Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Agricultural Systems xxx (2006) xxx–xxx
AGRICULTURAL SYSTEMS
www.elsevier.com/locate/agsy

Soil organic carbon dynamics, functions and management in West African agro-ecosystems

Andre Bationo *, Job Kihara, Bernard Vanlauwe, Boaz Waswa, Joseph Kimetu

Tropical Soil Biology and Fertility Institute of CIAT (TSBF-CIAT), P.O. Box 30677-00100, Nairobi, Kenya

Received 8 February 2005; accepted 18 August 2005

Abstract

Soil fertility depletion has been described as the single most important constraint to food security in West Africa. Over half of the African population is rural and directly dependent on locally grown crops. Further, 28% of the population is chronically hungry and over half of people are living on less than US$ 1 per day as a result of soil fertility depletion.

Soil organic carbon (SOC) is simultaneously a source and sink for nutrients and plays a vital role in soil fertility maintenance. In most parts of West Africa agro-ecosystems (except the forest zone), the soils are inherently low in SOC. The low SOC content is due to the low shoot and root growth of crops and natural vegetation, the rapid turnover rates of organic material as a result of high soil temperatures and fauna activity particularly termites and the low soil clay content. With kaolinite as the main clay type, the cation exchange capacity of the soils in this region, often less that 1 cmol kg^{-1}, depends heavily on the SOC. There is a rapid decline of SOC levels 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%. 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. There is need to increase crop biomass at farm level and future research should focus on improvement of nutrient use efficiency in order to increase crop biomass. Research should also focus on ways of alleviating socio-economic constraints in order to increase the legume component in the cropping systems. This will produce higher quality fodder for the livestock and also increase biomass at farm-level. This paper reviews various strategies and lessons learnt in improving soil organic carbon status in West Africa soils.
© 2006 Published by Elsevier Ltd.

Keywords: Nutrient use efficiency; Organic residues; Soil fertility; Soil organic carbon; West Africa

1. Introduction

Over half of the African population is rural, and directly dependent on locally grown crops or foods harvested from the immediate environment. The growth rate for cereals grain yield is about 1% while population growth is about 3% (UN, 2001). During the last 35 years, per capita cereals production has decreased from 150 to 130 kg/person, whereas in Asia and Latin America an increase from about 200–250 kg/person has been observed (FAO, 2001). Labor and land productivity in Africa are among the lowest in the world. Per capita food production in Africa has been declining over the past two decades, contrary to the global trend. Annual cereal deficit in sub-Saharan Africa amounts to 100 million tons and the food gap (requirements minus production) is widening. Food imports increased by about 185% between 1974 and 1990 while food aid increased by 295% (ECA, 2002). The average African consumes only about 87% of the calories needed for a healthy and productive life. Sixteen percent (16%) of Africa's current arable land base is so eroded that agriculturally it cannot be useful any longer. In addition to this, 70% of deforestation is caused by farmers who in their quest for food have no

* Corresponding author. Tel.: +254 20 7224755/59.
E-mail address: a.bationo@cgiar.org (A. Bationo).

0308-521X/$ - see front matter © 2006 Published by Elsevier Ltd.
doi:10.1016/j.agsy.2005.08.011

UNCORRECTED PROOF

incentive to ponder about long-term environmental consequences (ECA, 2002; FAO, 2001).

The Sudano-Sahelian zone of West Africa is the home of the world's poorest people, 90% of whom live in villages and gain their livelihood from subsistence agriculture (Bationo and Buerkert, 2001). Per capita food production has declined significantly over the past three decades. According to FAO (2003), total food production in Sahelian countries grew by an impressive 70% from 1961 to 1996, but it lagged behind as the population doubled causing per capita food production to decline by approximately 30% over the same period.

Increasing human population pressure has decreased the availability of arable land and it is no longer feasible to use extended fallow periods to restore soil fertility. The fallow period which would have restored soil fertility and organic carbon is reduced to lengths that cannot regenerate soil productivity leading to the non-sustainability of the farming systems (Nandwa, 2001). High population densities have necessitated the cultivation of marginal lands that are prone to erosion hence enhancing environmental degradation through soil erosion and nutrient mining. As a result, the increase in yield has been more due to land expansion than to crop improvement potential (FAO, 2003). For example, the 7.6% yield increase of yam in West Africa was mainly due to an area increase of 7.2% and only 0.4% due to improvement in crop productivity itself (Table 1).

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 tons are applied (Bationo et al., 2004a) (Fig. 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., 2004a). 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.

Various farm practices have been employed to build SOC stocks in West Africa. Crop (CR) residue 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 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

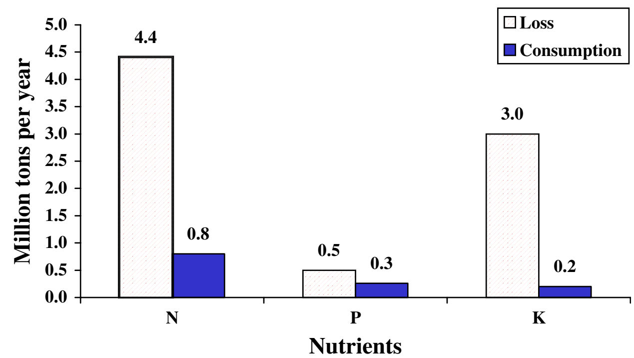

Fig. 1. Nutrient losses versus application rate in Africa.

Table 1
Percentage annual increase in crop yield due to land expansion and crop improvement potential in West Africa

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

Based on 3-year average for 1988–1990 and 1998–2000.
Source: FAO (2003).

UNCORRECTED PROOF

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 the use of the dual purpose grain legumes having 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.

The impact of organic resource quality on SOC is less clear. Low quality organic resources contain substantial amounts of soluble polyphenols and lignins that may affect the longer-term decomposition dynamics and contribute to the build up of SOC (Palm et al., 2001). Future research needs to focus more on whether the organic resource quality concept is also useful for predicting different degrees of stabilization of applied organic C in one or more of the organic matter pools.

The challenge in increasing SOC content is to embrace the holistic strategy of Integrated Soil Fertility Management (ISFM) that puts into consideration the biophysical and socio-economic constraints faced by the farmer community. The implementation of the ISFM strategy will break the vicious cycle responsible for land degradation, food insecurity and poverty in West Africa agro-ecosystems through improved knowledge of soil management and the capacity of farmers to invest in improved soil management technologies (Fig. 2).

This paper will discuss first the status of soil organic carbon at agro-ecosystem and farm level followed by the factors affecting SOC and functions of SOC before discussing the effects of soil and crop management on SOC and concluding on the future research challenges with emphasis on SOC quantity and quality.

2. Soil organic carbon status at agro-ecosystem and farm level

Soil organic carbon is an index of sustainable land management (Woomer et al., 1994; Nandwa, 2001) and is critical in determining response to N and P fertilization. There is however no clear agreement on the level of SOC below which response to N and P fertilization does not occur. For example, while Berger et al. (1987) reported such level to be 3.5 mg kg^{-1} in the northern Guinean zone, Bationo et al. (1998) in a study in West Africa found very strong response to mineral fertilizer at SOC levels as low as 1.7 mg kg^{-1}.

Total system carbon in different vegetation and land use types indicates that forests, woodland and parkland have the highest total and aboveground carbon contents (Fig. 3) demonstrating potential for carbon sequestration. For example, total system carbon in the Senegal River valley was 115 ton ha^{-1} in the forest zone and only 18 ton ha^{-1} when the land was under cultivation. Cultivated systems have reduced carbon contents due to reduced tree cover and increased mineralization due to surface disturbance. Windmeijer and Andriesse (1993) found levels of SOC for equatorial forest, Guinea savanna and Sudan savanna to be 24.5, 11.7, and 3.3 g kg^{-1}, respectively, and showed positive correlation with both N and P (Table 2).

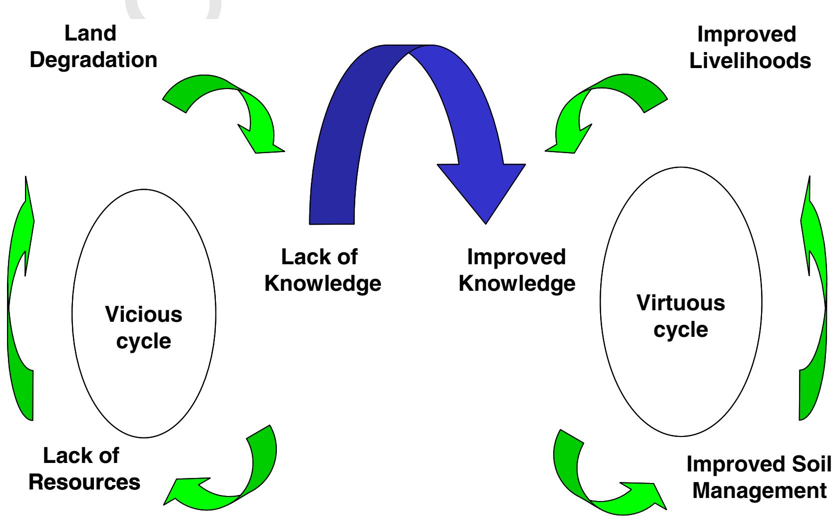

Fig. 2. The vicious and virtuous cycles of land degradation and soil fertility management.

Please cite this article as: Andre Bationo et al., Soil organic carbon dynamics, functions and management ..., Agricultural Systems (2006), doi:10.1016/j.agsy.2005.08.011

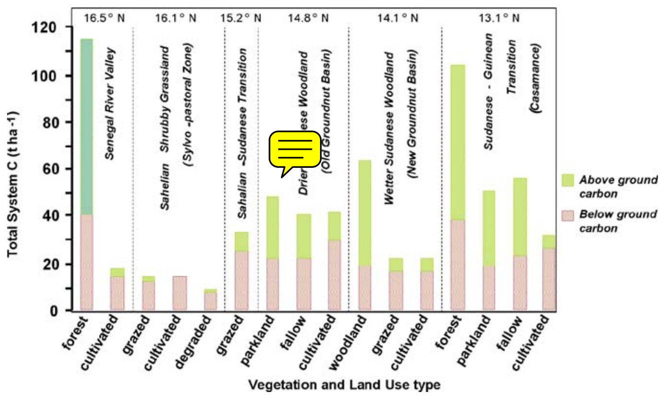

Fig. 3. Total system carbon in different agro-ecosystems and land use in West Africa.

Table 2
Carbon stocks and other fertility indicators of granitic soils in different agro-ecological zones in West Africa

AEZ	pH (H_2O)	OC (g kg^{-1})	Total N (g kg^{-1})	Total P (mg kg^{-1})
Equatorial forest	5.3	24.5	1.6	628
Guinea savanna	5.7	11.7	1.39	392
Sudan savanna	6.8	3.3	0.49	287

Source: Windmeijer and Andriesse (1993).

SOC levels across fields on-farm show steep gradients resulting from long-term site-specific soil management by the farmer. According to Prudencio (1993), SOC status of various fields within a farm in Burkina Faso showed great variations with home gardens (located near the homestead) having 11–22 g kg^{-1} (Table 3), village field (at intermediate distance) 5–10 g $kg^{-1}$and bush field (furthest) having only 2–5 g kg^{-1}. Usually, closer fields are supplied with more organic inputs as compared to distant fields due to the labor factor. 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.

3. Factors affecting SOC

Clay and silt play an important role in the stabilization of organic compounds and small variations in topsoil texture could have large effects on SOC (Bationo and Buerkert, 2001). In this context, a survey of West African soils (Manu et al., 1991) indicated that for the soils investigated cation exchange capacity (CEC) depended directly more on SOC ($r = 0.86$) than to soil clay content ($r = 0.46$) (Table 4). de Ridder and van Keulen (1990) found a difference of 1 g kg^{-1} in SOC to result in a difference of 0.25 cmol kg^{-1} for soil CEC.

Fig. 4 shows the relationship between silt and clay associated carbon and soil texture in different ecosystems and reflects the capacity of soil to preserve C based on its silt and clay particles. Carbon content and status in the soil is closely associated with clay and silt contents and clay type, which influences the stabilization of organic carbon. Aggregates physically protect SOC through formation of barriers between microbes and enzymes and their substrates thereby controlling microbial turnover (Six et al., 2002a,b).

Table 4
Correlation (r) between selected soil (0–20 cm) fertility parameters and average annual rainfall

	Ca	CEC	SOC	Total N	Clay	Rainfall
pH KCl	0.62^{***}	0.64^{***}	0.65^{***}	0.62^{***}	−0.02	0.25^{**}
Ca		0.98^{***}	0.88^{***}	0.92^{***}	0.36^{***}	0.31^{***}
CEC			0.86^{***}	0.91^{***}	0.40^{***}	0.36^{***}
SOC				0.97^{***}	0.46^{***}	0.42^{***}
Total N					0.44^{***}	0.34^{***}
Clay						0.40^{***}

** and *** indicates statistical significance at the 0.05 and 0.001 level, respectively.
Source: Manu et al. (1991).

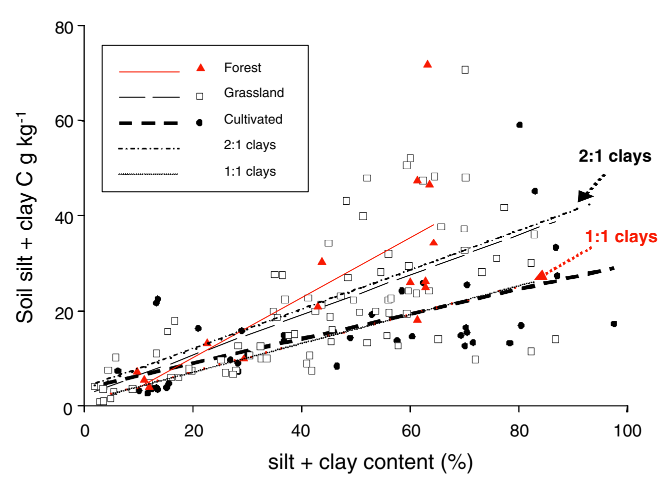

Fig. 4. Relationship between silt + clay content (0–20 μm) and silt + clay associated carbon for different systems.

Table 3
Carbon stocks of different subsystems in a typical upland farm in the Sudan-savanna zone

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

Source: Prudencio (1993).

UNCORRECTED PROOF

Please cite this article as: Andre Bationo et al., Soil organic carbon dynamics, functions and management ..., Agricultural Systems (2006), doi:10.1016/j.agsy.2005.08.011

4. Functions of soil organic carbon (SOC)

SOC plays an important role in supplying plant nutrients, enhancing cation exchange capacity, improving soil aggregation and water retention and supporting soil biological activity (Dudal and Deckers, 1993). Although it has been difficult to quantify the effects of SOC on crop and ecosystem productivity (Dudal and Deckers, 1993) results from experiments in some African countries already indicate favorable responses due to SOC.

Soil organic matter is not only a major regulator of various processes underlying the supply of nutrients and the creation of a favorable environment for plant growth but also regulates various processes governing the creation of soil-based environmental services (Fig. 5) (Vanlauwe, 2004). Therefore, SOC plays a vital role in crop production and environmental services.

4.1. Crop production

As already indicated, there is a steep gradient in SOC status between a field at the farm level scale caused by long-term site-specific soil management by farmers (Table 4). As shown in Fig. 6, high SOC status in the homestead fields is observed to relate positively with crop yields. This is due to multiple factors of production affected by SOC content (Swift and Woomer, 1993).

Over a period of 4 years in the Sahel, pearl millet yields on homestead fields with higher organic carbon were always significantly higher than yields in the bush fields lower in SOC content (Fig. 7).

Several scientists have reported the effect of organic amendments on crop yield increases partly due to effects of SOC (Abdulahi and Lombin, 1978; Mokwunye, 1980; Pichot et al., 1981; Pieri, 1986; Powell, 1986; de Ridder and van Keulen, 1990; Bationo and Mokwunye, 1991; Bationo et al., 1995, 1998). Research results from long-term field experiments in the West African agro-ecosystems

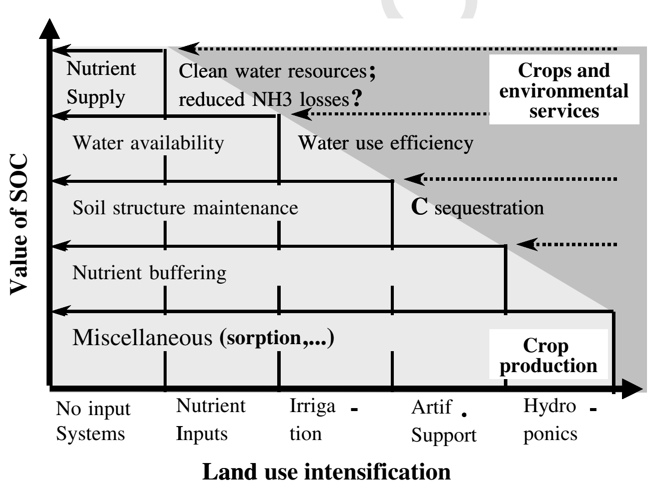

Fig. 5. Different functions of SOC and their regulation at different land intensification systems. (Adapted from Vanlauwe (2004).)

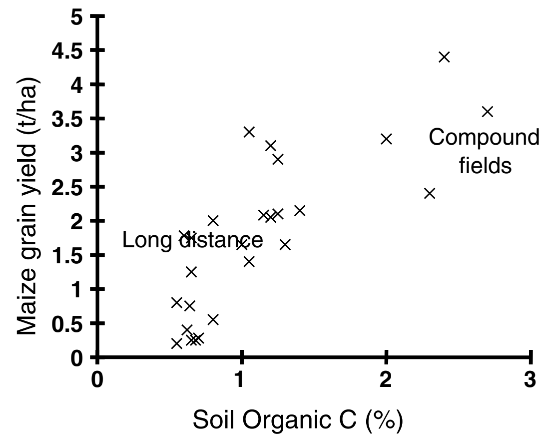

Fig. 6. Relationship between SOC content and maize grain yield for distant and compound fields in Northern Nigeria. Source: Carsky et al. (1998).

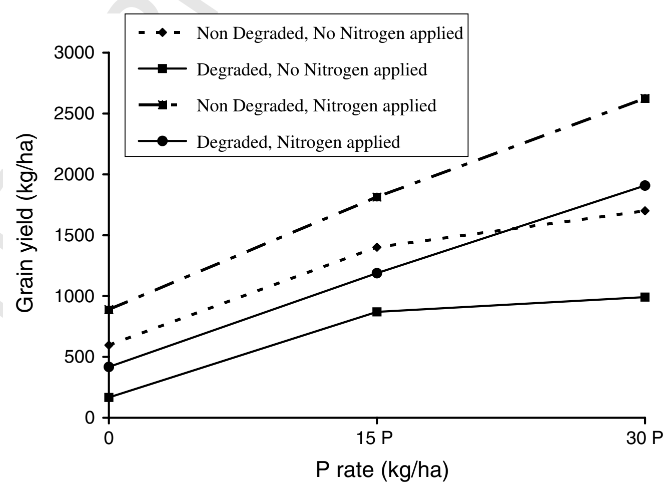

Fig. 7. Effect of SOC content on millet production in Karabedji, Niger in 2002.

showed that the use of mineral fertilizers without recycling of organic materials resulted in higher yields, but this increase was not sustainable (Bationo et al., 2004b).

As a result of the higher organic carbon content in mulched plots, Bationo et al. (1993) reported a large positive and additive effect of crop residue and mineral fertilizer application on pearl millet yield (Table 5). Over the duration of the study, grain yield in control plots (no fertilizer, no crop residue) were low and steadily declined. This indicated that the potential for continuous millet production on these soils is very limited in the absence of soil amendments. Except for the drought year in 1984, fertilizer application resulted in an approximately tenfold increase compared to the control. Since the P fixation of the sandy soils of the Sahel is low (Mokwunye et al., 1986) and residual effects of P-fertilizer application are evident even after three years, the use of P-fertilizer has important implications for sustainable soil management. The availability of cheap P fertilizers to small farmers may induce them to cultivate less land more intensively thereby leaving more area

Table 5
Effect of crop residue and fertilizer on pearl millet grain and stover yields at Sadore, Niger

	Grain yields (kg ha^{-1})				Stover yield (kg ha^{-1})			
	1983	1984	1985	1986	1983	1984	1985	1986
Control	280	215	160	75	NA	900	1100	1030
Crop residue (no fertilizer)	400	370	770	745	NA	1175	2950	2880
Fertilizer (no crop residue)	1040	460	1030	815	NA	1175	3540	3420
Crop residue plus fertilizer	1210	390	1940	1530	NA	1300	6650	5690
$LSD_{0.05}$	260	210	180	200		530	650	870

NA, not available.

under fallow or pasture. This, in turn, would decrease the negative effects of wind and water erosion on the soil productivity.

4.2. *Ecosystem services*

The relevance of SOC in regulating soil fertility decreases as natural capital is being replaced by manufactured or financial capital with increasing land use intensification (Fig. 5) (Vanlauwe, 2004).

Carbon sequestration has gained momentum in the recent decade and the amount of carbon in a system is a good measure of sustainability. The current importance on this subject is because carbon lost from these systems contributes significantly to atmospheric change, particularly CO_2 concentration (Woomer and Palm, 1998). Estimates of carbon stocks within different land management and cropping systems are an important element in the design of land use systems that protect or sequester carbon (*Ibid*). Tropical countries offer a large potential of carbon sequestration through reforestation and improvement of degraded agroecosystems (Dixon et al., 1993). The limited studies in small hold agricultural farms in Africa have already illustrated significant increases in system carbon and productivity through organic-inorganic resources management (Woomer et al., 1997; Roose and Barthes, 2001). The data in Table 6 indicates that cereal biomass production can be increased by over five times from 1030 to 5690 kg ha^{-1} when both crop residue and fertilizer are used in production. It is obvious that the application of crop residue and fertilizer will increase both below and above ground carbon sequestration.

Soil organic carbon plays an important role in ensuring good health of the soil environment and is critical in providing needed ecosystem services (Fig. 5). A higher content of SOC will result in a higher Fertilizer Use Efficiency (FUE) (Fig. 7). For example, as a consequence of higher SOC content in the homestead fields, fertilizer use efficiency was higher as compared to the bush field. With application of 26 kg P ha^{-1} in Karabedji Niger in 2000, P use efficiency was 42% in the degraded site as compared to 79% in the non-degraded site (Fig. 6). Comparative data of P FUE with and without crop residues mulch application in the Sahel clearly indicate better fertilizer use efficiency with organic amendments which improve SOC (Table 6).

Table 6
Increase in incremental millet grain and stover yield due to fertilizer application in Sadore, Niger

Year	Treatment	Fertilizer effect (kg kg^{-} P applied)	
		Grain	Stover
1983	Fertilizer	59[a]	NA
	Crop residues + fertilizer	72[b]	NA
1984	Fertilizer	34	21
	Crop residues + fertilizer	14	31
1985	Fertilizer	67	188
	Crop residues + fertilizer	137	427
1986	Fertilizer	57	184
	Crop residues + fertilizer	112	359

Source: Bationo et al. (1995).
NA, not available.
[a] Calculated as (Yield Fertilizer – Yield Control)/P applied.
[b] Calculated as (Yield Crop Residues + Fertilizer – Yield Control)/P applied.

The addition of manure and crop residue either alone or in combination with inorganic fertilizers frequently resulted in a substantial decrease in the soil's capacity to fix P. The maximum sorption of phosphorus calculated using the Langmuir Equation (Langmuir, 1918) decreased with the application of organic material (Fig. 8). This may partly explain the demonstrated increase of P-fertilizer use efficiency with organic inputs. In laboratory experiments using the sandy Sahelian soils of West Africa, Kretzschmar et al. (1991) found that the addition of crop residue resulted in an increased P availability which was attributed to the complexing of iron and aluminium by organic acids (Bationo et al., 1995).

5. Effect of soil and crop management on soil organic carbon

Soil organic carbon is lost through erosion, runoff and leaching (Roose and Barthes, 2001). Erosion and runoff contribute a large portion of carbon losses and these are highly accelerated in cultivated land as compared to undisturbed forest or savanna (Table 7). Topsoil nutrients and organic carbon generally decrease with increasing erosion (Kaihura et al., 1998) with the amount of eroded carbon depending more on the erosion quantity than on the carbon content of the eroded sediments (Roose, 1980).

UNCORRECTED PROOF

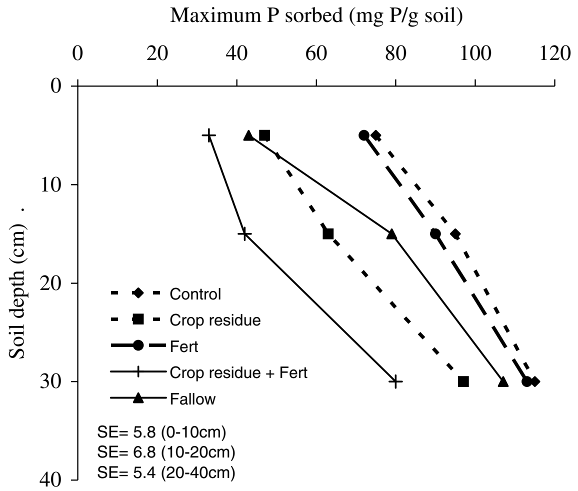

Fig. 8. Effect of soil amendments on maximum phosphorus sorbed in Sadore, Niger, 1991 (Source: Bationo et al. (1995)).

The importance of soil textural (clay and silt) properties for the SOC content of soils was stressed repeatedly as clays are an important component in the direct stabilization of organic molecules and microorganisms (Amato and Ladd, 1992; Feller et al., 1992). Thus Feller et al. (1992) reported that independent of climatic variations such as precipitation, temperature, and duration of the dry season, SOC increased with the clay and silt contents but there was a poor relationship with the amount of rainfall. Therefore, small variations in topsoil texture at the field or watershed level could have large effects on SOC.

There is much evidence for a rapid decline of SOC levels with continuous cultivation of crops in West Africa (Bationo et al., 1995). For the sandy soils, average annual losses in SOC, often expressed by the *k*-value (calculated as the percentage of organic carbon lost per year), may be as high as 4.7%, whereas for sandy loam soils, reported losses seem much lower at an average of 2% (Pieri, 1989; Table 9). Topsoil erosion may lead to significant increases in annual SOC losses of 2–6.3% at the Centre de Formation des Jeunes Agriculteurs (CFJA) in Burkina Faso (Table 8). However, such declines are site-specific and heavily depend on management practices such as the choice of the cropping system, soil tillage and the application of mineral and organic soil amendments (Zougmore, 2003; Ouedraogo, 2004).

Farming systems and cultural practices such as minimum tillage with crop residue can change erosion rate and SOC balance quite rapidly (Roose and Barthes, 2001; Six et al., 2002a). Accelerated mineralization following land clearing and continuous cropping has been reported to decrease SOC by up to 30% (Gregorich et al., 1998; Nandwa, 2001). Similarly, carbon losses by erosion from cropped land can be 4–20 times higher than on natural sites (Roose and Barthes, 2001). In a study by Roose and Barthes (2001) in Cameroon, a sharp decline in SOC was observed in the top layer (0–10 cm depth) of the conventional tillage sites due to accelerated mineralization. Under minimum tillage system, the decrease in SOC was slower because the topsoil was less disturbed. Pieri (1989) reported that without mineral fertilizer application, soil tillage increased the annual rate of SOC losses from 3.8% (with manual tillage) to 4.7% and 5.2% following light and heavy tillage respectively.

Rotations and intercropping systems have been reported by several authors to contribute to conservation of SOC. In Chad, cotton–cereal rotations reduced SOC losses from 2.8% in continuous cotton system to 2.4% in rotation systems (Pieri, 1989). Similarly, a rotation trial at Sadoré in the Sahel revealed significant effects of crop rotation on SOC contents. After 5 years, SOC levels were 2.8 g kg^{-1} in millet/cowpea intercrop plots that were rotated with pure cowpea compared to continuous millet plots with 2.2 g SOC kg^{-1} (Bationo and Buerkert, 2001). The higher SOC level in the cowpea system was at least partly due to the falling of leaves from the legume crop (Fig. 9).

Mulching decreases soil temperature, maintains favorable soil structure and infiltration rate, and enhance microbial and mesofaunal activities (Lal, 1975; Roose and Barthes, 2001). Mulches also contribute to carbon stock through their mineralization and the effect of reduced erosion (Nandwa, 2001).

Lone application of mineral fertilizer 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

UNCORRECTED PROOF

Table 7
Carbon losses (kg ha^{-1} yr^{-1}) by erosion, runoff and leaching in the topsoil (30 cm) in runoff plots at Adiopodoume, Korogho (Ivory Coast) and Saria (Burkina Faso)

	Adiopodoume (2100 mm rainfall)		Korogho (1300 mm rainfall)		Saria (800 mm rainfall)	
	Sub-equatorial forest (undisturbed)	Cereal cultivation	Sudanian savanna (Undisturbed)	Cereal with fertilizers	Sudano-Sahelian savanna (undisturbed)	Cereal cultivation
Erosion	13	1801	6	65	9	150
Runoff	1	65	2	18	1	5
Leaching	74	7	13	3	2	1
Total	88	1873	21	86	12	156

Adopted from Roose and Barthes (2001).

Please cite this article as: Andre Bationo et al., Soil organic carbon dynamics, functions and management ..., Agricultural Systems (2006), doi:10.1016/j.agsy.2005.08.011

Table 8
Annual loss rates of soil organic carbon measured at selected research stations in the SSWA

Place and source	Dominant cultural succession	Observations	Clay + Silt (%) (0–0.2 m)	Annual loss rates of soil organic carbon (*k*): Years of measurement	*k* (%)
Burkina Faso, with tillage					
Saria, INERA-IRAT	Sorghum monoculture	Without fertilizer	12	10	1.5
	Sorghum monoculture	Low fertilizer (lf)	12	10	1.9
	Sorghum monoculture	High fertilizer (hf)	12	10	2.6
	Sorghum monoculture	lf + crop residues	12	10	2.2
CFJA, INERA-IRCT	Cotton–cereals	Eroded watershed	19	15	6.3
Senegal, with tillage					
Bambey, ISRA-IRAT	Millet–groundnut	Without fertilizer	3	5	7.0
	Millet–groundnut	With fertilizer	3	5	4.3
	Millet–groundnut	Fertilizer + straw	3	5	6.0
Bambey, ISRA-IRAT	Millet monoculture	with PK fertilizer + tillage	4	3	4.6
Nioro-du-Rip, IRAT-ISRA	Cereal–leguminous	F0T0	11	17	3.8
	Cereal–leguminous	F0T2	11	17	5.2
	Cereal–leguminous	F2T0	11	17	3.2
	Cereal–leguminous	F2T2	11	17	3.9
	Cereal–leguminous	F1T1	11	17	4.7
Chad, with tillage					
Bebedjia, IRCT-IRA	Cotton monoculture		11	20	2.8
	Cotton–cereals			20	2.4
	+2 years fallow			20	1.2
	+4 years fallow			20	0.5

Source: Pieri (1989).
*F*0 = no fertilizer, *F*1 = 200 kg ha^{-1} of NPK fertilizer, *F*2 = 400 kg ha^{-1} of NPK fertilizer + Taiba phosphate rock, *T*0 = manual tillage, *T*1 = light tillage, *T*2 = heavy tillage.

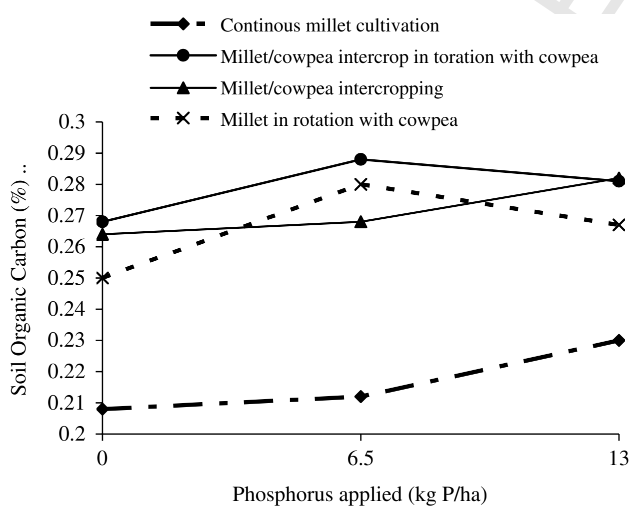

Fig. 9. Effect of cropping system and phosphorus on SOC in Sadore, Niger in 1995.

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 N_2-fixing leguminous species and chemical fertilizers.

In a long-term crop residue management trial in the Sadoré, Niger during the 1996 rainy season, Bationo and Buerkert (2001) found that levels of SOC were 1.7 g kg^{-1} and 3.3 g kg^{-1}, 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. 10).

The data in Table 9 shows that manure collected from stables and applied alone produced 20–60 kg N ha^{-1} in cereal grain and 70–178 kg of N ha^{-1} in stover per tonne of manure.

The data in Table 10 indicates that the application of 3 t ha^{-1} of manure plus urine produced grain and total biomass that were three to four times higher compared to when only manure was applied. Further, crop response to sheep manure was greater than to cattle manure. Research studies indicate that approximately 80–90% of the N, P, and K consumed by livestock is excreted (Mentis, 1981). Whereas N is voided in both urine and dung, most P is voided in dung (ARC, 1980).

Please cite this article as: Andre Bationo et al., Soil organic carbon dynamics, functions and management ..., Agricultural Systems (2006), doi:10.1016/j.agsy.2005.08.011

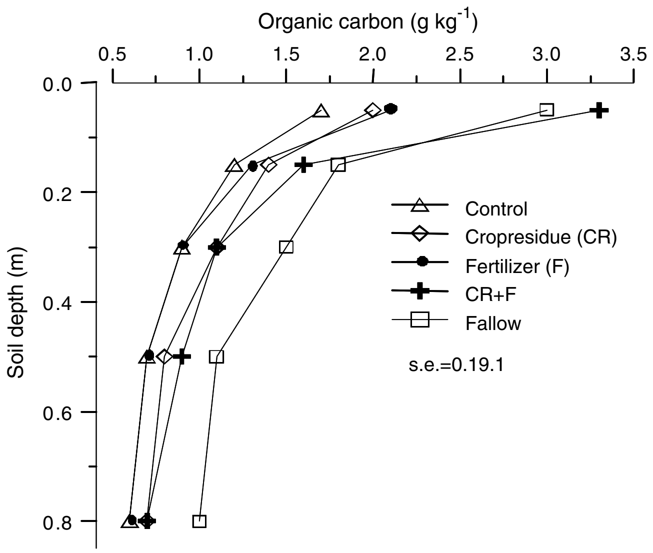

Fig. 10. Soil organic carbon (SOC) as affected by soil depth and management practices in Sadoré, Niger.

One important conclusion that emerges from the long-term experiments in West Africa is that application of mineral fertilizers is an effective technique for increasing crop yields in the Sudanian zone of West Africa. However for sustainability, higher production can be obtained when inorganic fertilizers are combined with manure (Fig. 11).

As previously indicated, SOC is significantly higher in rotation or intercropping systems of pearl millet and cowpea and this is one of the reasons for higher productivity of millet in the rotation than in the monoculture system (Fig. 12).

Fig. 13 gives a schematic representation of the different uses of crop residues. Traditionally, many farmers burnt whatever was left of their crop residue once their needs for fuel, animal feed, or housing and fencing material had been fulfilled. In West Africa, grazing animals remove more biomass and nutrients from cropland than they return in the form of manure. Therefore, Breman and Traore (1986) concluded that a sustainable nutrient supply in the southern Sahel based on a net transfer of nutrients from rangelands to cropland required between 4 and 40 ha of rangeland per hectare of cropland.

Availability of organic inputs in sufficient quantities and quality is one of the main challenges facing farmers and researchers today. In an inventory of crop residue availability in the Sudanian zone of central Burkina Faso, Sedga (1991) concluded that the production of cereal straw can meet the currently recommended optimum level of 5 ton ha^{-1} every 2 years. For the Sahelian zone, field experiments in millet showed that from a plant nutritional standpoint, the optimum level of crop residue to be applied to the soil as mulch may be as high as 2 ton ha^{-1} (Rebafka et al., 1994). However, McIntire and Fussel (1986) reported that on fields of unfertilized local cultivars, grain yield averaged only 236 kg ha^{-1} and mean residue yields barely reached 1300 kg ha^{-1}. These results imply that unless stover production is increased through application of fertilizers and or manure it is unlikely that the recommended levels of crop residue could be available for use as mulch.

However, the competition with other uses was not accounted for in this study. Lompo (1983) found in that zone that 90% of crop residue is used for cooking. This practice results in considerable loss of carbon and nutrients such as nitrogen and sulfur. Charraeu and Poulain (1964) reported that 20–40 kg N ha^{-1} and 5–10 kg S ha^{-1} are lost by burning crop residues. Other negative effects might be temporal changes in the population of microorganisms, particularly rhizobia, in the upper soil layers by the intense heat (Charreau and Nicou, 1971). Increasing the availability of crop residue to maintain soil fertility in West Africa will require enhanced fuel production to which agroforestry research might make a contribution by screening locally adapted fast-growing woody species.

Table 9
Results of manuring experiments at three sites in semi-arid West Africa

Location	Treatment	Crop	Crop response[a] (kg of DM ton^{-1} manure)	
			Grain	Stover
M'Pesoba, Mali[1]	10 ton ha^{-1} manure only	Sorghum	35[b]	n.s.
Saria, Burkina Faso[2]	10 ton ha^{-1} manure only	Sorghum	58	n.s.
Sadore, Niger 1987[3]	5 ton ha^{-1} manure only	Pearl millet	38	178
	20 ton ha^{-1} manure only	Pearl millet	34	106
M'Pesoba, Mali	5 ton ha^{-1} manure + NPK: 8-20-0	Sorghum	90[c]	n.s.
Saria, Burkina Faso	10 ton ha^{-1} manure + Urea N: 60	Sorghum	80	n.s.
Sadore, Niger 1987	5 ton ha^{-1} manure + SSP P: 8.7	Pearl millet	82	192
	20 ton ha^{-1} manure + SSP P: 17.5	Pearl millet	32	84

Source: Williams et al. (1995).
n.s. implies not specified.
References: [1]Pieri (1989), [2]Pieri (1986), and [3]Baidu-Forson and Bationo (1992).
[a] Responses were calculated at the reported treatment means for crop yields as: (treatment yield − control yield)/quantity of manure applied.
[b] Response of sorghum planted in the second year of a 4-year rotations involving cotton–sorghum–groundnut–sorghum. Manure was applied in the first year.
[c] Estimated from visual interpolation of graph.

UNCORRECTED PROOF

Please cite this article as: Andre Bationo et al., Soil organic carbon dynamics, functions and management ..., Agricultural Systems (2006), doi:10.1016/j.agsy.2005.08.011

Table 10
Effect of cattle and sheep dung and urine on pearl millet grain and total above-ground biomass, Sadore, Niger 1991

Type of manure	Dung application rate kg ha^{-1}	With urine		Without urine	
		Grain yield (kg ha^{-1})	Total biomass (kg ha^{-1})	Grain yield (kg ha^{-1})	Total biomass (kg ha^{-1})
Cattle	0	–	–	80	940
	2990	580	4170	320	2170
	6080	1150	7030	470	3850
	7360	1710	9290	560	3770
	S.E.M.	175	812	109	496
Sheep	0	–	–	80	940
	2010	340	2070	410	2440
	3530	1090	6100	380	2160
	6400	1170	6650	480	2970
	S.E.M.	154	931	78	339

Adapted from Powell et al. (1998).

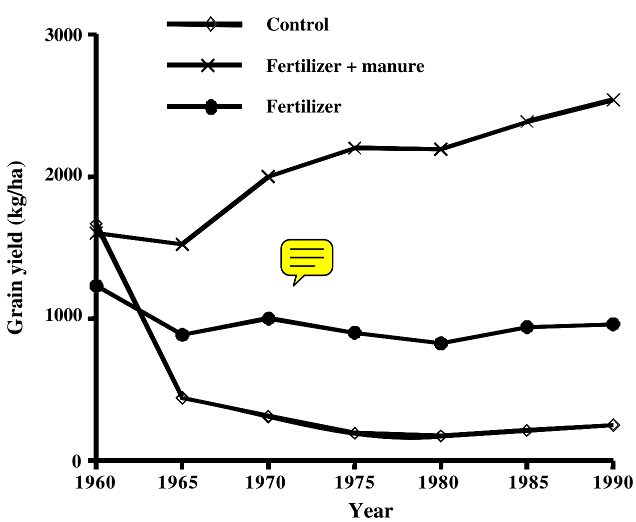

Fig. 11. Sorghum grain yield as affected by mineral and organic fertilizers over time.

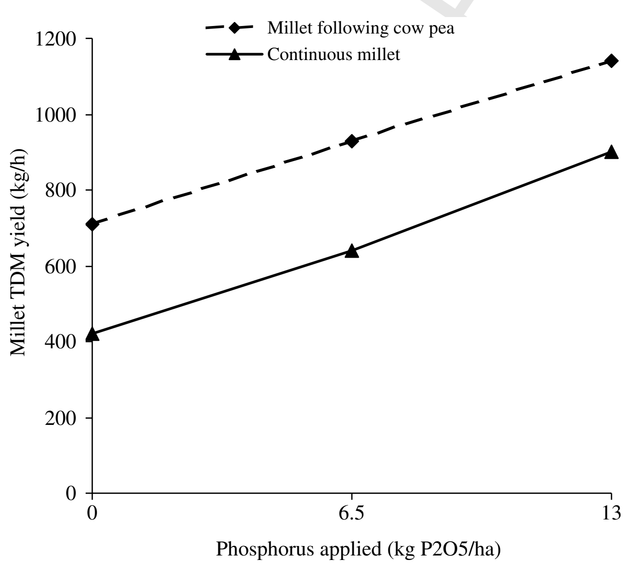

Fig. 12. Effect of P fertilization and rotation on millet total dry matter yield.

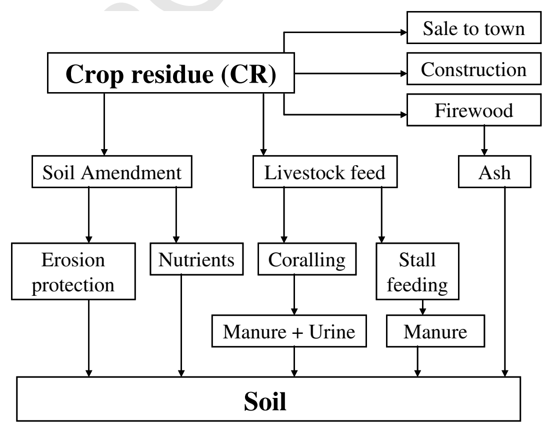

Fig. 13. The competing uses of crop residues in the West Africa Semi Arid Tropics.

In village level studies on crop residue along a north–south transect in three different agro-ecological zones of Niger, surveys were conducted to assess farm-level stover production, household requirements and residual stover remaining on-farm. The results of these surveys showed that the average amounts of stover removed from the field by a household represented only between 2% and 3.5% of the mean stover production (ICRISAT, 1993). At the onset of the rains the residual stover on-farm was only between 21% and 39% of the mean stover production at harvest time. Even if no data have been collected on the amount of crop residue lost by microbial decomposition and termites, cattle grazing is likely to be responsible for most of the disappearance of crop residues. Similar losses were reported by Powell (1985) who found that up to 49% of sorghum and 57% of millet stover disappearance on the humid zone of Nigeria was due to livestock grazing. Sandford (1989) reported that in the mixed farming systems, cattle derive up to 45% of their total annual feed intake from crop residues. The feed demand rises to 80% during periods of fodder shortage where virtually all available crop residues are used as animal feed. Up to 50% of the total amount of crop residue and up to 100% of the leaves are eaten by livestock (van Raay and de Leeuw, 1971).

Please cite this article as: Andre Bationo et al., Soil organic carbon dynamics, functions and management ..., Agricultural Systems (2006), doi:10.1016/j.agsy.2005.08.011

Most of the nutrients are voided in the animal excreta but when the animals are not stabled, nutrients contained in the droppings cannot be effectively utilized in the arable areas (Balasubramanian and Nnadi, 1980).

In an on-farm crop residue availability study, Bationo et al. (1991) showed that the use of fertilizers increased stover yields under on-farm conditions. Despite many competing uses of crop residue as already mentioned, the extra CR production led to significantly more mulch in the subsequent rainy season.

The availability of manure for sustainable crop production has been addressed by several scientists. de Leeuw et al. (1995) reported that with the present livestock systems in West Africa, the potential annual transfer of nutrient from manure will be 2.5 kg N and 0.6 kg P ha^{-1} of cropland. Although the manure rates applied are between 5 and 20 ton ha^{-1} in most of the on-station experiments, quantities used by farmers are very low and ranged from 1300 to 3800 kg ha^{-1} (Williams et al., 1995).

6. Conclusion

The complementarities of livestock and crop production suggests the need for research on possibilities to increase nutrient use efficiency for higher crop residue production and to improve the production of alternative feed supplies. The aim of such research should be to increase both fodder quantity and quality thus preserving more crop residue for soil application. Research should also focus on ways of alleviating socio-economic constraints in order to increase the legume component in the cropping systems. This will produce higher quality fodder for the livestock and also increase biomass at farm-level. As with nutrient depletion and replenishment, three technology categories of replenishing SOC hence SOM need to be pursued: (i) practices that save SOC from loss; (ii) practices that add SOC to the system either directly or indirectly; and (iii) practices that ensure efficient use of organic materials at different spatial scales.

~~7. Uncited reference~~

~~Sedogo (1993).~~

References

Abdulahi, A., Lombin., G., 1978. Long-term Fertility Studies at Samaru-Nigeria: Comparative Effectiveness of Separate and Combined Applications of Mineralizers and Farmyard Manure in Maintaining Soil Productivity Under Continuous Cultivation in the Savanna, Samaru, Samaru Miscellaneous Publication. No. 75, Ahmadu Bello University, Zaria, Nigeria.

Amato, M., Ladd, J.N., 1992. Decomposition of ^{14}C labelled glucose and legume material in soils: properties influencing the accumulation of organic residue-C and microbial biomass-C. Soil Biology and Biochemistry 24, 455–464.

ARC (Agricultural Research Council), 1980. The Nutrient Requirements of Ruminant Livestock. Farnham Royal, Slough, Commonwealth Agricultural Bureaux, U.K.

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.

Baidu-Forson, J., Bationo, A., 1992. An economic evaluation of a long-term experiment on phosphorus and manure amendments to sandy Sahelian soils: using a stochastic dominance model. Fertilizer Research 33, 193–202.

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

Balasubramanian, V., Nnadi, C.A., 1980. Crop residue management and soil productivity in savanna areas of Nigeria. In: Organic Recycling in Africa. FAO Soils Bulletin 43. FAO (Food and Agriculture Organization of the United Nations), Rome, Italy, pp. 106–120.

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. Fertilizer Research 29, 117–125.

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

Bationo, A., Christianson, C.B., Klaijm, M.C., 1993. The effects of crop residue and fertilizer use on pearl millet yield in Niger. Fertilizer Research 34, 251–258.

Bationo, A., Buerkert, A., Sedogo, M.P., Christianson, B.C., Mokwunye, A.U., 1995. A critical review of crop residue use as soil amendment in the West African semi-arid tropics. In: Powell, J.M., Fernandez Rivera, S., Williams, T.O., and Renard, C. (Eds)., Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of Sub-Saharan Africa. Proceedings of the International Conference ILCA, Addis Ababa, pp. 305–322.

Bationo, A., Rhodes, E., Smaling, E.M.A., Visker, C., 1996. Technologies for restoring soil fertility. In: Mokwunye, A.U., de Jager, A., Smaling, E.M.A. (Eds), Restoring and Maintaining Productivity of West African Soils: Key to Sustainable Development. IFDC-Africa, LEI-DLO and SC-DLO, Miscellaneous Fertilizer Studies No. 14. International Fertilizer Development Center.

Bationo, A., Lompo, F., Koala, S., 1998. Research on nutrient flows and balances in West Africa: State-of-the-art. In: Smaling, E.M.A. (Ed.), Nutrient Balances as Indicators of Production and Sustainability in Sub-Saharan African Agriculture. Agriculture, Ecosystem and Environment, vol. 71, pp. 19–36.

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., Kimetu, J., Ikerra, S., Kimani, S., Mugendi, D., Odendo, M., Silver, M., Swift, M.J., Sanginga, N., 2004a. The African network for soil biology and fertility: new challenges and opportunities. In: Bationo, A. (Ed.), Managing Nutrient Cycles to Sustain Soil Fertility in Sub-Saharan Africa. Academy Science Publishers, Nairobi, Kenya.

Bationo, A., Nandwa, S.M., Kimetu, J.M., Kinyangi, J.M., Bado, B.V., Lompo, F., Kimani, S., Kihanda, F., Koala, S., 2004b. Sustainable intensification of crop-livestock systems through manure management in eastern and western Africa: Lessons learned and emerging research opportunities. In: Williams, T.O., Tarawali, S.A., Hiernaux, P., Fernandez-Rivera, S. (Eds.), Sustainable Crop-livestock Production for Improved Livelihoods and Natural Resource Management in West Africa. Proceedings of an International Conference Held at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria, 19–22 November 2001. ILRI (International Livestock Research Institute) Nairobi, Kenya and CTA (Technical Centre for Agricultural and Rural Cooperation, ACP-EC, Wageningen, the Netherlands.

Berger, M., Belem, P.C., Dakoua, D., Hien, V., 1987. Le maintien de la fertilite des sols dans l'quest du Burkina Faso et la necessite de l'association agriculture-elevage. Cotton et Fibres Tropicales Vol XLII FASC 3, 210–211.

UNCORRECTED PROOF

Breman, H., Traore, N., (Eds.)., 1986. Analyses des conditions de l'élevage et propositions de politiques et de programmes. République du Niger. Sahel D. (86) 284, Club du Sahel/CILSS/OCDE, Paris.

Carsky, R.J., Jagtap, S., Tain, G., Sanginga, N., Vanlauwe, B., 1998. Maintenance of soil organic matter and N supply in the moist savanna zone of West Africa. In: Lal, R. (Ed.), Soil Quality and Agricultural Sustainability. Ann Arbor Press, Chelsea, Michigan, pp. 223–236.

Charraeu, C., Poulain, J., 1964. Manuring of millet and sorghum. Agricultural Soils 9, 177–191.

Charreau, C., Nicou, R., 1971. L'amélioration du profil cultural dans les sols sableux et sablo-argileux de la zone tropicale sèche ouest-africaine et ses incidences agronomiques. Agronomie Tropicale 26, 903–978, 1184–1247.

de Leeuw, P.N., Reynolds, L., Rey, B., 1995. Nutrient transfers from livestock in West African Agricultural Systems. In: Powell, J.M., Fernandez-Rivera, S., Williams, T.O., Renard, C. (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, Ethiopia, 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.

Dixon, R.K., Andrasko, K.J., Sussman, F.G., Lavinson, M.A., Trexler, M.C., Vinson, T.S., 1993. Forest sector carbon offset projects: near-term opportunities to mitigate greenhouse gas emissions. Water Air and Soil Pollution 70, 561–577.

Dudal, R., Deckers, J., 1993. Soil organic matter in relation to soil productivity. In: Mulongoy, K., Merckx, R. (Eds.), Soil Organic Matter Dynamics and Sustainability of Tropical Agriculture. John Wiley and Son, West Sussex, United Kingdom.

ECA (Economic Commission for Africa), 2002. Harnessing Technologies for Sustainable Development. ECA, Addis Ababa.

FAO (Food and Agriculture Organization of the United Nations, 2001. Soil Fertility Management in Support of Food Security in Sub-Saharan Africa. FAO, Rome.

FAO (Food and Agriculture Organization) 2003. FAOSTAT Agriculture Data, http://apps.fao/cgi-binnph-db.pl?suset=agriculture. FAO, Rome Italy.

Feller, C., Brossard, M., Frossard, E., 1992. Caractérisation et dynamique de la matière organique dans quelques sols ferrugineux et ferralitiques d'Afrique de l'Ouest. In: Tiessen, H., Frossard, E. (Eds.), Phosphorus Cycles in Terrestrial and Aquatic Ecosystems. Proceedings of a Workshop Arranged by the Scientific Committee on Problems of the Environment (SCOPE) and the United Nations Environmental Programme (UNEP), 18–22 March 1991. Nairobi, Kenya, pp. 94–107.

Fernandez-Rivera, S., Williams, T.O., Hiernaux, P., Powell, J.M., 1995. Faecal excretion by ruminants and manure availability for crop production in semi arid West Africa. In: Powell, J.M., Fernandez-Rivera, S., Williams, T.O., Renard, C. (Eds.), Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of Sub-Saharan Africa, vol. 2: Technical Papers. Proceedings of an International Conference, 22–26 November 1993. International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia, pp. 393–409.

Gregorich, E.G., Greer, K.J., Anderson, D.W., Liang, B.C., 1998. Carbon distribution and losses: erosion and deposition effects. Soil Tillage Research 47, 291–302.

ICRISAT (International Crop Research Institute for the Semi-Arid Tropics), 1993. Annual Report 1992. ICRISAT Sahelian center, Niamey, Niger.

Kaihura, F., Kullaya, I., Kilasara, M., Aune, J., Singh, B., Lal, R., 1998. Impact of soil erosion on soil productivity and crop yield in Tanzania. Advances in Geoecology 31, 375–381.

Kretzschmar, R.M., Hafner, H., Bationo, A., Marschner, H., 1991. Long and short-term of crop residues on aluminium toxicity, phosphorus availability and growth of pearl millet in an acid sandy soil. Plant and Soil 136, 215–223.

Lal, R., 1975. Role of mulching techniques in tropical soil and water management. Technical Bulletin 1. IITA, Ibada.

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

Langmuir, I., 1918. The absorption of gases on plain surface of glass, Mic and platinum. Journal of the American Chemistry Society 40, 1361–1403.

Lompo, F., 1983. Problématique de la matière organique dans la zone du plateau Mossi. Etude de la disponibilité des résidus culturaux et de leur mode de transformation. Mémoire de fin d'études. ISP/Université d'Ouagadougou, Burkina Faso, p. 108.

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.

McIntire, J., Fussel, L.K., 1986. On-farm experiments with millet in Niger. III. Yields and economic analyses. ISC (ICRISAT Sahelian Center), Niamey, Niger.

Mentis, M.T., 1981. Direct effects of animals on pasture and veld. In: NM, Tainton (Ed.), Veld and Pasture Management in Southern Africa. Shutter and Shooter. University of Natal, South Africa, pp. 299–321.

Mokwunye, A.U., 1980. Interaction between farmyard manure and NPK fertilizers in savanna soils. In: FAO (Food and Agriculture Organization of the United Nations), Organic Recycling in Africa. FAO Soils Bulletin 43. FAO, Rome, Italy, pp. 192–200.

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.

Mokwunye, U.A., Chien, S.H., Rhodes, E., 1986. Phosphate reactions with tropical Africa soils. In: Mokwunye, U.A., Vlek, P.L.G. (Eds.), Management of Nitrogen and Phosphorus Fertilizers in Sub-Saharan Africa. Proceedings of a Symposium held in Lome, Togo, 25–28 March 1985. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp. 253–281.

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.

Ouedraogo, E., 2004. Soil quality improvement for crop production in semi-arid West Africa. PhD Dissertation, Wageningen University.

Palm, C.A., Gachengo, C.N., Delve, R.J., Cadisch, G., Giller, K.E., 2001. Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. Agriculture, Ecosystems and Environment 83, 27–42.

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 minérales et organiques. Agronomie Tropicale 36, 122–133.

Pieri, C., 1986. Fertilisation des cultures vivrières et fertilité des sols en agriculture paysanne subsaharienne. Agronomie Tropicale 41, 1–20.

Pieri, C., 1989. Fertilité de terres de savane. Bilan de trente ans de recherché et de développement agricoles au sud du Sahara. Ministère de la Coopération. CIRAD. Paris, France, p. 444.

Powell, J.M., 1985. Yields of sorghum and millet and stover consumption of livestock in Nigeria. Tropical Agriculture (Trinidad) 62 (1), 77–81.

Powell, J.M., 1986. Manure for cropping: a case study from central Nigeria. Experimental Agriculture 22, 15–24.

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.

Powell, J.M., Ikpe, F.N., Somda, Z.C., Fernandez-Rivera, S., 1998. Urine effects on soil chemical properties and the impact of urine and dung on pearl millet yield. Experimental Agriculture 34, 259–276.

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, Ecosystem and Environment 47, 237–264.

Rebafka, F.P., Hebel, A., Bationo, A., Stahr, K., Marschner, H., 1994. Short- and long-term effects of crop residues and of phosphorus fertilization on pearl millet yield on an acid sandy soil in Niger, West Africa. Field Crops Res 36, 113–124.

UNCORRECTED PROOF

Please cite this article as: Andre Bationo et al., Soil organic carbon dynamics, functions and management ..., Agricultural Systems (2006), doi:10.1016/j.agsy.2005.08.011

Roose, E., 1980. Dynamique actuelle d'en sol ferralitiques et ferrugineux tropicaux. Etude des transferts hydrologiques et biologiques de matières sous végétations naturelles ou cultivées. Travaux et documents 130. Paris ORSTOM.

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.

Sandford, S.G., 1989. Crop residue/livestock relationships. In: Renard, C., Van Den Beldt, R.J., Parr, J.F. (Eds.), Soil, Crop, and Water Management Systems in the Sudano-Sahelian Zone. Proceedings of an International Workshop, ICRISAT Sahelian Center, Niamey, Niger, 11–16 January 1987. ICRISAT (International Crops Research institute for the Semi-Arid Tropics), Patancheru, Andrah Pradesh, India.

Sedga, Z., 1991. Contribution a la valorisation agricole des résidus de culture dans le plateau central du Burkina Faso. Inventaire de disponibilités en matière organique et étude des effets de l'inoculum, micro 110 IBF, Mémoire d'ingénieur des sciences appliqués, IPDR/Katibougou, p. 100.

~~Sedogo, M.P., 1993. Evolution des sols ferrugineux lessivés sous culture: influences des modes de gestion sur la fertilité. Thèse de Doctorat Es-Sciences, Abidjan, Université Nationale de Côte d'Ivoire.~~

Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002a. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant and Soil 241, 155–176.

Six, J., Feller, C., Denef, K., Ogle, S.M., Moraes, J.C., Albrecht, A., 2002b. Soil organic matter, biota and aggregation in temperate and tropical soil – effects of no-tillage. Agronomie 22, 755–775.

Stoorvogel, J., Smaling, E.M., 1990. Assessment of soil nutrient depletion in sub-Saharan Africa: 1983–2000Main Report, vol. 1. The Winand Staring Center, Wageningen, the Netherlands.

Swift, M.J., Woomer, P., 1993. Organic matter and the sustainability of agricultural systems: definition and measurement. In: Mulongoy, K., Merckx, R. (Eds.), Soil Organic Matter Dynamics and Sustainability of Tropical Agriculture. John Wiley and Son, West Sussex, United Kingdom.

UN (United Nations), 2001. World Population Prospects: The 2000 Revision. Department of Economic and Social Affairs, New York.

van Raay, J.G.T., de Leeuw, P.N., 1971. The Importance of Crop Residues as Fodder: A Resource Analysis in Katsina Province, Nigeria. Samaru Research Bulletin 139. Ahmadu Bello University University, Samaru, Zaria, Nigeria, p. 11.

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.

Williams, T.O., Powell, J.M., Fernandez-Rivera, S., 1995. Manure utilization, drought cycles and herd dynamics in the Sahel: implications for crop productivity. In: Powell, J.M., Fernandez-Rivera, S., Williams, T.O., Renard, C. (Eds.), Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of Sub-Saharan Africa, vol. 2: Technical Papers. Proceedings of an International Conference, 22–26 November 1993. International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia, pp. 393–409.

Windmeijer, P.N., Andriesse, W., 1993. Inland valleys in West Africa: an agro-ecological characterization of rice growing environments, ~~pp. ix + 160, 3 pp. of ref.~~

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.

Woomer, P.L., Palm, C.A., Qureshi, J.N., Kotto-same, J., 1997. Carbon sequestration and organic resource management in African smallholder agriculture. In: Lal, R., Kimble, J., Follet, R.F., Stewart, B.A. (Eds.), Management of Carbon Sequestration in Soil. Advances in Soil Science. CRC Press, BOCA Raton, Florida, pp. 58–78.

Woomer, P., Palm, C.A., 1998. An approach to estimating system carbon stocks in tropical forests and associated land uses. Commonwealth Forestry Review 77 (3), 181–190.

Zougmore, R., 2003. Integrated water and nutrient management for sorghum production in semiarid Burkina Faso. PhD Dissertation, Wageningen University.

UNCORRECTED PROOF

Please cite this article as: Andre Bationo et al., Soil organic carbon dynamics, functions and management ..., Agricultural Systems (2006), doi:10.1016/j.agsy.2005.08.011