Chapter 1
Soil Organic Carbon and Proper Fertilizer Recommendation

Andre Bationo and J.O. Fening

Abstract Soil carbon in the form of organic matter is a key component of the soil ecosystem structure. In most parts of West Africa agro-ecosystems (except the forest zone), the soils are inherently low in SOC content due to low organic matter additions, and accelerated degradation. The rapid turnover rates of organic material is as a result of high soil temperatures and fauna activity particularly termites. The SOC levels rapidly decline with continuous cultivation. For the sandy soils, average annual losses may be as high as 4.7% whereas with sandy loam soils, losses are lower, with an average of 2.0%. To maintain food production for a rapidly growing population, application of mineral fertilizers and the effective recycling of organic amendments such as crop residues and manures are essential especially in the smallholder farming systems that rely predominantly on organic residues to maintain soil fertility. The efficiency of fertilizer use is likely to be high where the organic matter content of the soil is also high. In unhealthy or depleted soils, crops use fertilizer supplied nutrients inefficiently. Where soils are highly degraded, crops hardly respond to fertilizer applications. When SOM levels are restored, fertilizer can help maintain the revolving fund of nutrients in the soil by increasing crop yields and, consequently, the amount of residues returned to the soil. Crop yields can be increased by 20–70 kg ha^{-1} for wheat, 10–50 kg ha^{-1} for rice, and 30–-300 kg ha^{-1} for maize with every 1 Mg ha^{-1} increase in soil organic carbon pool in the root zone. There is need to increase crop biomass at farm level and future research should therefore focus on improvement of nutrient use efficiency in order to increase crop biomass.

Keywords Soil degradation • Crop productivity • Nutrient use efficiency • Soil organic matter • Smallholder farmer

A. Bationo
IFDC, Accra, Ghana

J.O. Fening (✉)
CSIR-Soil Research Institute, Academy Post Office, PMB, Kwadaso-Kumasi, Ghana
e-mail: kofifening@yahoo.com

A. Bationo et al. (eds.), *Improving the Profitability, Sustainability and Efficiency of Nutrients Through Site Specific Fertilizer Recommendations in West Africa Agro-Ecosystems*, DOI 10.1007/978-3-319-58789-9_1

Contents

1.1 Introduction

Soil carbon in the form of organic matter is a key component of the soil ecosystem structure. The soil carbon content is an important contributing factor in the various flows and transformations of matter, energy and biodiversity - the essential soil functions that provide ecosystem services and life-sustaining benefits from soil. These goods and services include food production, water storage and filtration, carbon storage, nutrient supply to plants, habitat and biodiversity.

The natural soil carbon density is influenced by the balance between inputs (plant residues) and losses, mainly microbial decomposition and associated mineralization. This amount will vary with factors such as the specific land use undergoing change, soil type and texture, soil depth, bulk density, management and climate. Because of its superficial setting, small bulk density and organic constitution, soil organic carbon (SOC) is highly susceptible to water and wind erosion and chemical and physical degradation (Sombroek et al. 1993). The major drivers of SOC loss include demand for fuel, overgrazing, arable agriculture and other overexploitation of vegetation. The resulting depletion of the global SOC pool is estimated at 40–100 Pg.

Across the world, soil organic carbon (SOC) is decreasing due to changes in land use such as the conversion of natural systems to food or bioenergy production systems. The losses of SOC have impacted crop productivity and other ecosystem services adversely. In the past 25 years, one-quarter of the global land area has suffered a decline in productivity and in the ability to provide ecosystem services because of soil carbon losses (Bai et al. 2008). The situation is made worse in the tropical soils, which are considered as more risky because cropping is synonymous to nutrient removal in the already impoverished soils with insufficiently replenishment. There is considerable concern that, if SOM concentrations in soils are allowed to decrease too much, then the productive capacity of agriculture will be compromised. Soils exhibit different behaviour and as such we would expect to have different SOC levels. However, there is a general consensus among the scientists that a 2% soil carbon (3.5% SOM) as a critical level for soils below which potentially serious decline in soil quality will occur (Loveland and Webb 2003).

One of the grand challenges for society is to manage soil carbon stocks to optimize the mix of five essential services - provisioning of food, water and energy; maintaining biodiversity; and regulating climate. Scientific research has helped to develop an understanding of the general SOC dynamics and characteristics; the influence of soil management on SOC; and management practices that can restore SOC and reduce or stop carbon losses from terrestrial ecosystems. As the uptake of these practices has been very limited, it is necessary to identify and overcome barriers to the adoption of practices that enhance SOC. Actions should focus on multiple ecosystem services to optimize efforts and the benefits of SOC.

1.2 Soil Organic Carbon Management

Deficiency of SOM is widespread in tropical soils and particularly those under the influence of arid, semiarid and sub-humid climates due to the controlling influence of climatic factors on primary productivity and biomass decomposition. Since sustainability is not possible without equalizing the nutrient removals and additions, productivity declines steadily without application of fertilizers. In temperate regions, crop residues are routinely incorporated into the soil, but the practice of returning residues to the soil is practically non-existent in tropical regions. Thus, in the tropics, low organic matter additions as well as accelerated degradation and loss due to year round prevalence of biologically active temperature and moisture regimes leads to rapid reductions in SOM levels and consequently, reduced soil health due to the absence of the beneficial effects of the organic matter.

In general, the SOM content of tropical soils, when brought under cultivation, can fall to as low as about 30% of the original value of the uncultivated indigenous state, but most reports indicate about a 60% reduction after 10 years of cultivation. Katyal et al. (2001) documented such changes with arable cropping from long-term field experiments. In a virgin soil, SOM remained stable for 10 years after fertilizer application, but subsequently fell to about 40% of the initial value during the next 3 years. However, when manures and fertilizer were applied, the SOM level was stable for 25 years, thus illustrating the value of integrated use of organic and inorganic nutrient sources in stabilizing and maintaining SOM in cropping systems and ensuring sustainability regardless of the cropping system.

The quantity of organic carbon in soil and the quantity and type of organic inputs have profound impacts on the dynamics of nutrients. Soil organic matter itself represents a large reservoir of nutrients that are released gradually through the action of soil fauna and microorganisms: this is especially important for the supply of N, P and S to plants, whether agricultural crops or natural vegetation. Organic matter also modifies the behaviour and availability of nutrients through a range of mechanisms including increasing the cation exchange capacity of soil, thus leading to greater retention of positively charged nutrient ions such as Ca, Mg, K, Fe, Zn and many micronutrients.

In West Africa as the rest of the continent, removal of crop residues from the fields, coupled with a lower rate of macronutrient application compared to losses, has contributed to negative nutrient balances (Stoorvogel and Smaling 1990). For nitrogen as an example, whereas 4.4 million tons are lost per year, only 0.8 million

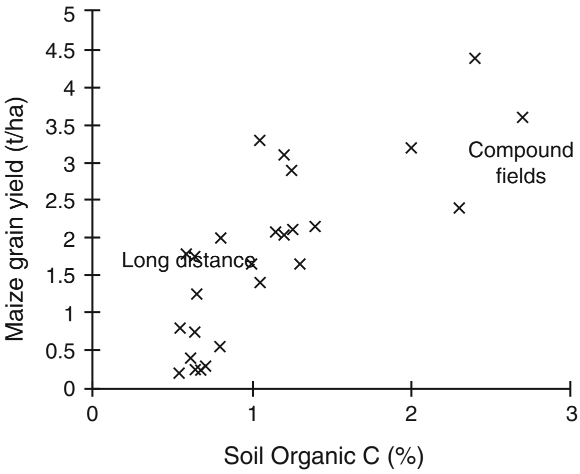

Fig. 1.1 Relationship between SOC content and maize grain yield for distant and compound fields in Northern Nigeria (Source: Carsky et al. 1998)

tons are applied (Bationo et al. 2004) (Fig. 1.1). Additionally, low and erratic rainfall, high ambient soil and air temperatures, inherent poor soil fertility, low water holding capacities and degraded soil structure lead to low crop productivity in this environment. Consequently, the present farming systems are not sustainable (Bationo and Buerkert 2001).

Transforming agriculture in West Africa agro-ecosystems and expanding its production capacity are prerequisites for alleviating rural poverty, household food deficits and environmental exploitation (Bationo et al. 2004).

Reversing the declining trend in agricultural productivity and preserving the environment for present and future generations in West Africa must begin with soil fertility restoration and maintenance (Bationo et al. 1996). Soil fertility is closely linked to soil organic matter, whose status depends on biomass input and management, mineralization, leaching and erosion (Roose and Barthes 2001; Nandwa 2001). It is well recognized that soil organic matter increases structure stability, resistance to rainfall impact, rate of infiltration and faunal activities (Roose and Barthes 2001). Optimum management of the soil resource for provision of goods and services requires the optimum management of organic resources, mineral inputs and the soil organic carbon (SOC) pool (Vanlauwe 2004). The importance of SOC has increased interest and research on its build up in the soil–plant system with current emphasis on conservation tillage. SOC can play an important role and its maintenance is an effective mechanism to combat land degradation and increase future food production. The SOM components such as humic molecules and polysaccharides increased aggregate stability by binding mineral particles into aggregates and reduced their susceptibility to erosion by wind or water (Tisdall and Oades 1982. In turn, formation of stable aggregates enhances physical protection of SOM against microbial decomposition (Six et al. 1998). Fertilizer additions also affect the chemical composition of soil solution which can be responsible for dispersion/flocculation of clay particles and thus, affects the soil aggregation stability (Haynes and Naidu 1998). Beneficial effects of increasing SOM concentration on enhancing soil structural stability have been widely documented (Barzegar et al. 1997). Reduction in SOM can degrade soil quality and fertility resulting in reduced agronomic productivity (Sharma and Subehia 2003). The SOM lowered the soil bulk density (Bronick and Lal 2005) and compaction (Dexter 1988), resulting in increased total porosity and water infiltration rate (Ndiaye et al. 2007).

Various farm practices have been employed to build SOC stocks in West Africa. Crop residue (CR) application as surface mulch can play an important role in the maintenance of SOC levels and productivity through increasing recycling of mineral nutrients, increasing fertilizer use efficiency, and improving soil physical and chemical properties and decreasing soil erosion. However, organic materials available for mulching are scarce due to low overall production levels of biomass in the region as well as their competitive use as fodder, construction material and cooking fuel (Lamers and Feil 1993). In a study to determine CR availability at farm level Baidu-Forson (1995) reported that at Diantandou in Niger with a long-term annual rainfall of 450 mm, an average of 1200 kg ha^{-1} of millet stover was produced at the end of the following year barely 250 kg ha^{-1} remained for mulching. Powel and Mohamed-Sallem (1987) showed that at least 50% of these large on-farm disappearance rates of millet stover could be attributed to livestock grazing. Animal manure has a similar role as residue mulching for the maintenance of soil productivity but it will require between 10 and 40 ha of dry season grazing and between 3 and 10 ha of rangeland of wet season grazing to maintain yields on 1 ha of cropland (Fernandez-Rivera et al. 1995). The potential of manure to maintain SOC levels and maintain crop production is thus limited by the number of animals and the size and quality of the rangeland. The potential livestock transfer of nutrients in West Africa is 2.5 kg N and 0.6 kg P ha^{-1} of cropland (de Leeuw et al. 1995).

Scarcity of organic matter calls for alternative options to increase its availability for improvement of SOC stock. Firstly, the application of mineral fertilizer is a prerequisite for more crop residues at the farm level and the maintenance of soil organic carbon in West African agro-ecosystems and therefore most research should focus on the improvement of nutrient use efficiency in order to offer to the smallholder farmers cost-effective mineral fertilizer recommendations. Secondly, recent success stories on increasing crop production and SOC at the farm level is as a result of the use of the dual purpose grain legumes having the ability to derive a large proportion of their N from biological N fixation, a low N harvest and substantial production of both grain and biomass. Legume residues can be used for improvement of soil organic carbon through litter fall, or for feeding livestock with the resultant manure being returned to the crop fields.

1.3 Soil Organic Carbon Status at Farm Level

SOC levels across fields on-farm show steep gradients resulting from long-term site-specific soil management by the farmer (Fig. 1.1). According to Prudencio (1993), SOC status of various fields within a farm in Burkina Faso showed great

Table 1.1 Carbon stocks of different subsystems in a typical upland farm in the Sudan-savanna zone

AEZ	pH (H_2O)	OC (g kg^{-1})
Home garden	6.7–8.3	11–22
Village field	5.7–7.0	5–10
Bush field	5.7–6.2	2–5

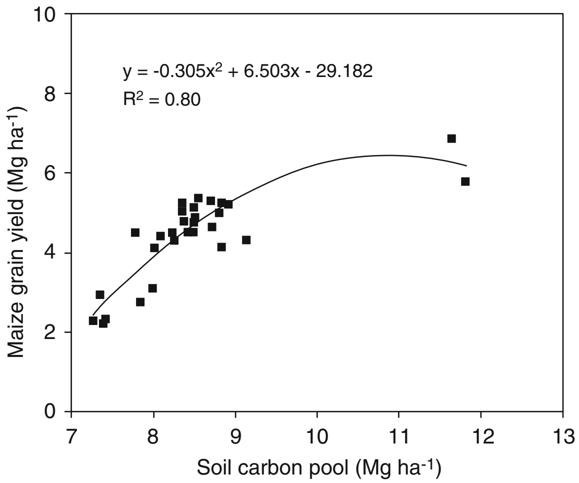

Fig. 1.2 Relationship between maize yield and soil organic carbon pool (Source: Brar et al. 2015)

variations with those of home gardens (located near the homestead) having 11–22 g kg^{-1} soil (Table 1.1), village field (at intermediate distance) 5–10 g kg^{-1} and bush field (furthest) having only 2–5 g kg^{-1}. Usually, fields closer to homesteads are supplied with more organic inputs as compared to distant fields. Manu et al. (1991) found that SOC contents were highly correlated with total N ($r = 0.97$) indicating that in the predominant agro-pastoral systems without application of mineral N, N nutrition of crops largely depends on the maintenance of SOC levels.

Crop yields increased by 490 kg ha^{-1} for maize wih every 1 Mg increase in SOC pool in the 0–15 cm depth under 100% NPK + FYM compared to 100% NPK treatment (Fig. 1.2). Lal (2006), also reported that crop yields increased by 20–70 kg ha^{-1} for wheat, 10–50 kg ha^{-1} for rice, and 30–300 kg ha^{-1} for maize with every 1 Mg increase in SOC pool in the surface 15 cm layer.

1.4 Fertilizer Use and Soil Organic Carbon Decline

Given the fundamental coupling of microbial C and N cycling, the dominant occurrence of both elements in SOM, and the close correlation between soil C and N mineralization, the practices that lead to loss of soil organic C also have serious implications for the storage of N in soil. Considerable evidence from

15 N-tracer investigations indicates that plant uptake is generally greater from native soil N than from N applied via fertilizers (Stevens et al. 2005). Thus, native soil N dictates the efficiency of applied fertilizer N as well as the quantity of N lost from the soil-plant system. Loss of organic N decreases soil productivity and the agronomic efficiency of fertilizer N and has been implicated in yield stagnation and the decline of grain production (Mulvaney et al. 2009). A decrease in soil N supply is inherently detrimental to productivity. Crop yields may be sustained or even increased by using improved varieties or due to higher fertilizer application rates despite the lower incremental return per unit of N applied, but eventually, soil degradation is likely to lead to a decline or stagnation in yield, an emerging concern for input-intensive agriculture. On the basis of the results of 45 long-term experiments ranging from 7 to 136 years in duration and mostly from temperate regions, Glendining and Powlson (1995) showed that long-term applications of N fertilizer increased total soil organic N as compared with treatments receiving no fertilizer N at 84% of the sites studied. On the other hand, in long-term experiments located in both temperate and tropical regions, continuous application of fertilizer N induced a net loss of soil organic N at 92% of the sites examined and a loss of soil organic C at 74%of the sites (Khan et al. 2007; Mulvaney et al. 2009).

Application of mineral fertilizer alone can cause decline in soil organic carbon. Pichot et al. (1981) reported from a ferruginous soil in Burkina Faso that with mineral fertilizer application, 25–50% of the indigenous organic matter disappeared during the first 2 years of cultivation. Bache and Heathcote, (1969), Mokwunye (1981), and Pichot et al., (1981) observed that continuous cultivation using mineral fertilizers increased nutrient leaching, lowered the base saturation and aggravated soil acidification. Also exchangeable aluminium was increased and crop yield declined. Application of organic material such as green manures, crop residues, compost, or animal manure can counteract the negative effects of mineral fertilizers (de Ridder and van Keulen 1990). This led Pieri (1986) to conclude that soil fertility in intensive arable farming in West Africa Semi-Arid Tropics (WASAT) can only be maintained through efficient recycling of organic material in combination with rotations of N2-fixing leguminous species and chemical fertilizers. In a long-term crop residue management trial in Sadore´, Niger during the 1996 rainy season, Bationo and Buerkert (2001) found that levels of SOC were 1.7 and 3.3 g kg^{-1}soil respectively, at 0.1 m for 2 ton ha^{-1} and 4 ton ha^{-1} of mulching with crop residue applied compared to unmulched plot (Fig. 1.3).

1.5 Conclusion

Soil organic carbon undoubtedly plays a key role in maintaining soil fertility and sustaining crop productivity in the soils in SSA. Given this importance, maintenance of an adequate level should be a guiding principle in developing management practices. However, just what constitutes an adequate level is likely to vary according to soil type, environmental conditions and farming systems. There are

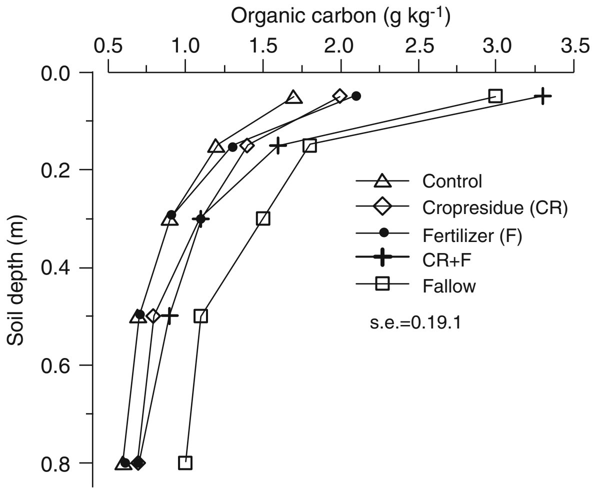

Fig. 1.3 Soil organic carbon (SOC) as affected by soil depth and management practices in Sadore´, Niger

numerous opportunities for improving soil carbon. Unfortunately the amount of organics available at farm level for use in soil improvement is limited by their alternatives uses as fuel, feed and fiber, and the labour required to collect and process these materials. Within most smallholder communities, the demand for animal manure is usually greater than its limited supply and in pastoral areas with substantial livestock, free grazing poses difficulties in collecting and transporting this important organic resource. These difficulties must not preclude the use of organic materials as inputs to soil but rather require that they be utilized in more labour efficient and cost effective ways. The use of inorganic fertilizer will remain an important option for increasing crop productivity and hence amount of residues available for the multiple uses among them soil improvement. The contribution of the organic resources to soil organic carbon will vary with the accompanying management and the quality of the resources. Integration of different qualities of organics is needed if the production objective is to achieve both immediate soil fertility and maintenance and crop improvement in the long term.

References

Bache, B. W., & Heathcote, R. G. (1969). Long-term effects of fertilizer and manures on soil and leaves of cotton in Nigeria. *Experimental Agriculture, 5*, 241–247.

Bai, Z. G., Dent, D. L., Olsson, L., & Schaepman, M. E. (2008). Proxy global assessment of land degradation. *Soil Use and Management, 24*, 223–234.

Baidu-Forson, J. (1995). Determinants of the availability of adequate millet stover for mulching in the Sahel. *Journal of Sustainable Agriculture, 5*, 101–116.

Barzegar, A. R., Nelson, P. N., Oades, J. M., & Rengasamy, P. (1997). Organic matter, sodicity, and clay type: Influence on soil aggregation. *Soil Science Society of America Journal, 61*, 1131–1137.

Bationo, A., & Buerkert, A. (2001). Soil organic carbon management for sustainable land use in Sudano-Sahelian West African. *Nutrient Cycling in Agroecosystems, 61*, 131–142.

Bationo, A., Rhodes, E., Smaling, E. M. A., & Visker, C. (1996). Technologies for restoring soil fertility. In A. U. Mokwunye, A. de Jager, & E. M. A. Smaling (Eds.), *Restoring and maintaining productivity of west African soils: Key to sustainable development*, *IFDC-Africa, LEIDLO and SC-DLO, miscellaneous fertilizer studies no. 14*. Muscle Shoals: International Fertilizer Development Center.

Bationo, A., Kimetu, J., Ikerra, S., Kimani, S., Mugendi, D., Odendo, M., Silver, M., Swift, M. J., & Sanginga, N. (2004). The African network for soil biology and fertility: New challenges and opportunities. In A. Bationo (Ed.), *Managing nutrient cycles to sustain soil fertility in Sub-Saharan Africa*. Nairobi: Academy Science Publishers.

Brar Singh, B., Singh, J., Singh, G., & Kaur, G. (2015). Effects of long term application of inorganic and organic fertilizers on soil organic carbon and physical properties in maize–wheat rotation. *Agronomy, 5*(2), 220–238.

Bronick, C. J., & Lal, R. (2005). Soil structure and management: A review. *Geoderma, 2005*(124), 3–22.

Carsky, R. J., Jagtap, S., Tian, G., Sanginga, N., & Vanlauwe, B. (1998). Maintenance of soil organic matter and N supply in the moist savanna zone of West Africa. In R. Lal (Ed.), *Soil quality and agricultural sustainability* (pp. 223–236). Chelsea: Ann Arbor Press.

de Leeuw, P.N., Reynolds, L., Rey, B., (1995). Nutrient transfers from livestock in West African agricultural systems. In J.M. Powell, S. Fernandez-Rivera, T.O. Williams, , C. Renard (Eds.), Livestock and sustainable nutrient cycling in mixed farming Systems of sub-Saharan Africa, vol II. Technical papers. *Proceedings of an international conference held in Addis-Ababa, 22–26 November 1993*. ILCA (International Livestock Center for Africa) , Addis Ababa, p. 569.

de Ridder, N., & van Keulen, H. (1990). Some aspects of the role of organic matter in sustainable intensified arable farming systems in the West African semi-arid tropics. *Fertilizer Research, 26*, 299–310.

Dexter, A. (1988). Advances in characterization of soil structure. *Soil and Tillage Research, 1988* (11), 199–238.

Fernandez-Rivera, S., Williams, T. O., Hiernaux, P., & Powell, J. M. (1995). Livestock, feed, and manure availability for crop production in semi-arid West Africa. In J. M. Powell, S. - Fernandez-Rivera, T. O. Williams, & C. Renard (Eds.), *Livestock and sustainable nutrient cycling in mixed farming systems of sub-Saharan Africa* (pp. 149–170). Addis Ababa: International Livestock Centre for Africa.

Glendining, M. J., & Powlson, D. S. (1995). The effects of long continued applications of inorganic nitrogen fertilizer on soil organic nitrogen – A review. In R. Lal & B. A. Stewart (Eds.), *Soil management: Experimental basis for sustainability and environmental quality, advances in soil science series* (pp. 385–446). Boca Raton: Lewis.

Haynes, R., & Naidu, R. (1998). Influence of lime, fertilizer and manure applications on soil organic mattercontent and soil physical conditions: A review. *Nutrient Cycling in Agroecosystems, 51*, 123–137.

Katyal, J. C., Rao, N. H., & Reddy, M. N. (2001). Critical aspects of organic matter management in the tropics: The example of India. *Nutrient Cycling in Agroecosystems, 61*, 77–88.

Khan, S. A., Mulvaney, R. L., Ellsworth, T. R., & Boast, C. W. (2007). The myth of nitrogen fertilization for soil carbon sequestration. *Journal of Environmental Quality, 36*, 1821–1832.

Lal, R. (2006). Enhancing crop yields in the developing countries through restoration of the soil organiccarbon pool in agricultural lands. *Land Degradation and Development, 17*, 197–209.

Lamers, J. P. A., & Feil, P. (1993). The many uses of millet residues. *ILEA Newsletter, 9*, 15.

Loveland, P., & Webb, J. (2003). Is there a critical level of organic matter in the agricultural soils of temperate regions: A review. *Soil & Tillage Research, 70*, 1–18.

Manu, A., Bationo, A., & Geiger, S. C. (1991). Fertility status of selected millet producing soils of West Africa with emphasis on phosphorus. *Soil Science, 152*, 315–320.

Mokwunye, A. U. (1981). Phosphorus fertilizers in Nigerian savanna soils. III. Effects of three phosphorus sources on available cations of a soil at Samaru. *Journal of Agricultural Research, 6*, 21–24.

Mulvaney, R. L., Khan, S. A., & Ellsworth, T. R. (2009). Synthetic nitrogen fertilizers deplete soil nitrogen: A global dilemma for sustainable cereal production. *Journal of Environmental Quality, 38*, 2295–2314.

Nandwa, S. M. (2001). Soil organic carbon (SOC) management for sustainable productivity of cropping and agro-forestry systems in eastern and southern Africa. *Nutrient Cycling in Agroecosystems, 61*, 143–158.

Ndiaye, B., Molénat, J., Hallaire, V., Gascuel, C., & Hamon, Y. (2007). Effects of agricultural practices on hydraulic properties and water movement in soils in Brittany (France). *Soil and Tillage Research, 2007*(93), 251–263.

Pichot, J., Sedogo, M. P., Poulain, J. F., & Arrivets, J. (1981). Evolution de la fertilité d'un sol ferrugineux tropical sous l'influence de fumures minerales et organiques. *Agronomie Tropicale, 36*, 122–133.

Pieri, C. (1986). Fertilisation des cultures vivrie'res et fertilite´ des sols en agriculture paysanne subsaharienne. *Agronomie Tropicale, 41*, 1–20.

Powel, J. M., & Mohamed-Sallem, M. A. (1987). Nitrogen and phosphorus transfers in a crop-livestock system in West Africa. *Agricultural Systems, 25*, 261–277.

Prudencio, C. Y. (1993). Ring management of soils and crops in the West African semi-arid tropics: The case of the mossi farming system in Burkina Faso. *Agriculture, Ecosystems and Environment, 47*, 237–264.

Roose, E., & Barthes, B. (2001). Organic matter management for soil conservation and productivity restoration in Africa: A contribution from francophone research. *Nutrient Cycling in Agroecosystems, 61*, 159–170.

Sharma, S., & Subehia, S. (2003). Effects of twenty-five years of fertilizer use on maize and wheat yields and quality of an acidic soil in the western himalayas. *Experimental Agriculture, 2003* (39), 55–64.

Six, J., Elliott, E., Paustian, K., & Doran, J. (1998). Aggregation and soil organic matter accumulation incultivated and native grassland soils. *Soil Science Society of America Journal, 62*, 1367–1377.

Sombroek, W. G., Nachtergaele, F. O., & Hebel, A. (1993). Amounts, dynamics and sequestrations of carbon in tropical and subtropical soils. *Ambio, 22*, 417–426.

Stevens, W. B., Hoeft, R. G., & Mulvaney, R. L. (2005). Fate of nitrogen-15 in a long-term nitrogen rate study: II. Nitrogen uptake efficiency. *Agronomy Journal, 97*, 1046–1053.

Stoorvoge J, Smaling EM, (1990). *Assessment of soil nutrient depletion in sub-Saharan Africa: 1983–2000 main report* (vol. 1). The Winand Staring Center, Wageningen, the Netherlands.

Tisdall, J., & Oades, J. M. (1982). Organic matter and water—Stable aggregates in soils. *Journal of Soil Science, 1982*(33), 141–163.

Vanlauwe, B. (2004). Integrated soil fertility management research at TSBF: The framework, the principles, and their application. In A. Bationo (Ed.), *Managing nutrient cycles to sustain soil fertility in Sub-Saharan Africa*. Nairobi: Academy Science Publishers.