Chapter 11

Integrated Nutrient Management: Concepts and Experience from Sub-Saharan Africa

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INTRODUCTION

In Africa, 28 percent of its landmass, 874 Mha, is potentially suitable for agricultural production. Of the potentially suitable agricultural land, 34 percent comprises arid and semiarid lands (ASAL) that are too dry for rainfed agriculture. The semiarid regions have a shortened length of growing period (75-129 days) compared to the subhumid (180-269 days), and the humid (>270 days) zones. The dynamics of agroecosystems show that the farming systems practiced have gone through diverse changes from traditional shifting farming systems to permanent and intensified arable and mixed farming systems. The changes are coping strategies to respond to the environment, and its changing biophysical and socioeconomic circumstances.

Africa has 340 million people, over half of its population living on less than US$1 per day, a mortality rate of children under five years of age, of 154 per 1,000, and a life expectancy of only forty-eight years (Benson, 2004). The average annual increase of cereal yield in Africa is about 10 kg ha^{-1} the rate known as that for extensive agriculture neglecting external in-

Integrated Nutrient Management for Sustainable Crop Production

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puts like improved seeds and plant nutrients (Bationo et al., 2004). In 1996, fertilizer use in sub-Saharan Africa (SSA) was about 9 kg ha^{-1} compared to the global average use of 98 kg ha^{-1} (Gruhn et al., 2000). With 9 percent of the world's population, SSA accounts for less than 1.8 percent of global fertilizer use, and less than 0.1 percent of global fertilizer production (Bationo et al., 2004).

Twenty-eight percent of Africa's population is chronically hungry and heavily dependent on food imports (2.8 m tonnes of food aid in 2000 alone). Due to a high population growth rate (3 percent) compared to cereal grain yield (< 1 percent) (Gruhn et al., 2000), per capita cereal production has decreased from 150 kg per person to 130 kg per person over the last thirty-five years, whereas Asia and Latin America realized per capita food increase from 200 kg per person to 250 kg per person during the same period. The increase in yields of the food crops has been more due to land expansion than realized from the crop productivity improvement potential (Table 11.1). The 7.6 percent yield increase of yam in west Africa for example, was mainly due to an area increase of 7.2 percent and only 0.4 percent due to improvement in crop productivity itself. Production of enough food for the growing population requires an increase from 1 billion tonnes per year at present to 2.5 billion t by 2030 (Walker et al., 1999). The Forum for Agricultural Research in Africa (FARA) and its member subregional organizations have developed a vision for agriculture in Africa, calling for a 6 percent annual growth in agricultural productivity (Bationo et al., 2004). In SSA, such increases in agricultural productivity are possible with judicious implementation of agricultural intensification programs to contribute 53 percent of the increase, with other increase coming from expansion in area (30 percent), and cultivation of cash crops (17 percent) (Nandwa, 2003).

TABLE 11.1. Percentage annual increase in crop yields of selected food crops due to land expansion and crop improvement potential in West Africa

Crops	**Area (%)/year**	**Productivity (%)/year**	**Production (%)/year**
Cassava	2.6	0.7	3.3
Maize	0.8	0.2	1.0
Yam	7.2	0.4	7.6
Cowpea	7.6	-1.1	6.5
Soybean	-0.1	4.8	4.7
Plantain	1.9	0.0	2.0

Source: Adapted from www.fao.org.

Macropolicy changes imposed externally in the last decade, such as structural adjustment and the removal of fertilizer subsidies, resulted in reduction in the use of external inputs (Gruhn et al., 2000), expansion in area of agriculture through the opening of new lands, and the reduction of the farmers' potential for investment in soil fertility restoration. Technological, environmental, sociocultural, economic, institutional, and policy constraints that hamper agricultural development in Africa have been identified. These constraints are:

1. low soil fertility;
2. fragile ecosystems;
3. overdependence on rainfall;
4. aging rural population and thus limited physical energies for production;
5. underdeveloped and degraded rural infrastructure;
6. insufficient research due to lack of motivation and inadequate facilities;
7. inadequate training and extension services;
8. high postharvest losses;
9. insufficient market;
10. lack of credit and insufficient agri-input delivery systems;
11. limited farmers' education and know-how;
12. brain-drain of African intellectuals;
13. policy instability; and
14. inconsistent agricultural policies and land tenure (Bationo et al., 2004).

Acquired immune deficiency syndrome (AIDS) has also emerged as a major constraint to agricultural production, especially in rural areas.

The problem of soil fertility degradation is not only a factor of biophysical aspects but also of socioeconomic factors (Figure 11.1). A wide range of socioeconomic factors such as macroeconomic policies, unfavorable exchange rates, poor producer prices, high inflation, poor infrastructure, and lack of markets diminish farmers' capacity to invest in soil fertility, as well as the returns obtained from such investments where value cost ratios are often less than two (2). These multiple causes of low soil fertility are strongly interrelated and the interactions between biophysical and socioeconomic factors call for a holistic approach in ameliorating the soil fertility constraints in SSA (Murwira, 2003).

There has been great concern that institutions of higher education are not making a significant contribution to the national agricultural research agenda. This is due in part to the limited funding of public agricultural research and development in SSA, which declined from 2.5 percent in the

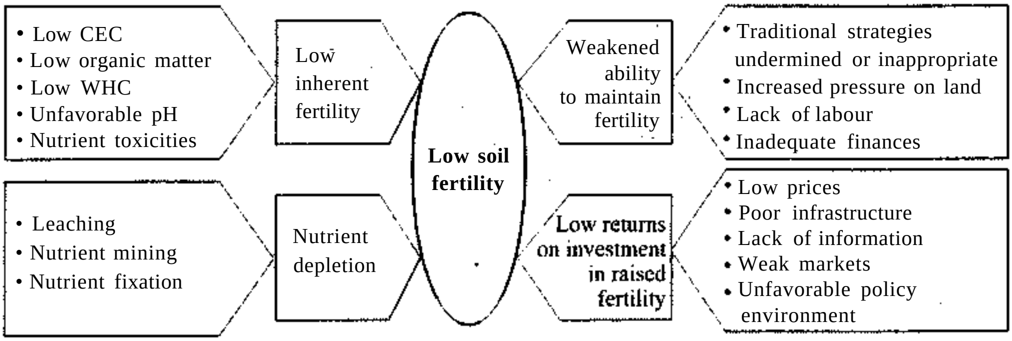

FIGURE 11.1. Biophysico-chemical and socioeconomic factors contributing to low soil fertility in Africa. *Source:* Adapted from Murwira (2003).

1970s to 0.7 percent in the 1980s. At the same time, agricultural investment in developed countries declined by 1 percent from 2.7 percent (Gruhn et al., 2000). From 1987 to 1997, World Bank global support to agricultural extension was 46.3 percent compared to 2.2 percent for agricultural higher education (Willett, 1998). The common trend in the African continent has been a decline in support for research in agricultural institutions.

Apart from water shortages, soil infertility is the major constraint to increased agricultural productivity in SSA. Soil fertility management is crucial for sustained production and requires inputs of nutrients to compensate those removed by crops and lost from the soil through various physical and biochemical processes. In the context of SSA, the approach based on supply of plant nutrients through organic and chemical sources, or integrated nutrient management (INM) needs to be followed. First, the use of chemical fertilizers is very low, and the use of manures and organic and crop residues (CRs) not only supply nutrients such as N, but also supply organic matter so essential for the soil's physical, chemical, and biological integrity. In this chapter, we will first provide an overview of soil fertility status in SSA, followed by the evolution of soil fertility paradigms before highlighting the experiences in the use of integrated soil fertility management (ISFM) in Africa.

OVERVIEW OF SOIL FERTILITY STATUS IN AFRICA

The fundamental biophysical root cause for declining per capita food production in smallholder farms in SSA (17 percent between 1980 and 1995) is soil fertility depletion. Although significant progress has been made in research, in developing principles, methodologies, and technologies for combating soil fertility depletion (Nandwa and Bekunda, 1998; Nandwa, 2001; Stoorvogel and Smaling, 1990; Smaling et al, 1997; Tian et al., 2001), soil infertility still remains the fundamental biophysical cause for the declining per capita food production in SSA over the past 3-5 decades (Sanchez et al., 1997). This is evident from the huge gaps between actual and potential crop yields (FAO, 1995).

During the past thirty years, soil fertility depletion has been estimated at an average of 660 kg N ha^{-1}, 75 kg P ha^{-1}, and 450 kg K ha^{-1} from about 200 Mha of cultivated land in thirty-seven African countries (Sanchez et al., 1997). Average depletion of major nutrients (N, P, and K) for the 1993-1995 period is shown in Figure 11.2. Stoorvogel et al. (1993) estimated annual net depletion of nutrients in excess of 30 kg N and 20 kg K per ha of arable

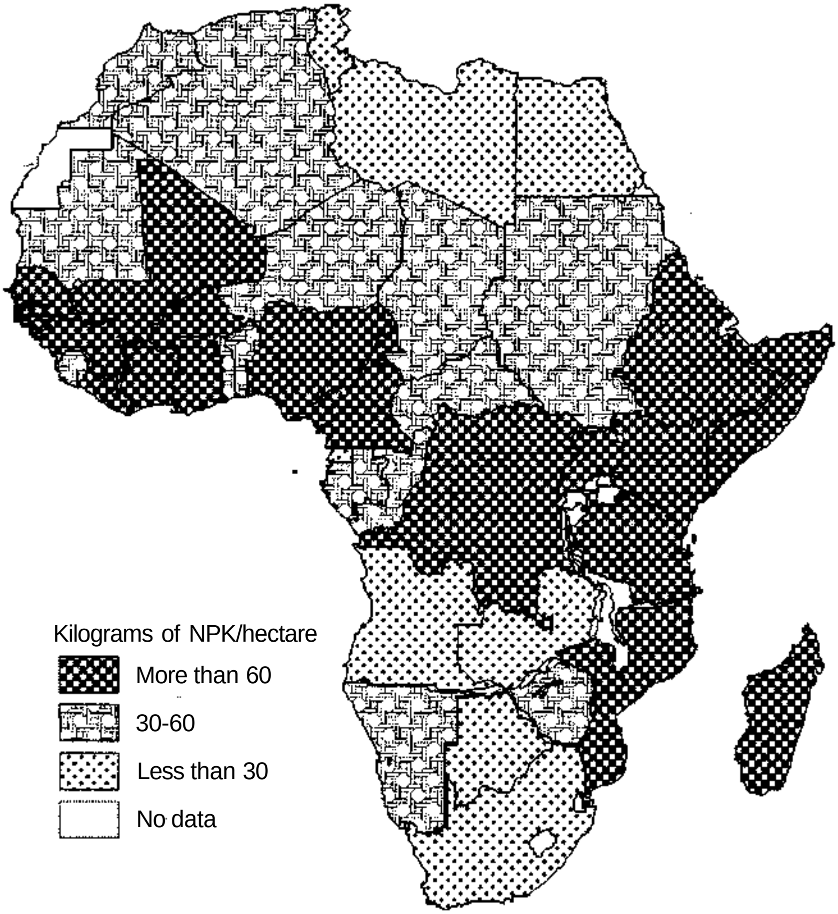

FIGURE 11.2. Fertilizer NPK depletion rates in Africa between 1993-1995. *Source:* Adapted from Nandwa (2003).

land per year in Ethiopia, Kenya, Malawi, Nigeria, Rwanda, and Zimbabwe (Table 11.2).

Soil nutrient depletion is a major bottleneck in increasing land productivity in the region and has largely contributed to poverty and food insecurity. Soil nutrient depletion occurs when nutrient inflows are less than outflows. Nutrient balances are negative for many cropping systems indicating that farmers are mining their soils of nutrient reserves (Figure 11.3).

The inherent constraints in some soils have been exacerbated by their overexploitation for agricultural production. Large areas of soils of high production potential in SSA have been degraded due to continuous cropping without replacement of nutrients taken up in harvests (Murwira, 2003). Increasing population pressure of up to 1,200 persons per square kilometer (Shepherd et al., 2000) have necessitated the cultivation of marginal lands that are prone to erosion and other types of environmental degradation, and it is also no longer feasible to use extended fallow periods to restore soil fertility. The shortened fallow periods cannot regenerate soil productivity leading to nonsustainability of the production systems (Nandwa, 2001).

The negative effects of nutrient outputs exceeding inputs, manifested in negative nutrient balances, and the deficiencies of major nutrients are attributed primarily to nonuseful outflows such as burning/removal of biomass,

TABLE 11.2. Average nutrient balance of N, P, and K (kg ha^{-1} $year^{-1}$) for the arable land for some SSA countries (average of 1982-1984)

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

Source: Adapted from Stoorvogel et al. (1993).

leaching, volatilization, erosion losses of nutrients, and the lack of water and waste recycling in agricultural systems (Figure 11.4). Considerable export of nutrients is via harvestable products, the goal and objective of agricultural production. Results from Nutrient Monitoring (NUTMON) (Gachimbi et al., 2002) studies demonstrate that for efficient return to increased agricultural production, enhanced nutrient availability will have to initially de-

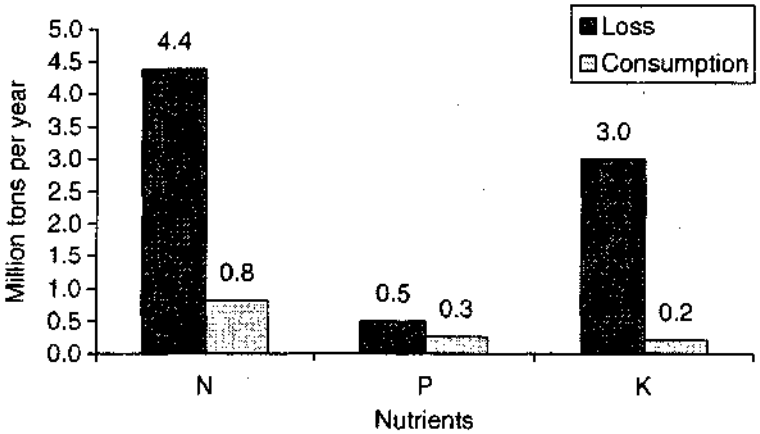

FIGURE 11.3. Major nutrient losses versus their application rates in Africa. *Source:* Adapted from Sanchez et al. (1997).

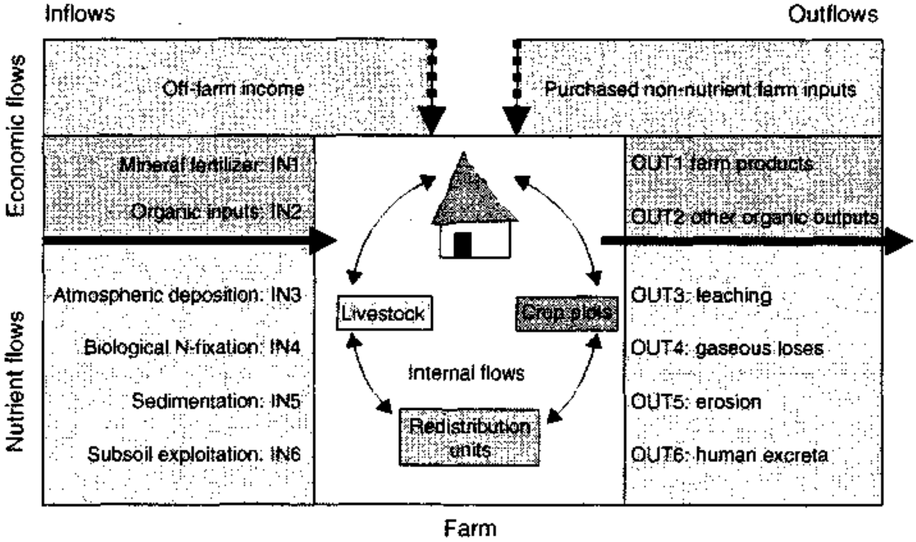

FIGURE 11.4. Nutrient inflows and outflows in a farm. *Source:* Adapted from Vlaming et al. (2001).

pend on the extent to which farmers minimize or eliminate nonuseful outflows including residue burning, the loss of nutrients especially N via leaching, volatilization, and denitrification and loss of nutrients through erosion.

Among the plant nutrients, N and P are the most limiting for crop production in SSA. For example, studies undertaken at the West Africa Rice Development Association (WARDA) along a north to south transect in Cote d'lvoire demonstrated that as one moved from north to south on a north-south transect, soil acidity increases and the deficiency of P becomes more important than that of N for cereals such as rice (*Oryza sativa* L.). These observations are in accordance with the findings that the deficiency of P is more important than that of N in the humid forest zone of West Africa (Sahrawat et al., 2000, 2001). On the other hand, on soils in the savanna and savanna-forest transition zones, N deficiency is more important than P deficiency. As a general rule, P deficiency becomes increasingly important from north to south on a north-south transect in West Africa (Sahrawat et al., 2001).

Soil fertility, especially the organic matter status of soils also varies with ecology. For example, wetland soils located in the valley bottoms or lowest portion of the continuum or toposequence, generally cultivated to wetland rice, are higher in organic matter compared to soils in upland and transition zones of the toposequence (Sahrawat, 2004). Thus, the fertility of soils varies among ecosystems and ecologies and generalizations about the nutrient status of soils of general fertility may at times prove hazardous.

Nitrogen is commonly deficient and limits crop production in cultivated soils of the tropics (Sanchez, 1976). For most farmers in SSA, the use of mineral N fertilizers is limited due to high prices and low profitability (Mclntire and Fussel, 1986). The only option is to source N from organic inputs, intercropping and rotations with N fixing crops, and through managed fallows using improved leguminous fallows (Tian et al., 2001).

High variability in total N content is observed both in different agroecological zones and farm sections in the same zone. Different agroecological zones in West Africa for example recorded total soil N values between 0.5 and 1.6 g kg^{-1} (Table 11.3). Nutrient distribution studies within the same farm show that farm sections close to the homestead have high N content (0.9-1.8 g kg^{-1}) with distant bush fields showing low total soil N values (0.2-0.5 g kg^{-1}). The differences are attributed to farm-specific management practices (Table 11.4).

Nitrogen, phosphorus and organic matter reserves in soils in African agroecosystems also vary with resource endowment (Table 11.5). Recent studies in Kenya showed that land belonging to low resource endowed farmers can lose up to ten times more soil through soil erosion compared to land

TABLE 11.3. Total nitrogen, total P, and OC stocks of granitic soils in different agroecological zones in West Africa

AEZ	**pH (H_2O)**	**OC ($g\ kg^{-1}$)**	**Total N ($g\ kg^{-1}$)**	**Total P ($mg\ kg^{-1}$)**
Equatorial forest	5.3	24.5	1.60	628
Guinea savanna	5.7	11.7	1.39	392
Sudan savanna	6.8	3.3	0.49	287

Source: Adapted from Windmeijer and Andriesse (1993).

TABLE 11.4. Total N, available P, and OC stocks of different subsystems in a typical upland farm in the Sudan-savanna zone

AEZ	**pH (H_2O)**	**OC ($g\ kg^{-1}$)**	**Total N ($g\ kg^{-1}$)**	**Available P ($mg\ kg^{-1}$)**	**Exchangeable K ($mmol\ kg^{-1}$)**
Home garden	6.7-8.3	11-22	0.9-1.8	20-220	4.0-24
Village field	5.7-7.0	5-10	0.5-0.9	13-16	4.0-11
Bush field	5.7-6.2	2-5	0.2-0.5	5-16	0.6-1

Source: Adapted from Prudencio (1993).

TABLE 11.5. Soil loss and soil fertility indicators (% of threshold level) as affected by farmers' wealth class in Machakos, Kenya

Group/Wealth class	**Soil loss ($t\ year^{-1}$)**	**soc**	**Total N**	**Total P**
High (wealthiest)	10	30	32	65
Medium (average)	40	29	30	63
Low (poorest)	100	28	29	62

Source: Adapted from Gachimbi et al. (2002).

belonging to high resource endowed farmers. The study showed that high- and medium-resource endowed farmers are better positioned to arrest or alleviate nutrient depletions in their farm holdings. They have better access to natural capital, manufactured or local resources, and can use external inputs, partly because of their financial status. Nutrient depletion studies at the farm level across Africa reveal a strong effect on socioeconomic conditions. Shepherd and Soule (1998) reported a negative carbon balance of 400 kg ha^{-1} $year^{-1}$ for farmers with low resource endowment whereas a positive balance of 190 kg ha^{-1} $year^{-1}$ was reported in fields of farmers with high resource endowment (Table 11.6).

Soil organic C (SOC) levels across farm fields show steep gradients resulting from long-term site-specific soil management by the farmer. According to Prudencio (1993), SOC status of various fields within a farm in Burkina Faso showed great variations with home gardens (located near the homestead) having 11-22 g kg^{-1} (Table 11.4), village field (at intermediate distance) 5-10 g kg^{-1}, and bush field (furthest) having only 2-5 g kg^{-1}. Usually, closer fields are supplied with more organic inputs as compared to distant fields due to the labor factor.

About 80 percent of the soils have inadequate supply of phosphorus, without which other inputs and technologies are not effective (Bationo et al., 2003; Gikonyo and Smithson, 2003). The importance of phosphorus in the integrated management of soil fertility is manifested by the fact that leguminous crops and cover crops in natural and managed fallows fail to take full advantage of biological nitrogen fixation (BNF) in the absence of adequate P levels in the soils (Sahrawat et al., 2001). Availability and total P levels of soil are low in SSA (Bache and Rogers, 1970; Mokwunye, 1974; Jones and Wild, 1975; Sahrawat et al., 2001). Despite its low levels of inherent soil P, the use of P in SSA is only 1.6 kg P ha^{-1} in cultivated land compared to 7.9 and 14.9 kg P ha^{-1} respectively for Latin America and Asia (Bationo et al, 2003).

The main factors contributing to soil fertility depletion in SSA are erosion by water and wind, especially in the semiarid and arid zone soils. The

TABLE 11.6. SOC balance, soil erosion, farm return, and household income at different farm resource endowment levels

		Farm resource endowment		
Variable	**Units**	**Low**	**Medium**	**High**
Soil C balance	Kg ha^{-1} $year^{-1}$	-400	-318	190
Soil erosion	T ha^{-1} $year^{-1}$	5.6	5.5	2.1
Farm returns	\$ $year^{-1}$	3	70	545
Household income	\$ $year^{-1}$	454	1,036	3,127

Source: Adapted from Shepherd and Soule (1998).

soil lost through erosion is about ten times greater than the rate of natural soil formation, while deforestation is thirty times greater than that in planned reforestation. Sterk et al. (1996) reported a total loss of 45.9 t ha^{-1} of soil by wind erosion during four consecutive storms. Buerkert et al. (1996) reported that in unprotected plots, up to 7 kg of available P and 180 kg ha^{-1} of organic carbon (OC) are lost from the soil profile within one year. The loss of the top soil, which can contain ten times more nutrients than the subsoil, is particularly worrying, since it potentially affects crop productivity in the long-term by removing the soil that is inherently rich in organic matter (Figure 11.5) and micronutrients. Runoff and soil loss will depend on soil types and their erodibility, and the implementation of landform configuration and soil and water conservation practices (Lal, 1980).

EVOLUTION OF SOIL FERTILITY PARADIGM IN AFRICA

During the past three decades, the paradigms underlying soil fertility management research and development efforts have undergone substantial change because of experiences gained with specific approaches, and changes in the overall social, economic, and political environment faced by various stakeholders. During the 1960s and 1970s, an external input paradigm was driving the agricultural research and development agenda. The appropriate use of external inputs, whether fertilizers, lime, or irrigation water, was believed to alleviate constraints to crop production (Vanlauwe, 2004). Following this paradigm together with the use of improved cereal germplasm, the "Green Revolution" boosted agricultural production in Asia and Latin

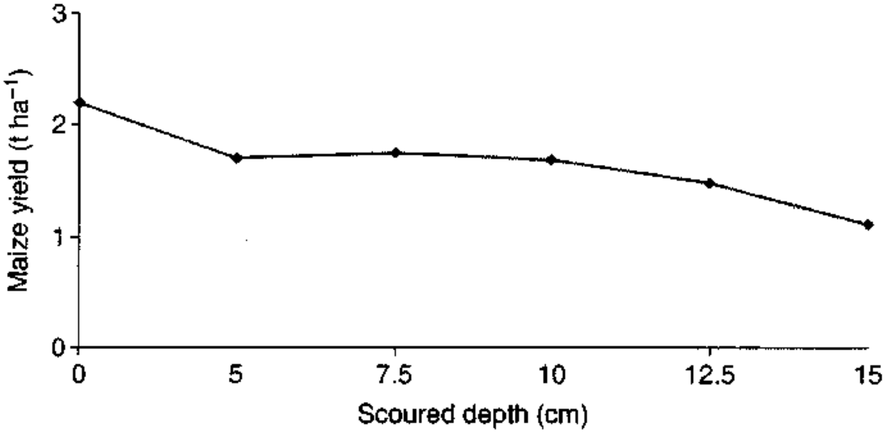

FIGURE 11.5. Effect of depth of soil mechanical desurfacing on maize grain yield at Mbissiri, north Cameroon. *Source:* Adapted from Roose and Barthes (2001).

America in ways not seen before. Organic resources were considered less essential. Sanchez (1976) stated that when mechanization is feasible and fertilizers are available at reasonable cost, there is no reason to consider the maintenance of soil organic matter (SOM) as a major management goal. However, application of the "Green Revolution" strategy in SSA resulted only in minor achievements for a variety of reasons (IITA, 1992). This, together with environmental degradation resulting from massive and injudicious applications of fertilizers and pesticides in Asia and Latin America between the mid-1980s and early 1990s (Theng, 1991), and the abolition of fertilizer subsidies in SSA (Smaling, 1993) imposed by structural adjustment programs, led to a renewed interest in organic resources in the early 1980s. The balance shifted from mineral inputs to low input sustainable agriculture (LISA) where organic resources were believed to enable sustainable agricultural production (Vanlauwe, 2004).

After a number of years of investment in research activities evaluating the potential of LISA technologies, such as alley cropping or live-mulch systems, several constraints were identified both at the technical (e.g., lack of sufficient organic resources) and the socioeconomic level (e.g., labor intensive technologies) (Vanlauwe, 2004). Sanchez (1994) also revised his earlier statement by formulating the Second Paradigm for tropical soil fertility research: "Rely more on biological processes by adapting germplasm to adverse soil conditions, enhancing soil biological activity and optimizing nutrient cycling to minimize external inputs and maximize the efficiency of their use." This paradigm recognized the need for both mineral and organic inputs to sustain crop production, giving way to the INM approach. The need for both organic and mineral inputs was advocated because (1) both resources fulfill different functions to maintain plant growth; (2) under most small-scale farming conditions, neither of them is available or affordable in sufficient quantities to be applied alone; and (3) several hypotheses could be formulated leading to added benefits when applying both inputs in combination (Vanlauwe, 2004).

INM is perceived as the judicious manipulation of nutrient inputs, outputs, and internal flows to achieve productive and sustainable agricultural systems (Smaling et al., 1996). It can be defined as a systematic, planned approach to soil fertility management on both a small and large scale in the context of both the farm and ecosystem as a whole, in which sound management principles and practices are followed throughout. This management approach involves the best possible combination of available nutrient management practices, in the context of biophysical resources, economic feasibility, and social acceptability. The INM concept is mostly applied to the use of organic and inorganic sources of nutrients in a judicious and efficient

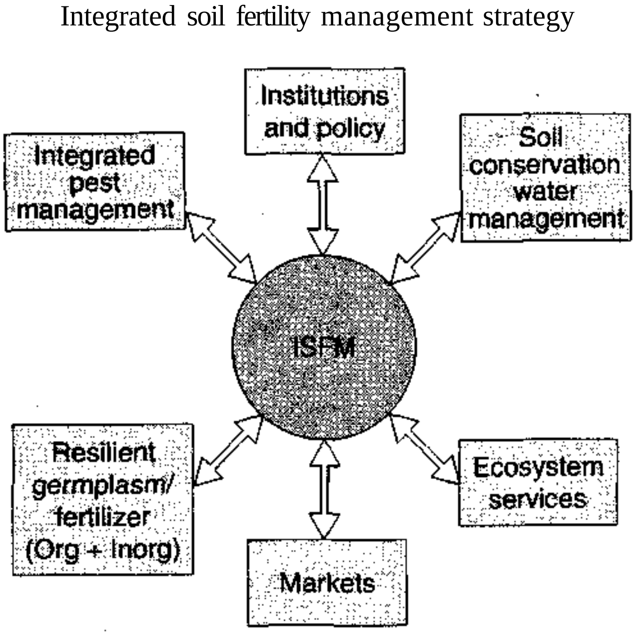

FIGURE 11.7. Integrated soil fertility management paradigm. *Source:* Bationo et al. (2003).

Within this new ISFM paradigm, considerable attention is given to the imbalances between nutrient inputs and outputs (nutrient(s) flows), and their agronomic, economic, and environmental consequences. Nutrient stocks, flows, and balances are increasingly being used for estimating nutrient depletion/accumulation. Nutrient depletion or enrichment of the system follows from the difference between total nutrient inputs (mineral fertilizer, organic inputs, deposition, BNF, sedimentation, and subsoil nutrient exploitation) and outputs (harvested products, (CR)s, leaching, gaseous losses, erosion, feces, and urine). Nutrient flows models are used at the plot and farm level to assist farmers and policymakers in evaluating the agronomic and environmental impact of their farm management practices. Nutrient balance may be characterized by a nutrient balance, made up of a number of nutrient inputs that exceed nutrient outputs (lN - OUT >> 0_1, termed surplus nutrient accumulation class); or where nutrient outputs exceed inputs (IN - OUT << 0_1, termed nutrient depletion class); or where IN - OUT = 0_+, which is termed balanced or equilibrium class.

The ISFM approach advocates careful management of soil fertility aspects that optimize production potential through the incorporation of a wide range of adoptable soil management principles, practices, and options for productive and sustainable agroecosystems. It entails the development of soil nutrient management technologies for adequate supply and feasible share of organic and inorganic inputs that meet the farmers' production goals and circumstances. The approach integrates the roles of soil and water conservation; land preparation and tillage; organic and inorganic nutrient sources; nutrient adding and saving practices; pests and diseases; livestock; rotation and intercropping; multipurpose role of legumes; and integrating the different research methods and knowledge systems (Kimani et al., 2003).

ISFM embraces multiplepurpose options (MPOs), which include INM (the technical backbone of the ISFM approach), biotic and abiotic factors and their relationships, livestock integration in crop production systems, use of local and indigenous knowledge together with science knowledge-based management system, and integration of policy and institutional framework. The major emphasis in the ISFM paradigm is on understanding and seeking to manage processes that contribute to change. This paradigm is closely related to the wider concepts of INRM, thereby representing a significant step beyond the earlier, narrower concept and approach of nutrient replenishment/recapitalization for soil fertility enhancement (Sanchez et al., 1997).

ISFM EXPERIENCES IN SSA

Semiarid Agroecological Zone

N and P Management

Nitrogen and P are the most limiting nutrients in the semiarid zones of Africa. Urea and calcium ammonium nitrate (CAN) are the most common sources of N used by farmers. Results of trials undertaken to evaluate these two sources and methods of application of nitrogen led to the conclusions that: (1) fertilizer N recovery by plant was low; (2) there is a higher loss of N with the surface point placement of urea (>50 percent) and the mechanism of N loss is believed to have been ammonia volatilization; (3) losses of N from CAN were less than from urea because one-half of the N in CAN is in the nonvolatile nitrate form; (4) although CAN is a lower N analysis fertilizer than urea, it is attractive as an N source because of its low potential for N loss via volatilization and its low soil acidifying properties (Table 11.7) (Bationo et al., 2003). Point placement of CAN outperformed urea point placed or broadcast, and ^{15}N data from similar trials indicate that uptake by plants was almost three times higher than that of urea applied in the same manner (Figure 11.8).

TABLE 11.7. Recovery ^{15}N fertilizer by pearl millet applied at Sadore, Niger, 1985

		^{15}N Recovery			
		Grain	Stover	Soil	Total
N source	Application method	(%)			
CAN	Point incorporated	21.3	16.8	30.0	68.1
CAN	Broadcast incorporated	10.9	10.9	42.9	64.7
Urea	Point incorporated	5.0	6.5	22.0	33.5
Urea	Broadcast incorporated	8.9	6.8	33.2	48.9
Urea	Point surface	5.3	8.6	18.0	31.9
SE		1.2	2.0	1.9	2.4

Source: Adapted from Christianson and Vlek (1991).

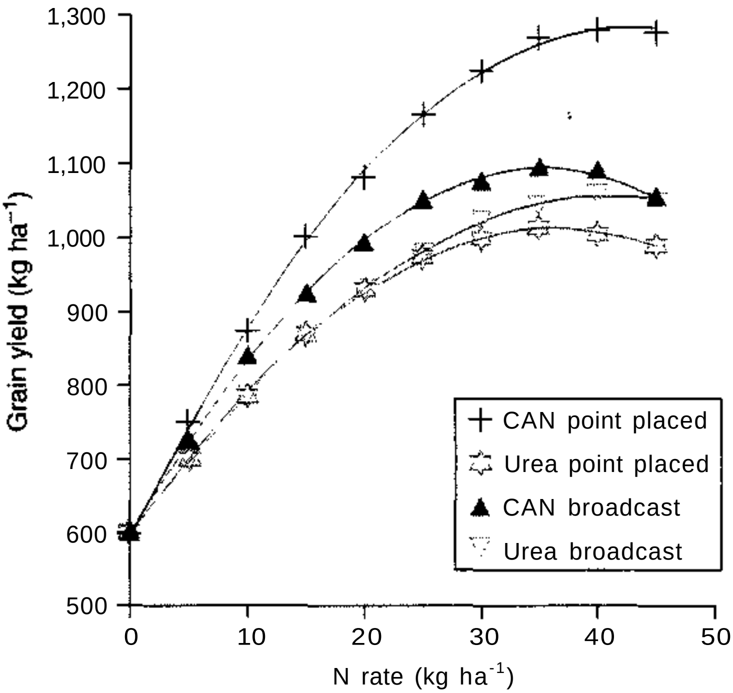

FIGURE 11.8. Effect of broadcast and point application methods for Urea and CAN on grain yield of pearl millet. *Source:* Adapted from Christianson and Vlek (1991).

Christianson and Vlek (1991) found that the optimum N rate for sorghum is 50 kg ha^{-1} and 30 kg ha^{-1} for pearl millet (*Pennisetum glaucum* L.). The N use efficiency can be increased through rotation of cereals with legumes and through the optimization of planting density. Bationo and

Vlek (1998) reported an N-use efficiency of 20 percent in the continuous cultivation of pearl millet, but its value increased to 28 percent when pearl millet was rotated with cowpea. Bationo et al. (1989) found a strong and positive correlation between planting density and response to N fertilizer.

Phosphorous deficiency is a major constraint to crop production and response to N is substantial only when both moisture and phosphorous are not limiting. Field trials were established to determine the relative importance of N, P, and K fertilizers in the Sahelian zone. The data in Table 11.8 indicates that from 1982 to 1986 the average control plot gave 190 kg grain ha^{-1} yield of pearl millet. The sole addition of 30 kg P_2O_5 ha^{-1} without N fertilizers increased the average pearl millet yield to 714 kg ha^{-1}. The addition of only 60 kg N ha^{-1} without P application did not increase the yield significantly over the control (average grain yield obtained was 283 kg ha^{-1}). Those data clearly indicate that P is the most limiting factor in those sandy Sahelian soils and there is no significant response to N without correcting first for P deficiency. Application of 120 kg N ha^{-1} resulted in pearl millet grain yield of 1,173 kg ha^{-1} compared to 714 kg ha^{-1} when only P fertilizers were applied. The addition of K did not increase significantly the yield of either grain or total dry matter of pearl millet in any year of the study.

Despite the fact that deficiency of P is acute on the soils of West Africa, local farmers use very low P fertilizers partly because of the high cost. The use of locally available phosphate rock (PR) could be an alternative to imported P fertilizers. For example, Bationo et al. (1987) showed that direct application of local PR may be more economical than imported water-soluble P fertilizers. Bationo et al. (1990) showed that Tahoua PR from Niger is suitable for direct application, but Parc-W from Burkina Faso has less potential for direct application. The effectiveness of local PR depends on its chemical and mineralogical composition (Lehr and McClellan, 1972; Chien and Hammond, 1978; Khasawneh and Doll, 1978). the most important feature being the ability of carbonate ions to substitute for phosphate in the apatite lattice which influences the solubility, and controls the amount of phosphorus available to crops (Smith and Lehr, 1966). The most reactive PR should have molar PO_4/CO_3 ratios less than 5. In Niger, Tahoua PR outperformed Kodjari PR (from Burkina Faso). The results are in agreement with the fact that the molar PO_4/CO_3 ratio is 23 for Kodjari PR and 4.88 for Tahoua PR, and Tahoua PR also has a higher solubility in Neutral Ammonium Citrate (NAC).

The solubility of PR in NAC is directly related to the level of carbonate substitution (Chien, 1977). Diamond (1979) classified African PR-based on citrate solubility as >5.4 percent high, 3.2-4.5 percent medium, and <2.7

TABLE 11.8. Effect of N, P, and K on pearl millet grain and total dry matter (kg ha^{-1}) at Sadoré and Gobery (Niger)

	1982 Sadoré		1983		1984 Sadoré		1985	1986 Sadoré	
			Sadoré	Gobery			Sadoré		
Treatments	Grain	TDM	Grain	Grain	Grain	TDM	Grain	Grain	TDM
N0P0K0	217	1,595	146	264	173	1,280	180	180	1,300
N0P30K30	849	2,865	608	964	713	2,299	440	710	2,300
N30P30K30	1,119	3,597	906	1,211	892	3,071	720	930	3,000
N60P30K30	1,155	3,278	758	1,224	838	3,159	900	880	3,200
N90P30K30	1,244	3,731	980	1,323	859	3,423	1,320	900	3,400
N120P30K30	1,147	4,184	1,069	1,364	1,059	3,293	1,400	1,000	3,300
N60P0K30	274	2,372	262	366	279	1,434	290	230	1,500
N60P15K30	816	2,639	614	1,100	918	3,089	710	920	3,100
N60P45K30	1,135	3,719	1,073	1,568	991	3,481	1,200	980	3,500
N60P30K0	1,010	3,213	908	1,281	923	3,377	920	910	3,400
SE.	107	349	120	232	140	320	162	250	400
CV (%)	24	22	26	30	24	22	28	32	25

Source: Bationo, unpublished data.

Note: Nutrients applied are N, P_2O_5, and K_2O kg ha^{-1}, TDM = Total dry matter.

percent low. Based on this classification, only Tilemsi PR has a medium reactivity.

Phosphorous placement can drastically increase P use efficiency as shown with pearl millet and cowpea in an experiment involving broadcast and/or hill placed of different P sources. For pearl millet grain, P use efficiency for broadcasting SSP at 13kg P ha^{-1} was 23 kg kg^{-1}, but hill placement of SSP at 4 kg P ha^{-1} gave a PUE of 83 kg kg^{-1} P. The PUE of 15-15-15 broadcast was 29 kg grain kg^{-1} P, whereas the value increased to 71 kg kg^{-1} P when additional SSP was applied as hill placed at 4 kg P ha^{-1}, and 102 when only hill placed of 4 kg P ha^{-1} of 15-15-15 was used. Hill placement of small quantities (4 kg ha^{-1}) of P attains the highest use efficiency with the efficiency decreasing with increasing quantity of P (Table 11.9).

TABLE 11.9. Effect of different sources of phosphorus (Single superphosphate-SSP, 15-15-15 NPK, and TPR-Tahoua rock phosphate) and the mode of application on pearl millet yield and phosphorus use efficiency (PUE in kg per kg P applied) in Karabedji, 1998 rainy season

	Grain		**Total dry matter**	
P sources and method of application (selected treatments)	**Yield (kg ha^{-1})**	**PUE (kg kg^{-1})**	**Yield (kg ha^{-1})**	**PUE** (kg kg^{-1})
Control	281		1,726	
SSP broadcast (13 kg P ha^{-1})	535	23	3,726	154
SSP broadcast + SSP hill placed (13 + 4 kg P ha^{-1})	743	27	5,563	226
SSP hill placed (4 kg P ha^{-1})	611	83	3,774	514
15-15-15 broadcast (13 kg P ha^{-1})	660	29	4,226	192
15-15-15 broadcast + hill placed (13 + 4 kg P ha^{-1})	1,493	71	7,677	350
15-15-15 (4 kg P ha^{-1})	690	102	4,767	760
TPR broadcast (13 kg P ha^{-1})	690	31	4,135	185
TPR broadcast + SSP HP (13 + 4 kg P ha^{-1})	663	22	4,365	155
TPR broadcast + 15-15-15 HP (13 + 4 kg P ha^{-1})	806	31	5,061	196
SE	84		194	

Source: Bationo, unpublished data.

Note: BC = broadcasting, HP = hill placement.

percent low. Based on this classification, only Tilemsi PR has a medium reactivity.

Phosphorous placement can drastically increase P use efficiency as shown with pearl millet and cowpea in an experiment involving broadcast and/or hill placed of different P sources. For pearl millet grain, P use efficiency for broadcasting SSP at 13 kg P ha^{-1} was 23 kg kg^{-1}, but hill placement of SSP at 4 kg P ha^{-1} gave a PUE of 83 kg kg^{-1} P. The PUE of 15-15-15 broadcast was 29 kg grain kg^{-1} P, whereas the value increased to 71 kg kg^{-1} P when additional SSP was applied as hill placed at 4 kg P ha^{-1}, and 102 when only hill placed of 4 kg P ha^{-1} of 15-15-15 was used. Hill placement of small quantities (4 kg ha^{-1}) of P attains the highest use efficiency with the efficiency decreasing with increasing quantity of P (Table 11.9).

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SE	84		194	

Source: Bationo, unpublished data.

Note: BC = broadcasting, HP = hill placement.

The efficiency of N fertilizers in the dryland soils depends on the level of land degradation. For example, whereas N efficiency was 8.6 kg grain per kg N, in degraded land, it increased to 15 kg grain per kg N in nondegraded land (Table 11.10).

Crop Residue Management

Crop residue management can play an important role in improving crop productivity in SSA. Numerous research reports show large crop yield increases as a consequence of organic amendments in the Sahelian zone of West Africa (Abdullahi and Lombin, 1978; Bationo et al., 1993; Bationo et al, 1998; Evequoz et al., 1998; Pieri, 1986, 1989). Bationo et al. (1995) reported from an experiment carried out in 1985 on a sandy soil at Sadore, Niger, that grain yield of pearl millet after a number of years had declined to only 160 kg ha^{-1} in unmulched and unfertilized control plots. However, grain yields could be increased to 770 kg ha^{-1} with a mulch application of 2 t CR ha^{-1} and to 1,030 kg ha^{-1} with 13 kg P as SSP plus 30 kg N ha^{-1}. The combination of CR and mineral fertilizers resulted in a grain yield of 1,940 kg ha^{-1}.

In different parts of SSA, crop or organic residue applications have been shown to increase soil P availability (Kretzschmar et al., 1991), enhance PR availability (Sahrawat et al., 2001), cause better root growth (Hafner et al., 1993), improve potassium (K) nutrition (Rebafka et al., 1994), protect young seedlings against soil coverage during sand storms (Michels et al., 1995), increase water availability (Buerkert et al., 1999), reduce soil surface resistance by 65 percent (Buerkert and Stern, 1995), and reduce topsoil temperature by over 4°C (Buerkert et al., 1999). These effects are stronger especially in the Sahelian zone, but weaker in other areas with lower temperatures, higher rainfall, and heavier soils (Buerkert et al, 1999). From incubation

TABLE 11.10. Use efficiency of N and P in degraded and nondegraded sites at Karabedji, Niger, 1998-2002

Fertilizer	Site condition	Efficiency (kg grain kg^{-1} N or P)
Nitrogen	Degraded	8.6
	Nondegraded	15.3
Phosphorus	Degraded	50
	Nondegraded	58

Source: Bationo, unpublished data.

studies under controlled conditions Kretzschmar et al. (1991) concluded that increases in P availability after CR application were due to a complexation of iron and aluminum by organic acids. The organic amendments have also been reported to reduce the capacity of the soil to fix P thereby increasing P availability for uptake and hence higher P use efficiency (Buresh et al., 1997; Sahrawat et al., 2001).

Availability of organic inputs in sufficient quantities and quality is one of the main challenges facing farmers and researchers today. In an inventory of CR availability in the Sudanian zone of central Burkina Faso, Sedga (1991) concluded that the production of cereal straw can meet the currently recommended optimum level of 5 t ha^{-1} every two years. However, McIntire and Fussell (1986) reported that on fields of unfertilized local cultivars, grain yield averaged only 236 kg ha^{-1} and mean residue yields barely reached 1,300 kg ha^{-1}. These results imply that unless stover production is increased through application of fertilizers and/or manure it is unlikely that the recommended levels of CR could be available for use as mulch. The availability of CR in smallholder farms in SSA is limited by the fact that there are many competing uses for biomass such as fodder and fuel for cooking (Figure 11.9).

In village level studies on CR, along a north-south transect in three different agroecological zones of Niger, surveys were conducted to assess

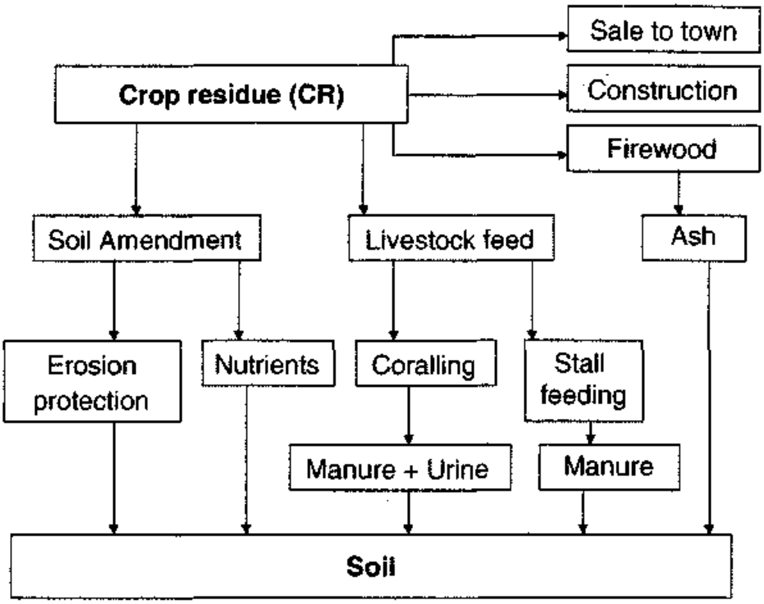


FIGURE 11.9. The competing uses of CRs in the West African semiarid tropics. *Source:* Bationo et al. (1995).

farm-level stover production, household requirements, and residual stover remaining on-farm. The results of these surveys showed that the average amounts of stover removed from the field by a household represented between 2 and 3.5 percent of the mean stover production (ICRISAT, 1993). At the onset of the rains the residual stover on-farm was between 21 and 39 percent of the mean stover production at harvest time. Although farmers require at least 2 T ha^{-1} of CR for mulch, only 250 kg ha^{-1} of CR is presently available on soil at planting time. Even if no data have been collected on the amount of CR lost by microbial decomposition and termites, cattle grazing is likely to be responsible for most of the disappearance of CRs. Similar losses were reported by Powell (1985) who found that up to 49 percent of sorghum and 57 percent of millet stover disappearance on the humid zone of Nigeria was due to livestock grazing. Sandford (1989) reported that in the mixed farming systems, cattle derive up to 45 percent of their total annual intake from CRs and up to 80 percent during periods of fodder shortage. Up to 50 percent of the total amount of CR and up to 100 percent of the leaves is eaten by livestock (van Raay and de Leeuw, 1971). Most of the nutrients are voided in the animal excreta, but when the animals are not stabled, nutrients contained in the droppings cannot be effectively utilized in the arable areas (Balasubramanian and Nnadi, 1980).

Manure Management

Manure, another farm-available soil amendment, is an important organic input in African agroecosystems. One of the earliest reported manure application studies in SSA was by Hartley (1937)in the Nigerian savannah. He observed that application of 2 t ha^{-1} farm yard manure (FYM) increased seed cotton yield by 100 percent, equivalent to fertilizers applied at the rate of 60 kg N and 20 kg P ha^{-1}. Palm (1995) has concluded that for a modest yield of 2 t ha^{-1} of maize the application of 5 t ha^{-1} of high quality manure can meet the N requirement, but this cannot meet the P requirements in areas where P is deficient. Bationo and Mokwunye (1991) found no difference between applying 5 t ha^{-1} of FYM compared to the application of 8.7 kg P ha^{-1} as single superphosphate (SSP) pointing to the role of manure in the availability of P through complexation of iron and aluminum (Kretzschmar et al., 1991). Other reports have shown that crop yields from the nutrient poor West African soils can be substantially enhanced through the use of manure (McIntire et al., 1992; Bationo and Buerkert, 2001; Sedogo, 1993). For Niger, McIntire et al. (1992) reported grain yield increases between 15 and 86 kg for millet and between 14 and 27 kg for groundnut per tonne of applied manure. Combined use of manure and mineral fertilizer show a long-term increase of sorghum yields over years (Figure 11.10).

The data in Table 11.11 (Panel A and B) summarizes the results of a number of trials on manure and manure + inorganic fertilizer conducted in research stations in some West African countries. The data shows that manure collected from stables and applied alone produces about 34 to 58 kg DM t^{-1} manure in cereal grain and 106 to 178 kg of DM t^{-1} manure in stover (Table 11.11 panel A). Application of manure with inorganic fertilizer gave yields of 80 to 90 kg of DM t^{-1} manure and 84 to 192 kg of DM t^{-1} manure grain and stover yields respectively (Table 11.11 panel B).

The quality of manure has been observed to vary with feeds, collection, and storage methods (Mueller-Samann and Kotschi, 1994; Mugwira, 1984; Ikombo, 1984; Probert et al., 1995; Kihanda, 1996). Current characterization studies indicate that manure quality is very variable, for example, %N 0.23-2.6; % P 0.08-1.0; % K 0.2-1.46; %Ca 0.2-1.3; and %Mg 0.1-0.5 (Table 11.12) (Williams et al., 1995). High quality manure has been defined as that with %N >1.6 or C:N ratios of <10; while low quality manure has N < 0.6 percent and C:N ratios of > 17.

Several scientists have addressed the availability of manure for sustainable crop production. De Leeuw et al. (1995) reported that with the present livestock systems in West Africa the potential annual transfer of nutrients

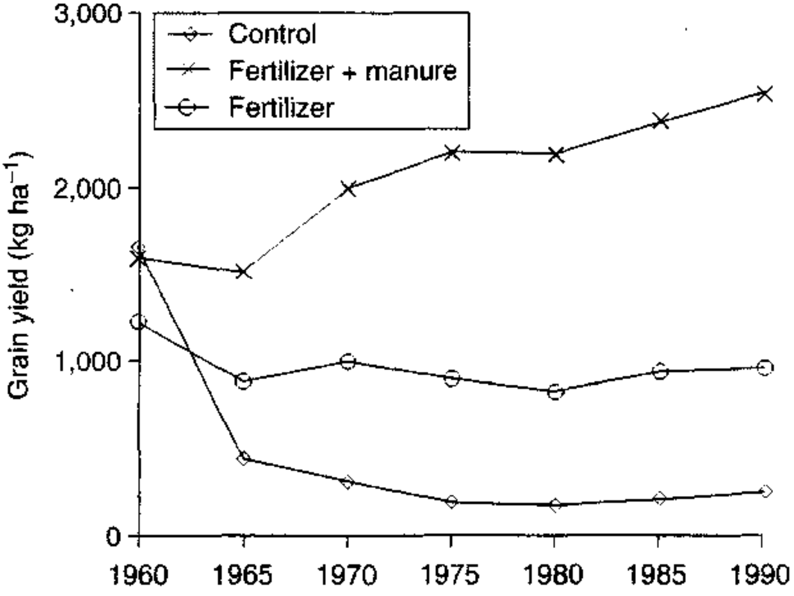


FIGURE 11.10. Sorghum grain yield as affected by mineral and organic fertilizers over time. *Source:* Adapted from Sedogo (1993).

TABLE 11.11. Results of manuring experiments at three sites in semiarid West Africa.

Location	Amount of manure applied (t ha^{-1})	Crop	Crop response[a] (kg of DM t^{-1} manure) Grain	Crop response[a] (kg of DM t^{-1} manure) Stover	Reference
Panel A: Manure only					
M'Pesoba, Mali	10	Sorghum	35[b]	n.s.	1
Saria, Burkina Faso	10	Sorghum	58	n.s.	2
Sadore, Niger, 1987	5	Pearl millet	38	178	3
	20	Pearl millet	34	106	3

Location	Amount of Manure (t ha^{-1})	Amount of Fertilizer (kg ha^{-1})	Crop	Crop response[a] (kg of DM t^{-1} manure) Grain	Crop response[a] (kg of DM t^{-1} manure) Stover
Panel B: Manure with inorganic fertilizer					
M'Pesoba, Mali	5	NPK: 8-20-0	Sorghum	90[c]	n.s.
Saria, Burkina Faso	10	Urea N: 60	Sorghum	80	n.s.
Sadore, Niger, 1987	5	SSP P: 8.7	Pearl millet	82	192
Sadore, Niger, 1987	20	SSP P: 17.5	Pearl millet	32	84

Source: Adapted from Williams et al. (1995).

Note: n.s. implies not specified. References: 1. Pieri (1989); 2. Pieri (1986); 3. Baidu-Forson and Bationo (1992).

[a] Responses were calculated at the reported treatment means for crop yields as: (treatment yield − control yield)/quantity of manure applied.

[b] Response of sorghum planted in the second year of a four-year rotation involving cotton-sorghum–groundnut-sorghum. Manure was applied in the first year.

[c] Estimated from visual interpolation of graph.

TABLE 11.12. Major nutrient (N, P, and K) composition of manure at selected sites in semiarid West Africa.

	Nutrient composition (%)		
Location and type of manure	**N**	**P**	**K**
Saria, Burkina Faso			
Farm yard manure	1.5-2.5	0.09-0.11	1.3-3.7
Northern Burkina Faso			
Cattle manure	1.28	0.11	0.46
Small ruminant manure	2.20	0.12	0.73
Senegal			
Fresh cattle dung	1.44	0.35	0.58
Dry cattle dung	0.89	0.13	0.25
Niger			
Cattle manure	1.2-1.7	0.15-0.21	
Sheep manure	1.0-2.2	0.13-0.27	-

Source: Adapted from Williams et al. (1995).

from manure is 2.5 kg N and 0.6 kg P per hectare of cropland. Although the manure rates are between 5 and 20 t ha^{-1} in most of the on-station experiments, quantities used by farmers are very low and ranged from 1,300 to 3,800 kg ha^{-1} (Williams et al., 1995). This is due to insufficient number of animals to provide the manure needed; the problem becomes more pronounced especially in postdrought years (Williams et al., 1995). The amount of livestock feed and land resources available are also limited. Depending on rangeland productivity, it will require between 10-40 hectares of dry season grazing land and 3-10 hectares of wet season grazing rangeland to maintain yields on one hectare of cropland using animal manure (Fernandez et al, 1995).

The method of manure placement could have a significant effect on crop yields. Hill placement of manure performed better than broadcasting in on-farm trials in the Sahel. Broadcasting 3 t ha^{-1} of manure resulted in a pearl millet grain yield of 700 kg ha^{-1} whereas the point placement of the same quantity of manure gave about 1,000 kg ha^{-1} (Figure 11.11).

Cropping Systems

The most common cropping systems in this zone involve growing several crops in association as mixtures. This practice provides the farmer with

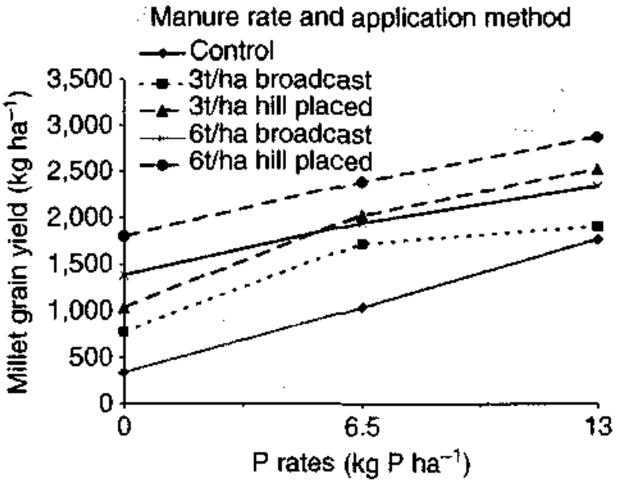


FIGURE 11.11. Millet grain yield response to P and manure rates and methods of application, Karabedji, Niger, 2002 rainy season. *Source:* Bationo, unpublished data.

several options for returns from land and labor, often increases efficiency with which scarce resources are used, and reduces dependence upon a single crop that is susceptible to environmental and economic fluctuations.

Intercropping. Traditional intercropping systems cover over 75 percent of the cultivated area in the semiarid Tropics (Steiner, 1984). In the Sudano-Sahelian zone, cereals such as millet and sorghum are traditionally intercropped with cowpea on small farms. In Niger, up to 87 percent of the millet area is intercropped (Swinton et al., 1984). A study by Norman (1974) in northern Nigeria has shown that only 8 percent of the area was planted to sole sorghum, while about 50 percent of the area was planted with sorghum in intercrop. Similar findings are reported by Fussell and Serafini (1985) for Nigeria, Niger, Burkina Faso, and Mali. The most common associations are cereal/cowpea, cereal/groundnut, and cereal/cereal such as millet/sorghum/maize, and millet/sorghum/cowpea. In these systems, cereals are normally sown first and act as the dominant crop. Norman (1974) concludes that mixed cropping is a strategy for the farmers' profit maximization and risk minimization. Production and income stability are important features of the systems, which also alleviate seasonal labor peaks (Abalu, 1976).

The yield advantages of intercrop systems vary from 10-100 percent in millet cropping systems (Fussell and Serafini, 1985). In western Niger, the combination of cowpea with millet has resulted in production advantages of 10-40 percent over four years and in Mali by 100 percent in maize/millet intercrop. For millet/groundnut systems there is a yield advantage of

28-53 percent (Table 11.13). There is a scarcity of data on nutrient use efficiency in intercropping systems as compared to monocropping systems.

Relay and sequential cropping systems: The performance of cultivars under relay and sequential systems has higher potential than traditional sole or mixed cropping (Shetty, 1984). In Mali, by introducing short season sorghum cultivars in relay cropping with other short duration cowpea and groundnut cultivars, substantial yields of legumes and sorghum were obtained as compared to traditional systems (IER, 1990; Sedogo and Shetty, 1991).

In the Sahelian zone, Sivakumar et al. (1990) analyzed the date of the onset and ending of the rains, and the length of the growing period. He found that an early onset of the rains offers the probability of a longer growing season while delayed onset results in a considerably shorter growing season. The analysis suggested that cropping management factors using relay cropping can increase soil productivity.

Crop rotation. Rotation of cereals and legumes can be used as a means of improving soil fertility and productivity. Several researchers (Bagayoko

TABLE 11.13. Yields of pearl millet and groundnut in sole crops and intercrops, and resultant land-equivalent ratio (LER) at Tara, Niger, rainy season 1989

Treatment[a]	**Ground nut pods ($t\ ha^{-1}$)**	**Millet grain ($t\ ha^{-1}$)**	**LER**[b]	**Ground nut haulms ($t\ ha^{-1}$)**	**Millet straw ($t\ ha^{-1}$)**	**LER**
Sole crop						
Groundnut (28-206)	1.29			2.62		
Groundnut (47-16)	0.99			3.13		
Groundnut [ICGS(E)11]	1.40			2.59		
Millet (CIVT)		1.29			3.70	
Intercrop						
CIVT and 28-206	0.71	1.20	1.48	1.28	2.95	1.29
CIVT and 47-16	0.66	1.04	1.46	1.44	3.05	1.28
CIVT and ICGS(E)11	0.71	1.31	1.53	1.22	3.32	1.37
SE	±0.08	±0.05		±0.17	±0.17	
CV (%)	16.6	16.2		16.8	19.0	

Source: Bationo, unpublished data.

[a] Randomized complete block design with four replications. Millet planted at 1 x 1 m and groundnut at 50 x 100 cm.

[b] LER = Sum of ratios of yield of each crop in mixture over yield of sole crop.

et al., 1996; Bationo et al., 1998; Klaij and Ntare, 1995; Sloop and Staveren, 1981; Bationo and Ntare, 2000) have reported cereal/legume rotation effects on cereal yields. Table 11.14 shows the effect of cowpea-millet rotation on millet grain and total biomass production. In a period of three years, there was an increase of about 3 t ha^{-1} of total dry matter production when millet was grown in rotation with cowpea.

Nitrogen use efficiency increased from 20 percent in continuous pearl millet cultivation to 28 percent when pearl millet was rotated with cowpea. Nitrogen derived from the soil is used better in rotation systems than with continuous millet (Bationo and Vlek, 1998). Nitrogen derived from the soil increased from 39 kg N ha^{-1} in continuous pearl millet cultivation to 62 kg N ha^{-1} when pearl millet was rotated with groundnut. Those data clearly indicate that although all the above biomass of the legume will be used to feed livestock and not returned to the soil, rotation will increase not only the yields of the succeeding cereal but also its nitrogen use efficiency (Bationo and Vlek, 1998).

The response of legumes to rotation was also significant and legume yields were consistently lower in monoculture than when rotated with millet (Figure 11.12). This suggests that factors other than N alone contributed to the yield increases in the cereal-legume rotations. It has been assumed by many workers that the positive effects of rotations arise from the added N from legumes in the cropping system. Some workers, however, have attributed the positive effects of rotations to the improvement of soil biological and physical properties, and the ability of some legumes to solubilize occluded P and highly insoluble calcium bounded phosphorus by legume root exudates (Gardner et al., 1981; Arhara and Ohwaki, 1989; Sahrawat et al., 2001). Other advantages of crop rotations include soil conservation (Stoop

TABLE 11.14. Millet grain and total dry matter yield at harvest as influenced by millet/cowpea cropping system at Sadore (Niger)

	Grain yield (kg ha^{-1})			**Total dry matter yield (kg ha^{-1})**		
Cropping system	**1996**	**1997**	**1998**	**1996**	**1997**	**1998**
Continuous millet	937	321	1,557	4,227	2,219	6,992
Millet after cowpea	1,255	340	1,904	5,785	2,832	8,613
P > F	<0.001	0.344	<0.001	<0.001	<0.001	<0.001

Source: Bationo and Ntare (2000).

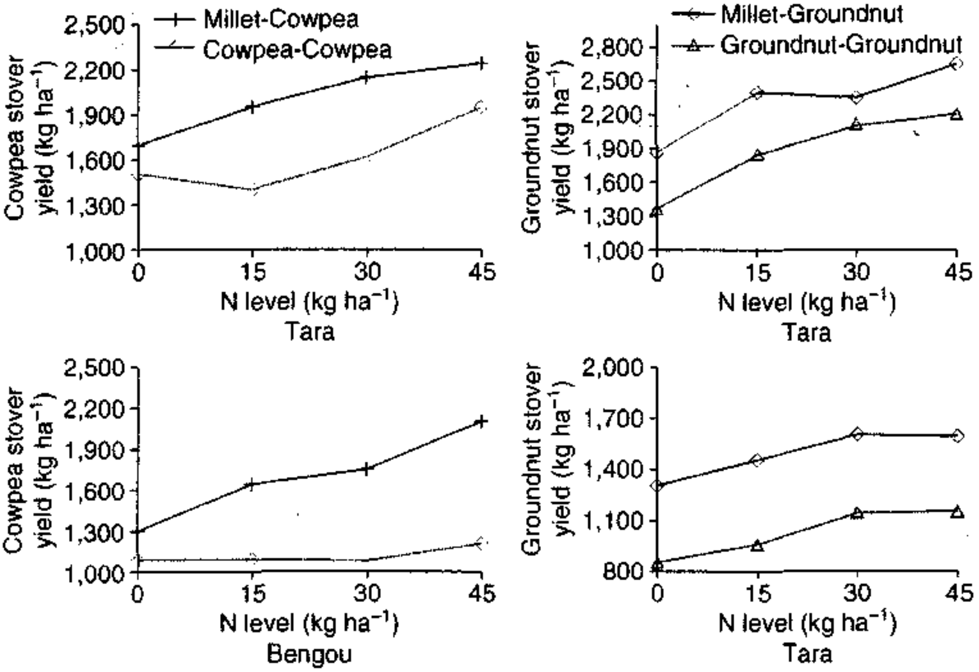


FIGURE 11.12. Effects of nitrogen and rotation on legume stover yield (kg ha^{-1}), average of four years (1989-1992) at Tara and Bengou, Niger. *Source:* Bationo and Ntare (2000).

and Staveren, 1981), organic matter restoration (Spurgeon and Grisson, 1965), and pest and disease control (Sunnadurai, 1973).

Changes in soil chemical properties from long-term cropping systems management trials, monitored in different agroecological zones of the Sudano-Sahelian region showed that rotations resulted in significantly higher soil pH, total N, and effective cation exchange capacity (ECEC) (Table 11.15). In the long-term cropping systems management studies in the Sahel, rotation systems were found to have higher levels of OC as compared to the continuous monocropping system (Figure 11.13). This could partially be due to the contribution made by the fallen leaves of the cowpea crop in the crop rotation.

Interaction Between Water and Nutrients

According to Rockstrom et al. (2003), the keys to improved water productivity and mitigating intraseason dry spells in rainfed agriculture are maximizing the amount of plant-available water and the plant water uptake capacity. This implies systems that partition more incident rainfall to soil storage and less to runoff, deep percolation, and evaporative loss, as well as

TABLE 11.15. Soil chemical properties after five years of experimentation at different sites in the Sudano-Sahelian region

	pH			Organic matter (%)			Total N (mg kg^{-1})			ECEC (cmol kg^{-1})		
Rotation	**Sadore**	**Bengou**	**Tara**	**Sadore**	**Bengou**	**Tara**	**Sadore**	**Bengou**	**Tara**	**Sadore**	**Bengou**	**Tara**
Initial	4.1	4.3	4.1	0.22	0.20	0.45	74	226	197	0.54	1.87	1.20
F-F	4.7	4.7	5.0	0.76	0.46	0.56	351	230	219	1.95	1.15	1.25
F-M	4.9	4.7	5.0	0.74	0.44	0.59	302	251	2.07	1.83	1.35	1.16
M-M	4.6	4.4	4.3	0.52	0.37	0.44	235	178	165	1.91	1.11	0.88
C-M	4.7	4.3	4.3	0.56	0.35	0.47	260	206	197	1.84	1.15	0.88
G-M	4.6	4.3	4.2	0.58	0.27	0.45	263	192	130	1.88	1.25	0.81
SE (DF 27)	0.11	0.09	0.10	0.03	0.04	0.033	12.0	10.67	21.3	0.123	0.107	0.077
CV (%)	4	4	4	9	20	13	8	10	23	13	17	15

Source: Bationo and Ntare (2000).

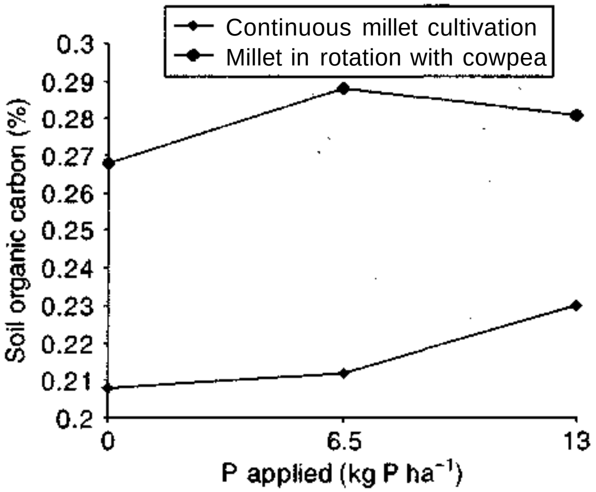


FIGURE 11.13. Effect of phosphorus and cropping system on SOC, Sadore, Niger, 1995. *Source:* Bationo and Buerkert (2001).

crops that provide more soil cover and root more deeply (Rockstrom et al., 2003). Loss of water and nutrients through runoff are major agriculture problems for inherently poor fertile soils in semiarid Africa. The intensification of crop production requires an integration of soil, water, and nutrient management that is locally acceptable and beneficial for smallholder farmers (Zougmore, 2003). In the central plateau of Burkina Faso, stone bounds alone doubled sorghum yield compared to plots without stone bounds and therefore, can reduce risks of crop failure in erratic rainfall years (Zougmore, 2003). Stone bounds consist of rows of stones constructed along the contours to check runoff and soil erosion (Rochette, 1989; Mando et al., 2001). Taonda et al. (2003) found that water harvesting alone with stone bounds did not improve yields, but the combination of water harvesting with stone bounds or zai plus manure increased sorghum yields over two times as compared to the control (Table 11.16).

A study by Zougmore and Zida (2000) has clearly shown the effects of the spacing between installations of stone bounds on decreasing runoff and erosion, and increasing yields (Table 11.17). A spacing of 50 m reduced runoff by 5 percent, a spacing of 33 m by 12 percent, and that of 25 m by 23 percent. Yield losses were reduced by 21 percent with a spacing of 50 m and 61 percent with a spacing of 25 m. With lower rainfall than normal, where yield increases were 58 percent with spacing of 50 m, it increased up to 343 percent with a spacing of 25 m. However, in a normal year, increases were

TABLE 11.16. Variation of the grain yields of sorghum during four years (kg ha^{-1})

Treatments	**2000**	**2001**	**2002**	**Average**
Control	353	393	215	331
Stone bounds	394	574	504	397
CP + Manure	1,026	1,168	1,072	789
Zai + Manure	1,188	176	1,267	805

Source: Adapted from Taonda et al. (2003).

TABLE 11.17. Effects of spacing stone bounds on percent runoff, erosion, and grain yield

			Total grain yield		
Spacing of stone bounds	**% Decrease in runoff**	**% Decrease in erosion**	**Poor rainfall year**	**Normal rainfall year**	**High rainfall years**
50 m	5	21	58	1	
33 m	12	46	109	73	
25 m	23	61	343	56	

Source: Adapted from Zougmore and Zida (2000).

not as much and the trend was even negative in years where rainfall was higher than the long-term average.

Zougmore, Mando et al. (2003) found an average reduction in runoff of up to 59 percent in plots with barriers alone, but the reduction reached 67 percent in plots with barriers plus mineral N, and 84 percent in plots with barriers + organic N. On average, stone bounds reduced soil erosion more than grass strips (66 percent versus 51 percent). Integrated water and nutrient management may help alleviate poverty and may empower small-holder farmers to invest in soil management for better crop production (Zougmore, 2003).

Restoring favorable soil moisture conditions by breaking up the surface crust to improve water infiltration (half-moon technique) with appropriate nutrient management could be an effective method for the rehabilitation of degraded soil and improving productivity (Zougmore, Zida et al., 2003).

Animal drawn rippers and subsoilers could increase water productivity by increasing water infiltration and storage as well as root penetration (Rockstrom et al., 2003). Considerable yield increases above "farmers' practices" (i.e., flat cultivation and no fertilizer) could be realized by combining tied-ridged tillage with inputs of mineral N and P fertilizer, reaching maize grain yield levels of six times the prevailing yield under farmers' practices of approximate 1 Mg ha^{-1} (Jensen et al., 2003). Tied-ridging is a water harvesting method where cross ridges (ties) are constructed at specified intervals across ridges to form basins for storing water.

Humid and SubHumid Zone

Soil Fertility Problems

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

Low nutrient reserves and cation exchange capacity are common in highly weathered soils such as Oxisols and Ultisols. These soils have limited capacity to retain and to supply cations and other major nutrients such as nitrogen (N), phosphorus (P), and sulfur (S) required by plants. Most of these soils are extremely nutrient-depleted and crop production can only be sustained by regular addition of external nutrients and by proper SOM management.

Nitrogen, a key nutrient for crop production, is the most mobile and also the most easily exhausted nutrient in the soil. Smallholder farmers rely on natural fallow periods and use of leguminous crops to restore soil nitrogen status (Nye and Greenland. 1960; Kwesiga and Coe, 1994). However, due to high population density and land pressure, long fallow periods are no longer sustainable. To sustain high crop yields in intensive and continuous crop production systems, nitrogen fertilizer input is required. Inclusion of legumes as green manure, cover crops, improved fallows, and use of agroforestry techniques in maize-based cropping systems are often employed to supply nitrogen and offer additional benefits such as weed suppression, soil erosion control, and soil structure amelioration.

The structural stability of many soils in subhumid zones, particularly the Alfisols. is very low and the aggregates are easily destroyed by rainfall. The breakdown of main aggregates is due to entrapped air and differential swelling, which results in the formation of microaggregates. Such crusting reduces aeration and infiltration of rainwater. Cultivation of such soils when wet leads to the formation of hard pans in the plough layer. Low organic matter content and low clay content are some of the conditions that lead to crusting and compaction.

N and P Management

In East Africa, evidence from a 23-year-old study at Kabete, Kenya, indicated that application of NP inorganic fertilizer, farmyard manure, and CRs is the best option to increase yield of crops such as maize (Figure 11.14) (Kapkiyai et al., 1999).

The data in Figure 11.15 clearly indicate the comparative advantage to combined organic and inorganic plant nutrients. The combination of both organic and inorganic P and N sources achieved more yield as compared to inorganic or organic sources alone. Many trials have been carried out on the usefulness of combining organic and inorganic plant nutrients using different proportions of each. The data in Figure 11.15 indicate for Mapira and Chinonda sites in Zimbabwe that there is advantage to combining the sources, whereas at Manjoro, the grain yield is the same when 100 percent of organic or inorganic plant nutrients are used.

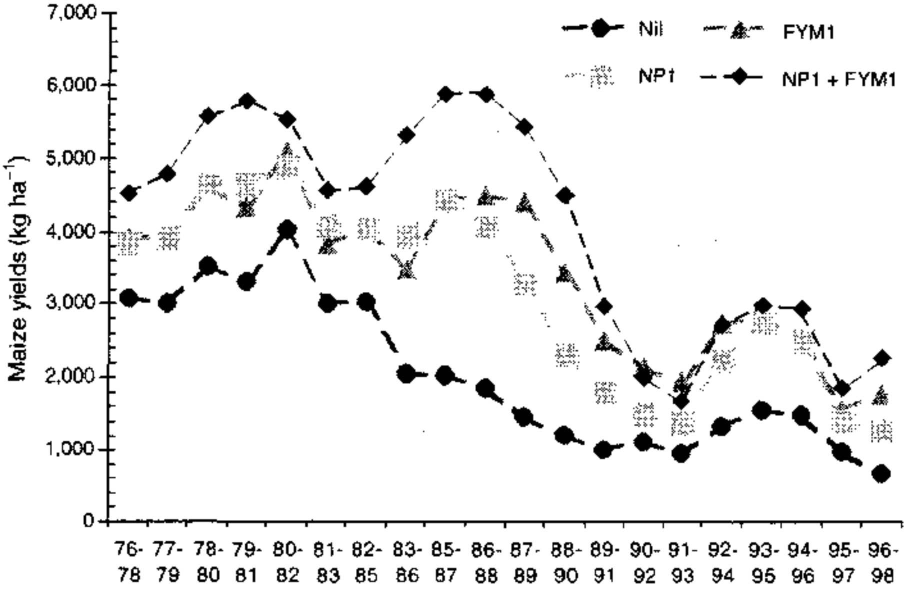


FIGURE 11.14. Effect of different soil fertility management strategies on average maize yields over a twenty-three-year period (1976-1998) of continuous cropping. *Source:* Adapted from Kapkiyai et al. (1999).

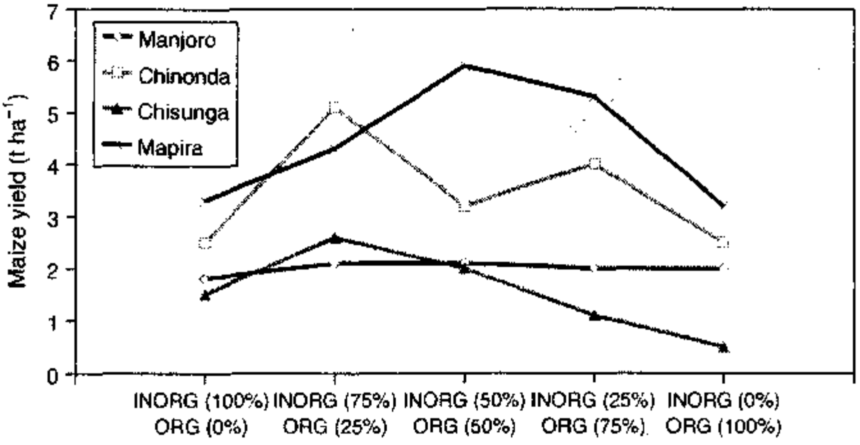


FIGURE 11.15. Maize grain yield obtained from 100 kg N applied in different proportions of manure and inorganic fertilizers, Murewa, Zimbabwe. *Source:* Nhamo and Murwira (2000).

The deficiency of P is found to be as important as or more important than that of N for crops such as upland rice grown in the humid forest or savanna zones in west Africa (Sahrawat et al., 2000, 2001). The direct application of PR to acidic pH soils (Uultisols and Oxisols) in the humid forest zone of SSA holds greater potential for boosting production of upland rice cultivars compared to production in acidic soils in the dry regions (Sahrawat et al., 2001). Somado et al. (2003) showed that in both pot and field experiments, significant responses of legume performance (*Aeschynomene afraspera)* including biomass production, nodulation, N accumulation and %N derived from atmosphere to PR application were observed in the lowland Ultisols of Cote d'Ivoire. The synergetic effects of PR and BNF on N and P cycling improved P nutrition and the total biomass of the subsequent lowland rice crop under pot conditions. However the impact of synergy between PR and BNF on the rice yield in the field was minimized due to asynchrony in legume manure nutrient release and demand. Nevertheless, the application of PR for driving the N and P cycles in legume-based rice production systems on acid Ultisols has potential and merits further evaluation under field conditions (Somado et al., 2003).

Agroforestry Systems

There is little doubt that under humid tropical conditions, agroforestry techniques are suited for the maintenance of soil fertility. This is because enhanced soil cover and root systems of the trees provide continuous soil protection, a favorable environment for soil biological processes and more efficient nutrient cycling.

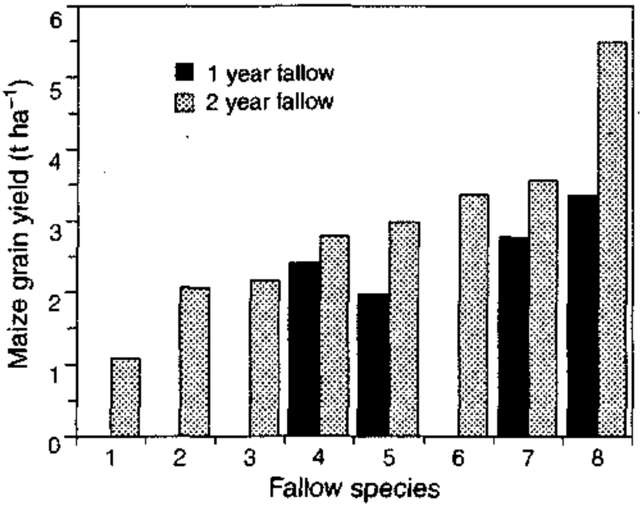
Many years of research and experience have produced various highly successful and stable management practices for crop production. Similarly, through many generations of traditional wisdom and practical experience, farmers developed stable and viable multistory home garden production systems in the uplands. The particular methods that are most appropriate in any given locality will vary both within and among the humid forest regions. Local needs and opportunities, ecological circumstances, economic opportunities, and social and cultural status, as well as the status of land and water resources, determine which methods are most suitable.

Improved Fallows

Experiments on fallows date back to the 1930s with a well-known example of the "corridor system" which was tried and applied by the Belgians in the Democratic Republic of Congo (DRC) founded on the principles of shifting cultivation (Eckholm, 1976). Studies show that both the type and age of the fallow greatly influence the fertility of the soil at the end of the fallow period (Padwick, 1983). Soil productivity generally increases with increasing fallow length when the appropriate tree or shrub species are present. Fast-growing species can be expected to restore soil fertility more quickly and contribute to higher soil fertility for subsequent crops (Aweto, 1981). Planted legume species have been shown to be effective in improving soil fertility (Juo and Lal, 1977; Kang and Wilson, 1987; Gichuru and Kang, 1989).

Improved fallows are probably the most exciting developments for soil fertility improvement. Improved fallow experiments conducted in the eastern province of Zambia both on-farm and on-station showed that fallows with *Sesbania sesban* performed very well. *Sesbania sesbati* planted fallows of one to two year rotation show potential in increasing maize yields with or without the application of inorganic fertilizers (Figure 11.16). Other multipurpose tree species (MPTs) such as *Tephrosia vogelii* and *Sesbania macrantha* have also shown promise for one to two year fallows.

In another study, maize grain yields were significantly increased by *Tephrosia Candida* compared to the natural regrowth fallow at all lime levels following two years of continuous cropping with lime application (Table 11.18) (Gichuru, 1994). Overall, the yield increase due to the planted fallow was more than 200 percent. There was a strong interaction between the previous lime application and the fallow treatments indicating that the highest lime rate produced a significant effect on maize grain but only with *Tephrosia Candida* fallow.



Key to Species
1 = Unfertilized maize
2 = Grass fallow
3 = Groundnut/maize
4 = Cajanus cajan
5 = Sesbania macrantha
6 = Fertilized maize
7 = Tephrosia vogelii
8 = Sesbania sesban

FIGURE 11.16. Effect of short rotation fallow on maize grain yield without inorganic fertilizer after one or two years fallow. *Source:* Mafongoya, unpublished data.

TABLE 11.18. Maize grain yields as influenced by fallow treatments and previous lime application

Lime rate	**Fallow (kg ha^{-1})**		
(t ha^{-1})	**Natural regrowth**	***Tephrosia Candida***	**Means**
0	675	1,199	937
0.5	603	1,414	1,009
1.0	794	1,204	999
2.0	888	1,351	1,119
4.0	761	2,816	1,789
Means	744	1,597	
SE ±	133		194.1

Source: Mafongoya, unpublished data.

species, the successful establishment of the hedgerows and their appropriate management, and the design in terms of factors such as spacing and periodicity of pruning (Kang et al., 1990). The legume woody species used play a productive and/or protective role depending upon the dominant function(s) of the species (Nair et al, 1993). The productive role includes production of food, fodder, firewood, and various products. Alley cropping contributes to the maintenance of soil fertility under annual cropping through improved nutrient cycling.

The application of inorganic N fertilizers usually increases considerably the yields of alley crops, although the response varies with the hedgerow species used. Responses to other nutrients in alley cropping have also been reported. For instance, the application of 30 and 60 kg of P increased the pole bean (*Phaseolus vulgaris*) production in N-fertilized *Sesbania sesban* alley cropped systems (Yamoah and Burleigh, 1990). The beneficial effects of fertilization are sometimes delayed. Pruning alone, especially on infertile soils, cannot sustain productivity of continuous alley cropping (Palm et al., 1991; Szott, Palm et al., 1991; Szott, Fernandez et al, 1991).

The use of Gliricidia green manure can greatly increase maize yields over those obtained through continuous sole cropping. The beneficial effect of the mulch was significant in four of the five cropping seasons, when maize yields from intercropped treatments were substantially higher than those from control plots (both with and without the addition of mineral fertilizer), as exemplified by the results of the maize grain yields in both 1996 and 1997 (Table 11.19). Topsoil ammonium, nitrate, and total inorganic nitrogen (ammonium + nitrate) were significantly correlated with maize grain yields.

TABLE 11.19. Maize grain yield (t ha^{-1}) with and without gliricidia intercropping and fertilizer nitrogen in 1996 and 1997 at Makoka, Malawi

	1996		**1997**	
Fertilizer added (kg N ha^{-1})	**No tree**	**Tree**	**No tree**	**Tree**
0	1.0	4.8	0.4	3.5
24	3.5	6.1	2.0	3.6
48	4.2	6.7	2.1	4.3

Source: Adapted from ICRAF (1997).

Note: Least Significant Difference (LSD) (0.05): N rate = 0.45, tree biomass = 0.36 for 1996. LSD (0.05): N rate = 0.50, tree biomass = 0.41 for 1997.

Biomass Transfer System

Traditionally, farmers in Zimbabwe collected leaf litter from Miombo secondary forest as a source of nutrients to maize (Nyathi and Campbell, 1993). This practice is not sustainable in the long term since it mines nutrients from the forest ecosystems, in addition to the fact that Miombo litter collected is of low quality (Mafongoya and Nair, 1997). An alternative means of producing high-quality biomass is through establishment of on-farm biomass banks from which the biomass is cut and transferred to crop fields in different parts of the farm. In western Kenya, for example, the use of *Tithonia diversifolia, Senna spectabilis, Sesbania sesban,* and *Calliandra calothyrsus* planted as farm boundaries, woodlots and fodder banks, or found along the roads has proven beneficial in improving maize production (Maroko et al., 1998; Nziguheba et al., 1998; Palm, 1995; Palm et al., 2001). In a study by Gachengo (1996), tithonia green biomass grown outside a field and transferred into a field was found to be as effective in supplying N, P, and K to maize as an equivalent amount of commercial NPK fertilizer, and in some cases maize yields were higher with tithonia biomass than commercial inorganic fertilizer.

The effectiveness of biomass transfer as nutrient sources using organic inputs from MPT species depends on their chemical composition (Mafongoya and Nair, 1997). Leguminous trees can produce up to 20 t dry matter ha^{-1} $year^{-1}$ prunings which contained enough nutrients to meet crop demand (Young, 1997; Szott, Palm et al., 1991). Biomass transfer using leguminous species is a far more sustainable means of maintaining nutrient balances in maize-based systems as these trees are able to fix atmospheric nitrogen. These systems can meet the N requirement of most crops in smallholder farming systems. Sometimes the biomass is first fed to livestock and then applied as manure to crops (Jama et al., 1997). However, these systems cannot meet the requirement of P and there is need to apply inorganic sources of P in addition to organic sources.

Integrated Nutrient Management trials in the continent have been used to establish the fertilizer equivalencies of locally available organic resources. Higher N content results in higher fertilizer equivalent values (Figure 11.17). For example *Tephrosia* (4 percent N), *Tithonia* (3.5 percent N), *Sesbania* (3.5 percent N), and Pigeon Pea (2.8 percent N) have been reported to have 93, 87, 36, and 33 percent fertilizer equivalencies, respectively (Palm et al., 2001). In a recent study in Kenya, *Tithonia diversifolia, Calliandra calothyrsus,* and *Senna spectabilis* had fertilizer equivalencies of 130, 72, and 68, respectively (Kimetu, 2002).

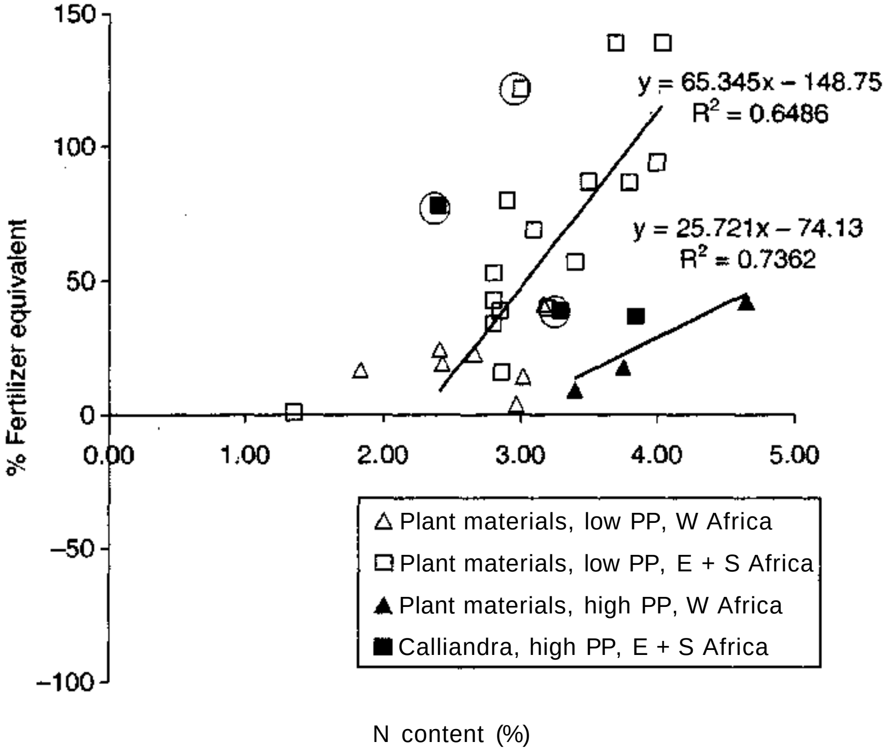


FIGURE 11.17. Fertilizer equivalency for different organic materials. *Source:* Adapted from Vanlauwe et al. (2002).

The varying quality of organic resources affects soil N balance through immobilization-mineralization processes. Research on characterization of organic materials has helped develop an organic resource database and translate the information into soil management practices relevant for, and targeted at, conditions experienced by farmers. A decision tree on the use of organic resources for INM, based on the amount of nitrogen, lignin, and polyphenol has been developed as a useful tool (Figure 11.18) (Palm et al., 1997, 2001; Singh et al., 2001). A farmer user-friendly decision tree provides indicators that farmers can use to predict the nutrient release potential of organic inputs (Figure 11.19) (Palm et al., 2001).

Cropping Systems

Intercropping and relay cropping. Intercropping and relay cropping of legume green manures have the advantage that crops are still produced while organic material is produced for soil amendment.

Mixed intercropping of cereals with legumes such as groundnuts (*Arachi hypogaea* L.), soybeans (*Glycine max* [L.] Merr), and *Phaseolus* beans or

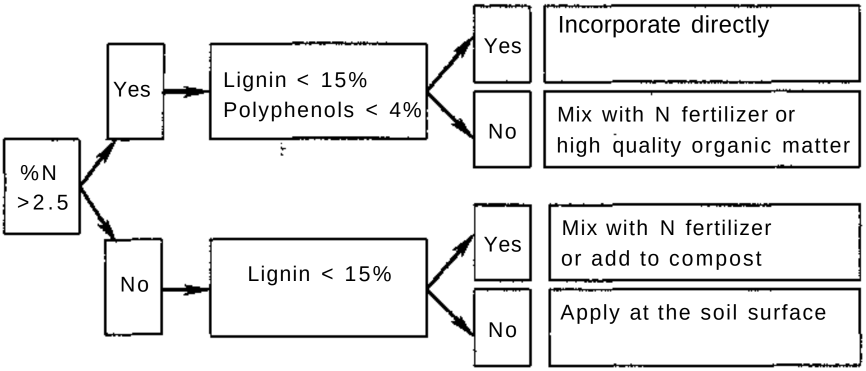


FIGURE 11.18. A decision support system tree for organic nutrient resources. *Source:* Adapted from Palm et al. (2001).

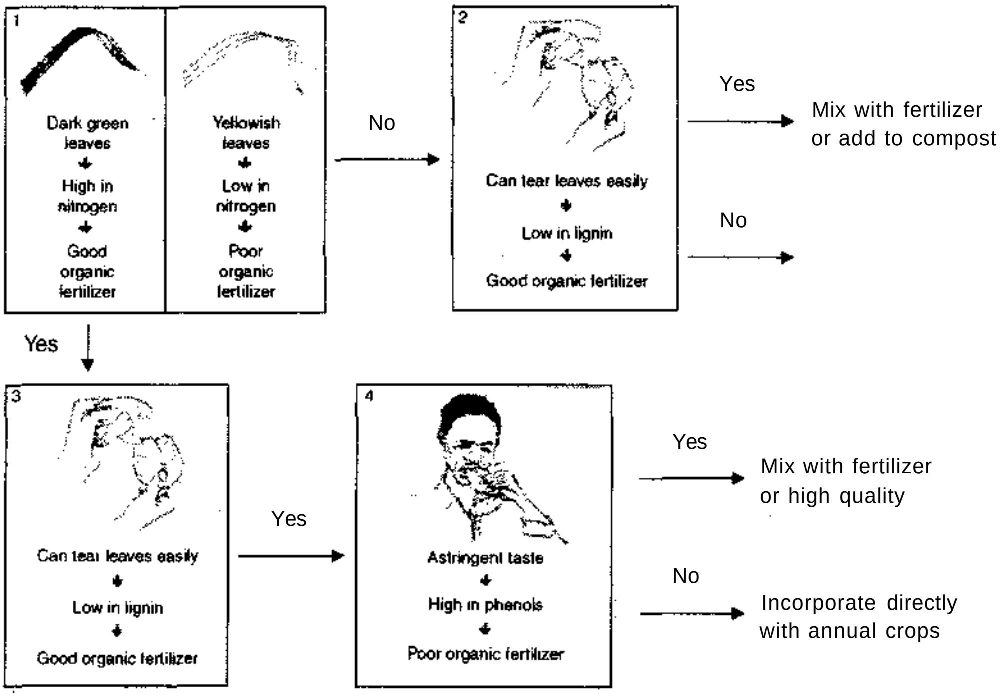


FIGURE 11.19. Farmer decision guide for selecting organic resource management options. *Source:* Adapted from Palm et al. (2001).

tree legumes such as pigeonpeas (*Cajanus cajan* L.) has been advocated (MacColl, 1989). Tropical grain legumes can certainly fix substantial amounts of N given favorable conditions, but the majority of this N is often harvested in the grain. Legumes such as soybean that have been subject to intense breeding efforts are very efficient at translocating their N into the grain, and, even when the residues are returned to the soil, there is generally a net removal of N from the field (Giller et al., 1994).

Relay planting can reduce the likelihood of competition with the crop where rainfall is limited, with the production of the green manure restricted by its ability to use residual water after the main cropping season (Mafongoya et al., 2003).

Rotation Systems. Many leguminous species are now grown as green manure and cover crops for erosion control, weed suppression, and for soil fertility restoration, often in rotation with food crops. Biological N contribution is probably the main reason why farmers include legume cover crops in cropping systems (Jeranyama et al, 1998). A legume cover crop may contribute N to a subsequent nonleguminous crop, reducing N fertilizer needs by 100 kg N ha^{-1} and more in some cases (Hesterman et al., 1992).

Many fast growing leguminous species such as mucuna (*Mucuna pruriens*), soya beans (*Glycine max*), *Lablab purpureus, Crotolaria ochroleuca,* and various species of the *Phaseolus* family can be especially useful as green manures and cover crops. In a study by Kamidi et al. (2000) at Matunda in western Kenya, Mucuna had the highest ground cover (72 percent) followed by *Crotalaria* (63 percent) and *Lablab* (54 percent). Soybeans and cowpeas gave the lowest ground cover (32 percent and 38 percent, respectively). The ground cover offered by these green manures greatly reduced soil erosion especially during the long rain season, as noted by Gachene et al. (2000).

A sole long-duration pigeonpea crop can provide up to 40 kg N ha^{-1} in fallen leaves and litter during its growth. A small harvest index, especially of the traditional, long-duration pigeonpea crop means that a relatively large proportion of the fixed N remains in the field which can give a substantial benefit to subsequent crops (Kumar-Rao et al., 1983; Mafongoya et al, 2003).

Leguminous plant materials provide higher quality organic inputs to meet N demands, but not P, but incorporating nonfood legumes in the farming systems require a sacrifice of space or time that is normally devoted to crop production. As such, legumes for soil fertility improvement have not been widely adopted by farmers (Jama et al., 1998).

CONCLUSIONS

Soil fertility depletion has been recognized as the major biophysical cause of declining food availability in smallholder farms in SSA. The latest figures show that some 200 million people or 28 percent of the SSA population are chronically hungry. Agricultural output should expand by at least 4 percent annually in order to ensure food security. Studies have clearly shown that the expansion of new farms cannot increase output by over 1 percent without accelerating environmental degradation. Consequently, productivity of land currently under cultivation should increase by at least 3 percent per annum. Any program aimed at reversing the declining trend in agricultural productivity, and preserving the environment for present and future generations must begin with soil fertility restoration and maintenance.

The low productivity of agriculture in SSA is strongly related to the low quality of the soil resource base. However, the general fertility and organic matter status of soils differ from upland to lowland ecologies. Wetland soils in the inland valley system of West and Central Africa are generally better endowed with fertility, especially SOM status, than their upland relatives. They have the potential for increasing agricultural productivity through an integrated use of crop genoptypes adapted to the ecology and INM. Many of the arable soils are characterized by inherent or induced deficiencies of nutrients, particularly N and P. Low nutrient holding capacities, high acidity, and low organic matter are also constraints to soil productivity in SSA. The problem of low soil fertility is driven by a wide range of socioeconomic factors which diminish farmers' capacity to invest in soil fertility restoration.

Macroeconomic policies play a vital role in influencing the availability and accessibility of external inputs to replenish soil fertility. Unfavorable exchange rates, poor producer prices, high inflation, poor infrastructure, and lack of markets contribute to diminishing the capacity of farmers in SSA to adopt soil fertility enhancing technologies. This calls for a holistic approach on ISFM, and the need has been recognized for integration of socioeconomic and policy research besides technical research. Soil fertility restoration and maintenance, organic and inorganic sources, and management of plants and nutrients cannot be regarded as simple issues. ISFM embraces the full range of driving factors and consequences, namely biological, chemical, social, economic, and political aspects. The long-term and holistic approach of ISFM requires an evolutionary and knowledge intensive process, participatory research, and development focus rather than a purely technical focus.

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