Integrated Management of Soil Fertility and Land Resources in Sub-Saharan Africa: Involving Local Communities

Vincent B. Bado[*,1], **André Bationo**[†]
[*]International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), West and Central Africa, Niamey, Niger
[†]International Center for Research on Soil Fertility and Agricultural Development (IFDC), Accra, Ghana
[1]Corresponding author: e-mail address: v.bado@cgiar.org

Contents

Advances in Agronomy
ISSN 0065-2113
https://doi.org/10.1016/bs.agron.2018.02.001

Abstract

The soils of sub-Saharan Africa are characterized by their poverty in nutrients along with low clay and organic carbon content and low exchange capacity. There is high pressure on land resources with the quick growth of population and demand for food. Maintaining the fertility of cultivated soils and land resources is a challenge. Since the paradigm of "external input" in the 1960s and 1970s, to the latest concept of integrated soil fertility management, most of the approaches remain crop oriented or livestock oriented with less attention to local communities (LC), which are at the heart of land resource management. This chapter suggests a new integrated and holistic approach involving LC for land resources management, including cultivated soils and rangelands. A global framework is proposed for development of management options of land resources with LC. It is a dynamic process of participative management of lands as providers of services for the entire community.

1. INTRODUCTION

In the context of food insecurity, rural poverty, and climate change in sub-Saharan Africa (SSA), the protection and sustainable management of soil and land resources are of paramount importance (Dewitte et al., 2013; Gisladottir and Stocking, 2005; Palm et al., 2007, 2010; Vlek et al., 2008). The African heads of state in 2001 declared that improved agricultural performance is a prerequisite of economic development, thereby highlighting the need for agriculture-led development in reducing hunger and poverty, generating economic growth, and reducing the burden of food imports (Bekunda et al., 2010). However, the importance of soil and land resources and the multitude of environmental services they provide are not widely appreciated by society (Dewitte et al., 2013). Rural communities, policy makers, land managers, and other keys actors and beneficiaries are inadequately engaged in management strategies of these important resources (Bouma et al., 2012; Dewitte et al., 2013; Hartemink and McBratney, 2008). Soil degradation in its diverse form is a persistent problem throughout Africa. The degradation of land resources is a major development issue and is often ignored because the observed impacts are gradual (Dewitte et al., 2013; Gisladottir and Stocking, 2005; Vlek et al., 2008).

The soils of SSA are poor in nutrients with low organic carbon (OC), clay contents, and exchange capacity (EC). It is estimated that more than 70% of African soils are inadequately fertile or depredated by agricultural practices, human, and animal pressure (Bationo et al., 2006). Many technologies and concepts have been developed over the years to improve soil fertility. More experiences have been made, mainly for cultivated soils. The paradigm of "external input" of the 1960s and 1970s focusing on fertilizers associated with improved cereal germplasm has certainly boosted agricultural production in Asia and Latin America in the form of the first "Green Revolution." However, the paradigm of external inputs did not start a "Green Revolution" in Africa, primarily because of high fertilizer costs (Smaling, 1993). The low external input sustainable agriculture (LEISA) approach of the 1990s considered the importance of organic resources, while the concept of integrated nutrient management (INM) combined organic and mineral fertilizers (Vanlauwe, 2004). These approaches have been more successful as farmers are able to afford mineral fertilizers.

The mid-1980s to the mid-1990s saw a shift in paradigm toward the combined use of organic and mineral inputs accompanied by a shift in approaches. This shift was driven by the "participatory" movement, which emphasized on involving various stakeholders in the process of research and development.

Considering that farmers' decision-making process is not merely driven by soil and climate but by a large set of factors cutting across the biophysical, socioeconomic, and political domain, the integrated natural resource management (INRM) approach was developed (Izac, 2000). The integrated soil fertility management (ISFM) approach was later developed with a focus on appropriate management of soil resources (Vanlauwe, 2004).

However, an important dilemma of sustainable soil fertility management is the growing demand for lands with rapid growth of population. Overgrazing of pasturelands and failure of smallholder farmers to apply fertilizers on cultivated soils, results in over exportation of nutrients. At the same time, soil erosion increases with the declining biomass and grass cover, resulting in soil fertility loss, land degradation, and desertification (FAO, 1991).

Biomass reduction and growth of annual and unpalatable species are the main indicators of aridification and pasture degradation through overgrazing in arid and semiarid regions (Holechek et al., 1999; Kiage, 2013; Mwendera et al., 1997; Penning De Vries and Djiteye, 1982; Savadogo et al., 2008). Poor soil quality, declining soil fertility with cropping activities, overgrazing and erosion, exhaustion of lands resources, increasing demand of food are the root causes of land degradation and deforestation (Kiage, 2013).

In general, rangelands are open areas for communal and unrestricted grazing which degrades vegetation and soils (Milchunas and Lauenroth, 1993; Teague and Barnes, 2017), declines productivity, and reduces the resilience of the ecosystem (Frank et al., 1998; Peterson et al., 1998). Sustainable management of rangelands will become increasingly important as the climate changes, yet rangeland dynamics are still a challenge to dryland ecologists. Breaking this vicious cycle for sustainable management of both cultivated soils and rangelands requires global, holistic, and integrated approaches.

Efficient management of soil fertility and land should be innovative and integrate individual fields of farmers and the farming systems at the community level.

The big challenge is to manage both cultivated soils and land resources under human and animal pressure in a global approach.

Increasing demand for food and land and incapacity of farmers to afford new technologies results in land degradation, deforestation, and desertification. Few approaches have really tackled this vicious cycle.

In the context of rapid demographic changes, few approaches have explored alternative farming systems along with the dynamic aspects of farming systems (Giller et al., 2011), availability and constraints for access to technologies, the social, institutional, and political environment.

This chapter reviews the main constraints of soils in SSA and the concepts and paradigms of soil fertility management over the last 50 years. The chapter discusses an alternative participatory approach to develop smart strategies and options for land resources management. This approach has a global vision which includes local communities (LC) as main actors and beneficiaries.

2. STATUS OF SOIL FERTILITY AND CONSTRAINTS

The African continent is covered by highly diverse soils with diverse physical, chemical, and agronomic characteristics. The soil patterns in the five major agroecological zones are determined by differences in age, parent material, physiography, and present and past climatic conditions. Bationo et al. (2006) summarized the main characteristics and constraints of the soils in SSA (Table 1); which are mainly: the poverty of parent material in nutrients and OC, low clay contents, and EC. Around 40% of African soils have low nutrient capital reserves, 25% have aluminum toxicity, 18% have high leaching potential, and 9% have high P-fixation capacity (Yanggen et al., 1998). The most important part of the soils in SSA (56%) are characterized as "acid infertile soils" (Oxisols and Ultisols in USDA Soil Taxonomy), 16% as "very infertile sandy soils" (Psamments), 12% as "poorly drained soils" (Aquepts), and 12% as "moderately fertile and well-drained soils" (Alfisols, Vertisols, Mollisols, Andepts, Tropepts, and Fluvents) (Brady, 1990).

Table 1 Soil Types, Extent and Constraints, in Sub-Saharan Africa

Soil Type	Percentage Total Land (%)	Main Constraints	Main Countries Covered
Andosol Nitosols	3.8	Fertile (volcanic ash), high P-fixation, Mn toxicity, medium water, and nutrient retention	Rift valley (Ethiopia, Kenya, Tanzania, and Zaire)
Vertisols	3.2	Heavy soils, medium mineral reserves, erodibility, and flooding	Sudan, Ethiopia, South Africa, and Lesotho
Ferrasols Acrisols	16.2	Low nutrient content, weathered, Al and Mn toxicity, high P-fixation, low nutrient and water retention, and susceptible to erosion	DRC, Angola, Zambia, Rwanda, Burundi, Uganda, Sudan, Central African Republic, Cameroon, Liberia, Sierra Leone, Madagascar, and Sub-humid zone of West Africa
Fluvisols, Gleysols Histosols	4.3	Poor to moderate drainage	West, Central, and southern Africa
Ferric Plintic Luvisols	5.8	Low nutrient content	Western and southern Africa
Regosols, Arenosols Podzols	18.7	Mainly quartz, low water, and nutrient holding capacity, wind erosion, and poor soils with nutrient leaching	West Africa/Sahel, Sudan, Botswana, Angola and DRC, and North Africa
Lithosols, Xerosols Yermosols, Solonchaks, Solonetz miscellaneous land units	40.3	Shallow soils subject to drought presence of salt	North African countries, South Africa, Namibia, Somalia, and Sahel
Inland water bodies	0.9	Flood zones	

Source: Bationo, A., Hartemink, A., Lungu, O., Naimi, M., Okoth, P., Smaling, E., Thiombiano, L., 2006. African soils: their productivity and profitability of fertilizer use. Background paper prepared for the African Fertilizer Summit. June 9–13, 2006. Abuja, Nigeria, pp. 25.

Uncultivated soils have natural fertility determined by soil-forming factors such as parent material, climate, and hydrology. For soils under natural vegetation, there is a virtual equilibrium, but as soon as the land is altered through clearing of natural vegetation, this equilibrium is broken. Under the hot climate of SSA, soil organic carbon (SOC) decreases quickly as a result of high soil temperatures and fauna activity particularly termites. The low soil clay content leads to decrease in EC, nutrient availability, and acidification. The removal of soil nutrients without replacement by fertilizer or recycling of crop residues (CRs) leads to quick decline in soil fertility (Bado et al., 1997; Bationo et al., 2007; Bostick et al., 2007; Pichot et al., 1981; Smaling, 1995; Woomer et al., 1994).

3. LAND DEGRADATION

Land degradation is defined by FAO (2000) as the loss of production capacity of land in terms of loss of soil fertility, soil biodiversity, and degradation of natural resources. Land degradation is caused by soil water erosion (46%), wind erosion (36%), loss of nutrients (9%), physical deterioration (4%), and salinization (3%). Overgrazing (49%) followed by agricultural activities (24%), deforestation (14%), and overexploitation of vegetative cover (13%) are the primary causes of land degradation in rural areas (Dunstan et al., 2004). Land degradation is the most serious threat to food production, food security, and natural resource conservation in Africa, particularly for the poor and vulnerable population of the drylands (UNDP/GEF, 2004). About 73% of the African drylands are degraded and 51% are severely degraded (Dregne and Chou, 1992). At least 485 million Africans are affected by land degradation which is a widespread problem that affects soils, landscapes, and human welfare (Thiombiano, 2000). The main causes of land degradation are: human population growth, poor soil management, deforestation, insecurity in land tenure, variation of climatic conditions, and intrinsic characteristics of fragile soils in diverse agroecological zones of SSA (Bationo et al., 2006).

3.1 Cropping Activities

The UNDP estimated that $42 billion in income and 6 million ha of productive land are lost every year due to land degradation (UNDP/GEF, 2004). According to the FAO, between 2000 and 2005, the net loss of forests in Africa exceeds 4 million ha/year due to conversion of forestlands to agriculture (Bationo et al., 2006). Yield losses due to land degradation in Africa range from 2% decline over several decades to a catastrophic level of 50% (Scherr, 1999). The combined effect of cropping activities and soil erosion lead to soil fertility depletion estimated at an average of 660 kg N ha^{-1}, 75 kg P ha^{-1}, and 450 kg K ha^{-1} from about 200 million ha of cultivated land in 37 African countries during the last 30 years (Bationo et al., 2006; Sanchez et al., 1997). Stoorvogel et al. (1993) estimated annual net depletion of nutrients in excess of 30 kg N and 20 kg K per ha of arable land per year in Ethiopia, Kenya, Malawi, Nigeria, Rwanda, and Zimbabwe. It is estimated that since the 1950s, Africa has lost about 20% of its soil productivity due to degradation (Dregne, 1990).

3.2 Grazing Activities

Rangelands cover more of Earth's land surface than any other type of land and as a common resource; they are mainly used for animal breeding. The traditional livestock breeding was mainly based on feed sourced from communal rangelands. However, the carrying capacities of communal rangelands are drastically decreasing due to human and animal population growth and the increasing demand for animal products. The decrease of communal rangelands is estimated at 15% over the past 30 years (Ayantunde et al., 2007). In response, pastoralists are creating new ways to manage rangelands through conservancies and community-based institutions on state, common, and private land. In Ethiopia, drought, aridity, and rangeland degradation have increased over time due to environmental degradation and mismanagement of rangeland resources. Traditional coping mechanisms are failing due to increasing environmental and rangeland degradation and lack of national policies to address these issues. Land resources available for farming are now fully used in several African countries. There is growing concern about the capability of land to feed the future projected population. As most African rangelands are now stocked at or above grazing capacity, Holechek et al. (1999) suggested maintaining "migration corridors," providing legal rights to historic grazing lands, and providing support services along migration corridors such as: watering points, markets, schools, and health as strategies to sustain pastoralism. Feed shortage (both quantity and quality), particularly in the dry season is a major constraint in achieving higher benefits from livestock production. Along with a decrease of feed sourced from communal rangelands, traditional approaches largely based on rangelands for livestock production can no longer sustain the production systems. The contribution of CRs to livestock nutrition has significantly increased, accounting for up to 50% of ruminant diets in the dryland areas (Ayantunde et al., 2007). Teagu and Barnes (2017) suggested that future research can provide better understanding of how grazing management can improve socioecological resilience in grazing ecosystems, while avoiding unintended consequences of possible management options, by involving realistic scale and context, partnering with innovative land managers on real operations, applying adaptive treatments, and combining field studies with modeling approaches.

4. MANAGING SOIL FERTILITY, TECHNOLOGIES, AND CONCEPTS

The development of technologies and concepts of land resources management have targeted the improvement of the production capacity of cultivated soils. Most of the time, the management strategies of rangeland are focused on measures of seasonal and special organization of communal grazing areas. The paradigm of "external input" of the 1960s has led the development of technologies to improve the productivity of cultivated soils. The types, techniques, and doses of mineral on organic fertilizers guided the development of recommendations to improve soil fertility. Organic and mineral fertilizers, agromineral resources such as rock phosphates, dolomite have been used as sources of nutrients. The agronomic efficiency of nutrients from each source depends not only on the soil type, biophysical and climatic factors but also on the management strategies and the social, economical, and environmental realities of farmers.

4.1 Mineral Fertilizers

As nutrient deficiencies, particularly nitrogen (N) and phosphorous (P) are the main constraints of soils in SSA, the beneficial impact of fertilizer applications on soil fertility and yield improvement are widely demonstrated (Bado et al., 2010; Bationo et al., 2003; Formoso, 1999; Giko and Smithson, 2003; Pichot et al., 1981; Pieri, 1989). For example, pearl millet yield could be increased by 376% by adding 13 kg P ha^{-1}. The combined application of N and P increases pearl millet yield by 600% on the degraded soils of West Africa Sahel (Bationo et al., 2006).

However, the efficiency of fertilizer nutrients varies with soil types and ecologies. For instance, while N deficiency is the most limiting factor than P in the humid forest zones (Sahrawat, 2004), P deficiency is more important in the savannah zones, the savanna-forest transition zones, and the arid and semiarid zones (Bationo et al., 2006).

In general, farmers are knowledgeable about the positive impact of mineral fertilizers on improving soil fertility. Nevertheless, there are factors influencing farmer's attitude that go beyond their control, for example, the availability of fertilizer in local markets (Enyong et al., 1999).

The applications of mineral fertilizers are limited mainly because of their high cost, land tenure, inefficient distribution systems, poor policies on agricultural production, and marketing support (Zapata and Roy, 2004).

However, data from many long-term experiments in upland soils reveal yield declines over time as a consequence of decreasing SOC, soil acidification, and decreasing nutrient use efficiency (Bado et al., 1997; Bationo, 2008; Bationo and Mokwunye, 1991; Pichot et al., 1981; Pieri, 1989).

In many cases, liming is frequently required to neutralize soil acidity induced by the continuous application of mineral fertilizer (Fig. 1) (Bado et al., 1997; Bationo et al., 2012). As an alternative to mineral fertilizer, the combined application of mineral fertilizers and organic amendments are more effective options for sustainable management of soil fertility. This is accomplished by delaying the decline of SOC (Bado et al., 1997; Bationo, 2008; Bationo and Mokwunye, 1991; Pichot et al., 1981). Based on the important

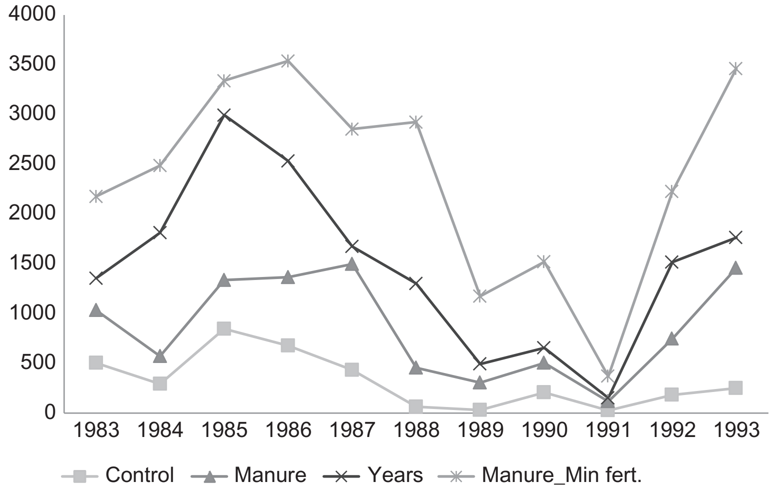

Fig. 1 Effect of long-term application of organic manure (5 ton ha^{-1} every 2 years), mineral fertilizer (74 N; 20 P; 14 K kg ha^{-1}); combined application of manure and mineral fertilizer and lime application (on all the treatments) in year 1992 on maize grain yields (Bado et al., 1997).

role of OC on soil fertility, the paradigm of LEISA was developed during the 1990s. The INM approach was developed later aiming to integrate nutrients management from both organic and mineral fertilizers (Vanlauwe, 2004).

4.2 Organic Fertilizers

The application of the LEISA and INM approaches pointed out the importance of organic resources and at the same time, the problem of availability, quality, accessibility, and affordability. Organic manure (or fertilizer) is a broad term that comprises: manure prepared from cattle dung, excreta of other animals, CRs, and rural and urban composts. Organic fertilizers have traditionally been the source of nutrient and an important factor for chemical, physical, and biological properties of soils.

4.2.1 Bare Fallow

The bare fallows with trees, shrubs, and herbaceous plants have been the traditional system of OC for restoring soil fertility. The maintenance or restoration of soil fertility was based on a relatively long fallow period (10–15 years) followed by a short cropping period (3–5 years) as a way of rebuilding SOC status (Beets, 1990; Guillemin, 1956). For example, the traditional slash and burn system with natural fallow vegetation are still the main agricultural practice in the humid forest zones of West and Central Africa. Land is continuously cultivated for long time with exportation of CRs without any or few nutrient inputs. Some research efforts have been invested on the improvement of the traditional fallow system. Experiments on fallows date back to the 1930s with the "corridor system" in Congo (DRC), based on the principles of shifting cultivation (Eckholm, 1976). Studies show that both the type and the age of the fallow greatly influence soil fertility at the end of the fallow period. In a long-term experiment, Bado (2002) and Bado et al. (2012) reported that 1-year bare fallow in rotation with sorghum maintained better level of SOC status, increased N uptake by 120% and grain yield of the succeeding crop by 57% compared to the monocropping of sorghum. Although the use of more frequent fallows is necessary for sustainable management of soil fertility, more fallows means reduction in land area under crop production for a fast growing population with high demand for food and high pressing on land resources.

4.2.2 CRs

CRs as mulch play an important role on soil fertility by protecting the soil against erosion while simultaneously providing OC and nutrients.

Bationo and Buerkert (2001) reported that applications of 4000 kg ha^{-1} of CR and fertilizer in a cropping system maintained the same SOC as an adjacent fallow plot, while plots without CR applications had rapid SOC loses. The agronomic efficiency of CR can be improved trough composting.

For example, composting of CR with local phosphate rock (PR) can contribute to solubilize P from PR by organic acids thus producing a compost of better quality (Bado, 1985; Lompo, 1983). In general, composting or direct applications of CRs enhance P availability (Sahrawat, 2004), K nutrition, protects young seedlings against soil coverage during sand storms, increases water availability, reduces soil surface resistance by 65%, and topsoil temperature by over 4°C (Buerkert and Stern, 1995). These effects are stronger especially in the Sahelian zone, but weaker in other areas with lower temperatures, higher rainfall, and heavier soils. In general, organic amendments can contribute to reducing the soil's capacity to fix P thereby increasing P availability for uptake and hence higher P use efficiency (Buresh et al., 1997; Sahrawat, 2004). However, impacts of residue applications on SOC may be less significant in the more humid agroecological zones (Bationo and Buerkert, 2001).

As a source of input for improving soil fertility, CR is facing many completions at farmer's levels for livestock feed, fuel, or building material (Pieri, 1989), which reduces their availability for field applications. As source of energy, building material and animal feed, it was estimated that 50%–79% of stover are annually removed from fields in Niger and Nigeria (Powell and Unger, 1998).

4.2.3 Farmyard Manure

Manure from cattle, sheep, poultry, and compost (farm yard manure—FYM) are the main traditional sources of fertilizer for smallholder farmers in SSA. The quality of manure varies with types of animals and feeds, collection, and storage methods. As source of both mineral and organic fertilizer, FYM of different domestic animals is an important organic input in African agroecosystems. While remaining the main source of nutrients in the smallholder farming systems, the yield potential production of crops, particularly of the improved germplasm cannot be achieved with the FYMs alone. In most of the cases using manure is part of an internal flow of nutrients within the farm and does not add nutrients from outside the farm. Furthermore, the quantities available are inadequate to meet nutrient demand on large areas.

Owing to weak integration of agriculture and livestock associated with high biomass demand for food and livestock feeding, CRs, and FYM alone cannot ensure sustainable management of soil fertility.

4.3 Local Agromineral Resources

SSA has high potential of agromineral resources as opportunities to improve soil fertility. Most important sources are PR depositions and primary raw material for producing P fertilizers. Under certain soil and climate conditions, the direct application of local PRs is agronomically and economically sound alternative to the more expensive imported P-fertilizers (Baanante, 1998; Chien et al., 1990; Zapata et al., 1986). Moreover, PRs are sources of several nutrients other than Phosphorus. Calcium (Ca) and Magnesium (Mg) deficiencies are chemical and nutritional constraints on crop growth on acid soils (Zapata and Roy, 2004). Extensive research on the agronomic potential and actual effectiveness of PRs as sources of P have been conducted in almost all countries (Chien, 1995; Chien and Friesen, 1992; Chien and Hammond, 1978; Chien and Menon, 1995b; Chien et al., 1987), including the partially acidulated PR products as well as their economic assessment (Baanante, 1998; Baanante and Hellums, 1998; Chien and Menon, 1995a; Henao and Baanante, 1999). In 1994, the World Bank launched the initiative, Development of National Strategies for Soil Fertility Recapitalization in SSA that aimed to utilize the available PR resources as capital investment to replenish soil P status (Baanante, 1998; Buresh et al., 1997). The underutilization of local agromineral resources such as PRs is part of the paradoxes of African agriculture. While Africa ranks first with 28.5% of the world's production of PR, yet it has the lowest phosphate consumption with 2.8% of the world's consumption (FAO, 1999). While the soils of SSA remain extremely poor in P, the high resources of PR are not adequately exploited to improve agricultural production (Baudet et al., 1986).

4.4 Nitrogen-Fixing Legumes

The cropping systems of small farmers comprised many nitrogen-fixing legume crops, which are usually cultivated in rotation or intercropping with cereals or other crops. The traditional intercropping systems cover over 50%–90% of the cultivated area in the semiarid tropics. Mixed cropping is a strategy to maximize farmer's profits and minimize risk, alleviate seasonal labor peaks and stabilize incomes (Abalu, 1976). Nitrogen-fixing legume helps improving soil fertility through biological nitrogen fixation (BNF) (Bado et al., 2006; Bagayoko et al., 2000; Bationo and Ntare, 2000; Chalk, 1998). Nitrogen-fixing legumes contribute to soil fertility improvement as a consequence of N supplied by legumes through BNF (Bado et al., 2006, 2012; Bagayoko et al., 2000; Bationo and Ntare, 2000; Chalk, 1998; Peoples and Crasswell, 1992; Peoples and Herridge, 1990). Moreover, the fodder and residues of legumes constitute an important source of animal feed. Although all the above legume biomass are used to feed livestock and not returned to the soil, the rest of the fallen senescent leaves and underground parts are source of organic matter of good quality that improve soil mineral N, fertilizer N use efficiency, increase not only the yields of succeeding cereal but also its nitrogen use efficiency (Bationo and Vlek, 1998). Bado et al. (2006, 2011) showed that groundnut and cowpea can increase soil mineral N by 36%–52% and the yields of succeeding sorghum by 50%–300% (Fig. 2). Many fast growing leguminous species such as mucuna (*Mucuna pruriens*), soya beans (*Glycine max*), *Lablab purpureus*, Crotolaria ochroleuca, and various species of the Phaseolus family can be especially useful as green manures and cover crops. The groundcover offered by these green manures greatly reduces soil erosion (Gachene et al., 2000).

The important role of legume on improving soil fertility is not the sole criteria that determine the decision of farmers to adopt a specific legume in

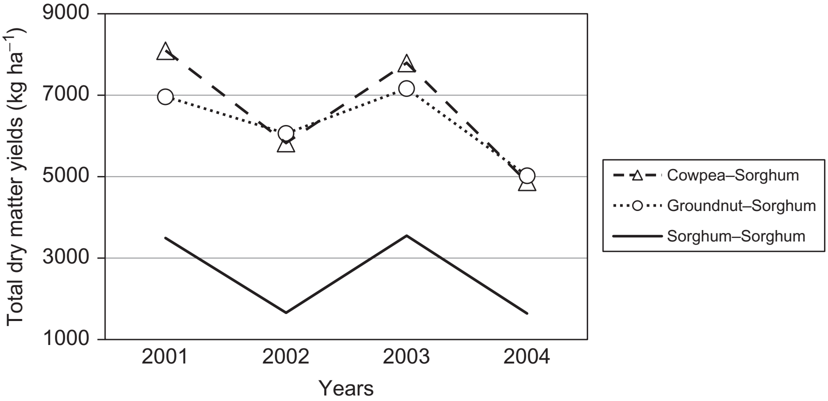

Fig. 2 Effect of sorghum rotation with groundnut (groundnut–sorghum) and cowpea (cowpea–sorghum) on sorghum total dry matter yields compared to the continuous cropping of sorghum (sorghum–sorghum) during 4 years in Burkia Faso (Bado et al., 2011).

their systems. Farmers more easily adopt dual-purpose legumes that provide both food and good quality fodder.

The improvement of soil fertility and yields (grain for food and/or market, fodder for animals and/or soil fertility), market opportunities (cash crops), and breakdown of diseases are some of the criteria that determine farmer's decision to adopt specific types of legumes.

5. PARADIGMS OF INTEGRATED MANAGEMENT OF SOIL FERTILITY

Different approaches have been developed with sometimes, contradictory discussions on appropriate options for sustainable management of soil fertility. The concepts of soil fertility management evolved from external inputs approaches focusing on supplying nutrients to crops; to more integrated management of both soil and external nutrients in cropping systems.

5.1 External Inputs

During the 1960s and 1970s, agricultural research and development agenda worldwide on improving soil fertility was driven by a paradigm of "external input." The quantity, quality, and appropriate use of external inputs, be it fertilizers, lime, or irrigation water, was believed to alleviate constraints to crop production (Vanlauwe, 2004). The associated effects of this paradigm of external inputs with the use of improved cereal germplasm, boosted agricultural production in Asia and Latin America through the first "Green Revolution" of the world. Organic resources were considered less essential. However, the paradigm of external inputs of the "Green Revolution" strategy in SSA resulted only in minor achievements because of a variety of reasons. Some of them were related to the cost of external inputs (mainly fertilizers), coupled with the abolition of the fertilizer subsidies imposed by structural adjustment programs in SSA (Smaling, 1993).

5.2 Low External Inputs Sustainable Agriculture (LEISA)

The paradigm of external inputs led to environmental degradation resulting from massive and injudicious applications of fertilizers and pesticides in Asia and Latin-America between the mid-1980 and early-1990s. This context and finding created a renewed interest of agricultural research and development in organic resources in the early 1980s. The balance shifted from mineral inputs to the paradigm of LEISA where organic resources were believed to enable sustainable agricultural production (Vanlauwe, 2004). From the experiences of the socioeconomic constraints and the complexity of the cropping systems of small farmers, the approaches of soil fertility management shifted from simple nutrient addition to more integrated approaches that aim to tackle the socioeconomic constraints and the complexity of the cropping systems of small farmers.

5.3 Integrated Nutrient Management (INM)

After several years of investment in research activities evaluating the potential of LEISA technologies, such as alley cropping or live-mulch systems, constraints were identified at the technical (e.g., lack of sufficient organic resources) and the socioeconomic levels (e.g., labor-intensive technologies) (Vanlauwe, 2004).

Recognizing the need for mineral and organic inputs to sustain crop production, this paradigm paved way to the INM approach. The need for both organic and mineral inputs was advocated because (i) both resources fulfill different functions to maintain plant growth, (ii) under most small-scale farming conditions, neither of them is available or affordable in sufficient quantities, and (iii) several hypotheses could be formulated leading to added benefits when applying both inputs in combination (Vanlauwe, 2004). The INM approach is perceived as the judicious manipulation of nutrient inputs, outputs, and internal flows to achieve productive and sustainable agricultural systems. It can be defined as a systematic, planned approach to manage soil fertility, at small and large scale in the context of farm and ecosystem as a whole. This management approach involves the best possible combination of available nutrient management practices, in the context of biophysical resources, economic feasibility, and social acceptability. The INM often comprises multidisciplinary teams of agronomists, soil scientists, livestock specialists, sociologists, anthropologists, and economists working together, thus optimizing all aspects of nutrient cycling.

5.4 Integrated Natural Resources Management (INMR)

From the mid-1980s to the mid-1990s, the shift in paradigm toward the use of organic and mineral inputs was accompanied by a shift toward participatory development. This was mainly driven by the "participatory movement" and included various stakeholders in the research and development process. One of the important lessons learnt from the participatory approach was that farmers' decision was not merely driven by soil and climate but by a large set of factors cutting across the biophysical, socioeconomic, and political domain. The INRM research approach was thus formulated which aimed at developing interventions that factor in the earlier aspects (Izac, 2000). The INRM approach focused on natural resource management. However, the socioeconomic realities of poor farmers that result in high pressure on natural resources were less consider.

5.5 Integrated Soil Fertility Management (ISFM)

With experiences gained from different approaches and changes in the overall social, economic, and political environment, the paradigms underlying soil fertility management research and development efforts have undergone substantial change during the last 3 decades (1980–2010). The ISFM paradigm was developed to include an integral part of the INRM approach with a focus on appropriate management of natural resources, farmers' capacities to afford technologies, and the complexity of cropping systems in line with local policies (cost, availability, and affordability of fertilizer and credit). The ISFM aims at adapting locally to soil fertility management practices of farmers to optimize agronomic efficiency of mineral fertilizers and organic inputs and to increase the productivity of cropping systems (Bationo and Waswa, 2011). The ISFM is defined as a set of soil fertility management practices of fertilizer, organic inputs, and improved germplasm. Combined with the knowledge of how to adapt practices to local conditions, the ISFM aims to maximize agronomic use efficiency of the applied nutrients and improve crop productivity (Vanlauwe et al., 2010). The ISFM recognizes the important role of social, cultural, and economic processes regulating soil fertility management strategies. This approach is broader than the INM approach as it recognizes the need of an appropriate physical and chemical environment for plants to grow optimally, besides a sufficient and timely supply of available nutrients (Vanlauwe, 2004). This paradigm is closely related to the wider concepts of INRM, thereby representing a significant step beyond the earlier narrower concept and approach of nutrient replenishment/recapitalization to enhance soil fertility (Sanchez et al., 1997). The approach integrates the roles of soil and water conservation; land preparation and tillage; organic and inorganic nutrient sources; nutrient adding and saving practices; pests and diseases; livestock; rotation and intercropping; multipurpose role of legumes; and integrating the different research methods and knowledge systems.

5.6 Management of Soil Fertility in Lowlands

Inland valleys constitute over 38% of the total wetlands in SSA (Africa Rice Center (WARDA), 2008). Lowland soils have specific characteristics that lead agronomic efficiency of nutrients and development of technologies and management strategies.

5.6.1 Characteristics of Lowlands

In contrast to the poor upland soils, the inland valley soils offer better conditions for crop production as they have higher OC and clay contents, a better EC and water retention capacity (Bado et al., 2010). Lowlands retain more water from rain or irrigation, resulting in a seasonal submergence, depletion of soil oxygen, and proliferation of anaerobic microorganisms. Therefore, the decomposition of organic residues is slower than in aerated upland soils, favoring the maintenance or accumulation of OC (Bronson et al., 1997; Cassman et al., 1995; Sahrawat, 2004; Witt et al., 2000). The drying period leads to aerobic conditions which favor faster decomposition of SOC. Frequent cycling between drying and wetting stimulate microbial activity (Sahrawat, 2004; Sahrawat et al., 2003). The decomposition or destruction of organic materials is reduced, and the humification of organic matter is decreased under flooded conditions. Consequently, the overall organic matter decomposition rates are slower in submerged soils than aerobic soils, resulting in net accumulation of organic matter (Mirasol et al., 2008; Olk et al., 1996; Powlson and Olk, 2000; Zhang and He, 2004). Owing to the high content and slow decomposition of SOC, soil fertility can be maintained for many years of cropping without the application of organic inputs (Bado et al., 2010; Mirasol et al., 2008; Olk et al., 1996; Powlson and Olk, 2000; Zhang and He, 2004). The soils of inland valleys present a high potential for agricultural production. In contrast with upland soils where phosphorous is the most limiting nutrient, nitrogen (N) is the main factor of rice production (Bado et al., 2008; Haefele et al., 2004, 2013). However, crop yields are generally limited by various biophysical constraints and poor crop management practices such as water control and iron (Fe) toxicity (Becker and Asch, 2005; Becker and Johnson, 2001; Touré et al., 2009). The high amounts of Fe^{2+} after flooding and the excessive Fe^{2+} uptake caused by an increased root permeability and enhanced microbial iron reduction in the rhizosphere lead to Fe^{2+} toxicity, nutritional imbalances due to low availability of P, K, Zn, Ca, or Mg (Prade et al., 1986), and reduction in the uptake of N and P (Diatta and Sahrawat, 2005; Yoshida, 1981). Zinc deficiency is frequently observed in lowland soils, associated with high pH, high organic matter content, and high availability of P, Si, and Mg/Ca ratio (Ponnamperuma and Deturck, 1993).

5.6.2 Main Achievements

The availability of water, relatively better fertility compared to upland soils, and the high solar radiation of SSA enables high potential of biomass production in lowlands. Traditionally, lowlands constitute an important source of grazing for livestock, particularly in the arid and semiarid zones during the dry season. Owing to better soil fertility, the soils of lowlands have high production potential for crops such as rice. An appropriate management of inputs and crop calendars are the most important factors of productivity. For example, rice can yield up to 12 t ha^{-1} of grain in the lowlands of Senegal River Valley (Dingkuhn and Sow, 1997; Haefele et al., 2004; Wopereis-Pura et al., 2002). In contrast with upland, the application of mineral fertilizer alone (without organic amendment) can maintain soil fertility for many years in lowlands (Bado et al., 2010) (Fig. 3). The International Rice Research Institute (IRRI) and AfricaRice (former WARDA) have

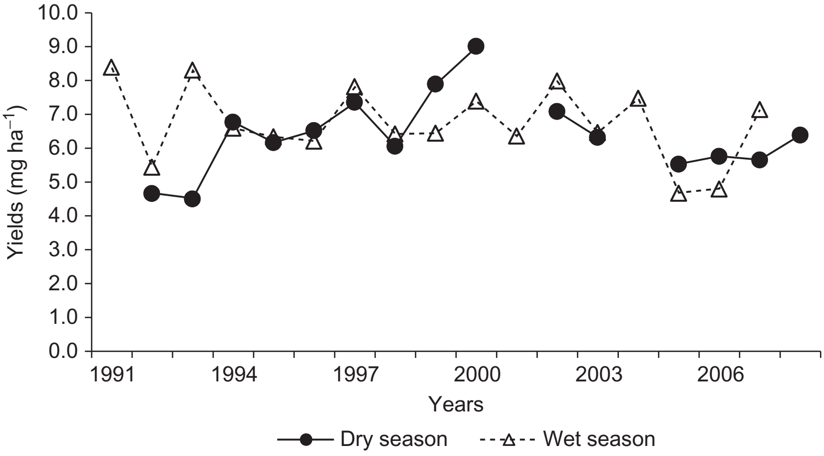

Fig. 3 Influence of fertilizer applications on rice grain yields in the Senegal River Valley during 36 continuous cropping seasons of rice (dry season and wet season) over 18 years (1991–2008). Only mineral fertilizer was applied at 120 N, 26 P, 50 K (kg ha^{-1} of nutrient). No yield decline was observed at $P < 0.05$ levels over the 18 years. *Source: Adapted from Bado, B.V., Aw, A., Ndiaye, M., 2010. Long-term effect of continuous cropping of irrigated rice on soil and yield trends in the Sahel of West Africa. Nutr. Cycl. Agro Ecosys. 88 (1), 133–141. https://doi.org/10.1007/s10705-010-9355-7.*

developed different concepts and methods to better manage fertilizer for rice, which is one of the main crops of lowlands. The IRRI developed the concept of site-specific nutrient management (SSNM) (Dobermann et al., 2002; Dobermann and White, 1999; Saito et al., 2015; Witt et al., 1999). The SSNM is the dynamic, field-specific management of nutrients in a particular cropping season to optimize the supply and demand of nutrients according to their differences in cycling through soil–plant systems (Dobermann and White, 1999; Wang et al., 2001). A cloud-based decision-support tool named nutrient manager for rice (NMR) was developed to deal with such specificity and provide farmers with field-specific nutrient management recommendations (Fairhurst et al., 2007; Saito et al., 2015). IRRI and AfricaRice worked together to develop NMR (Haefele et al., 2004; Wopereis et al., 1999). AfricaRice has developed the concept of integrated crop management (ICM) for rice (Kebbeh and Miezan, 2003; Wopereis et al., 1999). The concept of ICM recognizes that rice cultivation is a production system involving a wide range of components from land preparation to harvest and postharvest. These factors interact in an array of complex relationships and interdependencies that together determine crop growth, yield, and profitability. Thus, rice productivity and profitability can be boosted by integrated technologies adapted to the production environment of small-scale farmers, combined with optimum management of fertilizers, weed, varieties, seeds, and cultural calendar (Haefele et al., 2000, 2002; Kebbeh and Miezan, 2003; Wopereis et al., 1999). A change in the management of one factor can affect the performance of other factors and/or crop growth, yield, and profitability. The concept of ICM is a participative approach, focused on integrated management of resources, and inputs of farmers for increasing efficiency and productivity. It seeks to develop integrated technologies at the farm level (with the farmer as the ultimate integrator of management factors) to manage the cultivation of crops as a complete production system, taking into account all factors that impact crop growth, yield, quality, and profitability (Kebbeh and Miezan, 2003). AfricaRice has particularly used the ICM concept to develop different management options of fertilizer (dose and time of application) for cropping calendar of irrigated rice.

6. INTEGRATED MANAGEMENT OF LAND RESOURCES

At the individual farm level, many practices, technologies, and management approaches have been developed, from simple fertilizer recommendations to the integrated management technologies, options, and strategies. Significant progress was achieved during the last 30 years with the integrated management approaches (INM, INRM, ISFM, and ICM). However, farm-oriented technologies alone cannot prevent the decline of soil fertility, land degradation, and the decrease in productivity of the ecosystem due to high pressure on land resources. Similarly to cultivated soils, many researchers have identified major constraints to livestock productivity which are reducing rangelands, seasonal shortage in feed supply, absence of livestock routes, and lack of watering points (Ayantunde et al., 2007). For example, over 90 million smallholder farmers keep livestock in West Africa, 80% of whom are in the mixed crop-livestock/agro-pastoral systems (Herrero et al., 2014). Despite the reality of the traditional crop-livestock systems, many researchs are crop-oriented or livestock-oriented. The farm-oriented or livestock-oriented technologies alone cannot face the increasing demand in lands for crops and livestock (Adeel, 2003). Integrated crop and livestock systems and management of land resources with the rural communities allow for more efficient use of natural resources and inputs through recycling and increasing the overall output and efficiency of the system. During the last 20 years, there have been suggestions for more holistic soil science (Bridges and Catizzone, 1996), as part of a network society (Bouma, 2001), geared toward a soil care approach (Yaalon, 1996), or in closer relation with society (Yaalon and Arnold, 2000). A holistic approach is necessary for integrated management of soil fertility at farm level and also the land resources (cultivated lands and rangelands and protected forests) at the global community level.

6.1 The Concept

There is a need for a new concept of sustainable land resources management at the community level rather than for cultivated lands or rangelands for livestock. It is necessary to perceive all the land resources exploited by the entire community as the source of ecosystem services provider. To adapt our research approaches to the complex realities, it is necessary to incorporate an iterative approach involving stakeholders and LC (Giller et al., 2011). Many successful experiences on natural resource management such as the restoration of degraded lands are achieved with full participation of LC (Blay et al., 2004). With full participation from LC as primary actors, it is also necessary to involve local authorities and policy makers in the process of sustainable land resource management, which includes management of cultivated soils, pastoral lands, protected forests, and water resources. The proposed concept has three keys principles: (i) the management of land resources must be considered in the context of ecosystem service provider for the entire community; (ii) a decentralized and participative approach must be utilized to ensure the involvement of the entire community, local authorities, and stakeholders to identify the constraints, opportunities, and management scenarios; and (iii) tools for implementation and evaluation must be implemented for sustainable management of the process.

6.2 The Conceptual Framework

To bridge the gap between single-discipline, component research, and adaptive practices toward land resource management, a realistic approach at the relevant scale, and context has to partner with environmentally conscious farm managers (Provenza et al., 2013; Teagu and Barnes, 2017). The conceptual framework aims at combining scientific and local knowledge and expertise of stakeholders to identify suitable technologies or practices and developing context-specific management strategies or scenarios of land management. The main objective is to link researchers, development actors, policy-makers, and LC in a participative and interactive process to set-up global strategies. Tools such as stakeholder platforms (Bampton, 2003) could be used to coordinate the contributions of key actors. A lead institution (LI) can be identified within the keys actors to coordinate the stakeholder platform on land management (SP-LM). To ensure sustainability, the process should be led by LC through a local committee at various levels. Therefore, the main tools of implementations are the stakeholder platform, the committees of LC and the LI. This framework comprises three main components: (A) development/adaptation of land management options (LMOs); (B) testing of LMOs; and (C) evaluation of LMOs as presented in Fig. 4. The framework is built from the level of SP-LM to community levels (region, commune, and village) in five steps.

6.2.1 State of the Art (Step 1)

The high demand for food and land involves many actors at the national level and in many areas: agriculture, livestock, agro-pastoralism, environment, and natural resource management. Activities of these actors remain isolated as at times, actors do not always know the activities and achievements of others. As a stated point, there is a need to have a synthetic review and share the achievement of actors through literature reviews, meetings,

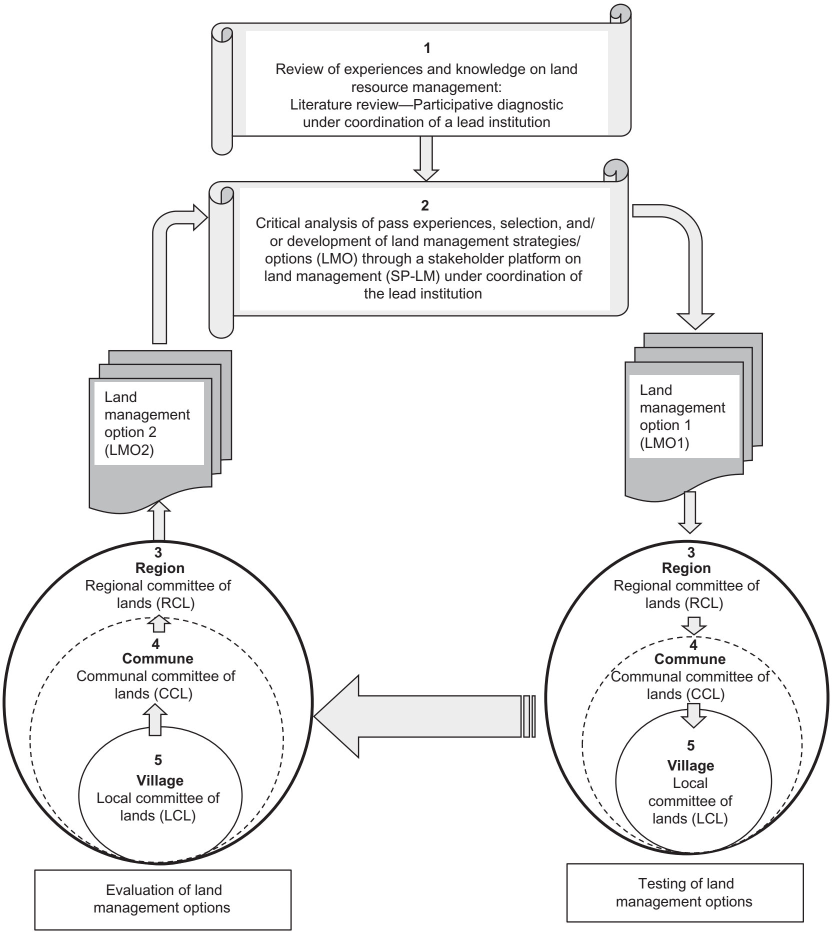

Fig. 4 A framework for participative diagnostic and development of integrated strategies, options, technologies, and practices for management of land resources from village to commune, region, and country levels with LC. The process starts with the review, identification of successful strategies, practices, and technologies of land resources management at the country level (step 1); development of improved strategies and land management options (LMOs) (step 2); implementation (LMO1 for first testing) at regional, commune, and village levels with LC (steps 3, 4, and 5); evaluation of the performances from village to commune and region and refinement to generate new improved management options and strategies (steps 3, 4, and 3).

and interactions among actors. An initial meeting of actors can be organized with the following terms of references: (i) creating of the SP-LM, (ii) identification of a LI to coordinate the process, and (iii) terms of references to help capitalize experiences of actors and achievements on land management. The LI will then coordinate the production of an initial report on the status of land resources, constraints of management and stakeholder involvement, policies, programs, successful experiences, failures, and innovations. Baseline studies could be used to collect more information at the community level including the perception and the proposed land management strategies from communities.

6.2.2 Identification/Development of LMOs (Step 2)

Under the coordination of the LI, the SP-LM will analyze and validate the initial report of the state of the art and achievements on land resources management. An inventory of technologies, practices, successful experiences, and innovations should be made for better land resource management including soil fertility (by farmers), rangelands, and protected forests (by the community) to be validated by keys actors. The promising practices, technologies, and successful management strategies will be selected for implementation as first level of LMO1. Some could be refined or improved for implementation.

6.2.3 Testing of LMOs (Steps 3–4–5)

The implementation of selected options and successful management strategies will be organized at the regional level. In general, the policy of decentralization goes from region or districts to communes and villages. Each region and commune can have a local development policy and plans of natural resource management. The LMOs will be implemented at regional and commune levels in three steps (region, commune, and village). At the regional level (step 3), the strategy of participative implementation of LMOs will be explained to regional authorities through meetings, visits, and focus group discussions. Some communes will be selected with the regional authorities based on the regional policy and priorities (step 4). Similarly, the same participative methodology will be used with communal authorities to select village sites (step 5). The selected villages of the same commune will organize their local committee of lands (LCL) at village level. The LCLs of the same commune will organize a communal committee of lands (CCL). Similarly, the CCLs of the region will organize the regional committee of lands (RCL). The SP-LM will be the national body of lands at the national level. The implementation of options (LMOs) and strategies will be coordinated and supervised at village, communal, regional, and national levels by the LCL, CCL, RCL, and SP-LM, respectively.

6.2.4 Evaluation of LMOs (Steps 5–4–3)

The evaluation of the performances and weaknesses of LMOs will be made from village (step 5), commune (step 4), and regional level (step 3). The similar participative process is used with land management committees (LCL, CCL, RCL, and SP-LM) at village, commune, region, and national levels. Based on suggestions and recommendation from the communities, the SP-LM analyzes and improves or refines the technologies, practices, and management innovations (step 1) to improve the LMOs or develop new LMO as second level of LMOs (LMO2). A workshop of the SP-LM including other resource persons or institutions could contribute to analyze, refine, or develop the new improved LMOs. Then, LMO2 is logically an improved version of LMO1 or new LMOs and strategies based on experience of field implementation of LMO1. LC, communal, regional, and national authorities and stakeholders will use the same process as long as necessary in the form of a participative and dynamic tool for sustainable and inclusive management of land resources.

Involving LC with the technical support from stakeholders is essential. The engagement of farmers through their communities gives more opportunities for empowerment than those working individually (Dolinska and Aquino, 2016). Using the concept of rural research center developed by ICRAF, Takoutsing et al. (2014) pointed out how farming communities can effectively participate in scaling-up agricultural practices when the process involves farmers, extension workers, and researchers in a mutual benefit: scientific results for researchers, better agricultural practices for extension workers, and economic success and free choice for farmers. With training support and sensitization on the need for sustainable management of land resources, LC can successfully play a key role in implementing local strategies.

7. CONCLUSION

Soil fertility depletion, land degradation, desertification, and deforestation are known to be the root causes of food insecurity, malnutrition, and poverty in sub-Sahara Africa. This review highlighted the progress made by the integrated management approaches (INM, INRM, ISFM, and ICM) during the last 30 years. Considering the challenge of increasing demand for land all over the world, thematic approaches like farm-oriented or livestock-oriented technologies alone cannot face the decline of soil fertility, land degradation, and deforestation. The proposed approach is a framework for action which involves LC as keys actors and beneficiaries of any strategy of sustainable land management. By giving a strategic role to LC, the process could stimulate their engagement with innovative actions.

This framework is a working strategy for integrated and sustainable management of land resources. This conceptual framework proposes a holistic and participative approach that involves stakeholders and LC. It is also a dynamic process giving space for continuous review to adjust strategies, tools, and methods of intervention and management. Depending on the context (number and profile of stakeholders, national policies, and engagement of LC), the framework can serve as a guideline to develop a detailed methodology of land resource management as an ecosystem services provider to the entire community.

REFERENCES

Abalu, G.O.I., 1976. A note on crop mixture under indigenous conditions in northern Nigeria. J. Dev. Stud. 12, 11–20.

Adeel, Z., 2003. Approaches towards the integration of land management practices: UNU's experience in networking and capacity development. In: International Workshop on Combating Desertification: Rehabilitation of Degraded Drylands and Biosphere Reserves. UNESCO, Aleppo, Syria, pp. 10–13.

Africa Rice Center (WARDA), 2008. Africa Rice Trends 2007. Africa Rice Center (WARDA), Cotonou, Benin, p. 84. http://www.africarice.org/publications/2007%20Africa%20Rice%20Trends%205th%20edition.pdf. Accessed 1 September 2017.

Ayantunde, A.A., Delfosse, P., Fernández-Rivera, S., Gerard, B., Dan Gomma, A., 2007. Supplementation with groundnut haulms for sheep fattening in the west African Sahel. Trop. Anim. Health Prod. 39, 207–216.

Baanante, C.A., 1998. Economic evaluation of the use of phosphate fertilizers as a capital investment. In: Johnston, A.E., Syers, J.K. (Eds.), Nutrient Management for Sustainable Agriculture in Asia. CAB International, Wallingford, UK, pp. 109–120.

Baanante, C.A., Hellums, D.T., 1998. An analysis of the potential demand for phosphate fertilizers: sources of change and projections to 2025. In: Currie, L.D., Loganathan, P. (Eds.), Long-Term Nutrient Needs for New Zealand's Primary Industries: global Supply, Production Requirements and Environmental Constraints. Occasional Report No. 11. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand, pp. 7–31.

Bado, B.V., 1985. Amelioration de l'efficacite des phosphates naturelles par l'utilisation des matieres organiques. Memoire de fin d'Etude. Universite de Ouagadougou, Ouagadougou, Burkina Faso, p. 124.

Bado, B.V., 2002. Rôle des légumineuses sur la fertilité des sols ferrugineux tropicaux des zones guinéenne et soudanienne du Burkina Faso (in French, with English abstract). PhD thesis, Université Laval, Québec.

Bado, B.V., Sedogo, M.P., Cescas, M.P., Lompo, F., 1997. Effet a long terme des fumures sur le sol et les rendements du mais au Burkina Faso. Cah. Agric. 6, 571–575.

Bado, B.V., Bationo, A., Cescas, M.P., 2006. How do cowpea and groundnut improve soil fertility and succeeding sorghum yields in the Guinean Savannah Zone of Burkina Faso West Africa. In: Proceedings Series on Management Practices for Improving Sustainable

Crop Production in Tropical Acid Soils. International Atomic Energy Agency, Vienna, Austria, pp. 287–305.

Bado, B.V., De Vries, M.E., Haefele, S.M., Marco, M.C.S., Ndiaye, M.K., 2008. Critical limit of extractable phosphorous in a Gleysol for rice production in the Senegal River valley of West Africa. Commun. Soil Sci. Plant Anal. 39, 202–206.

Bado, B.V., Aw, A., Ndiaye, M., 2010. Long-term effect of continuous cropping of irrigated rice on soil and yield trends in the Sahel of West Africa. Nutr. Cycl. Agroecosyst. 88 (1), 133–141. https://doi.org/10.1007/s10705-010-9355-7.

Bado, B.V., Sawadogo, A., Thio, B., Bationo, A., Traoré, K., Cescas, M.P., 2011. Nematode infestation and N-effect of legumes on soil and crop yields in legume-sorghum rotations. Agric. Sci. 2 (2), 49–55. https://doi.org/10.4236/as.2011.22008.

Bado, B.V., Bationo, A., Cescas, M.P., 2012. Rôle des légumineuses sur la fertilité des sols: opportunités pour une gestion intégrée de la fertilité des sols. Éditions Universitaires Européennes, Saarbrucken, Germany, p. 150.

Bagayoko, M., Buerkert, A., Lung, G., Bationo, A., Römheld, V., 2000. Cereal/legume rotation effects on cereal growth in Sudano-Sahelian West Africa: soil mineral nitrogen, mycorrhizae and nematodes. Plant Soil 218, 103–116.

Bampton, J.F.R., 2003. District Forest coordination committee: an emerging multi-stakeholder platform for collaborative forest management in Nepal's Terai; rural development forestry network, Overseas Development Institute (ODI), London, UK. J. Forest. Livelihood 2 (2), 35–47.

Bationo, A., 2008. Organic amendments for sustainable agri-cultural production in Sudano-Sahelian West Africa. In: Bationo, A. (Ed.), Integrated Soil Fertility Management Options for Agricultural Intensification in Sudano-Sahelian Zone of West Africa. Academy Science Publishers, Nairobi, p. 204.

Bationo, A., Buerkert, A., 2001. Soil organic carbon management for sustainable land use in Sudano-Sahelian west African. Nutr. Cycl. Agroecosyst. 61, 131–142.

Bationo, A., Mokwunye, A.U., 1991. Role of manures and crop residues in alleviating soil fertility constraints to crop production: with special reference to the Sahelian and Sudanian zones of West Africa. Fert. Res. 29, 117–125.

Bationo, A., Ntare, B.R., 2000. Rotation and nitrogen fertilizer effects on pearl millet, cowpea and groundnut yield and soil chemical properties in a sandy soil the semi arid tropics, West Africa. J. Agric. Sci. 134 (3), 277–284.

Bationo, A., Vlek, P.L.G., 1998. The role of nitrogen fertilizers applied to food crops in the Sudano-Sahelian Zone of West Africa. In: Renard, G., Neef, A., Becker, K., von Oppen, M. (Eds.), Soil Fertility Management in West African Land Use Systems. Margraf Verlag, Weikersheim, Germany, pp. 41–51.

Bationo, A., Waswa, B.S., 2011. New challenges and opportunities for integrated soil fertility management in Africa. In: Bationo, et al., (Eds.), Innovations as Key to the Green Revolution in Africa: Exploring the Scientific Facts. Springer, Dordrecht, The Netherlands, pp. 3–18.

Bationo, A., Mokwunye, U., Vlek, P.L.G., Koala, S., Shapiro, B.I., 2003. Soil fertility management for sustainable land use in the West African Sudano-Sahelian Zone. In: Gichuru, M.P., Bationo, A., Bekunda, M.A., Goma, H.C., Mafongonya, P.L., Mugendi, D.N., Murwira, H.M., Nandwa, S.M., Nyathi, P., Swift, M.J. (Eds.), Soil Fertility Management in Africa: A Regional Perspective. Academy Science Publishers, Nairobi, pp. 253–292.

Bationo, A., Hartemink, A., Lungu, O., Naimi, M., Okoth, P., Smaling, E., Thiombiano, L., 2006. African soils: their productivity and profitability of fertilizer use. In: Background paper prepared for the African Fertilizer Summit. vol. 2006. Abuja, Nigeria, p. 25. June 9–13.

Bationo, A., Job, K., Bernard, V., Boaz, W., Joseph, K., 2007. Soil organic carbon dynamics, functions and management in west African agro-ecosystems. Agric. Syst. 94, 13–25.

Bationo, A., Waswa, B., Adamou, A., Bado, V., Bonzi, M., Iwuafor, E., Kibunja, C., Kihara, J., Mucheru, M., Mugendi, D., Mugwe, J., Mwale, C., Okeyo, J., Olle, A., Roing, K., Sedego, M., Bationo, et al., 2012. Overview of long-term experiments in Africa. In: Lessons Learned From Long-Term Soil Fertility Management Experiments in Africa. Springer, Dordrecht, The Netherlands, pp. 1–26.

Baudet, G., Truong, B., Fayard, C., Sustrac, G., 1986. La filière phosphate: du mineral à l'engrais, principaux points de repère. Chron. Rech. Min. 484, 19–36.

Becker, M., Asch, F., 2005. Iron toxicity in rice conditions and management concepts. J. Plant Nutr. Soil Sci. 168, 558–573.

Becker, M., Johnson, D.E., 2001. Improved water control and crop management effects on lowland rice productivity in West Africa. Nutr. Cycl. Agroecosyst. 59, 119–127.

Beets, W., 1990. Raising and Sustaining Productivity of Small-Holder Farming Systems in the Tropics. AgBe Publishing, Alkmaar, The Netherlands.

Bekunda, M., Sanginga, N., Woomer, P.L., 2010. Restoring soil fertility in sub-Sahara Africa. Adv. Agron. 108, 183–236.

Blay, D.E., Bonkoudndou, E., Chanshama, S.A.O., Chikamai, B., 2004. Rehabilitation of degraded lands in sub-Saharan Africa: lessons learned from selected case studies. In: Forestry Research Network for Sub-Saharan Africa. Special Programme for Developing Countries.

Bostick, W.M., Bado, B.V., Bationo, A., Soler, C.T., Hoogenboom, G., Jones, J.W., 2007. Soil carbon dynamics and crop residue yields of cropping systems in the northern Guinea savanna of Burkina Faso. Soil Tillage Res. 93, 138–151.

Bouma, J., 2001. The new role of soil science in a network society. Soil Sci. 166, 874–879.

Bouma, J., Broll, G., Crane, T.A., Dewitte, O., Gardi, C., Schulte, R.P.O., Towers, W., 2012. Soil information in support of policy making and awareness raising. Curr. Opin. Environ. Sustain. 4, 552–558.

Brady, N., 1990. The Nature and Properties of Soils, 10th ed. MacMillan Publishers, New York.

Bridges, E.M., Catizzone, M., 1996. Soil science in a holistic framework—discussion of an improved integrated approach. Geoderma 71, 275–287.

Bronson, K.F., Cassman, K.G., Wassmann, R., Olk, D.C., van Noordwijk, M., Garrity, D.P., 1997. Soil carbon dynamics in different cropping systems in principal ecoregions of Asia. In: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), Management of Carbon Sequestration in Soil. CRC Press, Boca Raton, FL, pp. 35–57.

Buerkert, A.K., Stern, R.D., 1995. Crop residue and P application affect the spatial variability of non-destructively measured millet growth in the Sahel. Exp. Agric. 31, 429–449.

Buresh, R.J., Smithson, P., Hellums, D.T., 1997. Building soil phosphorus capital in Africa. In: Buresh, R.J., Sanchez, P.A., Calhoun, F. (Eds.), In: Replenishing Soil Fertility in Africa, vol. 51. SSSA Special Publication, Madison, pp. 111–149.

Cassman, K.G., De Datta, S.K., Olk, D.C., Alcantara, J., Samson, M., Descalsota, J., Dizon, M., 1995. Yield decline and the nitrogen economy of long-term experiments on continuous, irrigated rice systems in the tropics. In: Lal, R., Stewart, B.A. (Eds.), Soil Management: Experimental Basis for Sustainability and Environmental Quality. In: Advances in Soil Science CRC Press, Boca Raton, FL, pp. 181–222.

Chalk, P.M., 1998. Dynamics of biologically fixed N in legume–cereal rotations: a review. Aust. J. Res. 49, 303–316.

Chien, S.H., 1995. Chemical, mineralogical, and solubility characteristics of phosphate rock for direct application. In: Dahanayke, K., Van Kauwenbergh, S.J., Hellums, D.T. (Eds.), Direct Application of Phosphate Rock and Appropriate Technology Fertilizers in Asia: What Hinders Acceptance and Growth. Institute of Fundamental Studies, Muscle Shoals, USA, pp. 49–58.

Chien, S.H., Friesen, D.K., 1992. Phosphate rock for direct application. In: Sikora, F.J. (Ed.), Future Directions for Agricultural Phosphorus Research. Bulletin Y-224. Muscle Shoals, USA, Valley Authority, pp. 47–52.

Chien, S.H., Hammond, L.L., 1978. A comparison of various laboratory methods for predicting the agronomic potential of phosphate rock for direct application. Soil Sci. Soc. Am. J. 42, 1758–1760.

Chien, S.H., Menon, R.G., 1995a. Agronomic evaluation of modified phosphate rock products: IFDC's experience. Fert. Res. 41, 197–209.

Chien, S.H., Menon, R.G., 1995b. Factors affecting the agronomic effectiveness of phosphate rock for direct application. Fert. Res. 41, 227–234.

Chien, S.H., Hammond, L.L., Leon, L.A., 1987. Long term reactions of phosphate rocks with an oxisol in Colombia. Soil Sci. 144, 257–265.

Chien, S.H., Sale, P.W.G., Hammond, L.L., 1990. Comparison of effectiveness of various phosphate fertilizer products. In: Proceedings of International Symposium on Phosphorus Requirements for Sustainable Agriculture in Asia and Oceania. IRRI, Manila, pp. 143–156.

Dewitte, O., Arwyn, J., Otto, S., Henrik, B.M., Michel, B., Almami, D., Jozef, D., Tahar, G., Stephen, H., Robert, J., Method, K., Pieter, L.R., Erika, M., Luca, M., Thiombiano, L., Van Ranst, E., Martin, Y., Robert, Z., 2013. Harmonisation of the soil map of Africa at the continental scale. Geoderma 211–212, 138–153.

Diatta, S., Sahrawat, L.K., 2005. Iron toxicity of rice in West Africa: screening tolerant varieties and the role of N, P, K, and Zn. In: Audebert, A., Narteh, L.T., Kiepe, P., Millar, D., Beks, B. (Eds.), Iron Toxicity in Rice-Based Systems in West Africa. Africa Rice Center (WARDA), Cotonou, Benin, p. 75.

Dingkuhn, M., Sow, A., 1997. Potential yields of irrigated rice in the Sahel. In: Miezan, K.M., Wopereis, M.C.S., Dingkuhn, M., Deckers, J., Randolph, T.F. (Eds.), Irrigated Rice in the Sahel: Prospects for Sustainable Development. West Africa Rice Development Association, Bouake.

Dobermann, A., White, P.F., 1999. Strategies for nutrient management in irrigated and rainfed lowland rice systems. Nutr. Cycl. Agroecosyst. 53, 1–18.

Dobermann, A., George, T., Thevs, N., 2002. Phosphorus fertilizer effects on soil phosphorus pools in acid upland soils. Soil Sci. Soc. Am. J. 66, 652–660.

Dolinska, A., Aquino, P., 2016. Farmers as agents in innovation systems. Empowering framers for innovation though communities of practice. Agric. Syst. 142, 122–130.

Dregne, H.E., 1990. Erosion and soil productivity in Africa. J. Soil Water Conserv. 45, 431–436.

Dregne, H.E., Chou, N.T., 1992. Global desertification dimensions and costs. In: - Dregne, H.E. (Ed.), Degradation and Restoration of Arid Lands. Texas Technical University, Lubbock, TX.

Dunstan, S.C.S., Matlon, P.J., Löffler, H., 2004. African Agricultural Production and Productivity in Perspective. Background paper No. 1 was commissioned by the Inter-Academy Council (IAC) Study Panel on Science and Technology Strategies for Improving Agricultural Productivity and Food Security in Africa, Realizing the Promise of African Agriculture. ISBN: 90-6984-418-4.

Eckholm, E.P., 1976. Losing Ground: Myth and Reality in the Humid Tropics. Norton, New York.

Enyong, L.A., Debrah, S.K., Bationo, A., 1999. Farmers' perceptions and attitudes towards introduced soil-fertility enhancing technologies in western Africa. Nutr. Cycl. Agroecosyst. 53 (2), 177–187.

Fairhurst, T., Witt, C., Buresh, R., Dobermann, A., 2007. Rice: A Practical Guide to Nutrient Management. Nutrient Management, Nutrient Deficiencies, Mineral Toxicities, Tools and Information, second ed. International Rice Research Institute, International Plant Nutrition Institute and International Potash Institute.

Food and Agriculture Organization of the United Nations (FAO), 1991. Guidelines: Land Evaluation for Extensive Grazing. Soils Bulletin 58. Food and Agriculture Organization (FAO), Rome, Italy, p. 158.

Food and Agriculture Organization of the United Nations (FAO), 1999. Fertilizer yearbook 1998. FAO Statistics Series No. 150, Rome.

Food and Agriculture Organization of the United Nations (FAO), 2000. Guide diagnostic participatif des contraintes et des potentialités pour la gestion des sols et des éléments nutritifs des plantes. FAO, Land and Water Development Division, Rome.

Formoso, M.L.L., 1999. Workshop on Tropical Soils. Brazilian Academy of Sciences, Rio de Janeiro, Brazil, p. 192.

Frank, D.A., McNaughton, S.J., Tracy, B.F., 1998. The ecology of the earth's grazing ecosystems. Bioscience 48, 513–521.

Gachene, C.K.K., Karanja, N.K., Mureithi, J.G., 2000. Effect of soil erosion on soil productivity and subsequent restoration of productivity using green manure cover crops: data summary of a long-term field experiment. Legume Res. Network Project Newsletter 4 (4), 8–10.

Gikonyo, E.W., Smithson, P.C., 2003. Effects of farmyard manure, potassium and their combinations on maize yields in the high and medium rainfall areas of Kenya. In: Bationo, A. (Ed.), Managing Nutrient Cycles to Sustain Soil Fertility in Sub-Sahara Africa. AfNet-CIAT, 2004, Springer.

Giller, K.E., Tittonell, P., Rufino, M.C., van Wijk, M.T., Zingore, S., Mapfumo, P., Adjei-Nsiah, S., Herrero, M., Chikowo, R., Corbeels, M., Rowe, E.C., Baijukya, F., Mwijage, h.A., Smith, J., Yeboah, E., van der Burg, W.J., Sanogo, O.M., Misiko, M., de Ridder, N., Karanja, S., Kaizzi, C., K'ungu, J., Mwale, M., Nwaga, D., Pacini, C., Vanlauwe, B., 2011. Communicating complexity: integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. Agric. Syst. 104, 191–203.

Gisladottir, G., Stocking, M., 2005. Land degradation control and its global environmental benefits. Land Degrad. Dev. 16, 99–112.

Guillemin, R., 1956. Evolution de l'agriculture autochtone dans les savannes de l'Oubangui. Deuxie' me partie: L'agriculture Oubanguienne a ses origines. L'Agronomie Tropicale 11, 143–176.

Haefele, S.M., Johnson, D.E., Diallo, S., Wopereis, M.C.S., Janin, I., 2000. Improved soil fertility and weed management is profitable for irrigated rice farmers in the Sahel. Field Crop Res. 66, 101–113.

Haefele, S.M., Wopereis, M.C.S., Wiechmann, H., 2002. Long-term fertility experiments for irrigated rice in the west African Sahel: agronomic results. Field Crop Res. 78, 119–131.

Haefele, S.M., Wopereis, M.C.S., Schloebohm, A.M., Wiechmann, H., 2004. Long-term fertility experiments for irrigated rice in the west African Sahel: effects on soil characteristics. Field Crop Res. 83, 61–77.

Haefele, S.M., Saito, K., NDiaye, K.M., Mussgnug, F., Nelson, A., Wopereis, M.C.S., 2013. Increasing rice productivity through improved nutrient use in Africa. In: Wopereis, M.-C.S., Johnson, D.E., Ahmadi, N., Tollens, E., Jalloh, A. (Eds.), Realizing Africa′s Rice Promise. CAB International, Wallingford, UK, pp. 250–264.

Hartemink, A.E., McBratney, A., 2008. A soil science renaissance. Geoderma 148, 123–129.

Henao, J., Baanante, C.A., 1999. Estimating Rates of Nutrient Depletion in Soils of Agricultural Lands in Africa, IFDC. Muscle Shoals, Alabama.

Herrero, M., Havlik, P., McIntire, J., Palazzo, A., Valin, H., 2014. African Livestock Futures: Realizing the Potential of Livestock for Food Security, Poverty Reduction and the Environment in Sub-Saharan Africa. Office of the Special Representative of the UN Secretary General for Food Security and Nutrition and the United Nations System Influenza Coordination (UNSIC), Geneva, Switzerland.

Holechek, J.L., Gomez, H., Molinar, F., Galt, D., 1999. Grazing studies: what we've learned. Rangelands 21, 12–16.

Izac, A-M.N., 2000. What Paradigm for Linking Poverty Alleviation to Natural Resources Management? In: Proceedings of an International Workshop on Integrated Natural Resource Management in the CGIAR: Approaches and Lessons, August 21–25, 2000, Penang, Malaysia.

Kebbeh, M., Miezan, K., 2003. Ex-ante evaluation on integrated crop management options for irrigated rice production in the Senegal River valley. Field Crop Res. 81, 87–94.

Kiage, L.M., 2013. Perspectives on the assumed causes of land degradation in the rangelands of Sub-Saharan Africa. Prog. Phys. Geogr. 5, 664–684.

Lompo, F., 1983. Problématique de la matie're organique dans la zone du plateau Mossi. Etude de la disponibilité des reésidus culturaux et de leur mode de transformation. In: Meémoire de fin d'études. ISP/Université d'Ouagadougou, Burkina Faso, p. 108.

Milchunas, D.G., Lauenroth, W.K., 1993. Quantitative effects of grazing on vegetation and soils over a global range of environments. Ecol. Monogr. 63, 327–366.

Mirasol, F.P., Eufrocino, V.L., Gines, H.C., Buresh, J.R., 2008. Soil carbon and nitrogen changes in long-term continuous lowland rice cropping. Soil Sci. Soc. Am. J. 72, 798–807.

Mwendera, E.J., Saleem, M.A.M., Woldu, Z., 1997. Vegetation response to cattle grazing in the Ethiopian highlands. Agric. Ecosyst. Environ. 64, 43–51.

Olk, D.C., Cassman, K.G., Randall, E.W., Kinchesh, P., Sanger, L.J., Anderson, J.M., 1996. Changes in chemical properties of organic matter with intensified rice cropping in tropical lowland soil. Eur. J. Soil Sci. 47, 293–303.

Palm, C., Sanchez, P., Ahamed, S., Awiti, A., 2007. Soils: a contemporary perspective. Annu. Rev. Env. Resour. 32, 99–129.

Palm, C.A., Smukler, S.M., Sullivan, C.C., Mutuo, P.K., Nyadzi, G.I., Walsh, M.G., 2010. Identifying potential synergies and trade-offs for meeting food security and climate change objectives in sub-Saharan Africa. Proc. Natl. Acad. Sci. USA 107, 19661–19666.

Penning De Vries, F.W.T., Djiteye, M.A., 1982. La Productivité des Pâturages Sahéliens. Une Etude des Sols, des Végétations et de L'exploitation de Cette Ressource Naturelle. Agricultural Research Reports, 918, Pudoc, Wageningen.

Peoples, M.B., Crasswell, E.T., 1992. Biological nitrogen fixation: investment, expectation and actual contribution to agriculture. Plant Soil 141, 13–39.

Peoples, M.B., Herridge, D.F., 1990. Nitrogen fixation by legumes in tropical agriculture. Adv. Agron. 44, 155–223.

Peterson, G., Allen, G.R., Holling, C.S., 1998. Ecological resilience, biodiversity and scale. Ecosystems 1, 6–18.

Pichot, J., Sédogo, M.P., Poulain, J.F., 1981. Évolution de la fertilité d'un sol ferrugineux tropical sous l'influence des fumures minérales et organiques. Agron. Trop. 36, 122–133.

Pieri, C., 1989. Fertilité des Terres de Savane, Bilan de Trente ans de Recherche et de Développement Agricoles au Sud du Sahara. Ministère de la Coopération, CIRAD, Paris, France.

Ponnamperuma, F.N., Deturck, R., 1993. A review of fertilization in rice production. International Rice Commission Newsletter 42, 1–12.

Powell, J.M., Unger, P.W., 1998. Alternatives to crop residues for sustaining agricultural productivity and natural resource conservation. J. Sust. Agric. 11 (2–3), 59–84.

Powlson, D.S., Olk, D.C., 2000. Long-term soil organic matter dynamics. In: Kirk, G.J.D., Olk, D.C., (Eds.), Carbon and Nitrogen Dynamics in Flooded Soils. Paper Presented at the Workshop on Carbon and Nitrogen Dynamics in Flooded Soils. IRRI, Los Baños, 19–22 April 1999.

Prade, K., Ottow, J.C.G., Jacq, V.A., 1986. Excessive iron uptake (iron toxicity) by wetland rice (Oryza sativa L.) on an acid sulfate soil in the casamance/Senegal. Selected Papers of the Dakar Symposium on Acid Sulphate Soils. Dakar, Senegal. vol. 44, 150–163.

Provenza, F., Pringle, H., Revell, D., Bray, N., Hines, C., Teague, R., Steffens, T., Barnes, M., 2013. Complex creative systems. Rangelands 35, 6–13.

Sahrawat, K.L., 2004. Organic matter accumulation in submerged soils. Adv. Agron. 81, 169–201.

Sahrawat, K.L., Jones, M.P., Diatta, S., Sika, M., 2003. Long-term phosphorus fertilizer effects on phosphorus uptake, efficiency, and recovery by dryland rice on an Ultisol. Commun. Soil Sci. Plant Anal. 14, 999–1011.

Saito, K., Diack, S., Dieng, I., Ndiaye, M.K., 2015. On-farm testing of a nutrient management decision-support tool for rice in the Senegal River valley. Agriculture 116, 36–44.

Sanchez, P.A., Shepherd, K.D., Soule, M.J., Place, F.M., Buresh, R.J., Izac, A-M.N., Mokwunye, A.U., Kwesiga, F.R., Ndiritu, C.G., Woomer, P.L., 1997. Soil Fertility Replenishment in Africa: An Investment in Natural Resource Capital. In: Buresh, R.J., Sanchez, P.A., Calhoun, F. (Eds.), Replenishing Soil Fertility in Africa. SSSA Special Publication No. 51, Soil Science Society of America, Madison, WIisconsin, pp. 1–46.

Savadogo, P., Tiveau, D., Sawadogo, L., Tigabu, M., 2008. Herbaceous species responses to long term effects of prescribe fire, grazing and selective cutting tree in the savanna-woodland of West Africa. Perspect. Plant Ecol. Evol. Syst. 10, 179–195.

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

Smaling, E.M.A., 1993. An Agro-Ecological Framework of Integrated Nutrient Management with Special Reference to Kenya. Wageningen Agricultural University, Wageningen, The Netherlands.

Smaling, E.M.A., 1995. The balance may look fine when there is nothing you can mine: nutrient stocks and flows in West African soils. In: Gerner, H., Mokwunye, A.U. (Eds.), Proceedings of a Seminar on the Use of Local Mineral Resources for Sustainable Agriculture in West Africa. IFDC, Africa. November 21–23, 1994.

Stoorvogel, J.J., Smaling, E.M.A., Janssen, B.H., 1993. Calculating soil nutrient balances in Africa at different scales. I. Supra-National Scale. Fert. Res. 35, 227–235.

Takoutsing, B., Tchoundjeu, Z., Degrande, A., Asaah, E., Tsobeng, A., 2014. Scaling-up sustainable land management practices through the concept of the rural resource centre: reconciling farmers' interests with research agendas. J. Agric. Educ. Ext. 20 (5), 463–483.

Teague, R., Barnes, M., 2017. Grazing management that regenerates ecosystem function and grazingland livelihoods. Afr. J. Range Forage Sci. 34, 77–86.

Thiombiano, L., 2000. Etude des Facteurs édaphiques et Pédopaysagiques Dans le Développement de la Désertification en Zone Sahélienne du Burkina Faso. Thèse de Doctorat d'Etat, vol. I. plus Annexes, Université de Cocody, Abidjan, Côte d'Ivoire, 200 p.

Touré, A., Becker, M., Johnson, D.E., Koné, B., Kossou, D.K., Kiepe, P., 2009. Response of lowland rice to agronomic management under different hydrological regimes in an inland valley of Ivory Coast. Field Crop Res. 114, 304–310.

UNDP/GEF, 2004. Reclaiming the land sustaining livelihoods: lessons for the future. United Nations Development Fund/Global Environmental Facility, November 2004.

Vanlauwe, B., 2004. Integrated soil fertility management research at TSBF: the framework, the principles, and their application. In: Bationo, A. (Ed.), Managing Nutrient Cycles to Sustain Soil Fertility in Sub-Saharan Africa. Academy Science Publishers, Nairobi, Kenya.

Vanlauwe, B., Bationo, A., Giller, K.E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K.D., Smaling, E.M.A., Woomer, P.L., Sanginga, N.,

2010. Integrated soil fertility management. Operational definition and consequences for implementation and dissemination. Outlook Agr. 39, 17–24.

Vlek, P., Le, Q.B., Tamene, L., 2008. Land Decline in Land-Rich Africa—A Creeping Disaster in the Making. CGIAR Science Council Secretariat, Roma, Italy, 55 p.

Wang, G.H., Dobermann, A., Witt, C., Sun, Q.Z., Fu, R.X., 2001. Performance of site-specific nutrient management for irrigated rice in Southeast China. Agron. J. 93, 869–878.

Witt, C., Dobermann, A., Abdulrachman, S., Gines, H.C., Wang, G.H., Nagarajan, R., Satawathananont, S., Son, T.T., Tan, P.S., Tiem, L.V., Simbahan, G.C., Olk, D.C., 1999. Internal nutrient efficiencies of irrigated lowland rice in tropical and subtropical Asia. Field Crop Res. 63, 113–138.

Witt, C., Cassman, K.G., Olk, D.C., Biker, U., Liboon, S.P., Samson, M.I., Ottow, J.C.G., 2000. Crop rotation and residue management effects on carbon sequestration, nitrogen cycling and productivity of irrigated rice systems. Plant Soil 225, 263–278.

Woomer, P.L., Martin, A., Albretch, A., Resck, D.V.S., Scharpenseel, H.W., 1994. The importance and management of soil organic matter in the tropics. In: Woomer, P.L., Swift, M. (Eds.), The Biological Management of Tropical Soil Fertility. Wiley-Sayce, Chichester, UK, pp. 47–80.

Wopereis, M.C.S., Donovan, C., Nebié, B., Guindo, D., Ndiaye, M.K., 1999. Soil fertility management in irrigated rice systems in the Sahel and savanna regions of West Africa. Part I. Agronomic analysis. Field Crops Res. 61, 125–145.

Wopereis-Pura, M.M., Watanabe, H., Moreira, J., Wopereis, M.C.S., 2002. Effect of late nitrogen application on rice yield, grain quality and profitability in the Senegal River valley. Eur. J. Agron. 17, 191–198.

Yaalon, D.H., 1996. Soil science in transition—soil awareness and soil care research strategies. Soil Sci. 161, 3–8.

Yaalon, D.H., Arnold, R.W., 2000. Attitudes toward soils and their societal relevance: then and now. Soil Sci. 165, 5–12.

Yanggen, D., Kelly, V., Reardon, T., Naseem, A., 1998. Incentives for fertilizer use in sub-Saharan Africa: a review of empirical evidence on fertilizer response and profitability. MSU International Development Working Paper No. 70. http://www.aec.msu.edu/agecon/fs2/index.htm.

Yoshida, S., 1981. Fundamentals of Rice Crop Science. IRRI, Los Baños, Philippines. http://books.irri.org/9711040522_content.pdf (accessed 3 July 2017).

Zapata, F., Axmann, H., Braun, H., 1986. Agronomic evaluation of rock phosphate materials by means of radioisotope techniques. In: ISSS and BG, Eds. Trans. 13th Int. Cong. Soil Sci. 3, Hamburg, Germany, pp. 1012–1013.

Zapata, F., Roy, R.N., 2004. Use of phosphate rocks for sustainable agriculture. In: FAO Fertilizer and Plant Nutrition Bulletin 13. Rome.

Zhang, M., He, Z., 2004. Long term changes in organic carbon and nutrients of an Ultisol under rice cropping in south-East China. Geoderma 118, 167–179.

FURTHER READING

Bationo, A., Chien, S.H., Christianson, C.B., Henao, J., Mokwunye, A.U., 1990. A three year evaluation of two unacidulated and partially acidulated phosphate rocks indigenous to Niger. Soil Sci. Soc. Am. J. 54, 1772–1777.

Bationo, A., Baethgen, W.E., Christianson, C.B., Mokwunye, A.U., 1991. Comparison of five soil-testing methods to establish phosphorus sufficiency levels in soil fertilized with water-soluble and sparingly soluble phosphorus sources. Fert. Res. 28, 271–279.

Bationo, A., Christianson, B.C., Klaij, M.C., 1993. The effect of crop residue and fertilizer use on pearl millet yields in Niger. Fert. Res. 34, 251–258.

Deckers, J., 1993. Soil fertility and environmental problems in different ecological zones of the developing countries in sub-Saharan Africa. In: Van Reuler, H., Prins, W.H. (Eds.), The Role of Plant Nutrients and Sustainable Food Production in Sub-Saharan Africa. Vereniging Van Kunstmest Producenten, Laidschendam, The Netherlands.