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The Potential of Organic and Inorganic Nutrient Sources in Sub-Saharan African Crop Farming Systems

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1. Introduction

Soil nutrient balance studies in Africa show evidence of widespread nutrient mining (Speirs and Olsen, 1992). Amount of nutrients annually taken away in the form of harvested crops, crop residues transferred out of fields or lost through leaching, erosion and volatilization are higher than the amount of nutrient inputs through fertilizers, deposition and Biological N_2 fixation (Smaling and Braun, 1996). Soil nutrient mining has been estimated to average 660 kg of nitrogen (N), 75 kg of phosphorus (P) and 450 kg of potassium (K) per hectare per year during the last 30 years from about 200 million hectares of cultivated land in 37 countries in Africa (Smaling et al., 1997). Continuous nutrient depletion and low soil fertility has not only led to the development of integrated soil fertility management technologies that offer potential for improving soil fertility in Africa (Scoones and Toulmin, 1998), but almost simultaneously triggered extensive studies on nutrient balance in various African farming systems. Thus, this chapter reviews the potential of organic and inorganic nutrient sources to counteract nutrient mining in Sub-Saharan African (SSA) crop farming systems.

Lack of plant nutrients is one of the principal causes for low agricultural productivity and food insecurity in Africa (Sanchez, 2002). In SSA, smallholder farmers have been experiencing declining agricultural productivity, mostly due to soil fertility depletion, leading to food insecurity. The impacts of smallholder-induced nutrient depletion express themselves in form of continued declines in crop yields, which can be abrupt or gradual depending on soil type (Bekunda et al., 2010). Low and declining soil fertility arises from continuous cultivation where levels of soil replenishment, by whatever means, are too low to mitigate the process of soil nutrient mining, whereby the soil fertility is not restored by new inputs (Shisanya et al., 2009). Intensively cultivated highlands in East Africa lose an estimated 36 kg N ha^{-1} yr^{-1}, 5 kgP ha^{-1} yr^{-1}, and 25 kg K ha^{-1} yr^{-1}, while croplands in the Sahel decline by 10, 2, and 8 kg ha^{-1}, respectively (Bekunda et al., 2010). Hence, decline of soil fertility is seen as the most important constraint to crop production in SSA, where most agro-ecosystems remove more nutrients than are provided by external inputs making it a fundamental biophysical root cause for declining food security in the smallholder farms (Sanchez and Jama, 2002). As a result, it is widely appreciated that protecting and improving the soil makes economic and social sense (Bekunda et al., 2010).

Fertilizer use in the SSA region is very low compared with the world average, despite many African farmers being aware of the beneficial contribution of mineral fertilizers to crop production. Average rate of inorganic fertilizer use in SSA, excluding South Africa, is 10 kg ha^{-1} as compared to 87 kg ha^{-1} for the developed countries (Bationo et al., 2006). With 9% of the world's population, SSA accounts for less than 1.8% of the global fertilizer use and less than 0.1% of global fertilizer production (FAO, 2008). This laxity is attributed to farmers' lack of confidence in the economic returns of fertilizing food crops, and lack of knowledge as to which kinds and rates of fertilizers are recommended for their specific crops, soils, and agro-climatic conditions (Vlek, 1990). Further, due to high price of imported fertilizers at farm gate and delays in delivery due to poor infrastructure, smallholder farmers often apply very low rates of inorganic fertilizer late in the growing season, leading to poor crop-yield responses (Heisey and Mwangi, 1996).

Sustaining the nutrient base calls for measures that combat the loss of nutrients. These include: application of modest amounts of the appropriate fertilizer, complying with recommendations that are specific to both crop and agro-ecological zones; efficient use of animal manure and household waste; adopting more nitrogen-fixing species in cropping systems, leaving residues as mulch or ploughing them into the soil, properly timed or split application of mineral fertilizers to combat leaching; and appropriate tillage and soil conservation measures to combat erosion (Smaling et al., 1992).

2. Nutrient flows and balances in SSA crop farming systems

The use of nutrient audits and nutrient balances to assess the changes in soil nutrient status and the prospects for future food production is becoming increasingly important (Sheldrick et al., 2003). Nutrient flows and balances are currently and increasingly being used as powerful tools for estimating nutrient depletion or accumulation. The relevance of soil nutrient balances to agricultural potential of land has been emphasized by many scientists (Stoorvogel et al., 1993; Smaling, 1993; Van den Bosch et al., 1998). Soil nutrient flow is the amount of plants nutrients that flow in and out of a system (Nkonya et al., 2004). The difference between nutrient inflow (sum of nutrient inputs) and outflow (sum of nutrient outputs) is the nutrient balance. Nutrient output flows comprise removal of economic crop products and crop residues, leaching, gaseous losses, runoff and erosion. A situation where inputs exceed outputs is termed as surplus nutrient accumulation; when outputs exceed inputs, this is nutrient depletion. Negative nutrient balances indicate that a system is losing nutrients; on the contrary, excess nutrient accumulation may lead to extended losses as a result of toxicities. The net difference between inputs and outputs of nutrients expressed in kg nutrients integrated over a certain area and time gives the net soil nutrient budget (Stoorvogel and Smaling, 1990). Balanced or equilibrium nutrient levels occur when inputs equals outputs. Hence, a summary of nutrient inputs and outputs from a defined system over a defined period of time is the nutrient budget for that spatio-temporal unit (Oenema et al., 2003).

The concept of nutrient depletion is derived from quantifying nutrient flows resulting in nutrient balances and/or stocks (Vlaming et al., 2001). In assessing nutrient depletion through use of nutrient balances at any given time, a number of inputs and outputs are considered. Nutrient input processes are: application of mineral fertilizer and organic manure, atmospheric deposition, Biological N_2 fixation and sedimentation by irrigation and flooding. Even though a number of nutrient flows can easily be quantified and valued in monetary terms based on the input and output processes (partial balance), other flows are hard to quantify hence often estimated on the basis of transfer functions, for instance those developed for sub-Saharan Africa by Stoorvogel et al., (1993), adopted and critically reviewed by others (Smaling, 1998; Scoones and Toulmin, 1998; FAO, 2003). A partial nutrient balance considers direct nutrient inflows from mineral fertilizers and organic materials and outflows resulting from harvested products and crop residues (Harris, 1998).

Nutrient budgets are important indicators of potential land degradation, for optimizing nutrient use, and designing policy to support improved soil fertility management by smallholder farmers. They have been used extensively for improving natural resource management and/or for policy recommendations over the last decades (Grote et al., 2005). At a relatively small scale, nutrient budgeting can be used to assess the level of nutrient sources and flows, opportunities for improved use efficiency and scope for possible interventions.

Most studies for SSA point at declining nutrient stocks whereby outputs exceed inputs hence raising question on the impact of declining nutrient stocks on agricultural production in the region (Smaling, 1998). Regional and national estimates of nutrient balances are negative in most of sub-Saharan Africa. Consistently negative nutrient balances, be it full or partial, have been reported. The negative balances can be attributed to the several nutrient outflow channels especially through harvest and soil erosion. For instance, Stoorvogel et al. (1993) estimated annual N losses from arable land to be 31 kg ha^{-1} in Zimbabwe, 68 kg ha^{-1} in Malawi, 112 kg ha^{-1} in Kisii, Kenya and 27 kg ha $^{-1}$ in Tanzania. Similar results have been found in Mali, where aggregate N losses are reported for all districts, except the cotton growing zone where imports of inorganic fertilisers compensate for harvest exports and other losses (Van der Pol and Traore, 1993). For Africa as a whole, low level of inputs relative to outputs results in a consistently negative balance (Stoorvogel and Smaling, 1990; Stoorvogel et al., 1993).

3. Nutrient inputs in soils of SSA crop farming systems

From the previous discussion, it is apparent that crop yields cannot increase nor can yields be sustained over time without adequate levels of soil fertility and nutrient inputs are needed on most soils in SSA, due to their low inherent fertility. Sustained soil fertility replenishment in Africa requires increased use of both inorganic fertilizers and organic manures (Palm et al., 1997). Successful design and implementation of soil fertility replenishment initiatives in Africa requires an understanding of basic rationale of small-scale farming on the continent (Omamo et al., 2002). To achieve sufficient levels of nutrients in most soils, organic and inorganic fertilizers must be applied, and in any locality, the optimal mix between the two will depend on their availability and water supplies (Larson 1996). The most common nutrient inputs in SSA crop farming systems consists of inorganic fertilizers, Biological N_2 fixation, farmyard and animal manure and agroforestry trees.

3.1 Inorganic fertilizers

Whereas in developed world, excess applications of fertilizer and manure have damaged the environment, low use of inorganic fertilizer is one of the main causes of environmental degradation in Africa (Bationo et al., 2006). Except for countries where governments subsidize fertilizers use in cereal production, inorganic fertilizers account for about one-third of inputs in Africa (Smaling, 1993). However, they are used largely in mechanized agriculture and on export crops. By the turn of the century, fertilizer use in Africa was only 8 kg/ha, compared with 96 kg/ha in East and Southeast Asia and 101 kg/ha in South Asia (Morris et al., 2007). At the present time, Africa accounts for less than 1% of global fertilizer consumption (Denning et al., 2009).

Millions of smallholder farmers throughout Africa use fertilizers, most of which are imported. Limited use of fertilizers is determined by a variety of reasons including high costs, especially after market reforms removed subsidies, inefficient marketing systems, and restricted markets for outputs that constrain investment opportunities (Bekunda et al. 2010). Because of the high price of imported fertilizers at farm gate and delays in delivery due to poor infrastructure, smallholder farmers often apply very low rates of fertilizer and very late in the growing season, leading to poor crop-yield responses (Heisey and Mwangi, 1996).

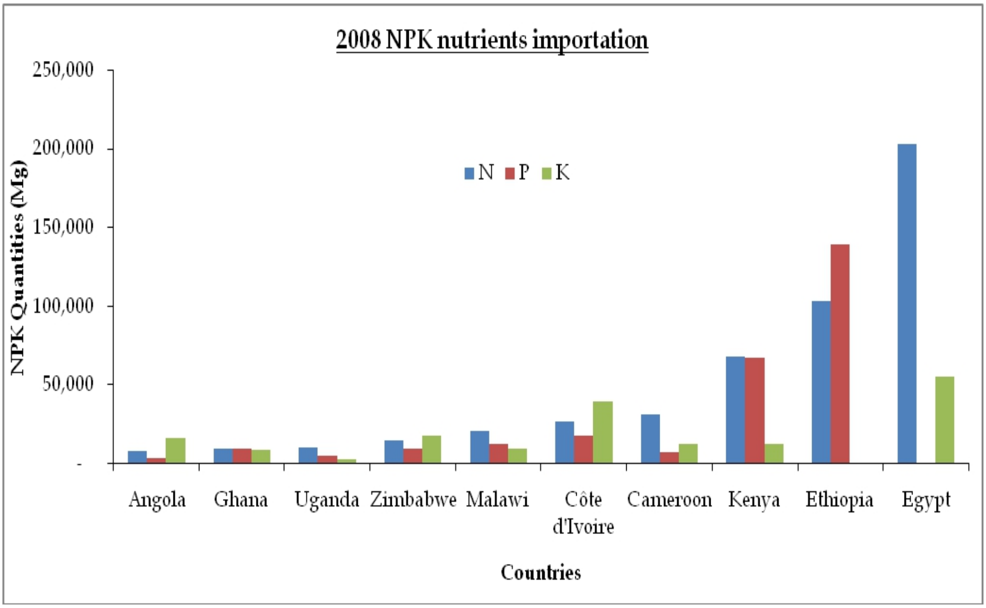

Fig. 1. Quantities of NPK nutrients imported by various African countries in 2008 (Source: FAO 2011)

Overall, inorganic fertilizer use in Africa is very low compared to other parts of the world. Based on the amount of N, P and K imported in the year 2008, Egypt leads in the amount of N imported followed by Ethiopia, and Kenya was in the third position (Fig 1). Ethiopia was the highest importer of phosphatic fertilizers, followed by Kenya while Côte d'Ivoire was third. Egypt imports negligible amounts, or in some years nil amounts, of P fertilizers but at the same time they are leading importers of K. The trend observed in the 2008 nutrient importation is on average identical to that observed as early as 2003. Given the high population in Ethiopia and Egypt, the large amounts of nutrient importations might not necessarily imply higher fertilizer consumption compared to other countries. Also, in Egypt, the crop production is mainly irrigated farming system implying high mechanization and agricultural intensification that facilitates better utilization of external inorganic inputs compared to other SSA countries where they depend on rainfed subsistence farming systems. Studies in Eastern and Central Kenya, for example, have shown that inorganic fertilizer application rates are sometimes as low as 5 kg ha^{-1} of N, P and K (Gakuo et al., 1996). With donor driven liberalization policies of 1990s in many African states, subsidies on fertilizer purchase and distribution were abandoned and the private sector was encouraged to take over supply systems, leading to high costs and sometimes shortages in the market (Winpenny et al., 1995), which dramatically affected nutrient management practices for some time. These economic disincentives to the use of inorganic fertilizers resulted to reduction in agricultural productivity. The trend has however been reversed with the introduction of smart subsidies by most African governments like Malawi, Kenya among others and the prospects of increase in the use of mineral fertilizers is promising. If average application rates of inorganic fertilizer in sub-Saharan Africa rose to 50 kg/ha, there can be substantial impact on agricultural yields (Larson 1996). There is therefore need to increase average fertilizer application rates in sub-Saharan Africa from the current10 kg/ha to 50 kg/ha, which can lead to substantial increase in agricultural productivity in the region. Without substantial additions of nutrients in the form of inorganic fertilizers, the conditions created through improved soil conservation (Larson 1996), improved crop varieties and field management practices cannot be exploited for sustained yield gains. Organic inputs, improved crop rotations, and soil conservation measures can all contribute significantly to many, but not all of Africa's plant nutrient requirements. Increased productivity will require that organic manures be supplemented with nutrients from inorganic sources for crops to receive a proper balance of nutrients. Therefore, soil fertility management must combine biological nutrient sources with inorganic fertilizer to maintain sustainable production

3.2 Biological N_2 fixation

Substantial nitrogen input into global agriculture comes from N_2 fixation. It has been estimated that global rate of nitrogen fixation has doubled during the last few decades, mostly through agricultural activities such as fertilizer manufacturing and increased use of dinitrogen (N_2) fixing crops (Galloway et al., 1995). About 60% of the total N demand by a nodulating leguminous crop can be supplied through symbiotic N_2 fixation (Stoorvogel & Smaling, 1990). Biological N_2 fixation becomes an N input after atmospheric N_2 gas is converted into plant N by symbiotic plants and the whole plant or its residues are incorporated into the soil. Potentially, this is an important N input into tropical African agro-ecosystems where legumes are a major component of the cropping systems (Giller and Cadisch, 1995). With judicious management of biological N_2 fixation in traditional cropping systems, most of the N required to maintain agricultural productivity in SSA can be achieved. The incorporation of nitrogen fixing legumes into cereal cropping systems either as intercrop or in rotation is common practice throughout SSA. It offers considerable benefits because of the legumes' ability to fix atmospheric nitrogen biologically in symbiosis with the *Rhizobium* bacteria. The contribution of N from legumes to the soil N supply can offset or reduce the amount of additional N fertilizers required for high cereal yields. It has been observed that Biological N_2 fixation from legumes can sustain tropical agriculture at moderate levels of output (Giller et al., 1997; Giller, 2001). According to Giller (2001), biological N_2-fixation can contribute as much as 300 kg N ha^{-1} in a season in grain legumes while Harris (1998) estimated nitrogen fixation by legumes to contribute up to 48 kg N ha^{-1} within individual fields, depending on the density of legumes in the field.

About 60% of the total N demand by a nodulating leguminous crop can be supplied through symbiotic N_2 fixation (Stoorvogel & Smaling, 1990). Several factors such as high cost have collectively limited N fertilizer use by subsistence and small-scale farmers throughout Africa. Consequently, most of the N required for agricultural productivity in the continent comes largely from a judicious management of biological N fixation mostly through cereal-legume intercropping systems. Due to this importance, biological N_2-fixation by legumes has been extensively researched as a potential source of N for many smallholder farming systems (Giller, 2001). It has substantially contributed to promotion and adoption of cereal-grain legume cropping systems either as intercrops or in rotation as a means of soil nitrogen enhancement strategy.

Even when legumes grow well, the contribution to soil fertility depends on the amount of N_2 fixed in relation to the amount removed from the system in the crop harvest, reflected in the N harvest index (Giller & Cadisch, 1995). Multi-purpose varieties of grain legumes such as cowpea and soybean produce a lot of biomass while still giving reasonable grain yields (Mpepereki et al., 2000). For an equivalent grain yield of 2 ton ha^{-1}, promiscuous soybean varieties can produce up to 150 kg N ha^{-1} in stover compared with new varieties that have about 40 kg N ha^{-1} in their stover (Sanginga et al., 2001). Sanginga et al., (2004) observed doubling in yields of maize grown after the promiscuous varieties compared to those of maize grown after the new varieties. Despite the benefits, the system is faced with various challenges such as inadequate soil moisture, soil fertility status, rhizobia inoculants production, quality, storage and distribution related issues that affect N_2 fixation of field legumes.

Biological N_2 fixation process is probably the cheapest and most effective tool for maintaining sustainable yields in African agriculture (Dakora & Keya, 1997). Therefore, there is need for comprehensive estimation of N balances of various leguminous crops to help guide their adoption and integration into legume-cereal rotation or intercrop systems.

3.3 Animal and farmyard manure

In SSA, animal and farm yard manure are important and frequently used resources to improve soil fertility. For instance, farmyard manure is common in central highlands of Kenya and has been estimated that more than 95% of smallholder farmers growing maize use it (Harris, 1998). Baijukya et al., (2005) reported that manure production in some farming systems was a major reason indicated by smallholder farmers for keeping cattle, whereas in other systems, such as arid areas of Zimbabwe, manure is a potential resource for nutrient recycling that is hardly used (Mapfumo and Giller, 2001). Studies have shown that use of manure can improve crop yields considerably (Lekasi et al., 1998). Crop yield responses to manure can be seen in crops for several years after application when the manure is supplied in sufficiently large amounts (Mugwira and Murwira, 1997).

On most farms, animal manure used is mainly from cattle (65%) with the rest coming from diverse sources such as sheep and goats (6%) and poultry (4%) (Lekasi et al., 2001). The amount and quality of manure available to a farmer depends on many factors: source, herd size and management system and seasonal climatic changes, which determine availability of feeds to livestock (Mugwira and Murwira, 1997). Given that external/free range grazing is the predominant livestock feeding system, the quality of manure with regard to nutrient release and crop uptake is mostly poor, posing a challenge to smallholder farmers. For instance, Dejager et al. (1998) reported an average N balance per head of different livestock activities where cattle in zero grazing system had 11 kg head$^{-1,}$ cattle in semi-grazing had 7 kg head$^{-1,}$ cattle in external grazing system had 3.7 kg head^{-1} while poultry had 0.2 kg head^{-1}. Also, Baijukya (2005) reported N as an inflow from cattle manure ranging from 0 to as high as 63 kg ha^{-1} yr^{-1} in a banana-based farming in Bukoba, Tanzania.

The variability in quality can also be attributed to management of manure produced (Mugwira and Murwira, 1997). For example, Lekasi et al. (1998) reported that when manure was stored in heaps or in pits until application, the buried manure had substantially greater contents of N. Similarly, Mugwira and Murwira (1997) reported that manures stored in pits had significantly higher N content compared to the manure stored in heaps. This could be due to large ammonia losses that occur throughout decomposition period, which was associated with alkaline conditions possibly due to mineralization of N and microbial NH_4^+ consumption under aerobic conditions. Quality of manure can be improved through provision of high quality feed such as calliandra and leucaena to animals and through proper management of manure (Delve, 2000). Such manure can provide substantial amounts of nutrients into the agro-ecosystem. For instance, in intensively managed smallholder farms in Kisii District of Kenya, application of manures to fields from cattle enclosures average 23 kg N ha^{-1}, or about one-third of total N inputs (Smaling, 1993).

Besides the soil fertility amelioration perspective, the contribution of manure in building up soil organic carbon (SOC), and total soil carbon stocks, is an important extra benefit of using manure as a soil amendment (Rufino et al., 2006). This is especially critical given that most SSA soils are inherently low in organic carbon (<20 to 30 mg/kg) due to: low root growth of crops and natural vegetation, continuous cultivation of crops and rapid turnover rates of organic materials with high soil temperature and microfauna (Bationo et al., 2006; Bationo et al., 1995). The loss of organic matter consequently results in soil acidity, nutrient imbalance and low crop yields (Ayoola et al. 2007). Based on field experiments, there are indications that additions of 5-10 t ha $^{-1}$ year $^{-1}$ of manure are sufficient to maintain SOC close to contents of soil under undisturbed savanna vegetation in West Africa (de Rouw and Rajot, 2004). In an experiment in Saria, Burkina Faso (Mando et al., 2005), additions of 2 tons of C ha^{-1} year $^{-1}$ to plots cropped with sorghum (Sorghum bicolor L.) and hand-hoed over a 10 year period resulted in a net increase of approximately 3.5 t ha^{-1} to the SOC pool.

Although manure is important for resource poor farmers in improving crop and soil productivity, drawbacks exists in its use as a sole source of nutrients for plants given that the quantities produced at farm level are more often inadequate to meet nutritional demands for various crop enterprises (Makokha et al., 2001). Integrated soil fertility management (ISFM) approach, which advocates for the combined use of organic residues and mineral fertilizers, has potential to resolve this practical limitation of input availability, and may also benefit crop-nutrient synchrony and nutrient loss reduction through interactive effects between both types of inputs (Gentile et al., 2009). High crop yield can be obtained with judicious and balanced inorganic fertilization combined with organic matter amendments (Palm et al., 1997).

There has been little research on manure handling and manure storage in Africa where most studies of soil N mineralization from manures comprise mainly laboratory incubations, with very few field experiments (Rufino et al., 2006). Limited research has been carried on the effects of manure on soil water retention and agricultural productivity. Potential benefits of animal and farmyard manure not only in improving soil fertility status but also boosting soil moisture retention, especially during dry spells, holds promise to address and correct water stress effects in smallholder farming systems.

3.4 Green manure

Green manures play a key role in providing subsequent crops with nutrients, maintaining soil quality, and helping to control weeds and pests (Krauss et al., 2010). Green manuring involves spreading plant material with high nitrogen content on fields and sometimes also working it into the soil (van der Werff et al., 1995). The most important features of a green manure are large dry matter production and high ability to fix nitrogen (Wivstad, 1997). Green manure can be used directly or after composting as a nutrient input that will, after decomposition, be taken up by crops to produce biomass and grain. The effectiveness of green manuring as a soil fertility management technology depends on the stage of crop during incorporation, placement (incorporated or surface placement), nutrient content and carbon to nitrogen ratio of material which influences decomposability and mineralization. Young and succulent plant materials tend to decompose at faster rate compared to materials from mature plants, while incorporation enhances mineralization relative to surface applied plant material. Using green manures from deep rooting perennial agro-forestry trees allows organic matter to be tapped and nutrients to be drawn from deeper levels of soil more than is possible from animal or annual plant manures (Larson 1996). For instance, use of Crotalaria as green manure has been found to improve productivity of maize-bean cropping systems in eastern Africa (Fischler et al., 1999).

As highlighted by Byerlee and Heisey (1992), green manures may not provide sufficient and balanced nutrients (such as phosphorus, potassium, etc) required by subsequent crop for improved productivity although they are a good source of nitrogen. The key to achieving the maximum benefit from green manure is synchronization of nutrient release from decomposing green manure with demands of subsequent crop. In addition to moisture, temperature and aeration of soil, rate of nutrient release from green manure debris is influenced by quantity, quality, placement and degree of incorporation into the soil (Fischler et al., 1999).

Herbaceous green manure legumes like mucuna grown specifically for soil fertility restoration have not been widely adopted by farmers in SSA. Lack of a direct usable food product is the principal disincentive in farmers readily adopting green manuring in most SSA farming systems. Given that green manures compete for land resources with other food crops, and do not contribute directly to income or food security (Snapp et al., 2002) and given that land is very limited, it pauses a challenge as this as this is a soil fertility management option that might not always or readily fit in farmers cropping cycles. A potentially practical solution to this challenge is utilization of alternative plants such as using water hyacinths. Gunnarsson and Petersen (2007) in a review entitled "water hyacinths as a resource in agriculture and energy production" concluded that dried water hyacinths was a feasible alternative as green manure in many developing countries since hyacinths can be rich in nitrogen, have up to 3.2% of dry matter and have a carbon to nitrogen (C/N) ratio of about 15. Chemical analyses have indicated a high nutrient content of water hyacinth, 20% crude protein and very high dry matter production (Abdelhamid and Gabr, 1991), making water hyacinth a potentially suitable alternative to traditional green manure crops.

3.5 Agroforestry trees

Agroforestry is a soil fertility enhancement system that combines agricultural and tree crops of varying longevity, arranged either temporally or spatially, to maximize and sustain agricultural yield and minimize degradation of soil and water resources (Lal, 1990). According to Nair (1989), agroforestry can be classified into various systems and practices such as: (i) agrisilvicultural system characterized by improved fallows, biomass transfer, the taungya/shamba system, hedgerow intercropping, tree gardens, trees/shrubs on farmlands, shelterbelts, soil conservation hedges, (ii) silvopastoral systems involving cut and carry fodder banks, live fences of fodder trees and hedges, trees and shrubs on pasture land, and (iii) agrosilvopastoral systems comprising of woody hedges for browse mulch, green manure and soil conservation among other systems such as apiculture, aqua-forestry etc. Ecological interactions between trees and crops in agroforestry system are beneficial because: leguminous trees have a beneficial effect on soil fertility through nitrogen fixation, greater organic matter production, and recycling of nutrients, a combination of annual crops and trees increases biomass production because differences in rooting depth enable uptake of more water and nutrients (Young, 1986). Finally, agroforestry trees act as a protective barrier against soil erosion and as windbreaks.

The most common agroforestry systems in most smallholder farms in SSA were designed for soil improvement, particularly for nutrient recycling and as a nutrient source for cropland. Among those that have received the most attention are alley cropping, improved fallows and biomass transfer.

3.5.1 Alley cropping

Alley cropping is an agro-forestry practice in which perennial crops are grown simultaneously with an arable crop (Alary et al., 2007). The perennial crops provide ecosystem functions (food production, nutrient cycling, erosion control, water conservation, habitats for other biota, etc.) The harvested aboveground biomass is either incorporated into the soil or applied as mulch on the soil surface. The potential of alley cropping to improve yields depends on the nutrients added or recycled through hedgerows if the local constraint is nutrient supply, and on the ability to retain soil water by increased infiltration and reducing runoff if the crop production is constrained by water availability (Mathuva et al., 1998). Alley farming has been successfully demonstrated in Benin and produced best yield, compared to annual legume cover planting and maize groundnut rotational farming (Versteeg et al., 1998). Shisanya et al (2009) in their study on the "effect of organic and inorganic nutrient sources on soil mineral nitrogen and maize yields in central highlands of Kenya" recommended that farmers in the area should be encouraged to incorporate non-competitive fast growing trees in their farming systems that would assist in 'capturing' the leached nutrients and recycling them back to the system. The net benefit of the system to crop production is however determined by the extent of competition between hedges and crops and by potential improvements in soil nutrient and water status (Mathuva et al., 1998).

3.5.2 Improved fallows

Traditionally, farmers have relied on long fallow periods to replenish the soil fertility depleted through cropping, but due to declining farm sizes, increase in human and animal population and land-use pressure, fallows have been reduced both in length and area or even abandoned in many farming systems (Kaya et al. 2000). In order to overcome the limitations and still enjoy benefits of natural fallows, improved fallows have been designed to achieve the same results as natural fallows in shorter time periods through purposeful selection and management of leguminous plants. Improved fallows are the deliberate planting of fast-growing trees, shrubs, and herbaceous legume species for rapid replenishment of soil fertility (Sanchez, 1999). Unlike the natural grass and bushy fallows, improved fallows consist of deliberately planted species, usually legumes, with the primary purpose of fixing nitrogen as part of a crop-fallow rotation (Sanchez, 1999). Short rotation improved fallows using various leguminous crops have been shown to replenish soil fertility (Kwesiga et al., 1999). Such crops include: sesbania (*Sesbania sesban*), pigeon pea (*Cajanus cajan*), tephrosia (*Tephrosia vogelii*), gliricidia (*Gliricidia sepium*) and Leucaena (*Leucaena leucocephala*) (Mafongoya & Dzowela, 1999) and increase agricultural productivity. Several studies in SSA countries have evaluated and ascertained the potentials of improved fallows for soil fertility replenishment (Palm and Sanchez, 1991; Mugendi and Nair, 1997). Legume fallow technologies improve nutrient cycling by enhancing availability of nutrients resulting from production and decomposition of substantial quantities of biomass, and deep roots of planted trees or shrubs acting as “safety nets” for nutrients, reducing leaching losses (van Noordwijk et al., 1996). Leguminous fallows accumulate nitrogen in the biomass, recycle other nutrients in the soil, and smother weeds (De Rouw, 1995). On nutrient-deficient sites, additional nitrogen, phosphorus and potassium supply from leguminous biomass may markedly improve crop vigour and resistance to pests and diseases (Schroth et al., 2000). For example, in southern Benin, improved tree fallow of *Acacia auriculiformis,* and a short season fallow of mucuna *(Mucuna puriens*) have been successfully applied to address soil fertility problems (Versteeg et al., 1998).

Merits of improved fallows include the diversity of farm sizes where improved fallows are used, the advantage of sequential versus simultaneous systems, the ability of fallow crops to grow during dry seasons that are unfavourable for crop production, the comparative advantages of woody versus herbaceous leguminous fallows, the magnitude of N accumulation, and the strategic use of N fertilizers. Other key services provided by fallows include fuel wood production, recycling of other nutrients besides N, provision of a C supply to soil microorganisms, weed suppression, Striga control, and improved soil water storage (Sanchez, 1999). Total farm production can be greater with improved fallow-crop rotations than with continuous cropping even though crop production is skipped for one or more seasons with improved fallows (Sanchez & Leakey, 1997). This is especially true for low input, family-based smallholder farming systems that are characterized by limited resources, technology and information, and rely on subsistence rather than producing surpluses for market. Although the overall productivity might be equal or slightly lower than that achievable with inorganic fertilizers, the improved fallow strategy is still a feasible option to resource poor smallholder farmers who operate in fragile environment where their integrated activities are strongly constrained by socioeconomic, biophysical and institutional factors.

Although large yield responses by subsequent crop have been reported after 9 to 18 months of improved monoculture-species fallows, with substantial residual benefits for the following crops (Jama et al., 1998), efficiency of improved fallows can be further enhanced through mixing species of leguminous plants. For example, mixed-species of improved legume fallows have potential to provide maize yields comparable or even above those obtained with 100 kg N ha^{-1} of mineral N fertilizer for at least two cropping season (Ndufa et al., 2009). Sileshi and Mafongoya (2003) recommend the use of mixed-species fallows of sesbania, pigeon pea and tephrosia for improvement of maize production in areas with nutrient-deficient soils in Zambia rather than crotalaria (*Crotalaria grahamiana*) (monocrop) fallows. Furthermore, mixing high quality fallow residues with polyphenol-rich legume material (e.g., from calliandra) may also result in the formation of complexes with proteins and carbohydrates that are resistant to microbial degradation (Handayanto et al., 1997) and hence increase soil organic matter and long-term benefits of such systems (Cadisch and Giller, 2001). The increased soil organic matter can improve soil physical conditions, root development and thereby the water and nutrient status of subsequent crops (Mafongoya and Dzowela, 1999; Chirwa et al., 2002). According to Sanchez (1999), the main limiting factor in the spread/adoption of improved fallows in Africa is the supply of germplasm of improved fallow species and accessions that must be overcome through seed orchards and nursery development before large scale impact on soil fertility is realized.

3.5.3 Biomass transfer

Biomass transfer is one of the nutrient source input in smallholder farms in SSA although it is an internal flow in the nutrient balance and flow. This technology involves ex-situ production of biomass away from the cropping land in designated areas, such as hedges around or within the farm. The biomass is then harvested, transferred to cropping land and applied as mulch or incorporated into the soil before and/or after the crop is planted. In this technology, interaction between the components is only through the nutrient release from applied mulch and uptake by crop. Research on biomass transfer is done mainly by scientists with interest in agroforestry tree species. Studies have been conducted in many countries in Africa (Mugendi et al., 2004). Some of the plant species that have been used for biomass transfer include *Tithonia diversifolia, Calliandra calothyrsus*, *Leucaena trichandra* and *Sesbania sesban.* For instance, tithonia applied at 5 t ha^{-1} on a dry weight basis contains about 60 kg N ha^{-1} (Gachengo, 1996). Jama et al. (1999) reported an average of 3.5% N in green biomass of tithonia on a dry matter basis. This coupled with its ease of decomposition and releases of nutrients make it an important source of N for crops. Leguminous trees like calliandra and leucaena have also been widely used as a source of nutrients, with positive results on crop yields (Mugwe et al., 2009). These trees produce high amounts of biomass (Delve et al., 2000). Biomass transfer offer opportunities on increasing production due to increased nutrients but, except for N_2 fixing trees, it is usually not an addition to the farm unit. It is a matter of transferring N from one part of the farm to the other.

3.6 Integrated Soil Fertility Management

Integrated Soil Fertility Management (ISFM) refers to making the best use of inherent soil nutrient stocks, locally available soil amendments (for instance, crop residues, compost, animal manure, green manure), and inorganic fertilisers to increase productivity while maintaining or enhancing the agricultural resource base (IFDC, 2003; TSBF, 2003). It is a holistic approach to soil fertility research that embraces the full range of driving factors and consequences; biological, physical, chemical, social, economic and political, of soil degradation (Barrios et al. 2006). Strategically targeted fertilizer use together with organic nutrient resources to ensure fertilizer use efficiency and crop productivity at farm scale are basic principles of ISFM (Vanlauwe and Giller, 2006). Although ISFM recognizes the absolute necessity of mineral fertilizer use (Vanlauwe et al., 2010), it advocates the best combination of available nutrient management technologies that are economically profitable and socially acceptable to different categories of farmers (Vanlauwe, 2004). It is rapidly becoming more accepted by development and extension programs in SSA, and, most importantly, by small-holder farmers (Place et al., 2003). Beneficial effects of ISFM on soil fertility have been shown to increase nutrient use efficiency associated with combined nutritional and non-nutritional effects of organic and inorganic inputs compared to inorganic fertilizer applied alone (Fofana et al., 2005; Wopereis et al., 2005). ISFM is a market-led technology build on the hypothesis that better market opportunities provide incentives for farmers to invest in the technologies (Sanginga et al., 2007). This market-led hypothesis is increasingly becoming a key pillar not only in ISFM research (TSBF, 2005) but also other areas of integrated agricultural research for development (Sanginga et al., 2007). It is about expanding the choice set of farmers by increasing their awareness of the variety of options available and how they may complement or substitute for one another (Place et al. 2003).

Effectiveness and beneficial effects of ISFM practices are likely to differ from place to place in Sub-Saharan Africa, due to the many heterogeneous agroecological zones in the region (Kato & Place, 2011). Available reviews on effects (Place et al. 2003) are mixed and inconclusive given that limited empirical evidence exists on the potential of ISFM for improving yields and profitability that can be used to support the arguments for use of ISFM as an alternative to high doses of fertilizers to maintain favourable nutrient balances and soil quality (World Bank, 2007).

In spite of development and availability of excellent methods, technologies and a wide range of tools, large scale adoption of ISFM remains a hurdle (Pound et al., 2003). Challenges in implementation of ISFM technologies include differing perceptions between farmers', needs and research which is limited due to time constraints and other resources (Misiko & Ramisch 2007). For instance, the farmers' immediate need for food might override perceived long-term soil fertility benefits associated with ISFM. There is also complexity of diversity in different farm situations relative to adaptive methods. Problems are inherent in the fact that broader use of ISFM concepts requires scaling up of knowledge itself, which is not the case with the spread of more simple technologies or goods (Misiko & Ramisch 2007). This calls for intensive training of farmer and extension service providers on the principles of ISFM, innovation and experimentation to tailor generic management technologies to diverse prevailing local conditions.

4. Challenges in utilization of organic and inorganic nutrient sources

Overall growth in agricultural research investments in Africa has effectively stagnated over the past two decades (Beintema & Stads, 2006). This among other major impediments to improved soil fertility management in the SSA include low levels of farmers' human, physical and financial capitals, low agricultural commodity prices relative to fertilizer and other input prices, lack of pro-agriculture policies, and the failure to view the maintenance of soil fertility as an important public good (Smaling and Dixon, 2006).

4.1 Low external nutrient strategies

Organic fertilizers will continue to play an important role in maintaining soil structure, moisture control, and nutrient levels, yet under farm conditions, they cannot supply all of the additional nutrients needed to sustain rapid yield growth (Larson and Frisvold, 1996) and are mostly labour intensive. Use of livestock manure to replenish nutrients for agricultural production is a land-extensive production method. About 23 ha of pasture per 1 ha of cropland would be needed in the Sahel to produce enough manure just to maintain, but not improve upon, current levels of soil fertility (Speirs and Olsen, 1992). This level of manure production may be unrealistic in SSA. Adverse effects of deforestation and increased demand for land limit the possibility of extending various agroforestry systems, such as improved fallows and alley cropping, in densely populated areas. These concerns, coupled with the continuous nutrient depletion and low soil fertility, have led to the development of ISFM technologies that offer potential for improving soil fertility in Africa (Scoones and Toulmin, 1998). The ISFM approach advocates for the combined use of organic residues and mineral fertilizers, which may resolve the practical limitation of input availability, and may also benefit crop N synchrony and N loss reduction through interactive effects between both types of inputs (Gentile et al., 2009). High crop yield can be obtained with judicious and balanced inorganic fertilization combined with organic amendments (Palm et. al., 1997). Donovan and Casey (1998) showed that technologies that combine mineral fertilizers with organic nutrient sources can be considered as better options in increasing fertilizer use efficiency, and providing a more balanced supply of nutrients. More specifically, Mugendi et al. (1999) reported higher crop yields in Leucaena biomass combined with mineral fertilizer treatment compared to sole use of mineral fertilizer or sole leucaena biomass.

4.2 Environmental considerations

Excessive fertilizer use, whether organic or inorganic, can create environmental problems associated with leaching of nitrogen into groundwater and deposition of phosphorous in surface waters through soil erosion (Larson, 1996), especially in regions with continuous high levels of fertilizer applications (often over 200 kg/ha) and large livestock operations. Over-intensification is not a widespread problem in SSA and will not become one; rather, future predictions indicate that the main environmental concerns in agriculture in sub-Saharan Africa will stem from the lack of intensification (Larson, 1996). Bationo et al. (2006) argues that, whereas in the developed world, excess applications of fertilizer and manure have damaged the environment, the low use of inorganic fertilizer is one of the main causes for environmental degradation in Africa. They advocate for increased inorganic fertilizer use which will, in addition to increased productivity, benefit the environment by reducing the pressure to convert forests and other fragile lands to agricultural uses and, by increasing biomass production, helps increase soil organic carbon content. Past studies document that simple physical availability of fertilizers to farmers, in the appropriate quantity, packages and at the appropriate time of year, remains a main constraint on increased fertilizer use in SSA (Larson and Frisvold, 1996). A strategic approach recognizes that a large number of technical, social, environmental, and market conditions must be met to achieve sustained agricultural growth at a national or regional level.

5. Policies

Population growth, the limited land for extensive agricultural production and the reduced external aid to agriculture now calls for governments to better utilize the continent's internal resources for intensification (Bekunda, 2010). This calls for enactment of enabling and conducive policies that will promote the use of both organic and inorganic inputs. For example, Sanginga and Woomer (2009) explain that policies supporting traditional rights to free grazing contradict the establishment of land tenure and increasing land use intensification with ISFM. Communal rather than freehold land tenure systems in most semi-arid regions and other areas with low agricultural potential in SSA countries also inhibit adoption of organic and inorganic inputs.

It is apparent that, for a successful "African Green Revolution" soil health needs to be restored, through agroforestry techniques and use of organic and mineral fertilizers among other solutions. As pointed out earlier, low levels of inorganic fertilizer use is one of the major cause of soil fertility depletion. This calls for deliberate efforts, policies and legislations that will boost the use inorganic inputs at farm level. Therefore, a policy objective for SSA should be to increase fertilizer application rates significantly. It is necessary to increase average application rates of inorganic fertilizer to around 50 kg/ha, which would provide the foundation for further sustained agricultural growth.

Because of high price of imported fertilizers at farm gate, most small holder farmers, although aware of benefits of nitrogenous fertilizers, cannot afford cost of standard 50 kg bag of fertilizer. While there is no immediate substitute for nutrient supplied by inorganic fertilizer, there is need to improve the access and efficiency of its use.

Inorganic fertilizer demand can significantly improve, if a lower cost effective means of getting many small bags of fertilizer to farmer's doorstep were found. With good technical training and access to credit to maintain stocks, local retailers can stimulate inorganic fertilizer demand (FAO, 2007). In a number of countries, including Malawi, Nigeria, and Zambia, retailers repackage fertilizer into smaller packs, for which they typically charge a premium of 14–15 percent (World Bank, 2007). In Zimbabwe, agro-dealers retailers are encouraged to repackage fertilizers in smaller amounts that are less financially daunting to farmers (World Agroforestry Centre, 2008). This encourages farmers to use small amounts of fertilizers to increase production rather than being turned off completely by high cost of bulky and expensive packaged fertilizers. Although adding value for the retailers and improving convenience for small-scale farmers, this practice adds to already high retail prices. There have been a variety of success stories in this area since market reforms were introduced, mostly associated with selling fertilizers in small packages. For these "small-pack" programmes to be successful, governments and manufacturers often need to change legislation or company rules that prohibit breaking down larger packages (World Bank, 2007). For instance, Kenya repealed a law in the early 1990s that prohibited sales of fertilizer in less than 50 kg bags; by 1996, 46% of fertilizer sales to smallholders were in 10 kg bags (Kelly et al., 2003). Authorized re-bagging raises the issue of quality control. Re-bagging increases the possibility for both intentional and unintentional adulteration at the retail level, yet most verification of fertilizer quality tends to be done much higher up the supply chain. Part of the wide fluctuations in the nutrient concentration (quality) in fertilizers can be accounted for by the absence of effective measurement, quality control and calibration facilities at the retail level.

Regulations relating to the chemical composition of fertilizer are important to deter product adulteration, which can easily happen when fertilizer is re-bagged than it is with sales of standard 50 kg sacks. This calls for appropriate introduction of regulations establishing clearly defined assay standards for a standardized and limited set of fertilizers, as well as penalties for distributors whose products do not conform to those standards. Because regulations are meaningless if they cannot be enforced, the introduction of product quality controls will often need to be accompanied by supporting investments in facilities for carrying out rapid, low-cost testing (World Bank, 2007). It also calls for: regular inspection of fertilizer at all stages of the marketing chain, compound fertilizers formulations to meet location-specific plant nitrogen requirements, fertilizer pack sizes adapted to local needs and information on packaging in local languages. In the long run, farmers in all countries need to acquire the skills to evaluate their own situation and make informed judgments about the most appropriate doses and combinations of inputs; this implies significant improvements in basic education as well as in extension.

6. Conclusions and recommendations

Maintaining soil quality and improving yields in SSA calls for conscious moves. First, external sources of inorganic fertilizers and seed-fertilizer technologies play a major role and could also lead to steady yield increases in rain-fed agriculture. Another approach is to make better use of organic fertilizer sources and adopting low-input strategies such as improved crop rotations to maintain internal recycling of nutrients and soil fertility. These approaches are not mutually exclusive as each has its merits and limitations, therefore the best strategy would be to combine them subject to local economic and environmental circumstances. Additionally, fertilizers remain a key element for sustained agricultural development in SSA. It is apparent that inorganic fertilizers are a prerequisite for sustained growth, but not just a simple solution. Other changes in the production and policy environment, education levels, such as seeds, water management, pest control, land tenure, taxes and regulations, are also required. However, without adequate fertilizers, returns from these other changes will be small and unsustainable.

Sustainability of agroforestry systems is challenge that needs to be addressed by evaluation of productivity from long-term experiments in relation to evolution of soil properties and environmental quality. Although combining various organic and inorganic inputs improves agricultural productivity and soil physical properties, their interactive effects with soil moisture especially during dry spells needs to be further researched, not only in the light of soil fertility replenishment but also as a potential means of mitigating low soil water availability to alleviate water stress effects in smallholder farming systems.

Replenishing soil fertility in SSA is paramount in the quest of food security. It is a necessary but not sufficient condition, and must be pursued in tandem with policies that may involve: new legislation and their enforcement, improving health, education, governance, infrastructure, improving market information systems, offering attractive credit schemes, or generally becoming more enabling, allowing land users to produce in a more profitable and environmentally benign way (UN Millennium Project, 2005), and trade. It may also require policy change at the global level, especially at international trade level, allowing SSA to be part of global sustainable development by developing policies that reduce the disparity between the world market and the prices paid by African farmers for mineral fertilizers.

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