaug, and Dowswell (1997, 82-4) lay out the long-term guiding principles of the programs as follows:

> The solution is clearly not to expand food production horizontally to keep pace with population growth at the cost of environmental degradation. Instead, the solution is to provide adequate soil nutrients by increasing the use of mineral fertilizer, combined with organic inputs that build-up organic matter in the soil, and the complementary practices of using improved seed and proper plant population, weed control, and other cultural practices.
>
> ... The core of the SG 2000 projects are dynamic field testing and demonstration programs for the major food crops in which improved technology exists but for various reasons was not being adequately extended to farmers (Borlaug and Dowswell 1995). The SG 2000 projects work under the leadership of the national extension departments of the relevant ministries of agriculture. Practically all the technical extension staff from

---

[87] Based on estimates for the Sudanian/Sahelian Zone of West Africa.

[88] Thus increasing associated benefits.

> those departments are thoroughly involved in the planning, implementation, and monitoring of SG 2000 field programs.

In the case of the Ethiopian program, SG 2000 has been successful in achieving its goal of expanding use of fertilizers and, consequently, food production. As a result of the government's "Intensified Extension Campaign," fertilizer imports increased from 47,000 tons N and P in 1993 to 137,000 tons in 1996. Increased fertilizer application combined with improved cultural practices as well as increased rainfall resulted in the highest yields ever recorded for major crops in the history of Ethiopia for the 1995-6 and 1996-7 crop seasons.

One reason for the apparent success of SG 2000 programs in achieving record yields is that they work primarily in high potential lands. Soils on these lands, as described in Section 3.2.1., have sufficient fertility and few constraints so they respond dramatically to high fertilizer inputs as in the earlier Kansas prairie example. Based on earlier calculations by Eswaran et al. (1997), however, only approximately 17% of SSA lands are high potential lands! How relevant will the SG 2000 approach be for lower potential and marginal lands (see below)?

Sanchez (1998) cautions against "single-factor silver bullet" approaches promoted by programs such as SG 2000. Instead, he suggests that governments develop broad, comprehensive policies which take advantage of new technologies. In countries where SG 2000 has pulled out, critics have blamed this "formula" approach for post-program declines in use of improved technologies, particularly fertilizers. This is based on the fact that there has been a tendency for SG 2000 to recommend packages that are often difficult for farmers to sustain when the program withdraws its support to extension and/or input distribution.

There are indications that the Ethiopia program is adapting a more flexible approach in which recommendations for management practices are increasingly adapted to local conditions and constraints. For example, the program has adopted strategies for (i) control of rust disease in its hard-hit wheat crop, (ii) expansion of activities onto non-prime lands such as semi-arid lands where sorghum is a primary crop, and (iii) development of post-harvest technologies such as maize storage so that higher prices can be obtained after a 6 month storage period (Howard et al. 1998a).

It is important to recognize the considerable strengths and achievements of the SG 2000 program and learn from them in the development of future programs. One key to this success has been the use of large-size demonstration plots on a national scale. By increasing the usual demonstration plot size, farmers have obtained yield figures in 100s of kgs rather than kgs. In Ethiopia, thousands of field days with demonstration plots have been carried out. They have been attended by hundreds of thousands of farmers who have learned about the potential yields and profits that can be achieved. Over an 11-year period, yields on demonstration plots have been two to three times higher than those on control plots or in traditional farmers' fields (Quinones, Borlaug, and Dowswell 1997).

A critical factor in the success of the SG 2000 demonstration plots in Ethiopia and other countries is that they are carried out through the existing extension services and require continual efforts to improve the skills of extension agents. The agents participate in the close supervision of farmers doing demonstrations so that good management practices are taught and significant results achieved. However, in some SG 2000 countries, such as Mozambique, there has been relatively poor supervision and limited results to date (Howard et al. 1998a; Howard et al. 1998b). Since the state extension services are the key actors in the SG 2000 system, a large factor in the success of the Ethiopian program has been the relatively advanced level of training and experience of the Ethiopian extension service agents. Lack of these advantages in other SG 2000 countries has been detrimental to the success of the program in those countries (Julie Howard, personal communication).

In developing new strategies and programs in SSA, it would be worthwhile to consider adopting core elements of the SG 2000 approach, particularly the key role played by government leadership at the highest level; the role of extension services in carrying out demonstration plots; the size of the plots as well as the level of effort in bringing them to large segments of the farming population; and the technological support in making fertilizers available on a national scale. It is also instructive to make comparisons between various SG 2000 programs and similar programs to assess why certain strategies appear to succeed in one country and not another.

In a number of countries, SG 2000 has had remarkable success in achieving its defined objectives of increased fertilizer inputs, yields, and profits for farmers given the difficulty of achieving these goals under the prevailing conditions of SSA. The next step for SG 2000, as recognized by Quinones, Borlaug, and Dowswell (cited on page 75), will be to expand the current fertilizer input strategy to include complementary organic input strategies, especially as the program expands into more marginal agroecosystems (Julie Howard, personal communication). A key factor in expanding the program to a wider range of soil and climate environments will be the adoption of recommendations for levels and types of fertilizer applications to the variability of environmental conditions.

6.2.1. Addressing Variability of Environmental Conditions

Besides economic risk factors, farmers are hindered by a lack of knowledge regarding the suitability of fertilizers to specific environmental conditions: “The main reasons why African farmers refrain from using fertilizer are lack of confidence in the economic returns to fertilizing food crops, and lack of knowledge as to which kinds and rates of fertilizers are recommended for their specific crops, soils, and agro-climatic conditions. Such recommendations have either not been transferred from research to extension departments or, more often, just do not exist (FAO 1983; Mudahar 1986; and Ulek 1990). Hence, the farmer [if using fertilizer at all] acts according to inappropriate blanket recommendations, such as “one bag per acre” of the most readily available kind of fertilizer.” (Smaling et al. 1992, 241-2)

Scientists and farmers have learned that such blanket recommendations, which are currently used in the SG 2000 programs, are usually quite inefficient and wasteful. Under western agriculture, where fertilizers have been cheap, farmers have gotten away with using blanket recommendations at high levels as “insurance” but this has led to over fertilization and non-point source pollution.

Farmers are beginning to see considerable savings and decreases in pollution by adapting fertilizer levels to the heterogeneity of soils.[89]

As stated by Van Keulen and Breman (1990, 194), referring to SSA: “The economic environment, however, leaves hardly any other option than aiming at maximizing the efficiency of water and nutrient utilization....” Perhaps the most critical economic constraint is the high cost of fertilizers in SSA. While it is not possible to adapt precision agriculture using high-tech equipment, it is possible to take advantage of current knowledge including climate data and national/regional soil maps. At the local level, extension personnel can work with farmers to adapt recommendations to indigenous knowledge of agricultural and soil variables.

Workers in Kenya developed 70 fertilizer trials under FURP, a national program integrating fertilizer, crop, soils and profitability data. In this case, soils information is only used as baseline data and not as a research variable. Factors include “agro-ecological units” (AEUs), major crops with yield data, and profitability indicators (investment, net return to fertilizer and value/cost ratio). Smaling et al. (1992) have written an evaluation of results from four years at three sites of very different AEUs with various hybrids of maize. The initial work required establishment of the AEUs based on available information and data on climate, land forms, geology and soils in Kenya. The trials were developed to ascertain crop responses and profitability to inputs of N, P, and manure within a range of AEUs. Crop residues were routinely included in all sites. The results were used as the basis for fertilizer recommendations for the specific AEUs, in an environment where there is minimal soil testing and extension expertise available.

Statistical analyses of trial results were extremely useful in showing the relationship between soil parameters, crop yields and profitability. One site had a relatively fertile soil with low pH and P and high N which resulted in profitable fertilizer application of P and manure. The most infertile site with sandy soils required both N and P with possible manure to achieve higher yields – but this investment was barely profitable.

An important aspect is the simplicity of the system making it adaptable on a large-scale. First, it has limited variables (N, P and manure). Second, soils data and other AEU information is only baseline data based on pre-existent maps and data. It was not necessary to carry out an expensive and difficult soil survey or soil monitoring system. Third, residue was included at all sites. This makes sense when an input, such as residue, is critical to recapitalization of soil. Scientists from donor countries and international research institutes continue to work with Kenyan scientists and extension workers to develop fertilizer recommendations and nutrient budgets that are realistic and efficient. Malawi is another of the few African countries that have utilized soil survey and classification as a basis for fertilizer recommendations and agricultural development (Saka, Green, and Ng’ong’ola 1995).

Sanders and Ahmed (1998, 4) point out that the success of the SG 2000 in Ethiopia for achieving increased yields and profits has had positive results for national crop science research, including efforts to take into account environmental variability factors:

---

[89] In addition to efficiency obtained from alternative crop management systems such as conservation tillage, described previously.

> Many of the gains [of the Ethiopia program] are region- and year-specific but program successes with the cereals are also now serving as useful input into the research system. The agroecological divisions in EARO (the national agricultural research organization of Ethiopia) have increased from three basic altitude definitions to over eighteen categories in their planning for sorghum breeding (Aberra Debella, director of the national sorghum program and now Deputy Director of EARO). Success is contagious and leads to the next level of developing technologies that respond better to the different constraints of many agroecological regions. One externality then is the improved morale in the research, extension, and public-policy sectors resulting from successfully increasing farm yields.

The next logical step is for the SG 2000 program to expand its soil science research around fertilizer recommendations, as illustrated in the FURP/Kenya example as well as other critical areas of soils research, especially monitoring of long-term SOM levels.

6.2.2. Historical and Regional Examples of Successful Strategies

Historical examples of rehabilitating soils with increased productivity on a national scale are worth examination so that lessons may be learned and, possibly, applied. One example is the similarity between the current situation in SSA and the U.S. in the 1930s. In both situations, the effects of long-term low-input agriculture have been severe, especially in more vulnerable regions, in terms of soil mining, loss of SOM, and erosion, with parallel losses in productivity and economic stagnation. Long term agronomic studies (e.g. Figures 2 and 6) provide historical examples for successful recapitalization via fertilizers and crop residues. Large scale soil conservation efforts of the U.S. Soil Conservation Service[90] were instrumental in mitigating severe soil degradation through intensive soil conservation programs since the 1930s, particularly in the Great Plains states.

More recent residue-based conservation tillage methods such as no-till are having an even larger impact on rehabilitating soil fertility and productivity in the U.S. due to improved biophysical effects, efficiency, profitability, and the large area being affected. Other crop management systems, especially cover crops, have been shown to be effective in this regard. The fundamental principle of this rehabilitation has been that fertilizers provide the catalyst that drives the system by increasing yields which translates into increased residue input and, hence, increased SOM (e.g. Donigian et al. [1997]; Figure 6).

Pieri (1998, 7), citing the work of others, writes that there has been a large-scale expansion of such techniques, based on agro-ecological principles, in the tropical developing world, particularly in South America:

> The interesting point is that this trend in favor of "agro-ecological" farming systems is growing under tropical conditions, based upon the application of skills and knowledge in

---

[90] Now the Natural Resources Conservation Service.

> managing the biological cycles and interactions that determine crop productivity, soil fertility and other aspects of agro-ecosystem characteristics (Woomer and Swift 1994).
>
> The combination of no-till cover crop and mulch, epitomizes this new way of doing agriculture, based upon crop rotation, integration with livestock production, inputs and management practices that *"foster positive ecological relationships and biological processes within the agro-ecosystem as a whole"* (National Research Council 1993). Latin America has achieved adoption in the 90's of no-till on more than 14 million hectares (Derpsch 1998), from an initial start in the agricultural year 1972/73....

6.2.3. Integrating Crop-Based Fertilizer Strategies with Soil-Based Organic Strategies

SFI is the preeminent example of recent efforts that focus on reversing the decline in soil fertility to achieve increased efficiency and profitability as opposed to crop production-focused "green revolution" approaches (see Section 6.2. re: SG2000 programs). According to Breman (1998, 2), SFI "was launched during the World Food Summit in Rome in November 1996.... The SFI's objective is to foster greater understanding of both the factors contributing to soil fertility decline and potential solutions, and to act as a catalyst for further participation in the design and implementation of comprehensive soil management programs." Partners include FAO, IFDC, ICRAF, International Fertilizer Industry Association (IFA), International Food Policy Research Institute (IFPRI), the United States Agency for International Development (USAID), and the World Bank.

From a biophysical standpoint, the underlying philosophy is the same as that of this paper, i.e., that fertilizers or organic inputs/systems are not enough on their own to rehabilitate the depleted soils of SSA and that they must be combined to be effective on a large scale. The SFI strategy is broad-based, however, and goes well beyond biophysical strategies, including economic and policy strategies. For example, the goals of IFDC under the partnership is summarized by Breman (1998, 2) as follows: "IFDC's contribution will be to provide baseline recommendations on improving and maintaining soil fertility in targeted countries and to promote fertilizer sector development through policy reform, capacity building, and the expansion of efficient private sector agribusiness enterprises."

The primary organizational vehicle of SFI is through the implementation of "National Action Plans" for the rehabilitation and management of soil fertility. To date, such action plans have been completed in Burkina Faso and Ghana; are in progress in Benin, Eritrea, Ethiopia, Guinea, Madagascar, Malawi, Mali, Niger, Rwanda, Senegal, Uganda, and Zambia; and are expected to be initiated in Nigeria, Tanzania, Togo, and Zimbabwe.

The principal constraint of the SFI approach may be opposite to that of the SG 2000 approach. Where SG 2000 may be too singularly focused and not sufficiently comprehensive, SFI may be too unfocussed, broad, and unwieldy with too many participating agencies and agendas. This creates the potential for an approach that is too diffuse or diluted. It is especially difficult to create an effective focused program using "participatory strategies," as SFI is attempting to do via national action strategies. The participatory approach can be useful and even critical, when program objectives are unknown and require input and implementation by stakeholders or at the field level, when farmers are poorly educated and/or unfamiliar with effective agronomic strategies.

However, this approach also has the potential to lead a program in a multitude of directions, in which strategies are focused on the specific goals and desires of the various participating groups (the underlying principle of the participatory approach). In the case of achieving increased productivity and rehabilitation for the soils of SSA, the objectives are clear. To achieve these objectives, relatively strict core strategies should be adopted (as in SG 2000) since the primary technical knowledge is well-established on how to reverse long-term declines.

Sanders and Ahmed (1998) have compared the Burkina Faso national action plan (under SFI) with the SG 2000 program in Ethiopia, discussed previously. According to the authors, the Burkina plan is inappropriately focused on developing a national plan for rehabilitation of soil fertility based on the projected success of the national rock phosphate industry as a source of P fertilizer: "Given the insolubility of rock phosphate, it is projected to take a long time to get farm level benefits. Governments appreciate the foreign exchange savings utilizing rock phosphate and often appeal to a type of economic nationalism. Rock phosphate may not be soluble or cost-efficient but it is a local resource not controlled by multi-national firms." (Sanders and Ahmed 1998, 5-6). Thus, the authors suggest that the Burkina plan, developed by the national government of Burkina Faso through SFI, is based on an unsound premise which may or may not show results for the farmers of that country.

The authors contrast this example with the SG 2000 Ethiopian program which is based on proven strategies that have been effective for raising productivity and profitability for farmers in many regions of the world: "The increased demands for seed and fertilizer, despite some decline in 1997-98 with the removal of the retail fertilizer subsidies, are demonstrating that the strategy is working. Farmers are getting higher yields, they are making money, and input markets are evolving with the entrance of new firms into the fertilizer industry." (Sanders and Ahmed 1998, 4)

This is not to say that alternative sources of nutrients such as rock phosphate should not be addressed. Successful on-farm research trials have shown positive results (both agronomic and economic) for combining rock phosphate with organic amendments in countries such as Kenya.[91] Use of alternative strategies that have not been proven on a large scale, however, should not become the centerpiece of national action plans or strategies. As stated by Sanders and Ahmed (1998, 9): "Is it really likely that sub-Saharan Africa will discover new methods to increase crop yields [on a continent-wide scale] that are different from what is being done in the rest of the world? For how long is it worthwhile to hold up on just adapting what is done in the rest of the world to increase crop yields while searching for new, unique solutions? The magic-solution

---

[91] In Kenya, ICRAF experiments with farmers compared traditional maize-bean intercropping with no external inputs to three alternative systems, each with an initial rock phosphate investment of 250 kg P/ha. The three treatments were urea (N) fertilizer; green manure biomass transfer of *Tithonia*; and improved agro-forestry fallow of *Sesbania* (Sanchez et al. 1997; Pieri 1998).

approach of national programs believing that they are going to make a breakthrough in soil fertility improvement without their farmers incurring out of pocket expenses and without utilizing foreign exchange for fertilizer imports threatens to further delay the improvement of yields in sub-Saharan Africa."

Taking the suggestion of Breman that the opposing schools of intensive high-input agriculture and “eco-intensive” farming work together in SSA, it seems logical that donors take advantage of high input programs that are already working, especially in terms of systems that deliver higher yields and profits to farmers (e.g., the SG2000-Ethiopia program) and "piggy-back" organic complementary systems (cover crops, agroforestry, etc) onto the already-existing system. Based on extensive research experience by its partner organizations, SFI has a broad array of complementary organic systems/amendments that are designed to work with intensive fertilizer inputs and have the potential of rehabilitating the soils of SSA based on SOM principles outlined in this paper.

As suggested by Pieri (1998), an important component of this rehabilitation effort will be to find successful ways to adapt “agro-ecological” farming systems that have been successful elsewhere (especially in tropical South America) such as no-till (or other mulch tillage) and specific cover crop/ agroforestry systems adapted to small-scale farms in SSA. While cover crop and agroforestry research by IFDC, ICRAF and other SFI partners has been extensive, mulch tillage research has been limited and will require special efforts to get up to speed.

Such an integrated approach would join the SG 2000 type of crop-focused program with programs such as SFI that promote more organic methods to develop a single comprehensive strategy. This approach combines the advantages of an effective crop-based system with a soils-based system that is needed to halt the degradation of African soils and create an efficient, sustainable agricultural base. The SFI, given its broad set of partners representing diverse approaches to soil fertility issues, should play a major role in promoting this type of integrated approach. In doing so, SFI must make an effort to build on existing programs (either soil or crop based) by promoting the introduction of missing elements rather than by trying to build new programs from scratch. This is critical given the limited funding that is currently available in SSA. Despite the enormous political difficulties of such an integrated approach, it is, arguably, the most direct and efficient strategy currently available in SSA to get fertilizers and complementary systems out to farmers via demonstration plots and extension support services.

There is, of course, the distinct possibility that some regions or countries in SSA are currently achieving increased productivity and soil fertility in their own ways. This is more likely to be the case in countries where sufficiently high levels of fertilizer, residue, and manure inputs are common practice, such as certain regions of Kenya and Zimbabwe (Palm, Myers, and Nandwa 1997). It would be worthwhile carrying out appraisals of these regions to learn if alternative strategies are available. Likewise, more information needs to be made available on the successes and failures of programs elsewhere in SSA if the region is to learn from past experiences and countries are to benefit from lessons learned by their neighbors.

Finally, it is important that long-term multi-country monitoring studies on SOM levels be supported, similar to those that have been carried out in North America, using predictive models such as CENTURY to estimate SOM trends over time. Estimates can be used in agronomic and agro-economic studies (e.g. Woomer et al. 1997) to arrive at better estimates of impacts and the possibility of making comparisons between countries.

This section has focused on national strategies for possible adoption by governments, donors, and international development organizations. Understandably, we have reviewed only a few of the more prominent programs and options for improving soil quality in SSA, with a focus on better documented programs such as the SFI and SG 2000. It is important to remember that there are alternative approaches which can be effective in adopting "agro-ecological" systems, as seen in South America. First, farmers can take the initiative in developing new strategies, especially through the leadership of farmer organizations. In this case, researchers as well as development and extension workers will need to learn from and assist farmers in their efforts. Secondly, NGO's can play a critical role in introducing new technologies or systems. For example, in the case of no-till in Paraguay, GTZ under the leadership of Rolf Derpsch worked first with large-scale farmers to develop successful models, then with both large and small-scale farmers (mixed stage). Now, in the third stage, they are working primarily with small-scale farmers to introduce integrated no-till systems with low-cost appropriate technology (Weight 1999).

7. CONCLUSIONS

- Declining soil fertility and SOM levels in SSA are primarily a result of agriculture-induced degradative processes (especially soil mining, tillage, and accelerated erosion) that can be reversed using high levels of nutrient inputs as part of "agro-ecological" farming systems to recapitalize the soil.[92] The extent to which farmers are willing to recapitalize soils depends on both technical feasibility and financial profitability.

- Fertilizer is recommended for recapitalization because nutrients available from organic sources in low-fertility African ecosystems are not adequate.

- The primary positive impact of fertilizers is to increase the biological base of the plant/soil system resulting in increased crop yields. If the system is properly managed, the outcome can be a fertile and efficient cycling system for nutrients and water due to improved soil structure associated with increased levels of SOM and impacts of roots and fungal hyphae. Since there is competition for uses of crop residues (fuel, construction, animal feed), biomass production needs to increase and alternatives need to be found to satisfy other demands for crop residues.

- Fertilizers and organic matter are complements rather than substitutes – both are recommended to recapitalize SSA soils. Fertilizer can increase crop yields and residues; maximum levels of residues (or equivalent manure) should be returned to the soil.

- Because of the very high quantities of residue or manure required to reverse declines in SOM and a lack of availability of these materials at these levels, integrated "eco-intensive" systems are recommended to create an aggrading system, including mulch or conservation tillage (CT) and agroforestry/cover crops (A/CC) and rotations.

- Both CT and A/CC systems address specific constraints to production in SSA, especially (i) soil mining due to low input agriculture, (ii) low rainfall levels,[93] (iii) poor soil structural stability resulting in very low water and nutrient-use efficiency as well as crusting and sealing, (iv) accelerated rates of decomposition due to tillage, and (v) lack of vegetative cover with increased erosion and soil temperatures.

- Fertilizers and organic inputs, in combination with these systems, address these constraints in the following ways: Providing ecologically based recapitalization strategies with long-term

---

[92] There are"agro-ecological" systems (e.g. "natural farming") which do not include use of fertilizers (or high inputs of organic matter). Unfortunately, there is little research or other material available on theses strategies, making it difficult to evaluate their effectiveness. Also, the systems are idiosyncratic by nature, requiring a certain philosophical approach by the farmer. For these reasons, it would be inappropriate to promote them on a national or large-scale basis. However, if found to be effective, they should be encouraged as alternative systems due to their potential to restore agro-ecosystems and avoid pollution.

[93] Relative to other continents.

build-up and stabilization of SOM[94] addresses constraints (i), (ii), and (iii); minimum tillage addresses constraint (iv); and providing vegetative cover near the soil surface addresses constraint (v). The estimated benefits for improved nutrient and water use efficiency are increased nutrient uptake (crop recuperation rate) at two times current levels and increased water uptake at three to five times current levels.

- To increase the return of organic inputs to the soil, SSA needs to encourage (i) increased biomass production (via use of inorganic fertilizers or alternative indigenous strategies), (ii) alternative fuel sources (e.g., bottled gas or kerosene for cooking – at least in urban areas), (iii) alternative construction materials (agroforestry-based sources, live fences rather than millet stalk fences, tin roofs rather than straw), (iv) integration of livestock and crop production in ways that protect residues or return equivalent manure to the soil (e.g. intensive rotational grazing adapted to SSA conditions), and (v) financial incentives for farmers to make recapitalization investments (fertilizer subsidies for farmers who adapt recommended strategies; funds for appropriate equipment; seeds for cover crops).

- Assuming SSA succeeds in substantially increasing the use of fertilizer, it will be necessary to monitor for signs of negative side effects and, when necessary, institute policies that adjust economic incentives so that private decisions to use fertilizer are made in an environmentally friendly way that diminishes these negative impacts. Of particular concern are:

    (i) Acidification of soils by ammonium-N fertilizers which can result in serious declines in yields and soil quality. This can be addressed by use of non-acidifying nitrate fertilizers and application of lime or lime plus manure.

    (ii) Negative impacts on traditional systems and environments especially when extensive management systems are implemented that take over from appropriate traditional soil management practices. Management systems need to be more sensitive to traditional values and knowledge systems.

    (iii) Non-point source pollution of water resources which is the result of excessive fertilizer use. This can be addressed by developing more efficient "agro-ecological" systems with minimal losses to leaching/ runoff and avoiding excessive use of fertilizers beyond crop nutrient requirements.

    (iv) Increased CO_2 emissions (greenhouse gasses) associated with fertilizer-based conventional agricultural systems. More efficient systems result in lower levels of SOC that are lost to atmospheric CO_2 via decomposition and increased sequestration of CO_2 into the plant/soil system.

Hopefully, these practices will be increasingly integrated into fertilizer-based management systems in SSA to minimize the negative impacts of fertilizers.

---

[94] Resulting in increased soil structural stability and increased water and nutrient use efficiency and infiltration rates.

- Strategies must be efficient and profitable for the farmer. Farmers in SSA are not interested in purchasing costly fertilizers if crop recuperation rates are only 15% (for P) and 35% (for N).[95] Estimated doubling of these rates due to increased nutrient-use efficiency should promote fertilizer use and serve as a basis for increased productivity and profitability (Breman 1998).

  Much of the success of no-till systems in tropical South America has been due to their efficiency and profitability, including limiting, and in some cases, suspending application of fertilizers once the system has been established. Similarly, water-use efficiency, perhaps the most critical factor for sustainability in African agriculture, has been shown to increase in established no-till systems with stable or increased yields during periods of drought stress. Lessons from these strategies should be transferable to SSA (Pieri 1998). Efforts are being made to determine economically sound integrated systems that combine nutrient recapitalization with integrated agricultural and/or agroforestry systems (Woomer et al. 1997).

- Farmers in SSA need to adapt systems to fit environmental conditions and learn the specific management skills of these systems. First, the system must be appropriate to climatic or soil conditions. Second, the level of intensity of the system(s) will depend on the quality/potential of the soil. Finally, specific management skills need to be learned for the systems being used. Extension agents can play an important role in providing training and demonstrations to farmers and will need to be trained themselves in order to be effective.

- Broad-based national programs to increase fertilizer use for recapitalization of soils (vs. small-scale uncoordinated research and NGO projects) have the greatest potential for large-scale impacts. National programs should integrate fertilizer/crop-based “green revolution” programs/strategies (e.g. SG 2000-Ethiopia) that are already in place, and showing positive results with new soil-based "agro-ecological" programs/strategies, (such as those promoted by the SFI).

SSA has an historic opportunity to reverse the current trends of stagnant productivity and declining soil fertility. The challenge is to begin the enormous process of moving SSA from the low point of the soil degradation curve to levels which are close to pre-disturbance (native) fertility. Effectively, this means that long-term fallows, which accomplished this task in the past, need to be replaced by (or adapted to) appropriate integrated systems that include fertilizers or other effective input sources, no-till (or mulch tillage), cover crops, rotations, and/or agroforestry practices based on sound "agro-ecological" principles. That is, systems that take advantage of natural restorative processes and are, therefore, efficient in terms of fertilizer and water requirements as well as costs and labor. This is especially critical for smallholder farmers who make up the vast majority of agricultural producers in SSA and are faced with severe economic and technical constraints. Once fertility and SOM levels are restored, the primary objective will be to maintain a "sustainable" balanced system with equivalent inputs/outputs of nutrients and C, as in a natural, undisturbed systems...

---

[95] Based on Sudanian/Sahelian West African estimates (Groot et al. 1998).

As has been illustrated in this paper, there is currently a fortuitous convergence of benefits associated with (i) sequestration of CO_2 into agroecosystems for reduction of greenhouse gasses which (ii) results in build-up of SOM for increased efficiency, productivity, and sustainability of farming systems (iii) including an efficient, "synchronistic" nutrient cycling system that minimizes losses to ground and surface water. In this period of decreased funding opportunities, such a convergence of interests and benefits has begun to result in more inter-disciplinary studies in which donors can see the potential for synergistic solutions to environmental, agricultural and economic problems. What is needed now is a concerted and coordinated effort among farmers and farmer organizations, governments, donors, scientific organizations, NGOs, and private industry to move forward in developing an effective strategy.

REFERENCES

Anderson, J. and J. Thampapillai. 1990. *Soil Conservation in Developing Countries: Project and Policy Intervention.* The World Bank: Washington, DC.

Angers, Denis A., and Claire Chenu. 1997. Dynamics of Soil Aggregation and C Sequestration. In *Soil Processes and the Carbon Cycle*, ed. Rattan Lal, John M. Kimble, Ronald F. Follett, and Bobby A. Stewart. Boca Raton: CRC Press.

Balesdent, J., G.H. Wagner, and A. Mariotti. 1988. Soil Organic Matter Turnover in Long-term Field Experiments as Revealed by Carbon-13 Natural Abundance. *Soil Science Society of America Journal* 52:118-124.

Bationo, A. 1998. Water Use Efficiency Review. Niamey, Niger: ICRISAT. Photocopy.

Bationo, A., A. Buerkert, M.P. Sedogo, C.B. Christianson, and A.U. Mokwunye. 1993. A Critical Review of Crop-Residue Use as Soil Amendment in the West African Semi-Arid Tropics. In *Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems in Sub-Saharan Africa. Volume II: Technical Papers: Proceedings of an International Conference held in Addis Ababa, Ethiopia, 22-26 November, 1993,* ed. J.M. Powell, S. Fernandez-Rivera, T. Williams, and C. Renard. Addis Ababa: International Livestock Centre for Africa.

Bationo, A., C.B. Christianson, and A.U. Mokwunye. 1989. Soil Fertility Management of the Pearl Millet-Producing Sandy Soils of Sahelian West Africa: The Niger Experience. In *Soil, Crop, and Water Management Systems for Rainfed Agriculture in the Sudano-Sahelian Zone: Proceedings of an International Workshop held in Niamey, Niger, Jan 7-11, 1987,* ICRISAT Conference Paper No. CP 413, Patancheru, India: ICRISAT.

Bationo, A., and A.U. Mokwunye. 1991. Role of Manures and Crop Residues in Alleviating Soil Fertility Constraints to Crop Production: With Special Reference to the Sahelian and Sudanian Zones of West Africa. In *Alleviating Soil Fertility Constraints to Increased Crop Production in West Africa,* ed. A.U. Mokwunye. Dordrecht: Kluwer Academic Publishers.

Bekunda, Mateete A., Andre Bationo, and Henry Ssali. 1997. Soil Fertility Management in Africa: A Review of Selected Research Trials. In *Replenishing Soil Fertility in Africa,* Soil Science Society of America (SSSA) Special Publication No. 51, ed. Roland Buresh, Pedro Sanchez, and Frank Calhoun. Madison: American Society of Agronomy and Soil Science Society of America.

Borlaug, N., and C. Dowswell. 1995. Mobilising Science and Technology to Get Agriculture Moving in Africa. *Development Policy Review* 13:115-29.

Brady, N. 1990. *The Nature and Properties of Soils*. Tenth Edition. New York: MacMillan Publishers.

Breman, Henk. 1998. Soil Fertility Improvement in Africa, A Tool for or a By-product of Sustainable Production. *African Fertilizer Market* 11.5 (June): 2-10.

Breman, Henk, and Jan-Joost Kessler. 1995. *Woody Plants in Agro-Ecosystems of Semi-Arid Regions*. Berlin: Springer-Verlag.

Breman, Henk, and Keffing Sissoko (ed.). 1998. *L'intensification Agricole au Sahel.* Paris: KARTHALA.

Brouwer, J. 1997. Agricultural Production in the Sahel: What Could Science Have to Add? *Haramata*, July.

Brouwer, J., and J. Bouma. 1997. *Soil and Crop Growth Variability in the Sahel: Highlights of Research (1990-95) at ICRISAT Sahelian Center*. Information Bulletin No. 49. ICRISAT, Patencheru, Andra Pradesh, India and Agricultural University of Wageningen, the Netherlands.

Cavigelli, Michel A. 1998. Carbon. In *Michigan Field Crop Ecology: Managing Biological Processes for Productivity and Environmental Quality*, Michigan State University Extension Bulletin E-2646, ed. M.A. Cavigelli, S.R. Deming, L.K. Probyn, and R.R. Harwood. East Lansing: Michigan State University Extension and Michigan Agricultural Experiment Station.

Conservation Technology Information Center. 1997. *National Crop Residue Management Survey: 1997 Executive Summary.* West Lafayette: Conservation Technology Information Center.

Cooperative Extension Service, Kansas State University. 1995. *Great Plains Dryland Conservation Technologies: Enhancing Agricultural Profitability & Sustainability.* Bulletin S-81. Manhattan: Cooperative Extension Service, Kansas State University.

Cross, Nigel, and Rhiannon Barker. 1991. *At the Desert's Edge: Oral Histories from the Sahel.* London: Panos Publications Ltd.

Diatta, S., and P. Siband. 1998. Evolution des sols sous culture continue: Le cas des sols rouges ferrallitiques du sud du Senegal. In *Soil Fertility Management in West African Land Use Systems: Proceedings of the Regional Workshop, University of Hohenheim, ICRISAT Sahelian Centre, and INRAN, 4-8 March 1997, Niamey, Niger*, ed. Genevieve Renard, Andreas Neef, Klaus Becker, and Matthias von Oppen. Weikersheim, Germany: Margraf Verlag.

Donigian, A.S., Jr., A.S. Patwardhan, R.V. Chinnaswamy, and T.O. Barnwell. 1997. Modeling Soil Carbon and Agricultural Practices in the Central U.S.: An Update of Preliminary Study Results. In *Soil Processes and the Carbon Cycle,* ed. Rattan Lal, John M. Kimble, Ronald F. Follett, and Bobby A. Stewart. Boca Raton: CRC Press.

Duxbury, John M., M. Scott Smith, and John W. Doran with Carl Jordan, Larry Szott, and Eric Vance. 1989. Soil Organic Matter as a Source and a Sink of Plant Nutrients. In *Dynamics of Soil Organic Matter in Tropical Ecosystems: Result of a Conference held at the Maui Beach Hotel, Kahului, Maui, Hawaii, October 7-15, 1988, hosted by the NifTAL Project, University of Hawaii,* ed. David C. Coleman, J. Malcolm Oades, and Goro Uehara. Manoa: NifTAL Project, University of Hawaii at Manoa.

Eswaran, Hari, Russell Almaraz, Evert van den Berg, and Paul Reich. 1997. An Assessment of the Soil Resources of Africa in Relation to Productivity. *Geoderma* 77: 1-18.

Eswaran, H., F.H. Beinroth, J. Kimble, and T. Cook. 1992. Soil Diversity in the Tropics: Implications for Agricultural Development. In *Myths and Science of Soils of the Tropics: Proceedings of an International Symposium held in Las Vegas, Nevada, Oct. 17, 1989,* SSSA Special Publication No. 29, ed. R. Lal and P.A. Sanchez. Madison: American Society of Agronomy and Soil Science Society of America.

Follett, Roy H., Larry S. Murphy, and Roy L. Donahue. 1981. *Fertilizers and Soil Amendments.* Englewood Cliffs, New Jersey: Prentice-Hall, Inc.

Food and Agriculture Organization of the United Nations (FAO). 1987. *Fertilizer Strategies,* FAO Land and Water Development Series, No. 10. Rome: FAO.

Fukuoka, Masanobu. 1978. *The One-Straw Revolution: An Introduction to Natural Farming.* Emmaus, Pennsylvania: Rodale Press.

Giller, Ken E., Georg Cadisch, Costas Ehaliotis, Edward Adams, Webster D. Sakala, and Paramu L. Mafongoya. 1997. Building Soil Nitrogen Capital in Africa. In *Replenishing Soil Fertility in Africa,* SSSA Special Publication No. 51, ed. Roland Buresh, Pedro Sanchez, and Frank Calhoun. Madison: American Society of Agronomy and Soil Science Society of America.

Greenland, D.J., A. Wild, and D. Adams. 1992. Organic Matter Dynamics in Soils of the Tropics – From Myth to Complex Reality. In *Myths and Science of Soils of the Tropics: Proceedings of an International Symposium held in Las Vegas, Nevada, Oct. 17, 1989,* SSSA Special Publication No. 29, ed. R. Lal and P.A. Sanchez. Madison: American Society of Agronomy and Soil Science Society of America.

Groot, J.J.R., D. Kone, and P. de Willigen. 1998. L'utilisation de l'engrais chimique pour une intensification durable de l'agriculture. In *L'intensification Agricole au Sahel,* ed. Henk Breman and Keffing Sissoko. Paris: KARTHALA.

Himes, F.L. 1997. Nitrogen, Sulfur, and Phosphorus and the Sequestering of Carbon. In *Soil Processes and the Carbon Cycle*, ed. Rattan Lal, John M. Kimble, Ronald F. Follett, and Bobby A. Stewart. Boca Raton: CRC Press.

Howard, J., Mulat Demeke, V. Kelly, M. Maredia, and J. Stepanek. 1998a. *Can the Momentum be Sustained? An Economic Analysis of the Ministry of Agriculture/Sasakawa-Global 2000's Experiement with Improved Cereals Technology in Ethiopia.* MSU Department of Agricultural Economics Staff Paper 98-25. East Lansing: Michigan State University.

Howard, J., J. Jeje, D. Tschirley, P. Strasberg, E. Crawford and M. Weber. 1998b. *What Makes Agricultural Intensification Profitable for Mozambican Smallholders? An Appraisal of the Inputs Subsector and the 1996/97 DNER/SG2000 Program.* MSU International Development Working Paper No. 69. East Lansing: Michigan State University.

Ibewiro, B., B. Vanlauwe, N. Sanginga, and R. Merckx. 1998. Nitrogen Contributions of Roots to Succeeding Maize in Herbaceous Legume Cover Cropping Systems in a Tropical Derived Savanna. In *Soil Fertility Management in West African Land Use Systems: Proceedings of the Regional Workshop, University of Hohenheim, ICRISAT Sahelian Centre, and INRAN, 4-8 March 1997, Niamey, Niger,* ed. Genevieve Renard, Andreas Neef, Klaus Becker, and Matthias von Oppen. Weikersheim: Margraf Verlag.

Janzen, H.H., C.A. Campbell, E.G. Gregorich, and B.H. Ellert. 1997. Soil Carbon Dynamics in Canadian Agroecosystems. In *Soil Processes and the Carbon Cycle*, ed. Rattan Lal, John M. Kimble, Ronald F. Follett, and Bobby A. Stewart. Boca Raton: CRC Press.

Jastrow, J. D., and R.M. Miller. 1997. Soil Aggregate Stabilization and Carbon Sequestration: Feedbacks through Organomineral Associations. In *Soil Processes and the Carbon Cycle*, ed. Rattan Lal, John M. Kimble, Ronald F. Follett, and Bobby A. Stewart. Boca Raton: CRC Press.

Kristof, Nicholas D. 1997. Poisoned Lands. *New York Times,* 28-29 November, sec. A.

Lal, R. 1987. *Tropical Ecology and Physical Edaphology*. New York: John Wiley and Sons.

Lal, R. 1997. Land Use and Soil Management Effects on Soil Organic Matter Dynamics on Alfisols in Western Nigeria. In *Soil Processes and the Carbon Cycle*, ed. Rattan Lal, John M. Kimble, Ronald F. Follett, and Bobby A. Stewart. Boca Raton: CRC Press.

Lal, R., J. Kimble, and R. Follett. 1997. Need for Research and Need for Action. In *Management of Carbon Sequestration in Soil*, ed. Rattan Lal, John M. Kimble, Ronald F. Follett, and Bobby A. Stewart. Boca Raton: CRC Press.

Lal, Rattan. 1990. *Soil Erosion in the Tropics: Principles and Management.* New York: McGraw-Hill, Inc.

Mokwunye, A. Uzo, and L.L. Hammond. 1992. Myths and Science of Fertilizer Use in the Tropics. In *Myths and Science of Soils of the Tropics: Proceedings of an International Symposium held in Las Vegas, Nevada, Oct. 17, 1989,* SSSA Special Publication No. 29, ed. R. Lal and P.A. Sanchez. Madison: American Society of Agronomy and Soil Science Society of America.

Mutch, Dale R., and Todd E. Martin. 1998. Cover Crops. In *Michigan Field Crop Ecology: Managing Biological Processes for Productivity and Environmental Quality*, Michigan State University Extension Bulletin E-2646, ed. M.A. Cavigelli, S.R. Deming, L.K. Probyn, RR. Harwood. East Lansing: Michigan State University Extension and Michigan Agricultural Experiment Station.

Myers R.J.K., C.A. Palm, E. Cuevas, I.U.N. Gunatilleke, and M. Brossard. 1994. The Synchronisation of Nutrient Mineralisation and Plant Nutrient Demand. In *The Biological Maintenance of Tropical Soil Fertility,* ed. P. Woomer and M. Swift. New York: J. Wiley & Sons.

Nicholson, S.E. 1996. Environmental Change Within the Historical Period. In *The Physical Geography of Africa,* ed. W.M. Adams, A.S. Goudie, and A.R. Orme. Oxford: Oxford University Press.

Omay, A., C. Rice, L. Maddux, and W. Gordon. 1997. Changes in Soil Microbial and Chemical Properties under Long-term Crop Rotation and Fertilization. *Soil Science Society of America Journal* 61: 1672-1678.

Palm, Cheryl A., Robert J.K. Myers, and Stephen M. Nandwa. 1997. Combined Use of Organic and Inorganic Nutrient Sources for Soil Fertility Maintenance and Replenishment. In *Replenishing Soil Fertility in Africa,* SSSA Special Publication No. 51, ed. Roland Buresh, Pedro Sanchez, and Frank Calhoun. Madison: American Society of Agronomy and Soil Science Society of America.

Parton, William J., Robert L. Sanford, Pedro A. Sanchez, and John W.B. Stewart with Torben A. Bonde, Dac Crosley, Hans van Veen, and Russell Yost. 1989. Modeling Soil Organic Matter Dynamics in Tropical Soils. In *Dynamics of Soil Organic Matter in Tropical Ecosystems: Result of a Conference held at the Maui Beach Hotel, Kahului, Maui, Hawaii, October 7-15, 1988, hosted by the NifTAL Project, University of Hawaii,* ed. David C. Coleman, J. Malcolm Oades, and Goro Uehara. Manoa: NifTAL Project, University of Hawaii at Manoa.

Patwardhan, A.S., A.S. Donigian, Jr., R.V. Chinnaswamy, and T.0. Barnwell. 1997. A Retrospective Modeling Assessment of Historic Changes in Soil Carbon and Impacts of Agricultural Development in Central U.S.A., 1900 to 1990. In *Soil Processes and the Carbon Cycle,* ed. Rattan Lal, John M. Kimble, Ronald F. Follett, and Bobby A. Stewart. Boca Raton: CRC Press.

Paustian, Keith, Harold P. Collins, and Elder A. Paul. 1997. Management Controls on Soil Carbon. In *Soil Organic Matter in Temperate Agroecosystems: Long-Term Experiments in North America,* ed. EA. Paul, E.T. Elliott, K. Paustian, and C.V. Cole. Boca Raton: CRC Press.

Pawluk, Roman R., Jonathan A. Sandor, and Joseph A. Tabor. 1992. The Role of Indigenous Soil Knowledge in Agricultural Development. *Journal of Soil and Water Conservation,* July-August: 298-302.

Penning de Vries, F.W.T., and M.A. Djiteye (ed.). 1991. *La productivite des paturages saheliens: Une etude des sols, des vegetations et de l'exploitation de cette resource naturelle.* Wageningen: Pudoc.

Pieri, Christian J.M.G. 1992. *Fertility of Soils: A Future for Farming in the West African Savannah.* Berlin: Springer-Verlag.

Pieri, Christian. 1998. *Soil Fertility Improvement as a Key Connection Between Sustainable Land Management and Rural Well Being.* Keynote address to the 16th World Congress of Soil Science, Commission IV, Soil Fertility and Plant Nutrition, August, Montpelier, France.

Place, Frank M. 1995. Cost-benefit Analyses of Selected Agroforestry Technologies. Nairobi: ICRAF. Photocopy.

Pretty, J. 1995. *Regenerating Agriculture*. London: Earthscan Publications Ltd.

Quinones, Marco A., Norman E. Borlaug, and Christopher R. Dowswell. 1997. A Fertilizer-Based Green Revolution for Africa. In *Replenishing Soil Fertility in Africa,* SSSA Special Publication No. 51, ed. Roland Buresh, Pedro Sanchez, and Frank Calhoun. Madison: American Society of Agronomy and Soil Science Society of America.

Reardon, Thomas. 1997. African Agriculture: Productivity and Sustainability Issues. In *Agricultural Development in the Third World,* Third Edition, ed. C. Eicher and J. Staatz. Baltimore: Johns Hopkins University Press.

Robertson, G. Philip. 1998. Field Crop Ecosystems. In *Michigan Field Crop Ecology: Managing Biological Processes for Productivity and Environmental Quality,* Michigan State University Extension Bulletin E-2646, ed. M.A. Cavigelli, S.R. Deming, L.K. Probyn, R.R. Harwood. East Lansing: Michigan State University Extension and Michigan Agricultural Experiment Station.

Saka, A.R., R.I. Green, and D.H. Ng'ong'ola. 1995. Soil Management in sub-Saharan Africa: Proposed Soil Management Action Plan for Malawi. Photocopy.

Sanchez, Pedro A. 1976. *Properties and Management of Soils in the Tropics*. New York: Wiley and Sons.

Sanchez, Pedro A. 1998. A Soil Scientist at an Economics Conference: USA Trip Report. E-Mail.

Sanchez, Pedro A., and Terry J. Logan. 1992. Myths and Science about the Chemistry and Fertility of Soils in the Tropics. In *Myths and Science of Soils of the Tropics: Proceedings of an International Symposium held in Las Vegas, Nevada, Oct. 17, 1989,* SSSA Special Publication No. 29, ed. R. Lal and P.A. Sanchez. Madison: American Society of Agronomy and Soil Science Society of America.

Sanchez, Pedro A., Keith D. Shepherd, Meredith J. Soule, Frank M. Place, Roland J. Buresh, Anne-Marie N. Izac, A. Uzo Mokwunye, Fred R. Kwesiga, Cyrus G. Ndiritu, and Paul L. Woomer. 1997. Soil Fertility Replenishment in Africa: An Investment in Natural Resource Capital. In *Replenishing Soil Fertility in Africa,* SSSA Special Publication No. 51, ed. Roland Buresh, Pedro Sanchez, and Frank Calhoun. Madison: American Society of Agronomy and Soil Science Society of America.

Sanders, John H., and Mohamed Ahmed. 1998. Developing a Fertilizer Strategy for Sub-Saharan Africa. West Lafayette: Purdue University. Photocopy.

Sanders, John H., Barry I. Shapiro, and Sunder Ramaswamy. 1996. *The Economics of Agricultural Technology in Semiarid Sub-Saharan Africa.* Baltimore: The Johns Hopkins University Press.

Schwab, A.P., C.E. Owensby, and S. Kulyingyong. 1990. Changes in Soil Chemical Properties due to 40 Years of Fertilization. *Soil Science* 149. 1:35-42.

Smaling, E.M.A. 1993a. An Agroecological Framework for Integrating Nutrient Management, with Special Reference to Kenya. Ph.D. dissertation, Agricultural University, Wageningen, the Netherlands.

Smaling, E.M.A. 1993b. Soil Nutrient Depletion in Sub-Saharan Africa. In H. van Reuler and W.H. Prins (eds.) *The Role of Plant Nutrients for Sustainable Food Crop Production in Sub-Saharan Africa*. Leidschendam (Netherlands): Dutch Association of Fertilizer Producers.

Smaling, E.M.A., S.M. Nandwa, H. Prestele, R. Roetter, and F.N. Muchena. 1992. Yield Response of Maize to Fertilizers and Manure under Different Agro-ecological Conditions in Kenya. *Agriculture, Ecosystems and Environment* 41: 241-252.

Stewart, B.A., R. Lal, and S.A. El-Swaify. 1991. Sustaining the Resource Base of an Expanding World Agriculture. In *Soil Management for Sustainability, Papers from a Workshop in Edmonton, Alberta, Aug. 1989,* ed. R. Lal and F.L. Pierce. Soil and Water Conservation Society.

Stocking, Michael A. 1996. Soil Erosion. In *The Physical Geography of Africa,* ed. W.M. Adams, A.S. Goudie, and A.R. Orme. Oxford: Oxford University Press.

Swift, M.J. 1996. *Sustainable Management of the Soil Resource: Developing a Framework for Research and Development.* Washington, DC: The World Bank.

Swift, M.J., P.D. Seward, P.G.H. Frost, J.N.Qureshi, and F.N. Muchena. 1994. Long-term Experiments in Africa: Developing a Database for Sustainable Land Use under Global Change. In *Long-term Experiments in Agricultural and Ecological Sciences: Proceedings of a conference to celebrate the 150th Anniversary of Rothamsted Experimental Station, held at Rothamsted, 14-17 July 1993,* ed. R.A.Leigh and A.E. Johnston. Wallingford, Great Britain: CAB International.

Van der Pol, Floris. 1992. *Soil Mining: An Unseen Contributor to Farm Income in Southern Mali.* Bulletin 325. Amsterdam: Royal Tropical Institute.

Van Keulen, H. and H. Breman. 1990. Agricultural Development in the West African Sahelian Region: A Cure against Land Hunger? *Agriculture, Ecosystems and Environment* 32: 177-197.

Wallace, Michael B. 1997. *Fertilizer Use and Environmental Impacts – Positive and Negative: A Review with Emphasis Upon Inorganic Fertilizers in Africa.* Winrock International Institute for Agricultural Development.

Weight, David. 1999. Report on the 10th International Soil Conservation Organization Conference and No-Till Workshop. Unpublished.

Weight, David and Valerie Kelly.1998. *Restoring Soil Fertility in Sub-Saharan Africa: Technical and Economic Issues.* MSU Policy Synthesis No. 37. East Lansing, Michigan State University.

Woomer, P.L., A. Martin, A. Albrecht, D.V.S. Resck, and H.W. Scharpenseel. 1994. The Importance and Management of Soil Organic Matter in the Tropics. In *The Biological Maintenance of Tropical Soil Fertility,* ed. P. Woomer and M. Swift. New York: J. Wiley and Sons.

Woomer, Paul L., Cheryl A. Palm, Javaid N. Qureshi, and Jean Kotto-Same. 1997. Carbon Sequestration and Organic Resource Management in African Smallholder Agriculture. In *Management of Carbon Sequestration in Soil*. ed. Rattan Lal, John M. Kimble, Ronald F. Follett, and Bobby A. Stewart. Boca Raton: CRC Press.

Yanggen, D., V. Kelly, T. Reardon, and A. Naseem. 1998. *Incentives for Fertilizer Use in Sub-Saharan Africa: A Review of Empirical Evidence on Fertilizer Response and Profitability.* MSU International Development Working Paper No. 70. East Lansing: Michigan State University.

MSU International Development Papers

How to order from the MSU Bulletin Office:

All domestic orders under $100 must be prepaid either by check or credit card. Make checks payable to MICHIGAN STATE UNIVERSITY. Charges against credit cards (VISA and MasterCard) must be accompanied by the card's full number and expiration date and the cardholder's signature and daytime business/home phone number. Orders totaling $100 or more can be billed by MSU. Institutions and firms should use their official purchase order.

All foreign orders must be prepaid only in U.S. dollars by American Express Money Order, International Money Order, U.S.A. Postal Money Order, U.S. Dollar World Money Order, or check, which must be drawn on a United States bank.

For foreign orders, include an additional 20 percent for surface postage. For air mail orders, please call for the appropriate amount due.

Please do not send cash. Payment must be included with orders. All sales are final. When ordering from the Bulletin Office by mail, you will need each item's complete identification number and price. Be sure to print your complete address, including ZIP code.

Fill out and send the order form provided to:

MSU Bulletin Office
10-B Agriculture Hall
Michigan State University
East Lansing, MI 48824-1039
Fax: (517)353-7168
Tel: (517)355-0240
E-mail: distbulk@msue.msu.edu

Selected copies are available free of charge to individuals in developing countries, although supplies of these are limited. If free copies are no longer available, MSU will send you order information. USAID officials may obtain free copies through USAID's Center for Development Information and Evaluation (CDIE) or single copies are available free of charge by writing to the above address at Michigan State University.

Available from the MSU Bulletin Office

MSU INTERNATIONAL DEVELOPMENT PAPERS

IDP 13 .... *Sources and Effects of Instability in the World Rice Market* by T. S. Jayne. 1993. 104 pp. $11.00 **(CDIE reference PN-ABJ-359)**

IDP 14 .... *The Impact of Agricultural Technology in Sub-Saharan Africa: A Synthesis of Symposium Findings* by James F. Oehmke and Eric C. Crawford. 1993. 33 pp. $7.00 **(CDIE reference PN-ABP-321)**

IDP 14F .... *L'Impact de la technologie agricole en Afrique subsaharienne: Synthese des conclusions du colloque* par James F. Oehmke and Eric W. Crawford. 1993. 34 pp. $7.00 **(CDIE reference PN-ABQ-056)**

IDP 15 .... *Market-Oriented Strategies to Improve Household Access to Food: Experience from Sub-Saharan Africa* by T.S. Jayne, D.L. Tschirley, John M. Staatz, James D. Shaffer, Michael T. Weber, Munhamo Chisvo, and Mulinge Mukumbu.* 1994. 61 pp. $9.00 **(CDIE reference PN-ABS-755)**

IDP 16 .... *Improving the Measurement and Analysis of African Agricultural Productivity: Promoting Complementarities between Micro and Macro Data* by Valerie Kelly, Jane Hopkins, Thomas Reardon, and Eric Crawford. 1995. 44 pp. $7.00 **(CDIE reference PN-ABX-166)**

IDP 17 .... *Promoting Food Security in Rwanda Through Sustainable Agricultural Productivity: Meeting the Challenges of Population Pressure, Land Degradation, and Poverty* by Daniel C. Clay, Fidele Byiringiro, Jaakko Kangasniemi, Thomas Reardon, Bosco Sibomana, Laurence Uwamariya, and David Tardif-Douglin. 1995. 115 pp. $11.00 **(CDIE reference PN-ABX-501)**

IDP 18 .... *Promoting Farm Investment for Sustainable Intensification of African Agriculture* by Thomas Reardon, Eric Crawford, and Valerie Kelly. 1995. 37 pp. $7.00 **(CDIE reference PN-ABX-753)**

IDP 19 .... *Effects of Market Reform on Access to Food by Low-Income Households: Evidence from Four Countries in Eastern and Southern Africa* by T.S. Jayne, L. Rubey, D. Tschirley, M. Mukumbu, M. Chisvo, A. Santos, M. Weber, and P. Diskin. 1995. 83 pp. $9.00. **(CDIE reference PN-ABX-754)**

IDP 20 .... *Cash Crop and Foodgrain Productivity in Senegal: Historical View, New Survey Evidence, and Policy Implications* by Valerie Kelly, Bocar Diagana, Thomas Reardon, Matar Gaye, and Eric Crawford. 1996. 140 pp. $13.00 **(CDIE reference PN-ABY-173)**

IDP 21 .... *Fertilizer Impacts on Soils and Crops of Sub-Saharan Africa* by David Weight and Valerie Kelly. 1999. 97 pp. $11.00 **(CDIE reference pending)**

IDP 22 .... *Determinants of Farm Productivity in Africa: A Synthesis of Four Case Studies* by Thomas Reardon, Valerie Kelly, Eric Crawford, Thomas Jayne, Kimseyinga Savadogo, and Daniel Clay. 1996. 50 pp. $7.00 **(CDIE reference PN-ABZ-220)**

WORKING PAPERS

IDWP 39/1 ..... *The Impact of Investments in Maize Research and Dissemination in Zambia. Part I: Main Report*. Julie Howard with George Chitalu and Sylvester Kalonge. 1993. 112 pp. $11.00 **(CDIE reference PN-ABS-724)**

IDWP 39/2 ..... *The Impact of Investments in maize Research and Dissemination in Zambia. Part II: Annexes.* Julie Howard with George Chitalu and Sylvester Kalonge. 1993. 81 pp. $9.00 **(CDIE reference PN-ABS-727)**

IDWP 40 .... *An Economic Analysis of Research and Technology Transfer of Millet, Sorghum, and Cowpeas in Niger* by Valentina Mazzucato and Samba Ly. 1994. 104 pp. $11.00. **(CDIE reference PN-ABT-283 or PN-ABS-728)**

IDWP 41 .... *Agricultural Research Impact Assessment: The Case of Maize Technology Adoption in Southern Mali* by Duncan Boughton and Bruno Henry de Frahan. 1994. 95 pp. $11.00 **(CDIE reference PN-ABS-729)**

IDWP 42 .... *The Rate of Return to Agricultural Research in Uganda: The Case of Oilseeds and Maize* by Rita Laker-Ojok. 1994. 56 pp. $7.00 **(CDIE reference PN-ABS-730)**

IDWP 43 .... *Assessing the Impact of Cowpea and Sorghum Research and Extension in Northern Cameroon* by James A. Sterns and Richard H. Bernsten. 1994. 48 pp. $7.00 **(CDIE reference PN-ABS-731)**

IDWP 44 .... *Food Security II Cooperative Agreement: Project Fact Sheets (1994 Version)* by MSU Food Security II Research Team. 1994. 104 pp. $11.00 **(CDIE reference PN-ABW-277)**

IDWP 45 .... *The Potential Returns to Oilseeds Research in Uganda: The Case of Groundnuts and Sesame* by Rita Laker-Ojok. 1994. 50 pp. $7.00 **(CDIE reference PN-ACF-662)**

IDWP 46 .... Understanding Linkages among Food Availability, Access, Consumption, and Nutrition in Africa: Empirical Findings and Issues from the Literature by Patrick Diskin.* 1994. 47 pp. $7.00 **(CDIE reference PN-ABS-732)**

IDWP 47 .... *Targeting Assistance to the Poor and Food Insecure: A Review of the Literature* by Mattias Lundberg and Patrick Diskin.* 1994. 56 pp. $7.00 **(CDIE reference PN-ABS-733)**

IDWP 48 .... *Interactions Between Food Market Reform and Regional Trade in Zimbabwe and South Africa: Implications for Food Security* by T.S. Jayne, T. Takavarasha, and Johan van Zyl. 1994. 39 pp. $7.00 **(CDIE reference PN-ACA-239)**

IDWP 49 .... *A Strategic Approach to Agricultural Research Program Planning in Sub-Saharan Africa*, by Duncan Boughton, Eric Crawford, Julie Howard, James Oehmke, James Shaffer, and John Staatz. 1995. 59 pp. $9.00 **(CDIE reference PN-ABU-948)**

IDWP 49F ..... *Une approche stratégique pour la planification du programme de recherche agricole en Afrique sub-saharienne*, by Duncan Boughton, Eric Crawford, Julie Howard, James Oehmke, James Shaffer et John Staatz. 1997. 67 pp. $9.00 **(CDIE reference PN-ACA-071)**

IDWP 50 .... *An Analysis of Alternative Maize Marketing Policies in South Africa*, by T.S. Jayne, Milan Hajek and Johan van Zyl. 1995. 51 pp. $7.00 **(CDIE reference PN-ABW-091)**

IDWP 51 .... *Confronting the Silent Challenge of Hunger: A Conference Synthesis,* by T.S. Jayne, David Tschirley, Lawrence Rubey, Thomas Reardon, John M. Staatz, and Michael Weber. 1995. 37 pp. $7.00 **(CDIE reference PN-ABW-276)**

IDWP 52 .... *An Ex-Ante Evaluation of Farming Systems Research in Northeastern Mali: Implications for Research and Extension Policy,* by Bruno Henry de Frahan. 1995. 82 pp. $9.00 **(CDIE reference PN-ABW-761)**

IDWP 53 .... *Who Eats Yellow Maize? Preliminary Results of a Survey of Consumer Maize Preferences in Maputo, Mozambique,* by David L. Tschirley and Ana Paula Santos. 1995. 16 pp. $7.00 **(CDIE reference PN-ABX-988)**

IDWP 54 .... *Food Security II Cooperative Agreement: Project Fact Sheets (1995/96 Version),* compiled by MSU Food Security II Research Team. 1996. 151 pp. $13.00. **(CDIE reference PN-ABY-072)**

IDWP 55 .... *Trends in Real Food Prices in Six Sub-Saharan African Countries*, by T.S. Jayne, et al. 1996. 70 pp. $9.00 **(CDIE reference PN-ABY-172)**

IDWP 56 .... *Food Marketing and Pricing Policy in Eastern and Southern Africa: Lessons for Increasing Agricultural Productivity and Access to Food*, by T.S. Jayne and Stephen Jones. 1996. 40 pp. $7.00 **(CDIE reference PN-ABY-547)**

IDWP 57 .... *An Economic and Institutional Analysis of Maize Research in Kenya*, by Daniel David Karanja. 1996. 24 pp. $7.00 **(CDIE reference PN-ABY-548)**

IDWP 58 .... *Fighting an Uphill Battle: Population Pressure and Declining Land Productivity in Rwanda* by Daniel C. Clay. 1996. 28 pp. $7.00 **(CDIE reference PN-ABM-627)**

IDWP 59 .... *Finding the Balance Between Agricultural and Trade Policy: Rwanda Coffee Policy in Flux* by David Tardif-Douglin, Jean-Léonard Ngirumwami, Jim Shaffer, Anastase Murekezi, and Théobald Kampayana. 1996. 14 pp. $7.00 **(CDIE reference PN-ABY-802)**

IDWP 60 .... *Agriculture R&D and Economic Growth* by Elias Dinopoulos. 1996. 25 pp. $7.00 **(CDIE reference PN-ABY-804)**

IDWP 61 .... *Zambia's Stop-And-Go Revolution: The Impact of Policies and Organizations on the Development and Spread of Maize Technology* by Julie A. Howard and Catherine Mungoma. 1996. 39 pp. $7.00 **(CDIE reference PN-ABY-803)**

IDWP 62 .... *Intrahousehold Allocations: A Review of Theories, Empirical Evidence and Policy Issues* by John Strauss and Kathleen Beegle. 1996. 60 pp. $9.00 **(CDIE reference PN-ABY-848)**

IDWP 63 .... *Transforming Poultry Production and Marketing in Developing Countries: Lessons Learned with Implications for Sub-Saharan Africa* by Laura L. Farrelly. 1996. 46 pp. $7.00 **(CDIE reference PN-ABY-849)**

IDWP 64 .... *Market Information Sources Available Through the Internet: Daily to Yearly Market and Outlook Reports, Prices, Commodities and Quotes* by Jean-Charles Le Vallée. 1999. 30 pp. $7.00 **(CDIE reference PN-ACF-672)**

IDWP 65 .... *Food Security II Cooperative Agreement: Project Fact Sheets (1996 Version)* by MSU Food Security II Research Team. 1997. 190 pp. $15.00 **(CDIE reference PN-ABZ-902)**

IDWP 66 .... *Improving the Impact of Market Reform on Agricultural Productivity in Africa: How Institutional Design Makes a Difference* by T.S. Jayne, James D. Shaffer, John M. Staatz, and Thomas Reardon. 1997. 39 pp. $7.00 **(CDIE reference PN-ACB-867)**

IDWP 67 .... *Final Report--Workshop on Experiences and Options for Priority Setting in NARS, August 12-16, 1996, Nairobi, Kenya,* edited by Julie Howard and Eric Crawford. 1997. 76 pp. $9.00 **(CDIE reference PN-ACB-868)**

IDWP 68 .... *The Effect of Liberalization on Grain Prices and Marketing Margins in Ethiopia,* by T.S. Jayne, Asfaw Negassa, and Robert J. Myers. 1998. 21 pp. $7.00 **(CDIE reference PN-ACC-230)**

IDWP 69 .... *What Makes Agricultural Intensification Profitable for Mozambican Smallholders?* by Julie A. Howard, José Jaime Jeje, David Tschirley, Paul Strasberg, Eric W. Crawford, and Michael T. Weber. 1998. 98 pp. $11.00. **(CDIE reference PN-ACD-889)**

IDWP 70 .... *Incentives for Fertilizer Use in Sub-Saharan Africa: A Review of Empirical Evidence on Fertilizer Response and Profitability* by David Yanggen, Valerie Kelly, Thomas Reardon, and Anwar Naseem. 1998. 109 pp. $11.00 **(CDIE reference PN-ACD-890)**

IDWP 71 .... *Effects of Agricultural Commercialization on Food Crop Input Use and Productivity in Kenya* by Paul J. Strasberg, T.S. Jayne, Takashi Yamano, James Nyoro, Daniel

Karanja, and John Strauss. 1999. 28 pp. $7.00 **(CDIE reference PN-ACE-364)**

IDWP 72 .... *Successes and Challenges of Food Market Reform: Experiences from Kenya, Mozambique, Zambia, and Zimbabwe* by T.S. Jayne, Mulinge Mukumbu, Munhamo Chisvo, David Tschirley, Michael T. Weber, Ballard Zulu, Robert Johansson, Paula Santos, and David Soroko. 1999. 45 pp. $7.00 **(CDIE reference PN-ACE-389)**

IDWP 73 .... *Macro Trends and Determinants of Fertilizer Use in Sub-Saharan Africa* by Anwar Naseem and Valerie Kelly. 1999. 31 pp. $7.00 **(CDIE reference PN-ACE-290)**

IDWP 74 .... *Effects of Cash Crop Production on Food Crop Productivity in Zimbabwe: Synergies Or Trade-offs?* by Jones Govereh and T.S. Jayne. 1999. 23 pp. $7.00 **(CDIE reference PN-ACF-371)**

IDWP 75 .... *Workshop on Agricultural Transformation in Africa: Abidjan, Cote d'Ivoire, September 26-29, 1995* by Moussa Batchily Ba, John M. Staatz, Laura Farrelly, Youssouf Camara, and Georges Dimithè. 1999. 51 pp. $7.00 **(CDIE reference PN-ACF-624)**

IDWP 75F ..... *Atelier Sur la Transformation de l'Agriculture en Afrique*, by Moussa Batchily Ba, John M. Staatz, Laura Farrelly, Youssouf Camara, et Georges Dimithe. 1999. 48 pp. $7.00 **(CDIE reference PN-ACF-390)**

IDWP 76 .... *Green Revolution Technology Takes Root in Africa* by Julie A. Howard, Valerie Kelly, Julie Stepanek, Eric W. Crawford, Mulat Demeke, and Mywish Maredia. 1999. 66 pp. $9.00 **(CDIE reference PN-ACF-370)**

Statistical Annex and Copies of Questionnaire **(CDIE reference PN-ACF-623)**

.... * Also published by A.I.D./Washington

Mail your marked form
(via mail or fax) to:

MSU Bulletin Office

10-B Agriculture Hall

Michigan State University

East Lansing, MI 48824-1039

Fax: (517) 353-7168

Phone: (517) 355-0240

E-mail:
distbulk@msue.msu.edu

ORDER FORM for Papers Available from MSU

Required with all charge card orders:

Check one: _____ VISA ___MasterCard

Card number: _______________________________________

Signature: ____

Expiration Date: _____ Daytime Phone Number: ( )_______

SHIP TO:
Name: ____
Address: ____
____
____
____

Domestic orders totaling $100 or more can be billed by MSU. Institutions and firms should use their official purchase order. All other orders, including foreign orders, must be pre-paid.

Mark each choice with the quantity needed and enter total charges.

___IDP 13 $11.00
___IDP 14 $7.00
___IDP 14F $7.00
___IDP 15 $9.00
___IDP 16 $7.00
___IDP 17 $11.00
___IDP 18 $7.00
___IDP 19 $9.00
___IDP 20 $13.00
___IDP 21 $11.00
___IDP 22 $7.00
___IDWP 39/1 $11.00
___IDWP 39/2 $9.00
___IDWP 40 $11.00
___IDWP 41 $11.00
___IDWP 42 $7.00
___IDWP 43 $7.00
___IDWP 44 $11.00
___IDWP 45 $7.00
___IDWP 46 $7.00
___IDWP 47 $7.00
___IDWP 48 $7.00
___IDWP 49 $9.00
___IDWP 49F $9.00
___IDWP 50 $7.00
___IDWP 51 $7.00
___IDWP 52 $9.00
___IDWP 53 $7.00
___IDWP 54 $13.00
___IDWP 55 $9.00
___IDWP 56 $7.00
___IDWP 57 $7.00
___IDWP 58 $7.00
___IDWP 59 $7.00
___IDWP 60 $7.00
___IDWP 61 $7.00
___IDWP 62 $9.00
___IDWP 63 $7.00
___IDWP 64 $7.00
___IDWP 65 $15.00
___IDWP 66 $7.00
___IDWP 67 $9.00
___IDWP 68 $7.00
___IDWP 69 $11.00
___IDWP 70 $11.00
___IDWP 71 $7.00
___IDWP 72 $7.00
___IDWP 73 $7.00
___IDWP 74 $7.00
___IDWP 75 $7.00
___IDWP 75F $7.00
___IDWP 76 $9.00

Sub-Total $______
20% (foreign orders, surface mail) $______
International Airmail postage $______
(call or e-mail for rates)
Total Amount $______

The MSU International Development Papers published before 1993 (IDP numbers 1-11, IDWP numbers 1-38, and RP numbers 1-31) may be obtained through USAID's Center for Development Information and Evaluation (CDIE) and are not available from the MSU Bulletin Office.

How to Order MSU International Development Papers from USAID:

The MSU International Development Papers published before 1993 (IDP numbers 1-11, IDWP numbers 1-38, and RP numbers 1-31) may be obtained **only** through USAID's Center for Development Information and Evaluation (CDIE).

The CDIE reference numbers are shown on the following list. Document identification necessary to order the full document in paper or microfiche form from the USAID Development Experience Clearinghouse (DEC) is included with the citations.

If you would like to order any of the pre-1993 IDP's, IDWP's or RP's, please do not request them from MSU, but send your request--with the correct CDIE reference number--directly to the DEC:

Mail: USAID Development Experience Clearinghouse

1611 North Kent Street, Suite 200

Arlington, VA 22209-2111 USA

Electronic:

Web site: http://www.dec.org

Email address: docorder@dec.cdie.org

Telephone: +1 703-351-4006

Fax: +1 703-351-4039

If you cannot provide the CDIE reference number for the publication you wish to order, contact the USAID Library, who will supply you with the complete order information:

Telephone: +1 202-712-0579
Fax: +1 202-216-3515

Prices

Documents are provided to USAID employees without charge. Others are required to pay reproduction and mailing/handling costs. Current prices may be obtained by contacting the Document Distribution Unit (docorder@dec.cdie.org) or by searching the Development Experience System (DEXS) available through the DEC's web site (http://www.dec.org). A limited number of microfiche copies are provided without charge to LDC institutions.

Exchange programs

CDIE has established reciprocal agreements with selected development organizations who provide documents or other information resources to CDIE in exchange for distribution of CDIE documents or information. The materials received as a result of these exchange agreements are located in CDIE.

Deposit accounts

Deposit accounts may be established by USAID contractors and other users to facilitate the payment for documents ordered.

Available in A.I.D.’s Development Information System (CDIE)

MSU INTERNATIONAL DEVELOPMENT PAPERS

IDP 1 .... *Research on Agricultural Development in Sub-Saharan Africa: A Critical Survey* by Carl K. Eicher and Doyle C. Baker. 1982. 346 pp. **(CDIE reference PN-AAL-692)**

IDP 1F .... *Etude Critique de la Recherche sur la Developpement Agricole en Afrique Subsaharienne* par Carl K. Eicher et Doyle C. Baker. 1982. 345 pp. **(CDIE reference PN-ABA-840)**

IDP 2 .... *A Simulation Study of Constraints on Traditional Farming Systems in Northern Nigeria* by Eric W. Crawford. 1982. 136 pp. **(CDIE reference PN-AAP-677)**

IDP 3 .... *Farming Systems Research in Eastern Africa: The Experience of CIMMYT and Some National Agricultural Research Services, 1976-81* by M.P. Collinson. 1982. 67 pp. **(CDIE reference PN-AAM-826)**

IDP 4 .... *Animal Traction in Eastern Upper Volta: A Technical, Economic and Institutional Analysis* by Vincent Barrett, Gregory Lassiter, David Wilcock, Doyle Baker, and Eric Crawford. 1982. 132 pp. **(CDIE reference PN-AAM-262)**

IDP 5 .... *Socio-Economic Determinants of Food Consumption and Production in Rural Sierra Leone: Application of an Agricultural Household Model with Several Commodities* by John Strauss. 1983. 91 pp. **(CDIE reference PN-AAM-031)**

IDP 6 .... *Applications of Decision Theory and the Measurement of Attitudes Towards Risk in Farm Management Research in Industrialized and Third World Settings* by Beverly Fleisher and Lindon J. Robison. 1985. 105 pp. **(CDIE reference PN-AAU-740)**

IDP 7 .... *Private Decisions and Public Policy: The Price Dilemma in Food Systems in Developing Countries* by Peter Timmer. 1986. 58 pp. **(CDIE reference PN-AAZ-091)**

IDP 8 .... *Rice Marketing in Senegal River Valley: Research Findings and Policy Reform Options* by Michael L. Morris. 1987. 89 pp. **(CDIE reference PN-AAZ-092)**

IDP 9 .... *Small Scale Industries in Developing Countries: Empirical Evidence and Policy Implications* by Carl Liedholm and Donald Mead. 1987. 141 pp. **(CDIE reference PN-AAX-734)**

IDP 10 .... *Maintaining the Momentum in Post-Green Revolution Agriculture: A Micro-Level Perspective from Asia* by Derek Byerlee. 1987. 57 pp. **(CDIE reference PN-AAZ-093)**

IDP 11 .... *The Economics of Smallholder Maize Production in Zimbabwe: Implications for Food Security* by David D. Rohrbach. 1989. 100 pp. **(CDIE reference PN-ABD-549)**

WORKING PAPERS

IDWP 1 .... *Farming Systems Research (FSR) in Honduras, 1977-81: A Case Study* by Daniel Galt, Alvaro Diaz, Mario Contreras, Frank Peairs, Joshua Posner, and Franklin Rosales. 1982. 48 pp. **(CDIE reference PN-AAM-827)**

IDWP 2 .... *Credit Agricole et Credit Informal dans la Region Orientale de Haute-Volta: Analyse Economique, Performance Institutionnelle et Implications en Matiere de Politique de Developpement Agricole* by Edouard K. Tapsoba. 1982. 125 pp. **(CDIE reference PN-AAZ-527)**

IDWP 3 .... *Employment and Construction: Multicountry Estimates of Costs and Substitutions Elasticities for Small Dwellings* by W.P. Strassmann. 1982. 42 pp. **(CDIE reference PN-AAM-455)**

IDWP 4 .... *Sub-Contracting in Rural Areas of Thailand* by Donald C. Mead. 1982. 53 pp. **(CDIE reference PN-AAN-192)**

IDWP 5 .... *Microcomputers and Programmable Calculators for Agricultural Research in Developing Countries* by Michael T. Weber, James Pease, Warren Vincent, Eric W. Crawford, and Thomas Stilwell. 1983. 113 pp. **(CDIE reference PN-AAN-441)**

IDWP 6 .... *Periodicals for Microcomputers: An Annotated Bibliography* by Thomas Stilwell. 1983. 70 pp. **(CDIE reference PN-AAN-443)**

IDWP 7 .... *Employment and Housing in Lima, Peru* by Paul Strassmann. 1983. 96 pp. **(CDIE reference PN-AAN-396)**

IDWP 8 .... *Faire Face a la Crise Alimentaire de l’Afrique* by Carl K. Eicher. 1983. 29 pp. **(CDIE reference PN-AAN-444)**

IDWP 9 .... *Software Directories for Microcomputers: An Annotated Bibliography* by Thomas C. Stilwell. 1983. 14 pp. **(CDIE reference PN-AAN-442)**

IDWP 10 .... *Instructional Aids for Teaching How to Use the TI-59 Programmable Calculator* by Ralph E. Hepp. 1983. 133 pp. **(CDIE reference PN-AAP-133)**

IDWP 11 .... *Programmable Calculator (TI-59) Programs for Marketing and Price Analysis in Third World Countries* by Michael L. Morris and Michael T. Weber. 1983. 105 pp. **(CDIE reference PN-AAP-134)**

IDWP 12 .... *An Annotated Directory of Statistical and Related Microcomputer Software for Socioeconomic Data Analysis* by Valerie Kelly, Robert D. Stevens, Thomas Stilwell and Michael T. Weber. 1983. 165 pp. **(CDIE reference PN-AAP-135)**

IDWP 13 .... *Guidelines for Selection of Microcomputer Hardware* by Chris Wolf. 1983. 90 pp. **(CDIE reference PN-AAR-106)**

IDWP 14 .... *User’s Guide to BENCOS A SuperCalc Template for Benefit-Cost Analysis* by Eric W. Crawford, Ting-Ing Ho and A. Allan Schmid. 1984. 35 pp. **(CDIE reference PN-AAQ-682)**

IDWP 15 .... *An Evaluation of Selected Microcomputer Statistical Programs* by James W. Pease and Raoul Lepage with Valerie Kelly, Rita Laker-Ojok, Brian Thelen, and Paul Wolberg. 1984. 187 pp. **(CDIE reference PN-AAQ-683)**

IDWP 16 .... *Small Enterprises in Egypt: A study of Two Governorates* by Stephen Davies, James Seale, Donald C. Mead, Mahmoud Badr, Nadia El Sheikh and Abdel Rahman Saidi. 1984. 187 pp. **(CDIE reference PN-AAU-610)**

IDWP 17 .... *Microcomputer Statistical Packages for Agricultural Research* by Thomas C. Stilwell. 1984. 23 pp. **(CDIE reference PN-AAZ-516)**

IDWP 18 .... *An Annotated Directory of Citation Database, Educational, System Diagnostics and Other Miscellaneous Microcomputer Software of Potential Use to Agricultural Scientists in Developing Countries* by Thomas C. Stilwell and P. Jordan Smith. 1984. 34 pp. **(CDIE reference PN-AAZ-523)**

IDWP 19 .... *Irrigation in Southern Africa: An Annotated Bibliography* by Amalia Rinaldi. 1985. 60 pp. **(CDIE reference PN-AAZ-524)**

IDWP 20 .... *A Microcomputer Based Planning and Budgeting System for Agricultural Research Programs* by Daniel C. Goodman, Jr., Thomas C. Stilwell and P. Jordan Smith. 1985. 75 pp. **(CDIE reference PN-AAZ-525)**

IDWP 21 .... *Periodicals for Microcomputers: An Annotated Bibliography, Second Edition* by Thomas C. Stilwell. 1985. 89 pp. **(CDIE reference PN-AAZ-526)**

IDWP 22 .... *Software Directories for Microcomputers: An Annotated Bibliography, Second Edition* by Thomas C. Stilwell. 1985. 21 pp. **(CDIE reference PN-AAZ-528)**

IDWP 23 .... *A diagnostic Perspective Assessment of the Production and Marketing System for Mangoes in the Eastern Caribbean* by Alan Hrapsky with Michael Weber and Harold Riley. 1985. 106 pp. **(CDIE reference PN-AAZ-529)**

IDWP 24 .... *Subcontracting Systems and Assistance Programs: Opportunities for Intervention* by Donald C. Mead. 1985. 32 pp. **(CDIE reference PN-AAZ-943)**

IDWP 25 .... *Small Scale Enterprise Credit Schemes: Administrative Costs and the Role of Inventory Norms* by Carl Liedholm. 1985. 23 pp. **(CDIE reference PN-AAU-615)**

IDWP 26 .... *Subsector Analysis: Its Nature, Conduct and Potential Contribution to Small Enterprise Development* by James J. Boomgard, Stephen P. Davies, Steve Haggblade and Donald Mead. 1986. 57 pp. **(CDIE reference PN-AAZ-101)**

IDWP 27 .... *The Effect of Policy and Policy Reforms on Non-Agricultural Enterprises and Employment in Developing Countries: A Review of Past Experiences* by Steve Haggblade, Carl Liedholm, and Donald C. Mead. 1986. 133 pp. **(CDIE reference PN-AAV-001)**

IDWP 28 .... *Rural Small Scale Enterprises in Zambia: Results of a 1985 Country-Wide Survey* by John T. Milimo and Yacob Fisseha. 1986. 76 pp. **(CDIE reference PN-AAZ-102)**

IDWP 29 .... *Fundamentals of Price Analysis in Developing Countries’ Food Systems: A Training Manual to Accompany the Microcomputer Software Program ’MSTAT’* by Stephen Goetz and Michael T. Weber. 1986. 148 pp. **(CDIE reference PN-AAZ-103)**

IDWP 30 .... *Rapid Reconnaissance Guidelines for Agricultural Marketing and Food System Research in Developing Countries* by John S. Holtzman. 1986. 75 pp. **(CDIE reference PN-AAZ-104)**

IDWP 31 .... *Contract Farming and Its Effect on Small Farmers in Less Developed Countries* by Nicholas William Minot. 1986. 86 pp. **(CDIE reference PN-AAZ-105)**

IDWP 32 .... *Food Security Policy and the Competitiveness of Agriculture in the Sahel: A Summary of the "Beyond Mindelo" Seminar* by Thomas S. Jayne and Nicholas Minot. 1989. 27 pp. **(CDIE reference PN-ABF-570)**

IDWP 33 .... *Small Scale Manufacturing Growth in Africa: Initial Evidence* by Carl Liedholm and Joan Parket. 1989. 18 pp. **(CDIE reference PN-ABB-945)**

IDWP 34 .... *Food Security and Economic Growth in the Sahel: A Summary of the September 1989 Cereals Workshop* by Victoire C. D’Agostino and John M. Staatz. 1989. 44 pp. **(CDIE reference PN-ABD-956)**

IDWP 35 .... *User’s Manual for the SADCC Cereals Trade Database Compiled by the University of Zimbabwe and Michigan State University* by David Kingsbury. 1989. 44 pp. **(CDIE reference PN-ABF-378)**

IDWP 36 .... *Managing Food Security Action Programs in Botswana* by Sisay Asefa. 1989. 36 pp. **(CDIE reference PN-ABF-377)**

IDWP 37 .... *User’s Guide to BENCOS Lotus 1-2-3 Templates for Benefit-Cost Analysis* by Eric Crawford and A. Allan Schmid. 1990. 23 pp. **(CDIE reference PN-ABF-530)**

IDWP 38 .... *Research Methods in the MSU Food Security in Africa Project: Conceptualizing and Implementing Policy Relevant Studies* by James F. Tefft with Michael T. Weber and John M. Staatz. 1990. 128 pp. **(CDIE reference PN-ABU-249)**

REPRINT PAPERS

RP 1 .... *The Private Sector Connection to Development* by Carl Liedholm. 1986. 19 pp. **(CDIE reference PN-AAW-353)**

RP 2 .... *Influencing the Design of Marketing Systems to Promote Development in Third World Countries* by James D. Shaffer with Michael Weber, Harold Riley and John Staatz. 1987. 21 pp. **(CDIE reference PN-AAV-230)**

RP 3 .... *Famine Prevention in Africa: The Long View* by Carl K. Eicher. 1987. 18 pp. **(CDIE reference PN-AAZ-119)**

RP 4 .... *Cereals Marketing in the Senegal River Valley* by Michael L. Morris. 1987. 126 pp. **(CDIE reference PN-AAZ-120)**

RP 5 .... *The Food Security Equation in Southern Africa* by Mandivamba Rukuni and Carl K. Eicher. 1987. 32 pp. **(CDIE reference PN-AAZ-121)**

RP 6 .... *Economic Analysis of Agronomic Trials for the Formulation of Farmer Recommendations* by Eric Crawford and Mulumba Kamuanga. 1988. 41 pp. **(CDIE reference PN-AAZ-370)**

RP 6F .... *L’Analyse Economiques des Essais Agronomiques pour la Formulation des Recommandations aux Paysans* par Eric Crawford et Mulumba Kamuanga. 1987. 33 pp. **(CDIE reference PN-AAZ-122)**

RP 7 .... *Economic Analysis of Livestock Trials* by Eric Crawford. 1987. 36 pp. **(CDIE reference PN-AAZ-371)**

RP 7F .... *L’Analyse Economique des Essais Zootechniques* par Eric Crawford. 1987. 36 pp. **(CDIE reference PN-AAZ-123)**

RP 8 .... *A Field Study of Fertilizer Distribution and Use in Senegal, 1984: Summary Report* by Eric Crawford and Valerie Kelly. 1987. 32 pp. **(CDIE reference PN-AAZ-124)**

RP 8F .... *Enquete sur la Distribution et l'Utilisation de l’Engrais au Sénégal, 1984: Résumé Analytique* par Eric Crawford et Valerie Kelly. 1988. 43 pp. **(CDIE reference PN-ABC-173)**

RP 9 .... *Improving Food Marketing Systems in Developing Countries: Experiences from Latin America* by Kelly Harrison, Donald Henley, Harold Riley and James Shaffer. 1987. 135 pp. **(CDIE reference PN-AAZ-125)**

RP 10 .... *Policy Relevant Research on the Food and Agricultural System in Senegal* by Mark Newman, Eric Crawford and Jacques Faye. 1987. 30 pp. **(CDIE reference PN-AAZ-126)**

RP 10F .... *Orientations et Programmes de Recherche Macro-Economiques sur le Systeme Agro-Alimentaire Sénégalais* par Mark Newman, Eric Crawford et Jacques Faye. 1987. 37 pp. **(CDIE reference PN-AAZ-127)**

RP 11 .... *A Field Study of Fertilizer Distribution and Use in Senegal, 1984: Final Report* by Eric Crawford, Curtis Jolly, Valerie Kelly, Philippe Lambrecht, Makhona Mbaye, and Matar Gaye. 1987. 106 pp. **(CDIE reference PN-AAZ-128)**

RP 11F .... *Enquête sur la Distribution et l’Utilisation de l'Engrais au Sénégal, 1984: Rapport Final* par Eric Crawford, Curtis Jolly, Valerie Kelly, Philippe Lambrecht, Makhona Mbaye, et Matar Gaye. 1987. 106 pp. **(CDIE reference PN-ABC-173)**

RP 12 .... *Private and Public Sectors in Developing Country Grain Markets: Organization Issues and Options in Senegal* by Mark D. Newman, P. Alassane Sow, and Ousseynou NDoye. 1987. 14 pp. **(CDIE reference PN-AAZ-129)**

RP 13 .... *Agricultural Research and Extension in Francophone West Africa: The Senegal Experience* by R. James Bingen and Jacques Faye. 1987. 23 pp. **(CDIE reference PN-AAV-929)**

RP 13F .... *La Liaison Recherche-Developpement en Afrique de l'Ouest Francophone: L'Experience du Sénégal* par James Bingen et Jacques Faye. 1987. 32 pp. **(CDIE reference PN-AAZ-130)**

RP 14 .... *Grain Marketing in Senegal's Peanut Basin: 1984/85 Situation and Issues* by Mark D. Newman. 1987. 16 pp. **(CDIE reference PN-AAZ-131)**

RP 15 .... *Tradeoffs between Domestic and Imported Cereals in Senegal: A Marketing Systems Perspective* by Mark D.

Newman, Ousseynou NDoye, and P. Alassane Sow. 1987. 41 pp. **(CDIE reference PN-AAZ-372)**

RP 15F .... *Céréales Locales et Céréales Importées au Sénégal: La Politique Alimentaire a Partier Systemes de Commercialisation* par Mark D. Newman, Ousseynou NDoye, et P. Alassane Sow. 1987. 48 pp. **(CDIE reference PN-ABC-326)**

RP 16 .... *An Orientation to Production Systems Research in Senegal* by R. James Bingen. 1987. 88 pp. **(CDIE reference PN-AAZ-373)**

RP 16F .... *Orientation de la Recherche sur les Systemes de Productions au Sénégal* par R. James Bingen. 1987. 94 pp. **(CDIE reference PN-AAZ-374)**

RP 17 .... *A Contribution to Agronomic Knowledge of the Lower Casamance (Bibliographical Synthesis)* by J.L. Posner. 1988. 47 pp. **(CDIE reference PN-AAZ-375)**

RP 17F .... *Contribution a la Connaissance Agronomique de la Basse Casamance (Synthese Biblographique)* par J.L. Posner. 1988. 47 pp. **(CDIE reference PN-ABC-167)**

RP 18 .... *Acquisition and Use of Agricultural Inputs in the Context of Senegal's New Agricultural Policy: The Implications of Farmers' Attitudes and Input Purchasing Behavior for the Design of Agricultural Policy and Research Programs* by Valerie Auserehl Kelly. 1988. 30 pp. **(CDIE reference PN-AAZ-376)**

RP 18F .... *Acquisition et Utilisation d'Intrants Agricoles dans le Context de la Nouvelle Politique Agricole du Sénégal: Implications des Attitudes et du Comportement d'Achat d'Intrants des Exploitants pour l'Elaboration d'une Politique Agricole et de Programmes de Recherches* par Valerie Auserehl Kelly. 1988. 35 pp. **(CDIE reference PN-AAZ-377)**

RP 19 .... *Farmers' Demand for Fertilizer in the Context of Senegal's New Agricultural Policy: A Study of Factors Influencing Farmers' Fertilizer Purchasing Decisions* by Valerie Auserehl Kelly. 1988. 47 pp. **(CDIE reference PN-AAZ-378)**

RP 19F .... *Demande d'Engrais de la Part des Exploitants dans les Contexte de la Nouvelle Politique Agricole au Sénégal: Une Etude des Facteurs Influencant les Decisions d'Achat d'Engrais Prises par les Exploitants* par Valerie Auserehl Kelly. 1988. 58 pp. **(CDIE reference PN-AAZ-379)**

RP 20 .... *Production Systems in the Lower Casamance and Farmer Strategies in Response to Rainfall Deficits* by J.L. Posner, M. Kamuanga, and S. Sall. 1988. 33 pp. **(CDIE reference PN-ABC-162)**

RP 20F .... *Les Systemes de Production en Basse Casamance et les Stratégies Paysannes Face du Deficit Pluviométrique* par J.L. Posner, M. Kamuanga, et S. Sall. 1988. 33 pp. **(CDIE reference PN-ABC-163)**

RP 21 .... *Informing Food Security Decisions in Africa: Empirical Analysis and Policy Dialogue* by Michael T. Weber, John M. Staatz, John S. Holtzman, Eric W. Crawford, and Richard H. Bernsten. 1989. 11 pp. **(CDIE reference PN-ABE-627)**

RP 21F .... *Comment Informer les Decisions Traitant de la Sécurité Alimentaire en Afrique: Analyses Empiriques et Dialogue Politique* par Michael T. Weber, John M. Staatz, John S. Holtzman, Eric W. Crawford, et Richard H. Bernsten. 1989. 13 pp. **(CDIE reference PN-ABD-104)**

RP 22 .... *The Creation and Establishment of Production Systems Research in a National Agricultural Research Institute: The Senegal Experience* by Jacques Faye, James Bingen, and Etienne Landais. 1988. 25 pp. **(CDIE reference PN-ABC-161)**

RP 23 .... *Foreign Trade of Agricultural Products and Inputs in Senegal from 1975 to 1984* by Frederic Martin and Alioune Dieng. 1988. 45 pp. **(CDIE reference PN-ABC-164)**

RP 23F .... *Le Commerce Exterieur de Produits et d'Intrants Agricoles du Sénégal de 1975 a 1984* par Frederic Martin et Alioune Dieng. 1990. 45 pp. **(CDIE reference PN-ABF-529)**

RP 24 .... *Regulatory Uncertainty and Government Objectives for the Organization and Performance of Cereal Markets: The Case of Senegal* by Mark D. Newman, P. Alassane Sow, and Ousseynou NDoye. 1988. 24 pp. **(CDIE reference PN-ABC-159)**

RP 24F .... *Incertitude Réglementaire, Objectifs Gouvernementaux, Organisation et Performances des Marchés Céréaliers: Le Cas du Sénégal* par Mark D. Newman, P. Alassane Sow, and Ousseynou NDoye. 1988. 24 pp. **(CDIE reference PN-ABC-160)**

RP 25F .... *Etude sur la Commercialisation des Céréales dans la Région du Fleuve Sénégal: Méthodologie* par Michael Morris. 1988. 48 pp. **(CDIE reference PN-ABC-172)**

RP 26 .... *The Regulation and Organization of Cereal Markets in Senegal: Report on the Marketing Campaigns of 1983/84 and 1984/85* by P. Alassane Sow and Mark D. Newman. 1988. 29 pp. **(CDIE reference PN-ABC-165)**

RP 26F .... *La Réglementation et l'Organisation des Marchés Céréaliers au Sénégal: Situation des Campagnes des Commercialisation 1983/84 et 1984/85* par P. Alassane Sow et Mark D. Newman. 1988. 35 pp. **(CDIE reference PN-ABC-166)**

RP 27 .... *Farm Level Cereal Situation in Lower Casamance: Results of a Field Study* by C.M. Jolly, M. Kamuanga, S. Sall, and J.L. Posner. 1988. 35 pp. **(CDIE reference PN-ABC-157)**

RP 27F .... *Situation Céréaliere en Milieu Paysan en Basse Casamance: Résultats d'une Enquête de Terrain* par C.M. Jolly, M. Kamuanga, S. Sall, et J.L. Posner. 1988. 41 pp. **(CDIE reference PN-ABC-158)**

RP 28F .... *Budgets de Culture au Sénégal* par Frédéric Martin. 1988. 54 pp. **(CDIE reference PN-ABC-168)**

.... *Annexe 1 Budgets de Culture et Analyse des Marges dans le Bassin Arachidier.* 1988. 134 pp. **(CDIE reference PN-ABC-169)**

.... *Annexe 2 Budgets de Culture et Analyse des Marges au Sénégal Oriental et en Casamance.* 1988. 204 pp. **(CDIE reference PN-ABC-170)**

.... *Annexe 3 Budgets de Culture et Analyse des Marges dans la Vallée du Fleuve Sénégal.* 1988. 214 pp. **(CDIE reference PN-ABC-171)**

RP 29 .... *Agricultural Development and Policy in Senegal: Annotated Bibliography of Recent Studies, 1983-89* by Eric Crawford, R. James Bingen, and Malcolm Versel. 1990. 254 pp. **(CDIE reference PN-ABE-271)**

RP 30 .... *Lowland Cropping Systems in the Lower Casamance of Senegal: Results of Four Years of Agronomic Research (1982-1985)* by Joshua Posner, Mulumba Kamuanga, and Mamadou Lo. 1990. 130 pp. **(CDIE reference PN-ABU-251)**

RP 31 .... *Farming Systems Research in Southern Senegal: The Djibelor Experience (1982-1986)* by Mulumba Kamuanga and Joshua L. Posner. 1992. 57 pp. **(CDIE reference PN-ABT-624)**