INTEGRATED NUTRIENT MANAGEMENT FOR SUSTAINED CROP PRODUCTION IN SUB-SAHARAN AFRICA

(A REVIEW)

Kathrin Franzluebbers, Lloyd R. Hossner, and Anthony S.R. Juo

Soil Management CRSP

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Foreword

The decline of food production in sub-Saharan Africa in recent decades has often been attributed to the lack of adoption of modern farming technologies. However, a primary limitation seems to be the farmer's inability to replenish lost nutrients in the widespread kaolinitic soils as the more sustainable bush fallow system is being replaced by continuous cultivation.

In this report, the authors review published work on soil nutrient management for food crop production in sub-Saharan Africa. It is intended for a wide range of users including soil scientists, agronomists, social scientists and extension workers.

Although a large volume of research results are available on this subject matter, the main body of this review has been drawn from English language publications, especially from more recent research from the USAID sponsored Soil Management CRSP (TropSoils) and its national collaborators and from the International Agricultural Research Centers, such as IITA, ICRISAT, ICRAF and IFDC. Efforts were also made to cover recent research findings by scientists at national agricultural research centers in the region as well as some earlier work published by European researchers. This review may seem somewhat 'biased' towards West Africa. The imbalance is by no means intentional.

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1. Abstract

'Slash and burn agriculture' remains the major food production system in sub-Saharan Africa. However, in a major part of the region, where fallow periods have been shortened below a critical level, the system can no longer sustain crop yield due to decline in soil fertility. In order to allow continuous crop production, principles and practices that mimic natural fallow and enhance soil organic matter build-up need to be integrated into new cropping systems that replace shifting cultivation or 'slash and burn agriculture'. These include (a) returning of organic materials to the soil, (b) ensuring minimum disturbance of the soil surface, and (c) use of multipurpose trees and perennials. At the same time, inorganic fertilizers are also needed to maintain a positive nutrient balance of the agroecosystem. On the widespread sandy kaolinitic soils in sub-Saharan Africa, numerous published results have shown that without appropriate organic inputs, inorganic fertilizer alone cannot sustain crop yield and maintain soil fertility in the long run because of soil acidification, loss of soil organic matter and compaction. The adoption of nutrient management practices that integrate organic, chemical and biological inputs into economically and environmentally sound production systems is an essential step towards sustaining high crop yields and preventing land degradation in the region. In the humid forest region, where root crops and tree crops are ecologically more suitable, agroforestry systems, such as multistory homestead gardens, plantation/crop combinations, and alley cropping, appear to have a high potential for maintaining soil organic matter at levels adequate for sustaining crop growth. In the subhumid and humid/subhumid transition zones, crop residue mulch, minimum tillage and leguminous cover crops are promising technologies for improving nutrient and water use efficiency and sustaining high yields of maize, sorghum and cowpea. In the semiarid regions, however, improvement of millet and sorghum yields is severely limited by the lack of organic inputs. The potential for increasing and sustaining food crop production in the semiarid zone ultimately depends upon successful integration of crop, fodder and fuelwood production within a farming community.

2. Introduction

Throughout the tropics, the "slash and burn" method has been widely used by small holding farmers as a means of land preparation and soil fertility maintenance. Practiced in different forms in different regions of the tropics, the so-called 'shifting cultivation' or 'slash and burn agriculture' involves manually clearing, burning and cropping a relatively small area of land (e.g. 0.5 - 1 ha.) for one or two years followed by a long period of natural fallow (e, g. 15 - 30 years). The land is usually allowed to return to forest or savanna vegetation to restore soil fertility (Nye and Greenland, 1960; Allan, 1965; Ruthenberg, 1976; Sanchez, 1976; Mokwunye and Hammond,1992).

In areas where the period of fallow has been shortened and cultivation has been extended for more than two years, crop yields generally decrease rapidly providing a constant pressure to clear new land (Ayodele, 1986; Sanchez et al., 1983). The detrimental effects of extensive clearing and burning of forest and grassland in the tropics are well known. For example, burning causes significant losses of most of the N, S, and C to the atmosphere. Large scale clearing accelerates soil erosion and surface sealing and crusting (Lal, et al., 1986; Kooistra et al., 1990; van der Watt and Valentin, 1992). Furthermore, subsequent cultivation may result in rapid deterioration of biological, chemical and physical properties of the soil (Lavelle et al., 1992; Mokwunye and Hammond, 1992; Allen, 1985).

Published results on continuous cropping of kaolinitic Alfisols and Ultisols in West Africa have shown a rapid decline in soil organic matter in the surface soil during the first few years following land clearing (Brams, 1971; Juo et al., 1995B). Continuous cultivation also causes significant decline in soil pH and exchangeable Ca and Mg levels, which is more pronounced when acidifying fertilizers are used (Cunningham, 1963; Adepetu et al., 1979; Juo and Kang, 1989; Bache and Heathcote, 1969; Kang and Balasubramanian, 1990; Pichot et al., 1981; Juo et al., 1995a).

The rate and magnitude of fertility decline are dependent on the lengths of fallow and cropping cycle, organic inputs, and the inherent fertility of the soil. In regions where increased land pressure has shortened the length of fallow below the critical level, the system has broken down because soil nutrient level became too low to support crop production (Atta-Krah and Kang, 1993; Juo and Manu, 1996).

Most cultivated soils of sub-Saharan Africa suffer from multiple nutrient deficiencies, and nutrient balances are generally negative (Tandon, 1993; Mokwunye, et al., 1996). External nutrient inputs are essential to improve and sustain crop production on these soils. Nutrient inputs may either be from organic sources (i.e., crop residue, green manure, and animal manure) or from inorganic sources (i.e., chemical fertilizers and lime). However, published results have shown that chemical fertilizers alone cannot sustain crop yield on poorly buffered kaolinitic soils. The decline of crop yields under continuous cultivation has been attributed to factors such as acidification, soil compaction and loss of soil organic matter (e.g., Juo et al., 1995a). Thus, application of organic materials is needed not only to replenish soil nutrients but also to improve soil physical, chemical and biological properties. To a large extent, this may be achieved by managing agroecosystems such that nutrient sources are generated, recycled and maintained.

The maintenance of soil fertility in small farm systems in sub-Saharan Africa has become a major issue as a consequence of continued land degradation and rapid population growth (FAO, 1981; Swaminathan, 1983; United Nations, 1989). In addition to socioeconomic constraints, major arable soils are not well-suited for high-input agriculture. Agricultural development efforts the refore, must be directed towards the improvement of productivity and sustainability of small-holder production systems. While external nutrient inputs are definitely needed for the poorly buffered sandy kaolinitic soils, major emphasis must be given to integrated systems of nutrient management using both organic and inorganic inputs and recycling. This manuscript describes the concept and approach of integrated nutrient management (INM) and review selected research findings to help illustrate the role of INM in increasing and sustaining food production in sub-Saharan Africa.

3. Environmental characteristics of sub-Saharan Africa

3.1 Climate

Sub-Saharan Africa comprises of several ecological zones. Wooded and grass savanna (or subhumid) zones and tropical forest (or humid) zones occupy approximately 20 and 8%, respectively, of the total land area of the continent. Tropical highlands are found in East Africa and a small area of western Cameroon. Because of the cooler climate and the more fertile volcanic soils, highlands are generally densely populated and intensively cultivated.

The growing season of rainfed farming in sub-Saharan Africa is determined by the length of the rainy season. The humid or forest zone is characterized by annual rainfall in excess of 1300 mm with a monomodal distribution. The length of rainy season in the humid zone is 8 months or more allowing two successive crops in each year. The subhumid or savanna zone receives approximately 700 to 1300 mm rain during a 5 to 8 months rainy season, generally with a bimodal or pseudo-bimodal distribution. The semiarid zone receives 200 to 700 mm annual rainfall with a monomodal distribution of 2 to 4 months (Hance, 1975; Grove, 1978, Mughogho et al., 1986). In the semiarid zone, rainfall is characterized by high intensity, short duration and there are large year-to-year variations in total rainfall (Sivakumar, 1987). The climatic inventory and length of growing season in Africa are further illustrated in Figure 1.

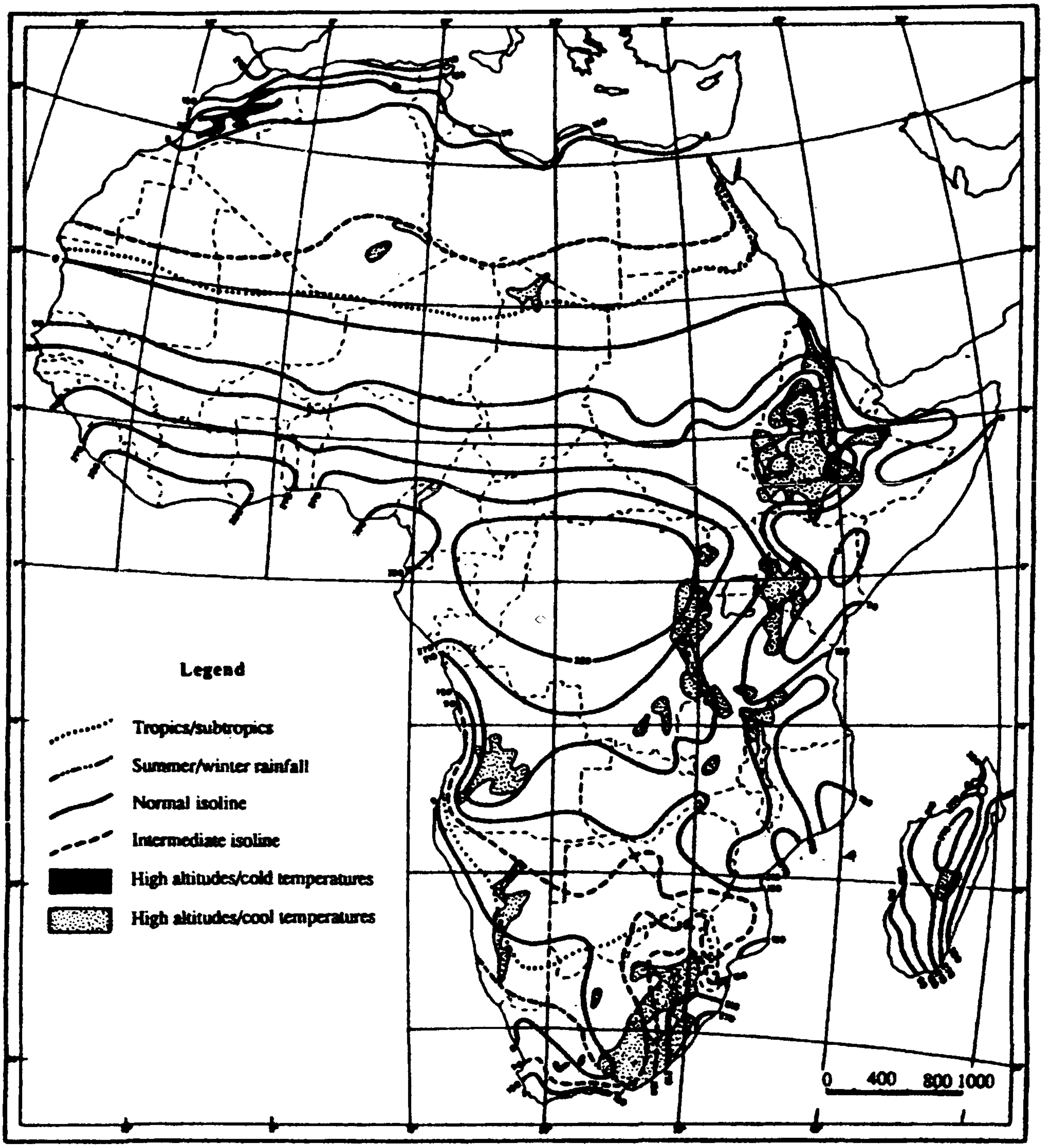

Figure 1. Climatic inventory and length of rainy season (days) in Africa (Source: Agroecological zone projects report, World Soil Resource Report No. 48, FAO, Rome, 1978)

3.2 Soils

The range in soil types of tropical Africa is relatively narrow and is dominated by the light-textured Alfisols and Ultisols, covering over 40% of tropical Africa, especially in the subhumid and semiarid regions (Sanchez, 1976). A generalized soil map of Africa is presented in Figure 2 showing the distribution of soil resources by soil order and suborder as classified by U.S. Soil Taxonomy.

A brief description of the eleven soil orders are given as follows:

Alfisols	Well developed and moderately leached inorganic soils with a clayey B horizon (or argillic horizon) due to downward clay movement (*Lessivage*). Base saturation of the lower B horizon or a defined depth of the pedon is 35 percent of more based on the CEC determined by neutral ammonium acetate displacement. Alfisols are widespread in both temperate and tropical regions.
Ultisols	Well weathered and strongly leached inorganic soils with a clayey B or argillic horizon. Base saturation of the lower B horizon or a defined depth of the pedon is less than 35 percent. Ultisols are extensive soils in the tropical and subtropical regions.
Oxisols	Intensively weathered and strongly developed inorganic soils on old land surfaces, or sediments derived therefrom. They are characterized by the presence of oxic or kandic horizons and uniform clay content throughout the pedon. Red Oxisols are found in the drier regions of the tropics, whereas, yellow Oxisols occur in the high rainfall tropics.
Entisols	Young or weakly developed soils commonly found on recent alluvial plains, beaches and eolian sand dunes. They have no horizon differentiation.
Inceptisols	Weakly developed, shallow soils with weak horizon differentiation. Commonly found in mountainous areas and alluvial plains.
Mollisols	Dark-colored soils rich in exchangeable Ca and Mg, commonly developed under prairie grass vegetation. Mollisols are among the richest agricultural soils in the world. Extensive areas of Mollisols are found in the Midwest United States (the Corn Belt), Ukraine, and Northeast China (Manchuria).
Vertisols	Dark-colored, clayey, inorganic soils commonly found in the inland depressions and old alluvial plains in sub-humid and semiarid regions with pronounced seasonal changes in soil moisture. They contain high amount of smectite in the clay fraction. They swell when wet and shrink and crack when dry. They are inherently fertile but require high energy demands for cultivation. Extensive areas of Vertisols are found in southern Sudan, central India, Ethiopia, Chad, Australia and Texas.

Aridisols	Weakly to strongly developed soils of the arid regions.
Spodosols	Moderately developed soils with a light-colored, ashy gray leached horizon overlying a reddish to blackish metal-organic enriched spodic horizon or placic horizon (thin iron pan) at shallow depth. They are acidic, sandy to loamy soils. They are commonly found in the temperate, humid regions, or at high elevations in the tropics under vegetation favoring acid litter.
Histosols	Organic soils developed on bogs and peat moss. These soils are characterized by low bulk density and high organic matter content (generally greater than 50 percent of organic materials in the upper 80 cm of the pedon). They have high water retention capacity and weak physical strength.
Andisols	Young soils derived from pyroclastic materials, especially volcanic ash and glass. They have low bulk density (i. e. less than 0.9 g/cm^3), high water retention capacity and high phosphate sorption capacity. They contain a high amount of amorphous aluminum silicates.

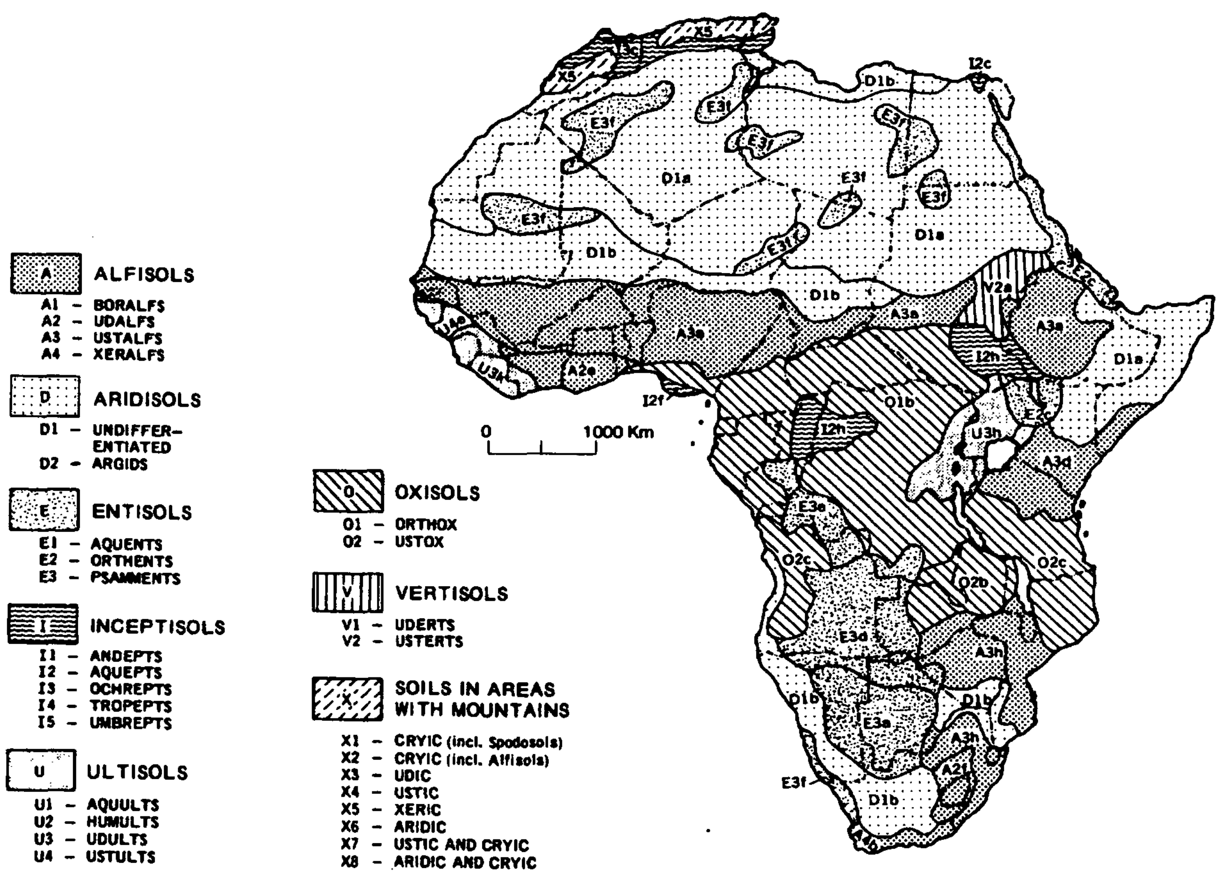

Figure 2. Distribution of soils in Africa (Source: World Soil Resources Division, USDA/NRCS, Washington, D. C.)

In the humid forest zone, major upland soils are the strongly weathered, kaolinitic Ultisols and Oxisols (Juo and Wilding, 1996). Both Ultisols and Oxisols are acidic and therefore, contain very low level of mineral nutrients (i.e, Ca, Mg, K, and P). The subhumid savanna and the savanna-forest transition zones are dominated by the relatively more fertile kaolinitic Alfisols. Soil erosion and compaction are major management constraints in this region (Lal, 1993). The semiarid zone is characterized by sandy Entisols and Alfisols that are weakly structured, have a very low soil organic matter content (generally less than 0.3%), a low water holding capacity, a low nutrient content (CEC of surface soils rarely exceeds 3.0 meq/100g or cmol/kg), and are prone to water and wind erosion (Deckers, 1993; Sivakumar et al., 1992).

With the exception of the more productive volcanic soils in the highlands of East Africa and western Cameroon, prospect for increasing food production in sub-Saharan Africa is restricted by poor soil resources (Greenland, 1981; Wilding and Hossner, 1989; Juo and Wilding, 1996). A unique feature of the major arable soils in sub-Saharan Africa is the small and easily consumable mineral nutrient pool once these soils are used for continuous cropping. These soils are also known as "soils with low activity clays" or LAC soils. They are characterized by a low cation exchange capacity (i.e., effective CEC value less than 14 meq per 100 g of clay in the diagnostic subsoil horizon) and kaolinitic and/or oxidic mineralogy (Soil Survey Staff, 1975; Gallez et al.,1977).

Although alluvial soils in inland valleys and coastal deltas are generally more fertile and well suited for rice cultivation available information indicates that sub-Saharan Africa has very limited areas of fertile alluvial soils in the valleys and deltas of its major rivers. This may be one of the reasons why intensive paddy rice systems have not been widely adopted in the region (Juo and Lowe, 1986).

Hanson (1992) reported that of the 3 billion ha of arable land in tropical Africa, only 14.7% is considered to be free of physical or chemical constraints, while 32.2% have physical constraints, 13.2% have limited nutrient retention capacities, 16.9% have high soil acidity, and 6.8% have high P fixation. Nitrogen and phosphorus are the most limiting elements for cereals and food legumes, respectively (Jones and Wild, 1975; Christianson and Vlek, 1991; Manu et al., 1991; Takow et al., 1991). Deficiencies of potassium in root crops, sulfur and zinc in maize, and boron in cotton and groundnuts have been reported in fields under continuous cultivation with little or no inputs of crop residue or animal manure (Drosdoff, 1972; Jones and Wild, 1975; Friessen, 1991; Hanson, 1992). Furthermore, aluminum toxicity and related calcium, magnesium and phosphorus deficiencies also limit growth and yield of cereals and legumes in acid soils in both humid and semiarid regions (Friessen et al., 1982; Scott-Wendt et al., 1988; Pieri, 1989; Wilding and Hossner, 1989).

3.3 Major food crops and prevailing cropping systems

Major food crops in sub-Saharan Africa include plantain, banana, rice and root crops (such as cassava, yam, sweet potato and cocoyam) in the humid zone, sorghum, maize and cowpea in the subhumid zone, and millet and cowpea in the semiarid zone (Mudahar, 1986).

Traditional cropping systems vary and have developed in response to prevailing soil and climatic conditions and socioeconomic and ethnological preferences (Kang, 1986). Traditional farmers often plant more than one crop species in a small patch of cleared and burned land after several years of bush fallow. Intercropping, the practice of growing two or more crops simultaneously in the same field, is common throughout the tropics. It is practiced in 80% of the cultivated area in West Africa (Steiner, 1984). The multistory homestead gardens where more than three annual crop and vegetable species are mixed-planted with tree crops are common in the humid forest regions (Juo and Ezumah, 1992).

In terms of rainfall distribution and solar radiation during the growing season, large areas of the savannas are better suited for a wide range of rainfed agriculture than the forest and semiarid zones. Most of the sorghum, millet, maize, cowpea, groundnuts and yams are produced on the high base-status Alfisols in savanna zones of sub-Saharan Africa. In the humid region, dominated by the low-base-status and acid Ultisols and Oxisols, tree-, shrub- and root crop-based systems are proving to be more stable than food crop production systems as shown by the existence of highly successful tree crop plantations of rubber and oil palm (Kang, 1986). The cassava-, plantain-, and rice-based systems are prevalent in the humid region dominated by acid and low-base-status soils, whereas the maize-, yam-, sorghum-, and millet-based systems are more common in the high-base-status soils in subhumid and savanna areas (Juo and Ezumah, 1992).

Six major food crop production systems have been identified in sub-Saharan Africa (Okigbo and Greenland, 1976; Steiner, 1984; Juo and Lowe, 1986; Kang, 1986; Juo and Ezumah, 1992). In all traditional systems briefly described below, bush fallow remains an integral part of the system though the length of fallow and cropping periods may vary depending upon soil condition and land use pressure.

(i) Cassava-based cropping systems are mainly found on sandy soils of the coastal belt (mainly Ultisols) in the humid forest region, where other food crops perform less satisfactorily except for coconuts or oil palm. Cassava is mainly intercropped with maize or upland rice. These fast growing cereals reduce nutrient loss through leaching, runoff and erosion by utilizing a substantial amount of N mineralized (100 to 300 kg N /ha) during the onset of the rainy season (Mueller-Harvey et al., 1985) and recycle nutrients by returning residue to the soil. Because of year-round high humidity, ears of maize are usually harvested and consumed as "green maize" (roasted or boiled).

(ii) The plantain or starchy banana-based cropping systems are common in the forest areas from the Ivory Coast to Cameroon and in East and Central Africa (e.g., Rwanda, Tanzania). Major crops intercropped with plantain are cocoyam, maize and beans in a spatial arrangement to maximize light use efficiency. Plantain/starchy banana - based multistory systems are commonly found near the farm compounds where animal manure and household wastes are used as sources of nutrients.

(iii) Rice-based cropping systems are also common in the forest areas from Western Ivory Coast to Sierra Leone and Liberia and in the lowland areas of Senegal and Gambia in the drier regions. Rice is cultivated both as upland rice intercropped with pearl millet on well-drained Ultisols and Oxisols and as rainfed wetland rice on the foot slope and in valley bottoms of small inland valleys. Mangrove rice is also cultivated in some coastal areas of Sierra Leone. During the past three decades, efforts to develop large and small scale intensive, irrigated paddy rice systems in various parts of sub-Saharan Africa have met with varied degree of success.

(iv) Yam-based systems: In the forest and derived savanna transition zone and in the southern Guinea savanna of West Africa, especially Nigeria, cropping systems are traditionally based on yams. Early and late yams are planted in the same field on relatively more fertile sandy upland soils in the first year after bush clearing and on large mounds in more fertile alluvial soils in river valleys and inland depressions. Yams are often intercropped with a number of food crops including cowpea, maize, cassava, vegetables, plantains, and groundnuts. Under upland condition, cassava is intercropped with maize or upland rice during the second year as soil nutrient levels become inadequate to support a yam crop.

(v) The maize-based system is widely practiced in the humid transitional zone as well as in the subhumid region and tropical highlands. In wetter areas, maize is usually intercropped with cassava and yam. In the subhumid regions, it is intercropped with cowpea in West Africa and with beans in East and Central Africa. Commercial maize monoculture is found on volcanic soils and other more fertile Alfisols in the highland areas of East and Southern Africa (e. g. Kenya, Zimbabwe, Zambia, and Congo formerly Zaire).

(vi) Sorghum/millet-based cropping systems are typical of the northern Guinea and the Sudan savanna zones of West Africa and semiarid regions of East and Southern Africa. These cereals are usually intercropped with groundnut (peanut), cowpea or Bambara groundnut. Millet/ cowpea intercropping is often found on sandy soils. Sorghum/legume intercropping is usually found on finer-textured soils. In areas where rainfall is less than 600 mm/year, millet monoculture and millet/cowpea intercropping are more common.

While the choices of crop species and cropping patterns in the traditional systems are adapted to the agroecological and social conditions, decline of soil fertility due to shortened fallow period in populated areas threatens the sustainability of the traditional systems of food production.

4. Inorganic fertilizer use

Because of scarcity and high cost, inorganic fertilizers are rarely used on food crops in sub-Saharan Africa. Moreover, many low-yielding local cultivars are developed to withstand low soil fertility and other environmental stresses and therefore are less responsive to fertilizer use (McIntire, 1986). Currently, on average only 5 to 10 kg nutrients are applied as fertilizer per ha of cropland in sub-Saharan Africa (Bumb and Baanate, 1996; Larson and Frisvold, 1996). Vlek (1993) estimates that at the current rate of fertilizer use (8.5 kg/ha), the soils of the African continent are effectively being mined for their nutrients, and have been for decades.

Nutrient inputs from chemical fertilizers are needed to replace nutrients exported and lost during cropping and to maintain a positive nutrient balance in the predominantly LAC or kaolinitic soils in the region. More research and development are needed to maximize and sustain the benefits of fertilizer use in production systems using high-yielding cultivars in an effort to increase food production while maintaining the natural resource base (Baanante et al., 1989).

On the other hand, continuous use of mineral fertilizer can have detrimental effects on soil properties. In temperate regions, continuous cereals monocropping with optimum fertilizer use can sustain crop yields on fertile soils, such as Mollisols and Alfisols with high activity clays (Jenkinson, 1989; Oldman and Boone, 1989; Unger, 1982). But on the strongly weathered, poorly buffered soils in the tropics (e.g., Alfisols, Ultisols and Oxisols with low activity clays) continuous cereals monoculture using chemical fertilizers as the main source of nutrient input has resulted in significant yield decline and soil degradation after only a few years of cropping (Kang and Juo, 1986). In the latter case, decline of soil organic matter in the surface soil, acidification and compaction were identified as major causes for the decline in soil productivity. Following are selected examples to illustrate the detrimental effects of continuous cropping and fertilizer use on kaolinitic or LAC soils in the region.

On Alfisols in Burkina Faso, fertilizer application increased and maintained sorghum yield for 8 years, but declined during the following 8 years to a very low level, similar to that of the control without fertilizer (Pichot et al., 1981). Also in Burkina Faso, continuous cropping with a weak dose of fertilizer resulted in a soil pH of 4.6 after 15 years, compared to a pH of 5.2 without fertilizer use (Pieri, 1989). Carbon and N contents in the surface soil were similar; but exchangeable Ca, Mg, and K contents were significantly lower, while Al was higher in the fertilized plots than in the control plot.

In northern Zambia, maize yield declined from 5000 kg/ha to about 1000 kg /ha during 17 years of cultivation with application of 190 kg N/ha on an Oxisol (Woode, 1983). Continuous fertilizer use resulted in decreasing contents of soil organic matter (from 59 to 32 t/ha) and exchangeable Mg and K and development of soil acidity.

On Alfisols in Nigeria, soil pH declined from 6.2 to 5.1 during 10 years of continuous cropping with maize, sweet potato and cowpea, manual tillage and annual application of 160 (200, years 5-8) kg N/ha as urea, resulting in pronounced Mn toxicity for cowpea (Kang, 1993). Without fertilizer, pH declined by 0.5 units, while a slight pH increase was observed in the bush fallow treatment. Exchangeable Ca and Mg and organic C declined to about half their initial values during the 10 years of the study. On this sandy soil, even the use of less acidifying N fertilizers (urea and calcium ammonium nitrate) resulted in rapid soil acidification after the initial 4 years.

Continuous cropping on an Alfisol (Oxic Kandiustalf) in Nigeria with two maize crops per year and application of 120 kg N as urea (150 kg N first three years), 26 kg P and 30 kg K to each crop during 13 years under no-tillage resulted in a steady decrease in pH from about 6.0 to 4.5 in the surface soil (0-15 cm) when maize residue was not returned (Juo et al., 1995b). Soil organic C content decreased with continuous cropping during the first 8 years, then remained at 65% of the initial soil C content, with similar trends for exchangeable Ca, Mg and ECEC.

These examples suffice to illustrate that chemical fertilizers alone without organic inputs do not sustain soil productivity on the poorly buffered kaolinitic soils of sub-Saharan Africa. Furthermore, the use of lime to amend soil acidity is economically prohibitive to small holding farmers in the region due to scarcity of lime sources as well as high cost of transportation.

5. Integrated nutrient management (INM)

5.1 Principles and approach

The primary goal of integrated nutrient management (INM) is to combine old and new methods of nutrient management into ecologically sound and economically viable farming systems that utilize available organic and inorganic sources of nutrients in a judicious and efficient way. Integrated nutrient management optimizes all aspects of nutrient cycling. It attempts to achieve tight nutrient cycling with synchrony between nutrient demand by crop and nutrient release in soil while minimizing losses through leaching, runoff, volatilization and immobilization (Figure 3).

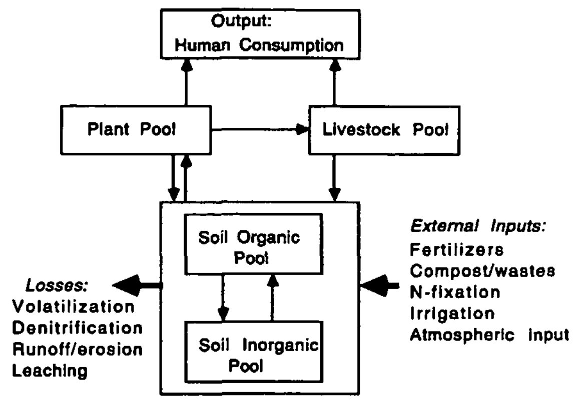

Figure 3. Pools and fluxes of nutrient cycling in agroecosystems

Sustainable soil nutrient-enhancing strategies involve the wise use and management of inorganic and organic nutrient sources in ecologically sound production systems such as, rotation, mixed cropping, and agroforestry (Janssen, 1993). Organic nutrient sources include plant residue, leguminous cover crops, mulches, green manure, animal manure, and household wastes. Under continuous cropping, recycling and reusing of nutrients from organic sources may not be sufficient to sustain crop yield. Nutrients exported from the soil through harvested biomass and lost from the soil through various processes must be replaced with nutrients from external sources. Decline in soil productivity can be attributed in part to negative nutrient budgets (or the amount of nutrient removed compared to the amount of nutrient being put into the system) in most agricultural land of sub-Saharan Africa (Mokunye, et al., 1996; Renard, et al, 1997). Thus, the judicious use of chemical fertilizer is essential to maintain soil fertility (Moorman and Greenland, 1980; Tandon, 1993; Ofori, 1995; Hossner and Dibb, 1995). In reviewing the results of long-term fertilizer trials conducted on Alfisols in West Africa, Kang and Balasubramanian (1990) concluded that high and sustained crop yields can be obtained with judicious and balanced NPK fertilization combined with organic matter amendments.

It has become increasingly evident that adoption of an integrated nutrient management strategy on LAC soils in the tropics not only is an ecological necessity, but also an economic reality. An important aspect of INM is the maintenance of soil organic matter. The beneficial effects of organic matter are well known. Physically, it improves soil structure and increases water holding capacity. Chemically, it increases the buffer capacity of the soil against pH change, increases the cation retention capacity (CEC), reduce phosphate fixation, and serves as a reservoir of secondary and micronutrients. Biologically, organic matter is the energy source for soil fauna and microorganisms, which are the primary agents that manipulate the decomposition and release of mineral nutrients in soil ecosystems.

Organic matter in soil exists in several forms, namely, partially decomposed plant and animal residues, living and dead microorganisms, and humidified organic matter or humus. Stable humus constitutes 50 to 75% of the total soil carbon and is little affected by management. The labile soil organic matter pool, that is important for nutrient release during the growing season, can be manipulated through various soil management practices (van Faassen and Smilde, 1985). In general, more than 95% of total N and S and up to 75% of the P in surface soils are in organic forms (Fernandes and Sanchez, 1990).

Because of the low nutrient reserves in the inorganic components of the predominantly kaolinitic and siliceous soils in sub-Saharan Africa, levels of organic matter in the surface soil are symptomatic of nutrient supplying power and soil productivity. In kaolinitic soils, humified organic matter is the major source of cation retention capacity in surface soils with pH greater than 5 (Lopes and Cox ,1977). In strongly acidic soils (i.e., Ultisols and Oxisols) with pH less than 5, the organic exchange sites and Al^{3+} ions form organo-mineral complexes (Juo and Kamprath, 1979; Bloom et al., 1987). Addition of Ca-rich organic materials can reduce Al and Mn toxicities in acid soils (Bache and Heathcote, 1969; Pichot et al., 1981; Hue and Amien, 1989).

Rates of decomposition of both fresh plant residues and humidified soil organic matter are 3 to 5 times greater in the humid tropical environment than under temperate conditions (Jenkinson and Ayanaba, 1977; Mueller-Harvey et al., 1985). Therefore, in cultivated fields of the humid tropics, more frequent application and larger quantities of organic materials are required to maintain adequate soil organic matter levels than in the temperate region (Mueller-Harvey et al., 1985; Juo and Kang, 1989; Pichot et al., 1981; Pieri, 1989; Bationo et al., 1993).

When forest is cleared or fallow brought into continuous production, soil organic matter will decline and reach a new steady-state level depending on quantity and quality of annual organic inputs and on tillage methods. Changes in soil organic matter arising from changes in input of organic residue were estimated by Greenland et al. (1992) using decomposition constants appropriate for tropical conditions. In conversion of forest to forest to cropland, soil organic carbon was predicted to fall from 43 to 25 t/ha in 15 years, with continuing inputs of 2 t /ha instead of 11 t /ha of organic dry matter per year. These levels correspond approximately to a change from forest cover to arable crop production under humid tropical conditions. For drier savanna conditions, a decrease of soil organic carbon from 18 to 14 /t ha was predicted, when natural vegetation was converted to cropland.

A number of strategies and practices for soil organic matter management have been studies in recent decades. They include: (a) returning of organic materials to the soil to replenish soil organic carbon lost through decomposition (recycling of plant and animal residues, green manuring, cover crop rotation); (b) ensuring minimum disturbance of the soil surface (residue mulch, conservation tillage) to reduce rate of decomposition; (c) reducing soil temperature and water evaporation by mulching the soil surface with plant residues; and (d) integration of multipurpose trees and perennials into cropping systems to increase production of organic materials. In view of fact that the slash and burn agriculture will invariably be replaced by some forms of permanent agriculture in the near future, the above-mentioned alternative soil organic matter enhancing practices need to be incorporated into new farming systems.

5.2 Technology options

5.2.1 Crop residue management

The term 'crop residue management' essentially means returning crop residue back to the soil either by incorporation or as surface mulch. The main purpose is to conserve nutrients and energy embodied in the residue. Whether in the humid, subhumid or semiarid zone, the accumulation of soil organic matter is dependent on the quantity and quality of crop residues and other organic materials added to the field. Crop residues can be left on the soil surface as mulch or incorporated into the soil. Published results have shown that the presence of a mulch cover has many beneficial effects on soil quality. Mulch enhances biological activity, modifies soil temperature, improves soil water conservation, reduces soil sealing and crusting, and reduces soil erosion (Lal, 1974; Padwick, 1983; Sivakumar et al.,1992).

In term of soil water conservation, mulching is a more effective soil conservation practice under subhumid than semiarid conditions. Crop residues left on the soil surface as mulch do not appear to be an effective technique for soil water conservation during the extended dry season (i. e., 6 months) in the semiarid zone (Papendick and Parr, 1989; Payne, 1990).

Crop residues can also be incorporated into the soil when animal traction is available. Release of nutrients during residue decomposition is usually accelerated with incorporation. Soil disturbance during incorporation increases soil organic matter decomposition. Because tillage accelerate soil erosion, residue incorporation should only be practiced on less erosive, well-structured soils.

In term of labor input, frequent and high rates of residue applications may be uneconomical in the short run, especially when the corresponding yield increases are not substantial. But this practice should be judged by soil productivity and sustained crop yields on a long-term basis. The following examples illustrate the benefits of crop residue management.

In the subhumid and semiarid tropics, high soil temperature is an important limiting factor for seed emergence and crop establishment. In the humid and subhumid transitional zone of West Africa, the use of straw mulch reduced temperature of the surface soil (0-5 cm) by 7°C as compared with the traditional ridging without mulch, where soil temperature reached 40°C during the peak period of a sunny day (Lal, 1976).

In the humid and subhumid regions of West Africa, sufficient crop residue (e. g. maize stover) can be spared for use as mulch. The long-term benefits of crop residue management for soil fertility maintenance following forest clearing has been shown by Juo and Kang (1989) and Juo et al. (1995b; 1996). With continuous maize cropping under a no-tillage system on a kaolinitic Alfisol in south-western Nigeria, retention of residue as mulch resulted in slower decline and higher soil organic matter, CEC, pH, exchangeable Mg status and crop yield compared to when crop residue had been removed. After 15 years of continuous maize with residue mulch, the amount of organic C (10.1 g C/kg) in the surface soil (0 to 10 cm) was almost double that of surface soil where residue was removed (5.7 g C/kg). Maize residue mulch also improved soil water holding capacity from 0.12 kg/kg with residue removal to 0.16 kg/kg under continuous no-tillage maize.

In the semiarid zone, application of millet residue as mulch at the beginning of rainy season increased millet yield dramatically from 100 to 650 kg/ha on a Alfisol (psammentic Haplustalf) in Niger (Bationo et al., 1987; IFDC, 1989). There was a significant additive effect of mineral fertilizer and residue with a millet grain yield triple that of residue alone and double that of fertilizer alone when both residue and fertilizer were applied. Zaongo et al.(1997) studied the interactions of water, mulch and nitrogen on sorghum growing in a Entisol (Ustifluvent) in Maradi, Niger. They found that mulching with sorghum residue (which was saved and stored from a previous crop) reduced evaporation by 28 percent. Irrigation, mulch and nitrogen fertilization as sole amendments increased sorghum biomass yield by 55, 20, and 30 percent, respectively, in comparison with the no amendment control.

These results suggest that crop residue management in semiarid regions can only be an effective practice for soil fertility maintenance providing that crop residues are harvested and stored for use as mulch for the cropping season in the following year. In humid and subhumid regions, because cropping seasons are separated by a relatively short dry season, the usual practice is to leave the crop residue in the field after each harvest.

On Alfisols in East Africa, a 50% yield increase of coffee was observed with banana trash mulch over a 10-year span (Sanders, 1953). Yield increases from the use of organic mulches were also reported by Jones et al.(1960) in Kenya, Martin (1935) in Uganda, and Bull (1963) in East Africa. Further, surface mulch was observed to increase soil pH and exchangeable bases in acidic soils cropped with tea (Smith, 1962a, b).

Returning crop residues to the soil can increase microbial activity during the rainy season. Free-living microorganisms can fix N_2 actively when they have access to large amounts of energetic substrate, a situation that occurs when straw or other residues are generously incorporated into the soil. Estimations of the N input through this process are still scanty (Dommergues and Ganry, 1986).

It should be pointed out that although the benefits of crop residue management have been studied by many researchers, in reality, the adoption of this technology by farmers in sub-Saharan Africa is associated with many larger issues in farming system development. In the semiarid tropics, crop residues are primarily used as fuel and fodder. For example, cowpea stover is usually harvested and sold in the market as dry season fodder. Sorghum and millet residues are left in the fields for grazing by the Fulani cattle during the dry season and manure is left in field in return. Thus, farmers would be reluctant to use crop residue as a nutrient source or mulch unless alte rnative sources of fuel and fodder are made available to them. On the other hand, crop residue management has a good potential in humid and subhumid regions when integrated into appropriate cropping systems.

5.2.2 Green manure and cover crops

In temperate regions, planting green manure or cover crops in rotation with cereals was a common practice of soil fertility enhancement long before low-cost nitrogen fertilizers became readily available. This practice, however, has not been widely adopted by farmers in sub-Saharan Africa. For short-cycle crops, such as maize, rice and soybean with high demands for nutrients, timely applications of organic materials with a low C/N ratio, such as green manure and compost, could synchronize nutrient release with plant demand, hence minimizing the amount of inorganic fertilizer needed to sustain high crop yield (Sanchez et al., 1989). Many fast growing luguminous species such as mucuna (*Mucuna utilis*) and kudzu (*Pueroria phseoloides*) can be especially useful as cover crops for erosion control, weed suppression and for soil fertility restoration. On highly erosive Alfisols in the humid and suhumid transitional zone of West Africa, strip tillage combined with in situ mulch from mucuna have been shown to sustain crop yield in continuous large-scale maize and copwea production for many years without reverting the land to natural fallow (Wilson et al., 1982).

Advantages of using legumes as green manures and cover crops include: (1) enriching the soil with biologically fixed N, (2) conserving and recycling soil mineral nutrients, (3) providing ground cover which helps minimize soil erosion, and (4) requiring little or no cash input. However, additional labor is required for timely establishment, maintenance and incorporation of the green manure crop. Further, most legumous crops are better suited for high base status soils (e. g. Alfisols) containing adequate available phosphorus and calcium.

A major contribution of green manuring to soil fertility is the annual addition of nitrogen to the soil ecosystem. It is estimated that up to 50 kg N per ha per year can be contributed by grain legumes to an associated or subsequent non-legume crop; but total N_2 fixation is two or three times this value (Greenland, 1985). Where soil moisture is not limiting, live leguminous mulches, e.g., *Arachia repens, Desmodium triflorum* and *Indigo spicata*, grown simultaneously with a cereal crop (e.g., maize) may contribute similar amounts of nitrogen as preceding green manures (Akobundu and Okigbo, 1984). In the humid lowland forest zones with bimodal rainfall distribution, it is possible to intercrop a slow-growing legume (e.g., Sesbania) with a food crop (e.g., maize) in the first season and allow full growth of the legume in the second season to be incorporated as green manure in the first season of the following year (Balasubramanian and Blaise, 1993). This practice gives significantly higher maize yields in the first season, with beneficial effects likely to increase in the long-term, but does not produce a food crop during the second season.

Leguminous cover crops, such as mucuna and kudzu have been widely used to establish young tree crop plantations throughout the tropics. In such systems, newly cleared land are immediately seeded with a cover crop to protect the soil surface from erosion, supress weed growth, enhance the N status of the soil, and conserve available mineral nutrients from leaching losses.

5.2.3 Farm yard manure and composting

Farm yard manure (FYM) supplies multiple nutrient elements to the crop and at the same time, maintains soil organic matter content. Although cattle dung potentially constitutes a significant source of plant nutrients in sub-Saharan Africa, this potential can only be realized in areas where farming systems and animal husbandry are organized to facilitate dung collection and storage.

Composting is a low-cost, efficient method of processing crop residue and household wastes through biological decomposition for small holding farmers, in spite of an additional labor requirement. The amount and type of mineral nutrients present in the compost vary widely depending on the type of raw materials used. The following examples from the literature have shown positive effects of farm yard manure and compost on soil productivity.

Peat and Brown (1962 a, b) have shown that increased yields resulting from a single addition of 17 t of farmyard manure or compost per ha were maintained for as long as 13 years in the case of cotton, and for 9 years with bulrush millet (*Pennisetum typhoideum*) in Tanzania. Long-term beneficial effects of farm-yard manure in western Tanzania were also reported by Scaife (1971).

On a fine-textured high base-status Alfisol at Kabete, Kenya, maise grain yield had declined from 3 to 1 t/ha during 14 years of continuous cropping without inputs. Addition of an adequate amount of FYM during the 14th year increased maise grain yield to 2.9 t/ha while the trreatment with N and P fertilizers gave a grain yield of 2.0 t/ha (Swift et al., 1994).

At Zaria, located in the Sudan savanna zone of northern Nigeria, annual application of cattle manure (2.5 and 5 t /ha) to a loamy Alfisol cropped with cotton increased organic C content by more than 40%, and N by 33%, after 15 years compared to a treatment receiving annual an application of N, P and K fertilizer (Bache and Heathcote, 1969). Cattle manure also increased the cation exchange capacity and exchangeable Ca, Mg, and K contents of the soil.

At Serere, Uganda, after three cycles of a 5-year rotation, Jameson and Kerkham (1960) concluded that a system with 4 years cropping and one year fallow may be sustainable providing FYM is applied once in 5 years at a rate of 12 t/ha. Contents of total N and P, organic C, and exchangeable bases in the surface soil were significantly greater in fields received manure application compared to the control plots which received no manure application.

Other studies have shown that on the coarse-textured Alfisols and Inceptisols in West Africa, favorable results were obtained when mineral fertilizers were used in conjunction with relatively lower rates of manure application. In Burkina Faso, soil pH was maintained at 5.2 with application of 5 t /ha of manure per year with a low dose of NPK fertilizer for 15 years; whereas pH decreased to 4.6 with a low dose of NPK fertilizer without manure (Pieri, 1989). Organic C content in the surface soil was 0.35 % with manure and fertilizer, compared to 0.24 % without manure with or without fertilizer in the 15th year. Total N and exchangeable Ca and Mg contents were not affected by manure application, but exchangeable K content was increased from 0.09 to 0.22 meq/ 100 g in the manure plus fertilizer treatment. Similarly, results from Samaru (Zaria) in northern Nigeria also illustrated the effectiveness of combined use of FYM and inorganic fertilizers on kaolinitic soils in maintaining crop yields under continuous cropping (Jones, 1971). Moreover, with an application of 5 t FYM per ha, soil organic C level was maintained at 0.34 % during 8 years of cropping, despite removal of above-ground crop residue at each harvest.

The use of farm yard manure or compost as a nutrient source for food crop production depends largely on the prevailing farming systems. In some areas of East and Southern Africa, where crop and livestock production are somewhat integrated, FYM could become a major nutrient source and reduce the need for fertilizer for food crops. In the humid forest zone of West Africa and Central Africa, where livestock is limited to a few sheep and goats in each farm compound, the use of crop residue and green manure composts, though not common at present, could become a major source of nutrient input in more permanent cropping systems replacing 'slash and burn' agriculture.

In the semiarid zone of West Africa, composting is not a common practice because of lack of water and limited availability of plant and crop residues (Poulain, 1980). Adequate amounts of animal manure and household wastes are available only for small cropped areas surrounding the farm compound (Williams et al., 1993; Sanders et al., 1996). Another traditional system of manure utilization in West Africa is known as 'Kraaling'. In this system, livestock, mainly cattle from nomadic Fulani herders, are confined in a designated field during the night by the host farmer during the dry season to ensure concentrated application of manure and urine. Generally, scattered manure droppings during crop residue grazing is considered insignificant by local farmers in term of soil fertility improvement (Taylor-Power, 1991).

5.2.4 Cereal-legume intercropping or rotation

Inclusion of legumes in intercropping or in rotation offers considerable benefits because of their ability to fix atmospheric nitrogen biologically in symbiosis with Rhizobium. There are two main types of mechanisms postulated for the beneficial effects of legumes in multiple cropping systems: (1) through immediate transfer, in which nitrogen travels from the legume directly to the associated crop, and (2) through residual effects in which nitrogen fixed by the legume is available to an associated sequentially cropped non-legume after senescence of the legume and decomposition of its organic residue. Although some research workers have reported evidence of direct transfer of N in a maize/cowpea intercrop (Eaglesham et al., 1982), it is believed that N benefits of these systems may accrue more to subsequent crops after root and nodule senescence and decomposition of fallen leaves (Agboola and Fayemi, 1972; Ledgard and Giller, 1995). It is generally known that soil conditions, such as P, Ca and Mo deficiencies, Al and Mn toxicities, and drought stress are limiting factors for N_2 fixation.

Approximately 60% of the total N demand of a leguminous crop can be supplied through symbiotic N_2 fixation (Stoorvogel and Smaling, 1990). In Senegal for example, N_2 fixation by groundnut and soybean was 50 to 70 kg N/ha (Gigou et al., 1985). However, grain legumes, especially soybean and to a much lesser extent cowpea, transport a large amount of N (60 to 70%) to the seeds and pods which are removed during harvest (Henzell and Vallis, 1977). Consequently, negative N balances can be observed in rotations comprising grain legumes. Thus, to improve the soil N status in such systems, the following practices are recommended: (a) use of cultivars that actively fix atmospheric nitrogen, (b) return of above ground residues to the soil, and (c) use of minimum rate of N fertilizers to the cereal crop (Dommergues and Ganry, 1986). Moreover, legume biomass contains more N than non-legume species and release a greater portion of it in a shorter period of time upon return of biomass to the soil.

Where certain legumes are not indigenous, compatible Rhizobium strains may not be present, and inoculation with appropriate Rhozobium strain may be required. In sub-Saharan Africa, legumes commonly used as intercrops with maize, sorghum or millet are cowpea, common beans and groundnut. African cowpea cultivars are mostly promiscuous and they nodulate with indigenous Rhozobium strains present in the soil. For common beans and groundnuts, Rhizobium inoculates are rarely used by farmers (Kang, 1986; Ofori and Stern, 1987). Inoculation with Rhizobium resulted in significant yield increase of beans and soybean in Tanzania (Chowdhury et al., 1983). For soybean, inoculation resulted in a yield equivalent to that obtained with application of 90 kg N/ha. In East Africa, mainly soybean responded to the use of inoculates (Woomer et al., 1996).

Bationo et al. (1996) showed that in Niger, millet/cowpea and millet/groundnut rotations performed markedly better than millet monoculture across all N fertilizer rates. Similar results were obtained for a maize/cowpea rotation in the northern Guinea savanna of Ghana (Härdter and Horst, 1991), in Zimbabwe (Mukurumbira, 1985) and for a maize/pigeon pea rotation in Malawi (MacColl, 1989). A long-term field trial conducted at the Cinzana Station in Mali showed that a sorghum/cowpea rotation increased sorghum grain yield by 40% without cowpea stover incorporation (Kouyate, et al., 1998). At Kuola, Mali, cotton seed and groundnut yields were increased by 60, and 40 %, respectively, in a cotton/groundnut rotation with residues of both crops returned and incorporated in the soil compared to sorghum or cotton monoculture (Kouyate, 1998).

Sorghum rotated with peanut or cowpea in Burkina Faso resulted in significantly greater sorghum yields, that could not be explained by measured soil properties. It was assumed that allelopathic effects that were expressed in poor germination and establishment of sorghum due to phenolic compounds in the soil played an important role (Burgos-Leon, 1979). The same observation was also made by Pichot et al. (1981) in Burkina Faso, and by Kouyate et al., (1998) in Mali.

5.2.5 Agroforestry

Agroforestry refers to all forms of land-use systems in which trees or woody perennials are deliberately planted on the same land management unit in association with livestock and/or annual crops with significant economic and ecological interactions between the woody and non-woody components (ICRAF, 1983). Agroforestry systems that interplant tree legumes with annual cereals can be effective in soil nutrient cycling and enhancement. Buresh and Tian (1997) pointed out the following benefits of tree-annual crop association: (a) retrieval of nutrients from below the rooting zone of annual crops, (b) reduction of nutrient losses from leaching, runoff and erosion, and (c) legume trees increase the supply of nutrients within the rooting zone of annual crops through input of N by biological N_2 fixation. In this context, we discuss the agroforestry systems of alley cropping and multistory homestead gardens in the sub-humid and humid zones, and the *Acacia albida* parkland system in the semiarid zone.

5.2.5.1 Alley cropping

The traditional cropping and bush fallow land rotation system relies on trees and shrubs for nutrient recycling and soil fertility regeneration. In an effort to improve this system and allow continuous crop production on the erosive but high base-status Alfisols in the humid and subhumid regions of West Africa, researchers at the International Institute of Tropical Agriculture (IITA) in Nigera have developed the 'alley cropping' system. In this system, food crops are grown in the 3 to 4 meter wide alleys along the contour formed by hedgerows of planted, fast-growing, leguminous shrubs and trees, such as Leucaea (*Leucaena leucocephala*). The hedgerows are periodically pruned during the cropping season to prevent shading. Prunings are used as mulch and green manure for the associated food crop (Kang et al., 1981). The Woody portion of the pruning can also be used as fuelwood or sticks for yams. Leaves may also be used as fodder during the dry season. Trees and shrubs with their deep root system planted along contours on sloping land not only are able to recycle soil nutrients, but also minimize water runoff and soil erosion (Lal, 1989; Hauser and Kang, 1993; Juo et al., 1994).

Kang and Mulongoy (1992) reported that the five tree legume species, namely, *Cassia siamea, Leucaena luecocephala, Calliandra calothyrsus, Gliricidia sepium*, and *Flemingia macrophylla*, grown in 4 m spaced hedgerows on an Alfisol in Ibadan, Nigeria, can produce 21.3, 7.4, 6.1, 5.5, and 5.7 t/ha/yr of dry matter from pruning, respectively. The corresponding nitrogen yield by each species were 394, 247, 218, 169, and 149 kg N per ha per year, respectively. A review of published data also indicated that on high base-status soils (Alfisols, Entisols, and Andisols), nutrients recycled in hedgerow pruning from several legume shrubs ranged from 50 to 180 kg N, 2 to 10 kg P, 10 to 15 kg K, 10 to 60 kg Ca, and 5 to 25 kg Mg per ha (Yamoah, et al., 1986; Duguma et al., 1988; Kang et al., 1990; Gichuru and Kang, 1990).

Results of seven years of observations indicated that on high base-status soils, alley cropping with Leucaena can contribute between 40 and 60 kg N/ha to the companion maize crop and can be used as a low-input (nitrogen) soil fertility maintenance system for food crop production (Kang et al., 1984). A long-term maize-leucaena alley cropping experiment conducted on an Alfisol in Ibadan, Nigeria, showed that maize grain yields of 2 to 3 t/ha could be sustained for over 10 years without fertilizer input. The average yield of the control was 500 kg/ha. For higher maize yields of 4 to 5 t/ha using improved cultivars, 45 to 90 kg N fertilizer per ha would be needed (Kang and Duguma, 1985; Hauser and Kang, 1993).

Leucaena pruning on a high base-status Oxisol of northern Zambia contained 203 kg N/ha and doubled maize yield without any N fertilizer while Flemingia pruning containing only 58 kg N/ha were less effective (Dalland et al., 1993). Application of leucaena pruning increased the contents of organic C, Mg, and K in the soil.

It should be pointed out that another benefit of the tree/crop interplanting system is the increased exploitation of soil P by tree roots through the symbiotic association between tree species and vesicular-arbuscular mycorrhizal (VAM) fungi (Janos, 1980). Mycorrhizal associations therefore enhance P cycling and increase available P status in the surface soil through application of tree pruning.

Economical analysis of alley cropping with maize and maize/cowpea rotation on highly erosive Alfisols in southern Nigeria indicated that income from alley cropped maize was more than double that of the control. A major benefit was that the use of N fertilizer was reduced by more than half with alley cropping (Ngambeki, 1983). Thus, in spite of the high labor requirement for in initial hedgerow establishment and subsequent pruning operation, the alley system could be very beneficial for small farmers (e. g. 0.5 to 2 ha) in the humid and subhumid regions of Africa, especially in areas where the availability of farm labor is not a major limiting factor.

Most of the earlier research on alley cropping was conducted on high base-status Alfisols and Entisols in the humid and subhumid regions. For the strongly acidic soils (Ultisols and Oxisols) in high rainfall regions, a number of indigenous acid tolerant tree legumes such as *Inga edulis*. *Flamingia macrophylla*, *Acioa bateri*, and *Calliandra calothyrsus* may be used for alley cropping

Plate 1. "Our land is old and tired", said a Zarma farmer in Niger, West Africa.
Photograph courtesy of Andrew Manu.

Plate 2. A rotation experiment conducted on a loamy sand soil at the Cinzana Station, IER, Mali. Plot in the foreground shows continuous sorghum with crop residue removed after each harvest resulted in poor crop growth and establishment. Plots in the background show good growth and establishment of sorghum after rotation with cowpea and green manure crops *Sesbania rostrata* and *Dolichos lablab*. All plots received a moderate dose of Tilemsi rock phosphate. *Photograph courtesy of Zoumana Kouyate.*

Plate 3. *Acacia albida* trees are seen in farmer's field in the Niger River Valley near Segou, Mali, West Africa. The trees are protected and known as 'the fertilizer tree'.
Photograph courtesy of Mamadou Doumbia.

Plate 4. A large bean field on a fine-textured Alfisol (Eutric Nitosol) derived from basic igneous rocks in the tropical highlands of Kenya, East Africa. Phosphorus is a major limiting plant nutrient in these well-structured, oxide-rich soils.

Plate 5. On the highly erosive kaolinitic Alfisols in the subhumid and humid/subhumid transition zones, rotation of cereals with a leguminous cover crop, such as *Mucuna utilis*, helps restore soil biological properties, provide ground cover and supply nitrogen to the maize crop. As shown in the photograph, Mucuna died off during the dry season thus providing a in-situ mulch for the maize crop in no-till system.
Photograph courtesy of George F. Wilson and International Institute of Tropical Agriculture (IITA)

Plate 6. In humid tropics, the strongly leached Ultisols are highly acidic (e. g., pH below 5.0 measured in water suspension) and contain very low nutrient reserve (e. g., exchangeable Ca less than 0.5 meq/100g). Cassava/maize and cassava/upland rice intercrop is a common practice in densely populated humid areas. This farmer's field showed a well established first crop of maize and cassava planted in a 'slash and burn' field after 7 years of bush fallow. The field is then returned to bush fallow after one or two seasons of cropping.

Plate 7. A young oil palm plantation established in field planted with a leguminous cover crop, *Pueraria phaseoloides* on a Ultisol in the humid coastal region of Ivory Coast, West Africa.

Plate 8. A forest dweller with multistory homestead gardens in the humid region of West Africa. "As many as 50 annual, perennial and tree species are cultivated and the system provides basic food and nutrition needs for the indigenous people", said Bede N. Okigbo, a well-known African botanist.

(Evans and Szott, 1994). However, because of potential Al toxicity and multiple nutrient deficiencies, an initial investment of P, K and Mg fertilizers and lime is needed to achieve optimum growth and yield of the annual food crop and to enhance root growth and nutrient cycling of tree legumes (Juo et al., 1994; Evensen et al., 1994; Evensen et al., 1995). Thus, in view of the need for heavy external nutrient inputs, alley cropping is not well suited for strongly acidic soils in the humid tropics with annual food crops such as maize, upland rice, cowpea and beans.

A beneficial effect of alley cropping on acid soils in that the use pruning as leguminous green manure can reduce soluble and exchangeable Al in soil by forming less soluble organo-Al complexes (Hue and Amien, 1989). On an acidic Oxisol from Burundi with a high degree of Al saturation, application of tree legume pruning and farm manure decreased the concentration of Al^{3+} in soil solution from 2.9 ppm in the control to 0.75 ppm in plots receiving 6 t/ha of calliandra pruning (Wong et al., 1995).

5.2.5.2 Multistory homestead gardens

Multistory homestead gardens may be environmentally the most ecologically viable farming system for the indigenous people in the humid tropics (Marten, 1986; Juo, 1989). It is characterized by complete internal recycling of nutrients and organic matter by exploiting ecological balance of plant species in association with livestock production to meet the human needs on a family farm. Homestead gardens comprise a diversity of crop, animal and off-farm enterprises which contribute to the income of the farming system. The area around the house or farmyard is normally planted to a wide assortment of crops that require no purchased inputs and only low management. In advanced farms, the number of economic plant species may be 50 to 60, such as 5 or 6 tall growing species, 5 or 6 medium height tree species, 5 to 6 bush or shrub species, 4 or 5 root crops, and up to 30 shade-tolerant, short or vine type annuals (Okigbo and Greenland, 1976; Okigbo, 1980; Marten, 1986). The basic external inputs to the system, such as labor, manure, night-soil, and household wastes, are provided by the farm household. Soil productivity is maintained and enhanced by recycling plant residues and manure, and by biological N_2 fixation by annual and woody legumes. Soil erosion is minimized by maintaining continuous ground cover and good water infiltration (Michon, 1985; Juo, 1989).

The most intensively managed, productive multistory system is the Kandy gardens in Sri Lanka (Martens, 1986). In the forest regions of Africa, less sophisticated multistory homestead gardens are common in densely populated areas including southeastern Nigeria, western Cameroon, and eastern Congo (formerly Zaire).

5.2.5.3 Acacia albida parkland system

The tree legume *Acacia albida* (syn. *Faidherbia albida*), otherwise known as the 'fertilizer tree', is commonly found in farmers' fields throughout the subhumid and semiarid zones of sub-Saharan Africa. Generally tree stands are not planted but naturally established in farmers' field in a random pattern. More stands are usually found in fields located in river valleys and inland depressions where groundwater is available during the dry season. *Acacia albida* has been protected from cutting by traditional rulers (e. g., the Emir of Zinder in Niger) as well as national governments in Africa and crops have been maintained in agroforestry settings for centuries (NAS, 1984).

Crops such as sorghum and millet grown in association with *Acacia albida* grow better than outside its canopy. This tree legume has the unusual habit of growing new foliage during the dry season and losing its leaves early in the rainy season. Therefore, light and water competition with associated crops are minimized. The improved crop growth and yield under the tree canopy have been attributed at a variety of factors: (a) the improved fertility of the soil under the tree is due mainly to N_2 fixation by the tree and timely release of fixed N from fallen leaves to the associated crop, (b) the recycling of nutrients from the subsoil, (c) accumulation of windblown organic residues and mineral-rich soil particles within the vicinity of the tree trunk, and (d) nutrient inputs due to gathering human and livestock activities under the tree during the dry season (Dommergues and Ganry, 1986; Dancette and Poulain, 1969). Nutrient amounts in leaf litter of *Acacia albida* directly below the tree canopy were found to be equivalent to 110 to 185 kg N/ha, 4 to 40 kg P/ha, and 220 to 275 kg Ca/ha (Weil and Mughogho, 1993). Field studies trying to imitate the effects of *Prosopis cineraria* and *Acacia albida* on crop yield in the semiarid tropics have been inconclusive (Vandenbeldt, 1989). Thus, the potential of developing a more intensively managed agroforestry system using this tree legume remains an open question.

5.2.6 Managed fallow

Natural bush regrowth is currently considered the most efficient type of fallow for nutrient recycling and biomass accumulation in the subhumid and humid zones because it consists of many plant species with different types of root systems (Ewel, 1986; Jaiyebo and Moore, 1964). However, planted fallow systems will likely establish faster than bush fallow due to slow natural regrowth during the first year (Uhl and Jordan, 1984). Further, plant species composition in planted fallow systems can be selected to include fast-growing, deep- and shallow-rooting, as well as N_2-fixing species. A few examples from the literature highlight the main aspects of managed fallow.

Higher bulk density of a kaolinitic Alfisol in south-western Nigeria after 15 years of guinea grass fallow (1.30 Mg/m^3) compared to bush and leucaena fallow (1.04 Mg/m^3) indicated that trees are an important component of a fallow system in maintaining favorable soil physical properties (Juo et al., 1996).

Grass fallow plays an important role in improving soil fertility in the savanna zone; but it is less effective in nutrient recycling than are the deep rooted trees and shrubs grown in the humid zone (Kang, 1986). Jaiyebo and Moore (1964) showed that mixed bush was more effective in nutrient recycling than grass fallow (star grass) or annual leguminous cover crop (kudzu).

A one-year Tephrosia (*Tephrosia vogelii* Hook.f.) fallow at Kagasa, Rwanda, produced dry weight equivalents of 4.8 t/ha of leaf litter, 2.6 t/ha of foliage, and 9.5 t /ha of woody stems at harvest (Balasubramanian and Blaise, 1993). The leaf litter plus fresh foliage returned 238 kg N/ha/yr to soil in contrast to 38 kg N/ha/yr from natural regrowth. Maize grain yield increased by 72% over the natural fallow control in the second season after the incorporation of fallow vegetation (Balasubramanian and Sekayange, 1986). In addition to improvement in soil N status, the Tephrosia fallow produced 9.5 t ha^{-1} of woody stems which can be used as firewood. Increases in food crop yields due to rotation of short season fallow with food crops were reported from the subhumid zone of Nigeria (Agboola, 1980; Lal, 1983; Wilson et al., 1982) and Tanzania (Rupper, 1987).

In terms of nutrient cycling, kudzu (*Pueraria Phaceoloides*) fallow showed the largest relative increase in system N, when 6 leguminous fallows and bush fallow were compared, but had poor accumulation in P, Ca, K, Mg, and soil organic matter. Thus, if the accumulation of two or more macronutrients determines the duration of the fallow period, then a biologically more diverse system is required (Szott, 1987).

When different fallow vegetation types were compared for 25 years at Serere, Uganda, first year cotton gave smaller yields following leguminous cover than after grass or natural regeneration (Jameson and Kerkham, 1960; McWalter and Wimble, 1976). When grass was grazed during fallow periods, crop yields were not significantly affected, suggesting potential benefits when crop and livestock systems are combined.

Legume-based pasture and livestock management systems for Africa savanna regions, combined with periodic cereal production, have been advocated for many years (Jones and Wild, 1975). However, only a few forage legumes appear to be adapted to the semiarid region with its high soil and air temperatures and prolonged dry seasons.

A system of grass-fallow strip cropping was advocated by Kerr (1942) in Uganda. It involved the planting of elephant grass (*Pennisetum purpureum*) in place of a three-year fallow, alternating with three years of an annual crop. The system was claimed to be sustainable, maintaining soil fertility, improving the crumb structure, and preventing erosion by wind and water, since the grass was grown in 18 m wide strips along the contours of the hilly terrain.

The quantity of N accumulated in savanna grasslands is 30 to 40 kg N/ha/yr. Legumes planted as pasture components such as *Centrosema* and *Stylosanthes* may contribute substantially more to a mixed grassland ecosystem with adequate P supply in the soil. Inclusion of *Centrosema pubescens* for a two-year period significantly increased the amount of organic matter, total N and nitrifiable N in the soil at Ibadan, Nigeria (Moore, 1962). Several *Centrosema* species have been identified which are very productive in acidic soils with relatively low P and K status.

Leguminous cover crops in Africa, such as mucuna and kudzu have used on research stations, such as IITA in Nigeria, and some large commercial farms to rejuvenate soil fertility after several years of continuous cropping. However, the use of leguminous cover crops as a planted fallow to rejuvenate soil fertility is not very common on small farms.

5.2.7 Minimum tillage

Numerous research findings from both temperate and tropical regions have shown that with minimum tillage the rate of decomposition of soil organic matter and added organic materials is reduced, thereby aiding organic matter build-up and maintenance. Without major tillage events, the continuity of pores in the soil is maintained, which increases infiltration thus, reduced runoff and erosion. Further, increased structural stability with minimum tillage reduces wind erosion which can severely degrade soil by removing nutrient-rich topsoil. Additional benefits of residue mulch in conjunction with minimum tillage were discussed earlier.

Higher maize yields (4 to 5 t/ha) were maintained on a large mechanically operated field (e. g., 20 ha) on a kaolinitic Alfisol in the humid and subhumid transitional zone of Nigeria, with no-tillage for 12 consecutive crops (2 crops per year) than with conventional plowing (IITA, 1983; Lal, et al. 1984). The field was then used for maize/cowpea rotation and intermittent fallow to prevent soil compaction. In other field trials in Nigeria on similar soil types, soil organic C was found to decrease at a slower rate during 15 years after forest clearing and was maintained at approximately double the value with residue return than with residue removal under a minimum tillage system (Juo et al., 1995b; 1996). With a manually tilled field, however, the annual incorporation of over 5 t/ha of maize stover into the surface soil during a 10-year study resulted in an only slightly higher soil organic C level compared to residue (Kang, 1993), suggesting higher rate of decomposition in the tilled soil.

Minimum tillage and no-tillage systems have been developed in temperate regions in recent decades to control soil erosion and reduce fossil fuel input on large commercial farms. In North America and Western Europe, major governmental efforts including economic incentives, have been made to promote minimum tillage and no-tillage farming. A prerequisite of no-till or strip till system is the availability of pre-planting herbicides (e. g. Glyphosate or Roundup) and pre-emergence herbicides (e. g. Paraquat). Moreover, crop residue mulch is also an integral part of the no-till operation.

The potential for adopting small or medium-scale no-till or minimum tillage farming in West Africa is very promising in the highly erosive Alfisol regions, particularly when intermittent leguminous cover crop fallow (e. g. mucuna) is included into the system to prevent soil compaction due to continuous tractor traffic (George F. Wilson, and Douglas C. Couper, personal communication). In areas where herbicides are not available or are economically prohibitive, weeding and seedbed preparation are usually done manually. In Eastern and Southern Africa, where large scale commercial farms are operative, no-till farming with intermittent cover crop fallow could become a sustainable practice for enhancing nutrient and water availability for maize and bean production.

5.2.8 Variety

Crop varieties with higher yield potential, better response to fertilization, improved resistance to diseases and pests and with differing growth periods to maturity are being introduced but not yet adopted on a wide scale in sub-Saharan Africa. While the choice of variety may not be considered a nutrient management strategy in itself, it can strongly affect the success of a land use system.

In view of the low and variable rainfall in the semiarid region, early maturing cultivars have a better chance of success in most of the years (Matlon, 1990; Shapiro et al., 1993). Millet cultivars that mature in 90 to 95 d are more likely to avoid long dry spells during the grain-filling stage than the long duration cultivars of millet that mature in 110 d (Sivakumar et al., 1992). Although adoption is ongoing, the shorter-cycle cultivars are unable physiologically to take advantage of normal or longer rainfall. Millet breeders at the local research station in Niger have now begun selecting for late maturity traits to develop long-cycle cultivars that can respond more to fertilizer in better rainfall years.

5.2.9 Judicious use of chemical fertilizers

Judicious use (i. e., lower rates, split application, banding) of inorganic fertilizers on the infertile kaolinitic and oxidic soils are needed to sustain high crop yield and maintain an optimum balance of nutrient in agroecosystems. Published results have shown that continuous use of relatively high rates of nitrogen fertilizers on kaolinitic Alfisols, especially under cereal monoculture, can reduce soil pH (acidifcation) and seriously degrade soil fertility (Jones, 1976; Nnadi and Arora, 1985; Pieri, 1989; Mokwunye and Hammond, 1992; Juo et al, 1995a). Acidification occurs mainly through the leaching loss of exchangeable bases (Ca, Mg, K) and acid production during Al hydrolysis and nitrification.

Juo et al. (1995a) compared the rate of acidification of three forms of nitrogen fertilizers under continuous maize cropping and maize/cowpea rotation on a kaolinitic Alfisol in near Ibadan, Nigeria. All treatments were under no-till with crop residues returned to the field as mulch after each harvest. Results of this study showed the rate of acidification among the three N sources was greatest with ammonium sulfate and moderate with urea and calcium ammonium nitrate (CAN). Initial pH value of the surface soil (0-15 cm) was 5.8. In the treatment received ammonium sulfate, soil pH declined to 4.5 after the fifth year under continuous maize (2 crops/yr and 150 kg N/ha/crop in 2 splits). Soil pH in the urea and CAN treatments was affected less but also declined to about 5.0 after the fifth year under continuous maize. The amounts of exchangeable Al and Mn in the surface soils were also raised from near 0 to 1.0 and 0.3 meq/100g, respectively, in the ammonium sulfate treatment after the fifth year. Under maize/cowpea rotation with N fertilizer applied only to the maize crop in the main season, the rate of acidification was significantly slower than continuous maize. These results suggest that continuous cropping systems requiring high rates of N fertilizers should not be recommended for the poorly buffered kaolinitic Alfisols - a major type of arable soil in the subhumid and semiarid regions of sub-Saharan Africa.

While fertilizer use is needed to maintain soil productivity, it must always be in conjunction with management practices that help maintain soil organic matter, such as return of residue or other organic materials and minimum tillage.

In the semiarid region of sub-Saharan Africa with monomodal rainfall, nutrient deficiency is usually a more important limiting factor than water in sorghum and millet cropping. When nutrients are deficient, the limited amount of soil water is used inefficiently. The use of fertilizer nitrogen was shown to increase water use efficiency (Sivakumar, 1987; Payne et al., 1990; 1991; Zaongo et al., 1997).

While fertilizer management, especially the type of nutrient and the application rate, is best based on site-specific experiments and farmer's experience, the following examples from the literature are cited to illustrate some of the underlining principles and practices for long-term maintenance of soil and crop productivity.

In the humid/subhumid transition zone of West Africa, high maize grain yields (4 to 6 t/ha) of improved varieties were maintained in a maize/cowpea rotation over 10 years on a kaolinitic Alfisols at the International Institute of Tropical Agriculture (IITA) with annual application of 60-120 kg N/ha as urea, 0- 60 kg P/ha as triple superphosphate (TSP), and 0-80 kg K/ha as KCl. Grain yield of planted in the second or minor season without additional fertilizer application was maintained at about 1.0 t/ha. In this study, important components for continuous sustainable cropping are (a) cereal/legume rotation, (b) retention of crop residues as mulch, (c) use of soil testing to determine annual fertilizer need, and (d) monitoring changes in soil properties (e. g. pH, bulk density) to determine when the field should be reverted to natural or planted fallow (Kang, 1985; Juo and Kang, 1989).

On a strongly acidic Ultisol (Typic Paleudult, pH 4.3) in the high rainfall humid zone of southeastern Nigeria (annual precipitation 2400 mm), maize and cowpea yields could be sustained at about 3.5 t/ha and 1 t/ha, respectively, for seven years on small farms with application of low rates of lime (200-400 kg/ha annually) in combination with applications of 120-50-30-5 kg/ha as N-P-K-Mg (plus S and Zn) applied to the first season maize crop (IITA, 1983; Friessen, et al, 1982; Kang, 1985). The cowpea crop planted in the second season received no fertilizer. Lime, at a relatively low rate (200 to 400 kg/ha) can be regarded as a fertilizer rather than a major soil amendment.

The use of external nutrient inputs, such as fertilizers and lime for cereals, such as maize, on strongly acidic soils in the high rainfall region, however, depends not only upon farmer's food preference, but also upon the availability and costs of these inputs. Moreover, edible plant species with low nutrient demands, such as root crops (cassava, cocoyam and sweet potato), plantain, starchy banana and edible tree crops are ecologically better suited for such soil and climate conditions.

Cassava and sweet potato are commonly grown on weathered acid soils (Ultisols and Oxisols) with low nutrient reserves. Improved cultivars are responsive to K and N fertilization and can produce relatively large root or tuber yields under good management (Obigbesan, 1974; Juo, 1985; van der Heide, 1988). In West Africa, cassava yield ranged between 30 and 60 t/ha in research trials with fertilizer inputs, and 5 to 15 t/ha on small holder farms without fertilizer input (Ezumah, et al., 1980; Juo, 1985).

Although phosphorus deficiency is widespread in sub-Saharan Africa, with the exception of soils derived from volcanic and ferro-magnesian rocks, the surface horizons of the most arable soils are coarse-textured and kaolinitic. These soils have a relatively low capacity to immobilize or 'fix' added P (Juo and Fox, 1977; Bationo and Mokwunye, 1991). Therefore, small to moderate doses of P fertilizers (i.e., 20 to 40 P kg ha^{-1}) would satisfy P requirements of major crop species grown in the region (Mokwunye, 1979). Furthermore, continued phosphate applications will increase the labile P pool in the surface soils, and this residual effect will reduce the need for fertilizer P in the long term. Immobilization or fixation of P is encouraged in the fine-textured, oxidic, base-rich Alfisols, Oxisols and Andisols commonly found in East and Southern Africa. Higher rates of P fertilizers (e. g., 60 to 200 kg P_20_5/ha) may be required for optimum crop growth, especially for grain legumes of known high P requirement, such as beans and soybean (Mokwunye et al., 1986).

On a kaolinitic Alfisol in the highlands of western Kenya, Jama, et al. (1997) compared triple superphosphate (TSP), cattle manure and *Calliandra calothysus* leaf biomass both individually and as mixtures as sources of P for maize. They found that the application 10 kg P/ha as inorganic, organic or mixtures of P sources significantly increased maize grain yield. Grain yields from treatments received urea alone at a rate of 44 kg N/ha, and spot placement of (urea+TSP) and (TSP+manure) were 0.6, 1.0 and 1.7 t/ha, respectively.

Fertilization of millet in a millet/cowpea intercrop in the semiarid zone resulted in increased yield of millet, but did not influence cowpea yield (Davis et al., 1994). The use of P by millet was most efficient at an application rate of 22.5 kg P/ha, but the greatest millet biomass production, grain yield, leaf P concentration, and economic return were obtained at 45 kg P/ha. Research conducted on sandy soils at the ICRISAT Sahelian Center in Niger showed that the application of as little as 20 kg P_2O_5/ha doubled millet yields (Bationo et al., 1987). For the loamy Alfisols in northern Nigeria, the optimum N and P rates for maize were found to be 65 kg N/ha and 38 kg P_2O_5ha, when tested in 50 trials between 1957 and 1964 (Goldsworthy, 1967a). In the same region, 154 trials resulted in an optimum N rate for sorghum of 25 kg N/ha when combined with 16 to 19 kg P_2O_5/ha (Goldsworthy, 1967b).

Split application of N fertilizer in high rainfall zone may become more advantageous where leaching is more severe. In an experiment with upland rice in southeastern Nigeria, Arora and Juo (1982) found that leaching loss of nitrate was reduced from 58% to 28% of the applied N when fertilizer was applied in three splits instead of a single dose applied at the time of planting. Consequently, this resulted in increased N uptake and yield by the crop.

Mughogho et al. (1986) reviewed research on nitrogen fertilization in Africa and concluded that split applications of urea were superior to basally applied urea in all three climatic zones. In the presence of an actively growing crop, losses of fertilizer N from urea or CAN, can be relatively low when N is applied in 2 or 3 splits. Urea and CAN were found to be equally effective over the entire range of rates at several sites in the humid and subhumid zones. Urea performed better than CAN at only two of the nine locations in the subhumid zone. In the semiarid zone, the initial response to CAN tended to be better than to urea, and maximum millet yields were attained at 50 kg N/ha with CAN as opposed to with 75 kg N/ha with urea. Labeled fertilizer N that remained in the soil tended to stay near the soil surface for all urea treatments, whereas with CAN it moved into the soil to deeper layers where it was easily taken up by the plant.

In a summary of N-15 research by the International Fertilizer Development Center (IFDC) in semiarid areas of West Africa, Mughogho et al. (1986) and Christianson and Vlek (1991) reported that CAN significantly outperformed urea in terms of plant N uptake, which translated into higher yield of millet. Total plant uptake of fertilizer N, however, was low (20 to 37%), and losses were severe (25 to 53%). Plant uptake of N-15 from point-placed CAN was almost three times that of urea applied in the same manner. The majority of N remaining in the soil was found in the 0 to 15 cm layer. The major cause of N loss from urea in the semiarid zone is believed to be through ammonia volatilization. Replacement of urea with CAN or urea amended with unease inhibitors could increase N use efficiency in the widespread sandy soils in the drier regions of Africa.

Placement methods also affect fertilizer use efficiency, When comparing the entire urea response curve of the IFDC field trials, broadcasting performed significantly better than either band or point placement in the humid and subhumid tropics. In the semiarid tropics, point placement significantly decreased the performance of urea, whereas broadcast and band applications behaved similarly, except at high application rates (Mughogho et al., 1986). Concentrated placement of urea in points or bands may lead to increased leaching of fertilizer N because of limited access to the sorption sites of the soil. in the case of CAN, however, a 57% reduction in fertilizer N uptake by the plant was found when CAN was broadcast rather than point-placed (Christianson and Vlek, 1991).

5.2.10 Lime

Limestone sources in sub-Saharan Africa are generally scarce, especially in humid regions where strongly acid soils (pH less than 5.2) are widespread. In areas where sizable limestone deposits are found, they are usually mined for cement production. Soils where a response to liming can be expected are Ultisols of the high rainfall regions of coastal West Africa and the acidic Oxisols in the high altitude of Madagascar, Cameroon, Rwanda and Burundi.

The purposes of liming acid tropical soils are to correct Al and/or Mn toxicity as well as supply Ca and Mg as plant nutrients. An important criterion for determining lime requirement for acid tropical soils is to attain soil pH value about 5.5 or to achieve a desired value of exchangeable Al saturation for the particular crop to be grown (Kamprath, 1980). Overliming (e. g. liming soils to pH 7 or higher) can induce phosphorus and micronutrient deficiencies. Thus, annual application of relatively small doses of lime are usually recommended. For example, on a coarse-textured kaolinitic Ultisol (pH 4.3) in the high rainfall area of southeastern Nigeria, lime requirement for maize and cowpea rotation can be as low as 0.5 t/ha/yr (Friessen et al., 1982). On fine-textured acidic Oxisols in Rwanda, higher rates (1 - 2 t/ha) are needed to give optimum maize and bean yields (Yamoah et al., 1992).

Results from a groundnut/maize rotation on an Oxisol in the subhumid region East Africa suggest that lime applied at a rate of 4000 kg/ha initially or 500 kg/ha annually along with a basal application of recommended fertilizer nutrients could maintain yield at economically viable levels (Singh and Goma, 1995). On an acidic Ultisol in Northern Zambia, differences in cereal and legume yields between limed and unlimed treatments became larger over the years, and maize performed very poorly or failed completely after the fifth cropping season on the unlimed soil. The positive effect of liming was still present after 9 years (McKenzie et al., 1988).

Continuous cereal cropping with nitrogen fertilization on the high base-status but poorly buffered Alfisols (i. e., pH 5.5 to 7.0) can cause soil acidification within a relatively short period of time (e. g. 3 to 5 years). In most instances, when soil pH has declined to below 5.0, the application of lime may be needed to correct Mg and Ca deficiency as well as Al and/or Mn toxicity (Jones, 1976; Ssali et al., 1986; Pieri, 1987; Mokwunye and Hammond, 1992). Thus, appropriate crop rotations or planted fallow systems need to be included to prevent acidification of Alfisols under more intensive cultivation (Juo et al., 1995a).

5.2.11 Water harvesting

The semiarid region of sub-Saharan Africa is to a large extent, blessed by a monomodal rainfall distribution, however, in areas with predominantly sandy soils, drought stress can become a limiting factor for crop growth. Rainfall is often received in intense storms, and soils tend to form surface seals. Nutrient loss through runoff and erosion can be greatly reduced by certain water harvesting techniques.

Some traditional practices have been developed for capturing water (Ohm et al., 1985). Techniques to retain water include microcattchments, the earth and rock bunds, and the "zai" (holes to collect water around the plants). These water retention methods are usually combined with application of manure and plant residues. Severely degraded soils can be partially recovered and yields moderately increased. Other water retention techniques include improved land preparation or tillage practices, such as ridging and tied ridging. Ridging is usually done with animal traction.

In the semiarid zone with sandy clay loam soils, tied ridging (perpendicular ridges with earth dams at regular intervals along the ridges) has produced yield increases when implemented at the first weeding (Sanders, 1989). While the water retention technique had little effect in a good rainfall year, in a poor year the impact was substantial (Sanders et al., 1996; Kouyate et al., 1998). Farmer-managed trials with fertilizer and tied ridges in Burkina Faso more than doubled sorghum grain yield (Nagy et al., 1990).

Nutrient use efficiency, particularly N, in the semiarid zone, is closely related to soil moisture availability. Thus, soil management practices such as residue mulch and tied ridges can increase N use efficiencies by maize, sorghum and millet (Bationo et al., 1993; Kouyate and Wendt, 1992).

The combination of ridging and fertilizer in Mali increased water use efficiency (Kouyate and Wendt, 1992). In Niger, runoff harvesting increased rooting depth, rainfall use efficiency and nutrient uptake by sorghum and millet (Zaongo et al., 1994). Because soil compaction and surface sealing are major constraints for crop growth and establishment in the absence of adequate organic inputs, the traditional practice of ridging and other tillage operations are essential to improve nutrient and water use efficiency by crops.

6. An agroecoystem approach to INM

Low soil nutrient reserve is a major limiting factor for increased crop production in sub-Saharan Africa. Because of this situation, a modest initial investment in external nutrient inputs and subsequent replenishment and recycling of nutrients are essential steps to increase and sustain crop production. Thus, in a nutrient-stressed environment, sustainable crop production systems must strongly emphasize nutrient recycling. Within the agroecosystem context, the role of INM in a whole farm system may be illustrated in the Figure 4. The choice of INM strategy not only depends upon crops and cropping patterns, but also upon the available resources, which in turn, are influenced by the ecological, social and economic environment of the farming community.

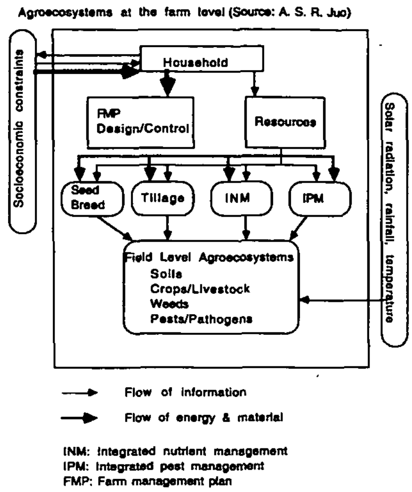

Figure 4. An agroecosystem model depicting the flows of energy, material and information

In the humid forest region, where root crops and tree crops are ecologically more suitable, three agroforestry systems appear to have a high potential for maintaining soil organic matter at levels adequate for sustaining crop growth, multistory homestead gardens, plantation/crop combinations, and alley cropping. This potential arises from the production of large amounts of biomass which provides an effective cover of the soil surface by litter and canopy, biological N_2 fixation, and recycling of mineral nutrients (Juo, 1989; Young, 1990).

In the subhumid and humid/subhumid transition zones, crop residue mulch, minimum tillage and leguminous cover crops are promising technologies for improving nutrient and water use efficiency and sustaining high yields of maize, sorghum and cowpea (Lal et al., 1984; Juo and Kang, 1989). In these zones, climate and soil constraints for crop production are least severe compared to the humid and semiarid zones. Adoption of the principles and strategies of integrated nutrient management outlined above could produce a sizable surplus of food grains for the small family farms in the African savannas.

In the semiarid regions, however, improvement of millet and sorghum yields is severely limited by the lack of organic inputs. Crop residues are often harvested for uses with higher economic value, such as building materials, fuel, and fodder during the dry season. The use of crop residues as mulch and nutrient sources will depend upon the availability of alternative sources of fuel and fodder to the farming communities. Thus, the potential for increasing and sustaining food crop production in the semiarid zone is limited, and would depend upon successful integration of crop, livestock and fuelwood production on the same farm or in a watershed unit (Manu et al., 1994).

Based on published results, the importance of INM on the sustainability of crop yield on the kaolinitic soils in the subhumid and semiarid regions of Africa may be illustrated by the four conceptual models given in Fig. 5. Returning crop residues to the soil and reverting cropland periodically to natural or planted fallow are essential practices for the maintenance of soil fertility.

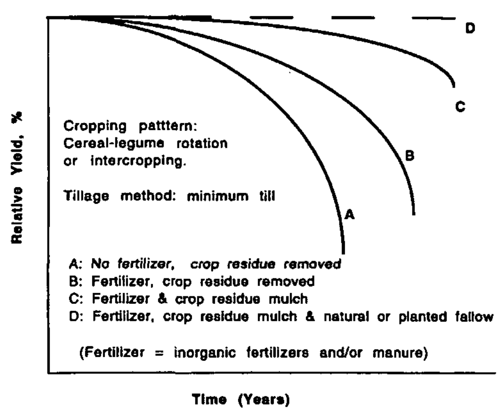

Figure 5. Simplified relationships between sustainability of crop yields and nutrient management strategies on kaolinitic soils newly cleared from natural forest fallow under minimum tillage

7. Summary and conclusions

The agroecological environment of sub-Saharan Africa may be characterized by the following nutrient management features: (1) low nutrient reserve in arable soils is a major factor limiting sustainable food production; (2) overall nutrient balance on cropland is negative. Published evidences have indicated that cropland is losing mineral nutrients at an alarming rate; (3) food is mainly produced by small family farms; and (4) mixed cropping with two or more crop species is commonly practiced with little or no external nutrient input.

Achieving food security in sub-Saharan Africa for a rapidly expanding population will require intensification of food production on existing cropland through enhanced nutrient inputs. While nitrogen sources may be generated through biological N fixation, the needs for other nutrients, especially phosphorus, must be supplied by external sources to achieve higher crop yields. The use of organic inputs is essential to maintain adequate physical and chemical properties of the predominantly kaolinitic and poorly buffered soils. Thus, a sustainable crop production system must adopt an integrated nutrient management strategy using balanced organic, biological and chemical nutrient inputs.

More research is needed in the following areas: (1) Development of economically viable and nutrient conserving cropping systems that integrate N-fixing plant species with food crops; (2)

development of fuelwood and fodder production systems through an integrated watershed management approach, thus allowing crop residue to be spared for use as mulch material or for compost production; and (3) establishment of economic phosphorus requirement thresholds needed to sustain crop yields on major soil types; and (4) integration of livestock and food crop production to allow more efficient use of animal manure and household waste on cropland.

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