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

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Abstract

Soil fertility depletion (mainly N, P and carbon) 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. Furher, 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

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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.

Crop 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 a low overall production levels of biomass in the region as well as their competitive use as fodder, construction material and cooking fuel. Animal manure has 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 one hectare of cropland. 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 per hectare of cropland.

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 story 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.

In the decision support system for organic matter management, recommendations for appropriate use of organic material was made based on their resource quality, expressed as a function of N, polyphenol and lignin content. High quality organic materials release a high proportion of their N quickly. 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. 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.

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%. 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 to 250 kg/person have been observed. Both 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%. 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 addioton to this, 70% of deforestation is caused by farmers who in their quest for food have no incentive to ponder abut long-term environmental consequences.

Soil fertility depletion (mainly N, P and carbon) has been described as the single most important constraint to food security in West Africa. The Sudano-Sahelian zone of West Africa is the home of the world poorest people; 90% of who 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, 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 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 systems non-sustainability (Nandwa, 2001). High population densities have necessitated the cultivation of marginal lands that are prone to erosion hence further 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. The 7.6% yield increase of yam in West Africa was manly due to an area increase of 7.2% and only 0.4% due to improvement in crop productivity itself (**Table** 1).

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 three-year average for 1988-1990 and 1998-2000. Source: www.fao.org.

Removal of crop residues from the fields, coupled with 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 is lost per year, only 0.8 million tons is applied (Bationo et al., 2004) (**Figure** 1). Shepherd and Soule (1998) reported a negative carbon balance of 400 kg ha^{-1} yr^{-1} for farmers with low resource endowment whereas positive balance of 190 kg ha^{-1} yr^{-1} was reported on fields of farmers with high resource endowment (**Table** 2). 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).

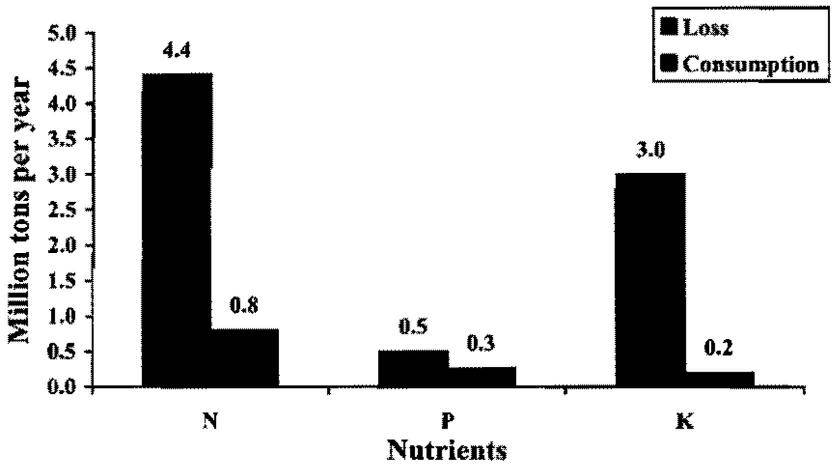


Figure 1: Nutrient losses versus application rate in Africa

Table 2: Soil organic carbon balance, soil erosion, farm return and household income at different farm resource endowment levels

Variable	Units	Farm resource endowment		
		Low	Medium	High
Soil C balance	Kg ha^{-1} yr^{-1}	-400	-318	190
Soil erosion	T ha^{-1} yr^{-1}	5.6	5.5	2.1
Farm returns	\$ yr^{-1}	3	70	545
Household income	\$ yr^{-1}	454	1036	3127

Source: Shepherd and Soule (1998)

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). Reverting 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 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 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 (**Figure** 2).

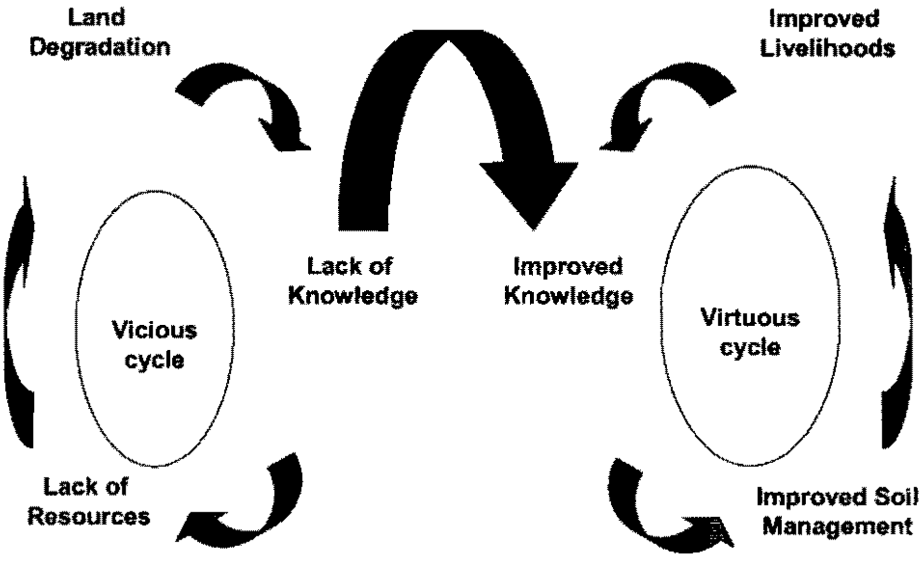


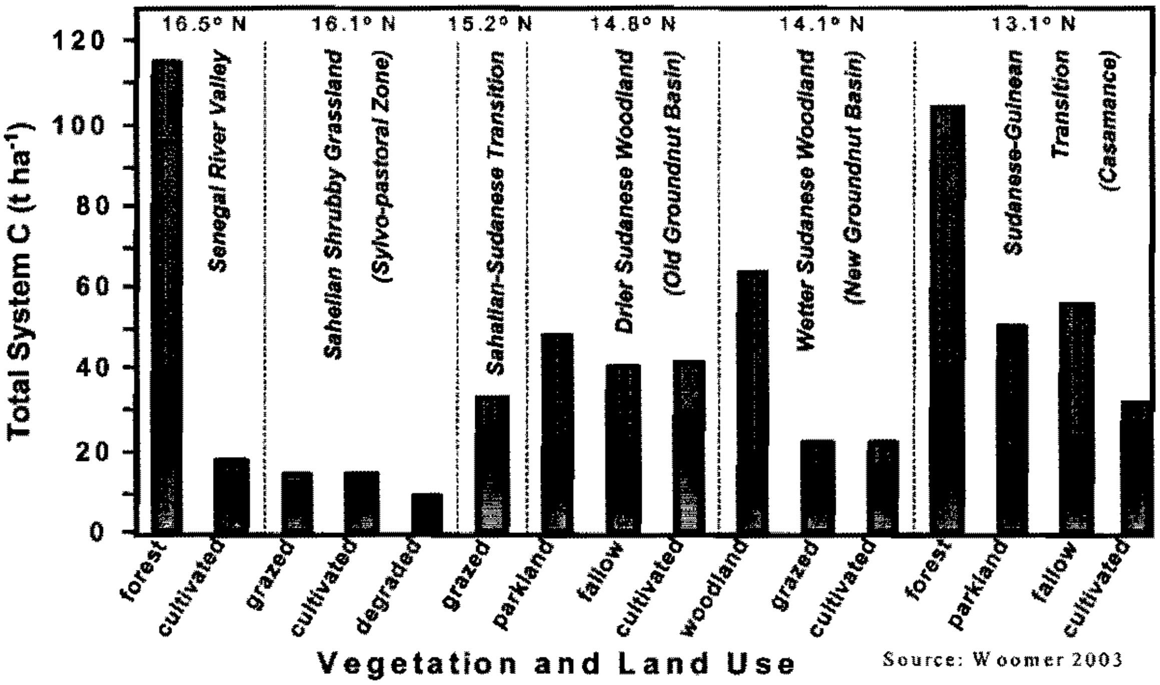
Figure 2. The vicious and virtuous cycles of land degradation and soil fertility management

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) 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 (**Figure** 3) demonstrating potential for carbon sequestration. For example, total system carbon in the Senegal River valley was 115 t ha^{-1} in the forest zone and only 18 t 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** 3).



Source: Woomer 2003

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

Table 3: 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** 4), 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 labour 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 depend on the maintenance of SOC levels.

Table 4: 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)

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 5**). 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.

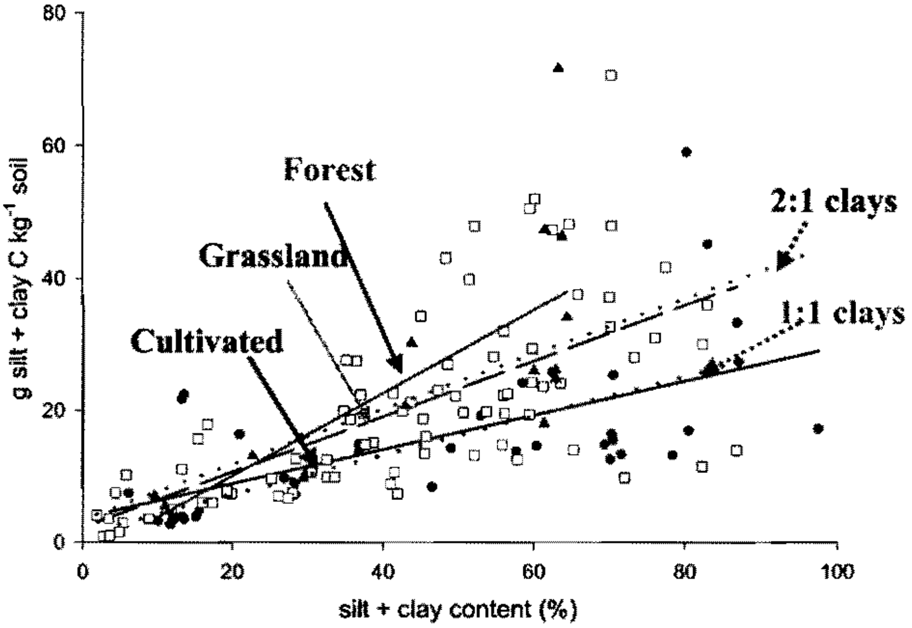
Table 5: Correlation (r) between selected soil (0-20 cm) fertility parameters and average annual rainfall

	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 *** indicate statistical significance at the 0.05 and 0.001 level, respectively.

Source: Manu et al. (1991)

Figure 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., 2002b).



Source: Six et al., 2002b

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

4) Functions of 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 (*Ibid*) results from experiments in some African countries already indicate favourable 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 favourable environment for plant growth but also regulates various processes governing the creation of soil-based environmental services

(**Figure 5**) (Vanlauwe, 2004). Therefore, SOC plays a vital role in crop production and environmental services.

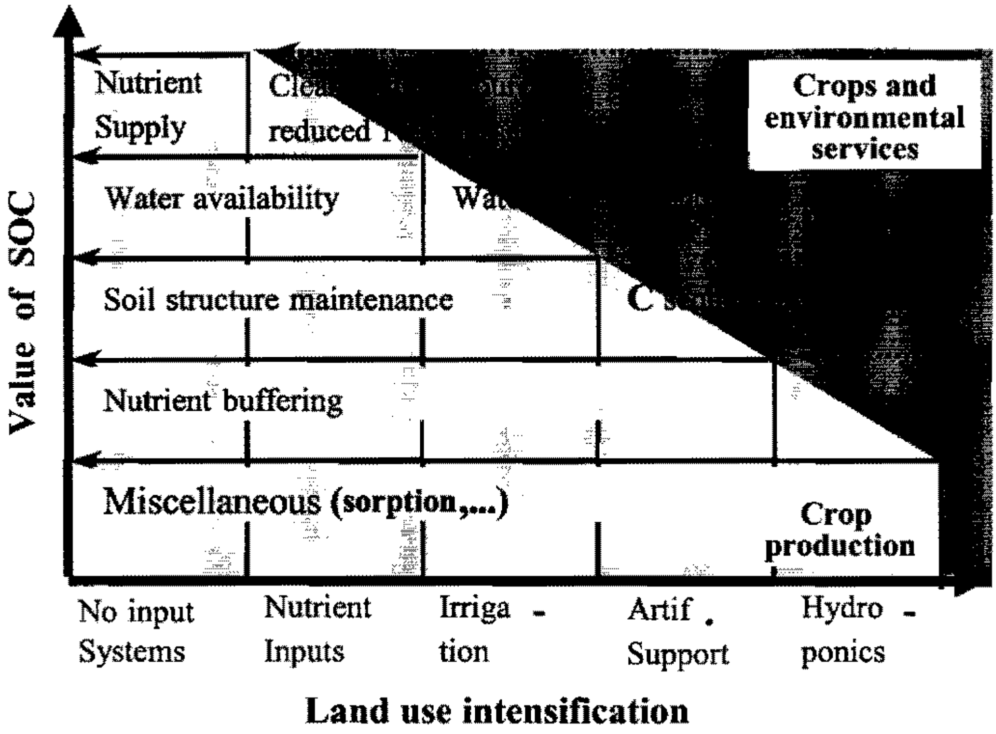


Figure 5. Different functions of SOC and their regulation at different land intensification systems (Adapted from Vanlauwe, 2004)

a) 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 **Figure** 6, high SOC status in the homestead fields is observed to relate positively with crop yields (**Figure** 6). This is due to multiple factors of production affected by SOC content (Swift and Woomer, 1993).

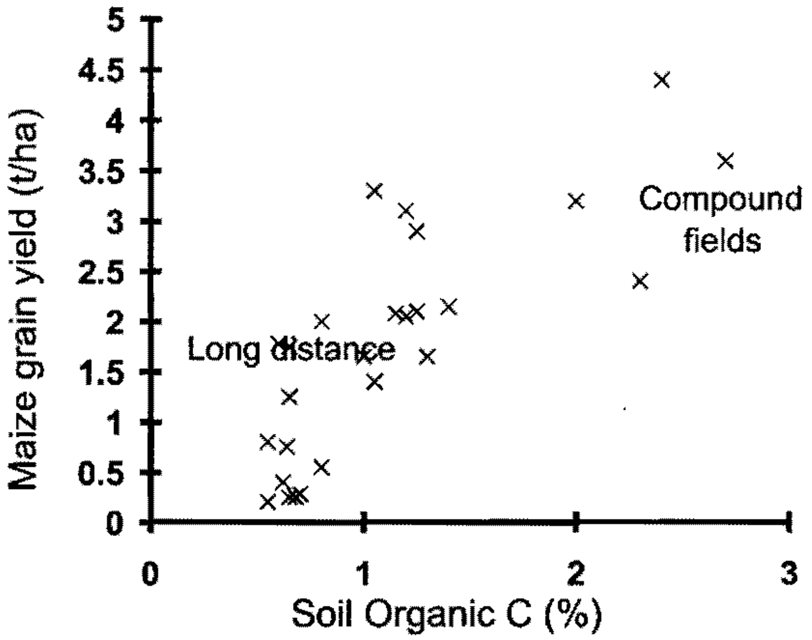


Figure 6. Relationship between SOC content and maize grain yield for distant and compound fields in Northern Nigeria. **Source: Carsky et al. (1998)**

Over a period of four 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 (**Figure 7**).

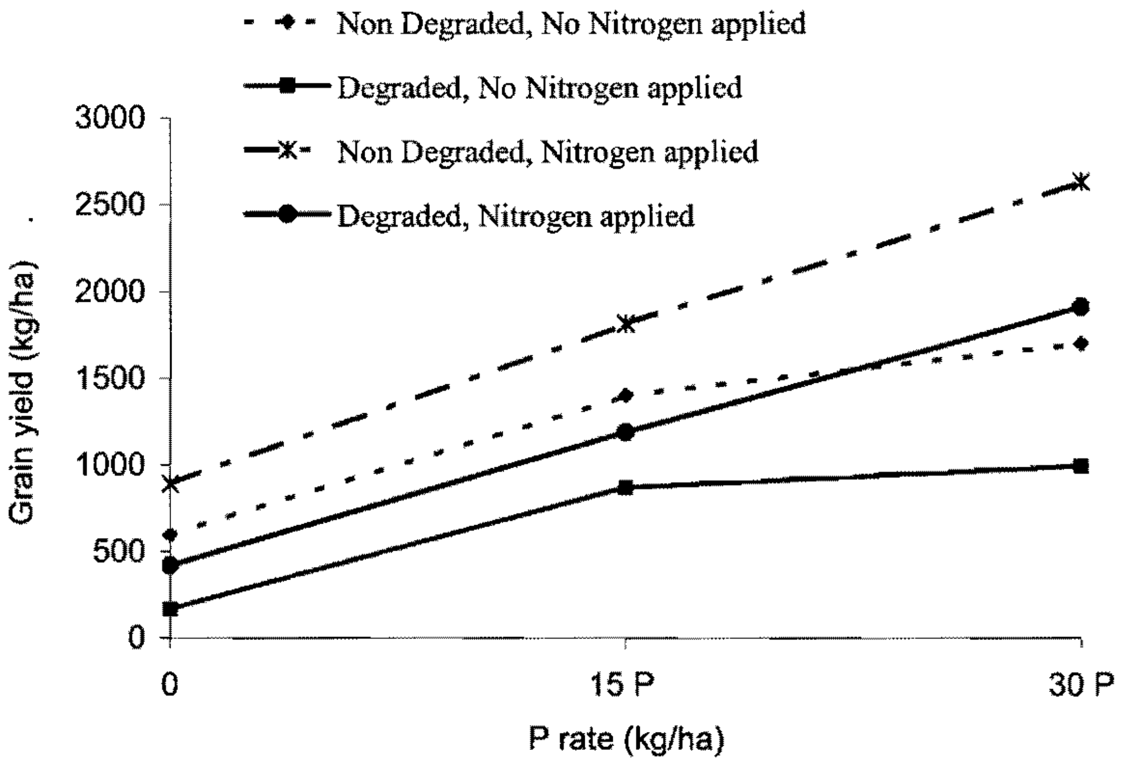


Figure 7. Effect of SOC content on millet production in Karabedji, Niger in 2002

Several scientists have reported the effect of organic amendments on crop yield increases partly due to effects of SOC (Bationo and Mokwunye, 1991; Bationo et al., 1995; Mokwunye, 1980; Pichot et al., 1981; Pieri, 1986; de Ridder and van Keulen, 1990; Abdulahi and Lombin, 1978; Powell, 1986 and Bationo et al., 1998). Research results from long-term field experiments in the West African agro-ecosystems showed that the use of mineral fertilizers without recycling of organic materials resulted in higher yields, but this increase was not sustainable (Jones, 1976; Bationo and Mokwunye, 1991).

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

Table 6: Effect of crop residue and fertilizer on pearl millet grain and stover yields at Sadore, Niger.

Treatment	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

b) 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 (**Figure** 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 and Roose and Barthes, 2001). The data in **Table** 6 indicates that cereal biomass production can be increased by over 5 times from 1,030 to 5,690 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 (**Figure** 5). A higher content of SOC will result in a higher Fertilizer Use Efficiency (FUE) (Figure 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 degraded site as compared to 79% in the non-degraded site (**Figure 7**). Comparative data of P FUE with and without crop residues mulch application in the Sahel clearly indicate a better fertilizer use efficiency with organic amendments which improve SOC (**Table** 7).

Table 7. Increase in incremental millet grain and stover yield due to fertiliser application in Sadore, Niger

Year	**Treatment**	**Fertilizer effect (kg per kg P applied)**	
		Grain	**Stover**
1983	Crop Residues	-	-
	Fertilizer	59[1]	NA
	Crop Residues + Fertilizer	72[2]	NA
1984	Crop Residues	-	-
	Fertilizer	34	21
	Crop Residues + Fertilizer	14	31
1985	Crop Residues	-	-
	Fertilizer	67	188
	Crop Residues + Fertilizer	137	427
1986	Crop Residues	-	-
	Fertilizer	57	184
	Crop Residues + Fertilizer	112	359

1. Calculated as (Yield Fertilizer - Yield Control) / P applied
2. Calculated as (Yield Crop Residues + Fertilizer - Yield Control) / P applied
NA = not available
Source: Bationo et al. (1995)

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 (**Figure** 8). This may at least 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).

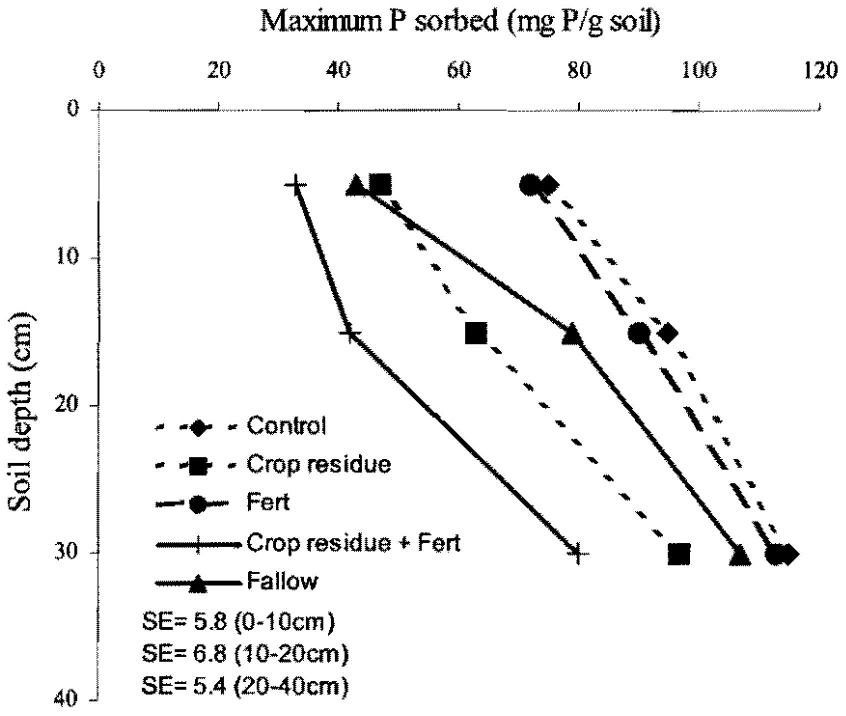


Figure 8. Effect of soil amendments on maximum phosphorus sorbed in Sadore, Niger, 1991 (Source: Bationo et al., 1995)

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 8**). 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). Roose and Barthes (2001) illustrated the importance of preserving the topsoil when by de-surfacing 5 cm of topsoil noted yield decline by about one-third in north Cameroon (**Figure 9**).

Table 8. Carbon losses (kg ha-1 yr^{-1}) by erosion, runoff and leaching in the topsoil (30cm) in runoff plots at Adiopodoume, Korogho (Ivory Coast) and Saria (Burkina Faso)

C losses	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)

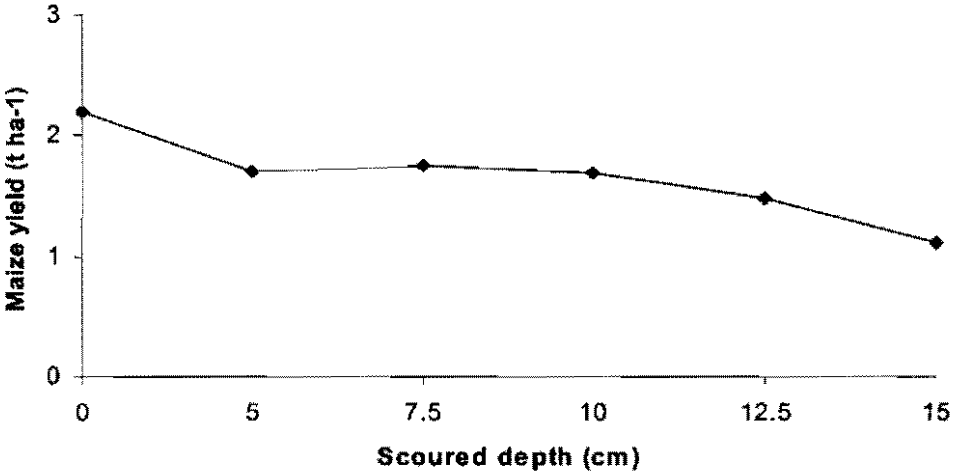


Figure 9. Effect of depth of soil mechanical desurfacing on maize grain yield at Mbissiri, North Cameroon (Source: Roose and Barthes, 2001)

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; Greenland and Nye, 1959; 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 such as from 2% to 6.3% at the Centre de Formation des Jeunes Agriculteurs (CFJA) in Burkina Faso (**Table** 9). 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.

Table 9. 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 fertiliser	12	10	1.5
	Sorghum monoculture	Low fertilizser (lf)	12	10	1.9
	Sorghum monoculture	High fertiliser (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 fertiliser	3	5	7.0
	Millet-groundnut	With fertiliser	3	5	4.3
	Millet-groundnut	Fertiliser + straw	3	5	6.0
Bambey, ISRA-IRAT	Millet monoculture	with PK fertiliser + 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, high fertility soil			
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

F0 = no fertiliser, F1 = 200 kg ha^{-1} of NPK fertiliser, F2 = 400 kg ha^{-1} of NPK fertiliser + Taiba phosphate rock, T0 = manual tillage, T1 = light tillage, T2 = heavy tillage.

Source: Pieri, (1989)

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; Pedro et al., 2001; Six et al., 2002). 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 due to accelerated mineralization **(Figure 10)**. 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 annual rate of SOC losses from 3.8% (with manual tillage) to 4.7% and 5.2% following light and heavy tillage respectively.

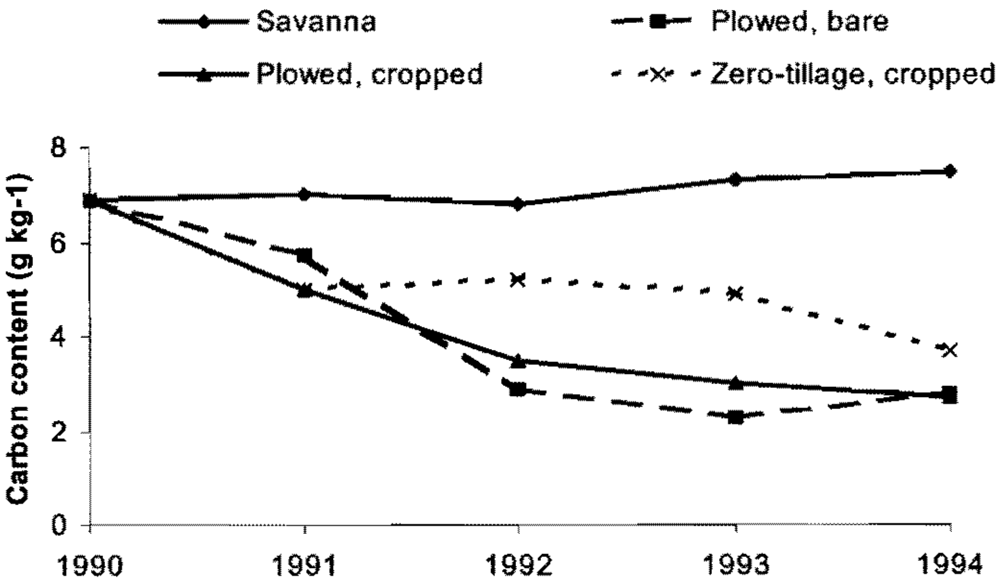


Figure 10. Evolution of carbon content in the 0-10 cm horizon, as affected by time and treatment in runoff plots of Mbissiri Station, Cameroon (Adapted from Roose and Barthes, 2001)

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 five 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. **Figure** 11 shows the effect of cowpea-millet rotation, millet-cowpea-intercrop rotated with cowpea and continuous millet cowpea intercrop on SOC.

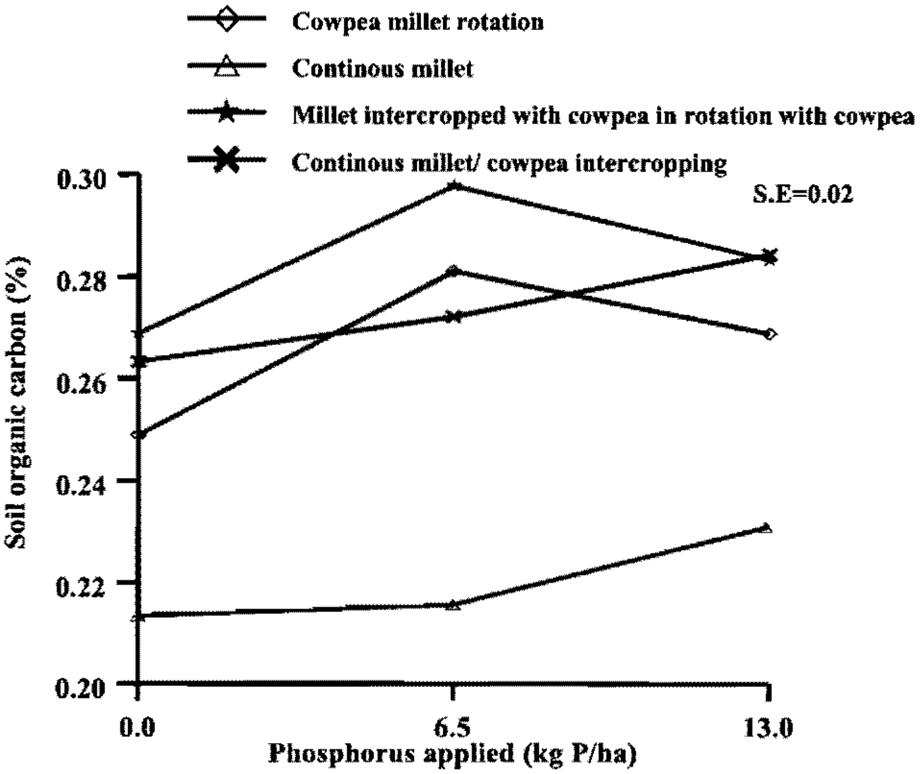


Figure 11. Effect of cropping system and phosphorus on SOC in Sadore, Niger in 1995

Mulching decreases soil temperature, maintains favorable soil structure and infiltration rate, and enhance microbial and mesofaunal activities (Lal, 1975; Boli et al., 1993; 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 two 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 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 Saheian Zone, Bationo and Buerkert (2001) found that levels of SOC were 1.7 g kg^{-1} and 3.3 g kg^{-1} respectively at 0.1m for 2t ha^{-1} and 4 t ha^{-1} of mulching with crop residue applied as compared to unmulched plot (**Figure** 12)

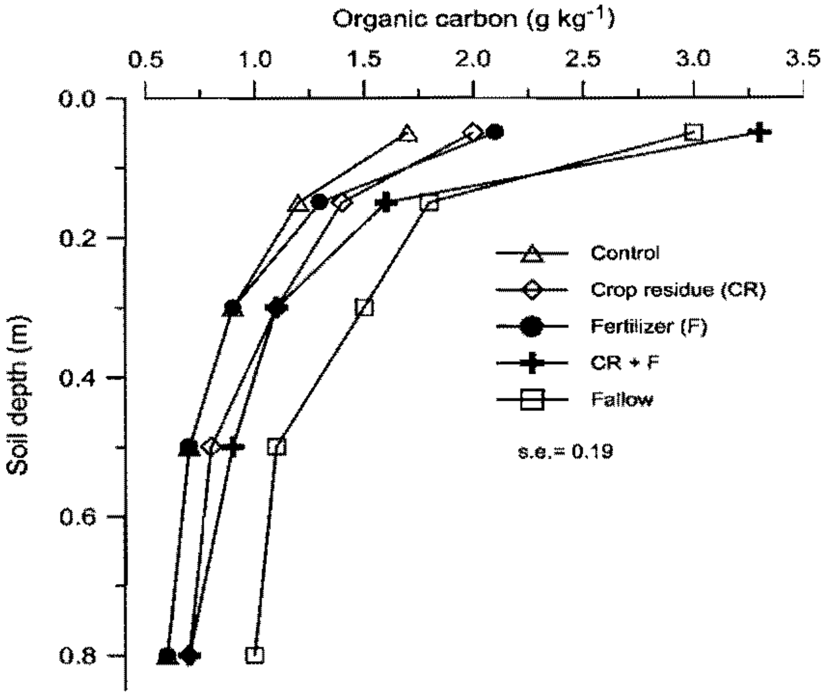


Figure 12. Soil organic carbon (SOC) as affected by soil depth and management practices. Sadoré, Niger, rainy season, 1996.

Another example from Central Africa reported the importance of mulching on soil losses and subsequent productivity restoration (**Figure** 13). Total erosion during three years decreases from 154t ha^{-1} on bare fallow to 0.15t ha^{-1} on entirely mulched plots. The effect of erosion on subsequent land productivity reported maize yield of over 4t ha^{-1} on non-eroded plots against yields of less than 1t ha^{-1} on eroded plots (soil loss of 150t ha^{-1}) even with the application of mineral and organic plant nutrients (Rushirumuhirwa 1997, Rushirumuhirwa and Roose 1998).

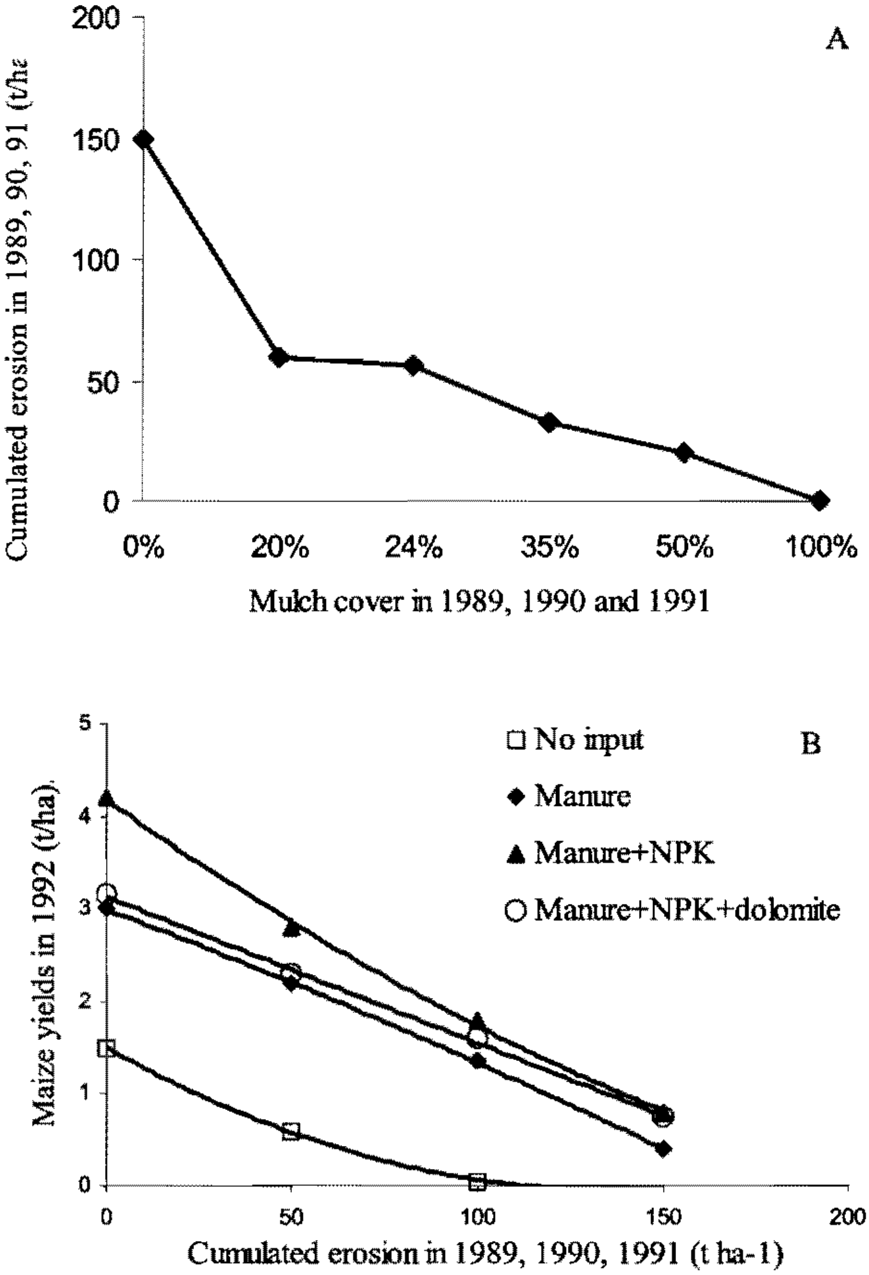


Figure 13: Influence of mulch cover (linked to banana plantation density) on erosion (13a), and effect of this previous erosion on grain yield of the next maize crop (13b), in runoff plots (8% slope) of Mashitsi station (Burundi). During maize crop, manure input was 20 t ha^{-1}, fertilizer level was 60N, 40P, 60K and dolomite, 500kg ha^{-1}. Source: Roose and Barthes, 2001.

The data in **Table** 10 shows that manure collected from stables and applied alone produces about 20 to 60 kg N ha^{-1} in cereal grain and 70 to 178 kg of kg N ha^{-1} in stover per tonne of manure.

Table 10: Results of manuring experiments at three sites in semi-arid West Africa

Panel A: Manure only

Location	Amount of manure applied (t ha^{-1})	Crop	Crop response[1] (kg of DM t^{-1} manure)		Reference
			Grain	Stover	
M□Pesoba, Mali	10	Sorghum	35[2]	n.s.	1
Saria, Burkina Faso	10	Sorghum	58	n.s.	2
Sadore, Niger 1987	5	Pearl millet	38	178	3
	20	Pearl millet	34	106	3

Panel B: Manure with inorganic fertilizer

	Amount of			Crop response[1] (kg of DM/t manure0	
Location	Manure (t/ha)	Fertiliser (kg/ha)	Crop	Grain	Stover
M□Pesoba, Mali	5	NPK: 8-20-0	Sorghum	90[3]	n.s.

Saria, Burkina Faso	10	Urea N: 60	Sorghum	80	n.s.
Sadore, Niger 1987	5	SSP P: 8.7	Pearl millet	82	192
Sadore, Niger 1987	20	SSP P: 17.5	Pearl millet	32	84

1. Responses were calculated at the reported treatment means for crop yields as: (treatment yield - control yield)/quantity of manure applied.

2. Response of sorghum planted in the second year of a 4-year rotation involving cotton-sorghum-groundnut-sorghum. Manure was applied in the first year.

3. Estimated from visual interpolation of graph

n.s. implies not specified

References: 1. Pieri (1989); 2. Pieri (1986); 3. Baidu-Forson and Bationo (1992)

Source: Williams et al. 1995

The data in **Table** 11 indicates that the application of 3 t ha^{-1} of manure plus urine produced grain and total bio-mass that were three to four times as high compared to when only manure was applied and crop response to sheep manure was greater than to cattle manure. Research studies indicate that approximately 80-95% of the N and P consumed by livestock is excreted. Whereas N is voided in both urine and faeces, most P is voided in faeces (ARC, 1980; Termouth, 1989).

Table 11: 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

One important conclusion that emerged from the long-term experiments is that application of mineral fertilizers is an effective technique for increasing crop yields in the Sudanian zone of West Africa. However, in the long run the use of mineral fertilizers alone will decrease crop yields but sustainable and higher production is obtained when inorganic fertilizers are combined with manure (**Figure 14**).

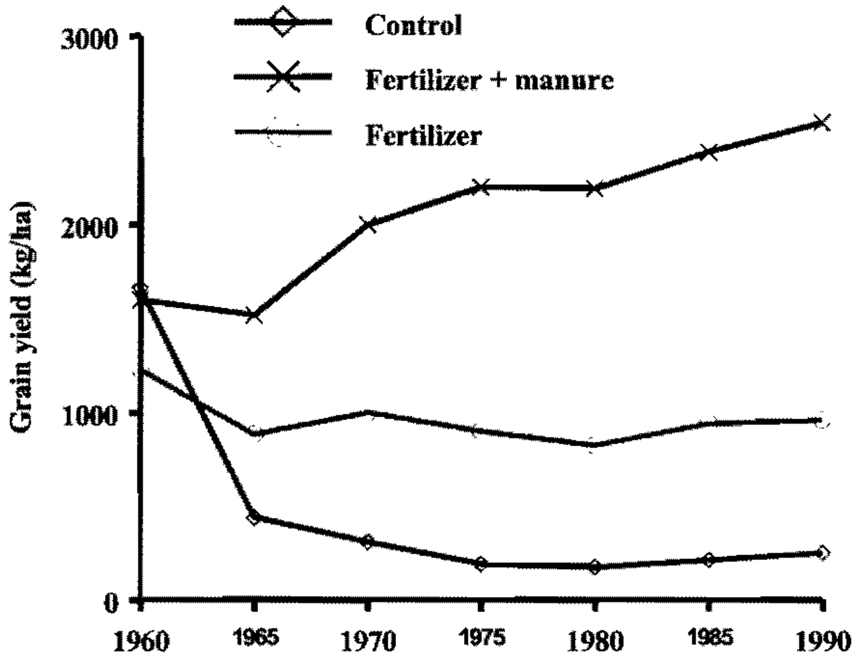


Figure 14: Sorghum grain yield as affected by mineral and organic fertilizers over time.

Source: Sedogo (1993)

As already indicated, SOC is significantly higher in rotation or intercropping systems of pearl millet and cowpea and this is one of the reason of higher productivity of millet in the rotation than in monoculture system (**Figure** 15)

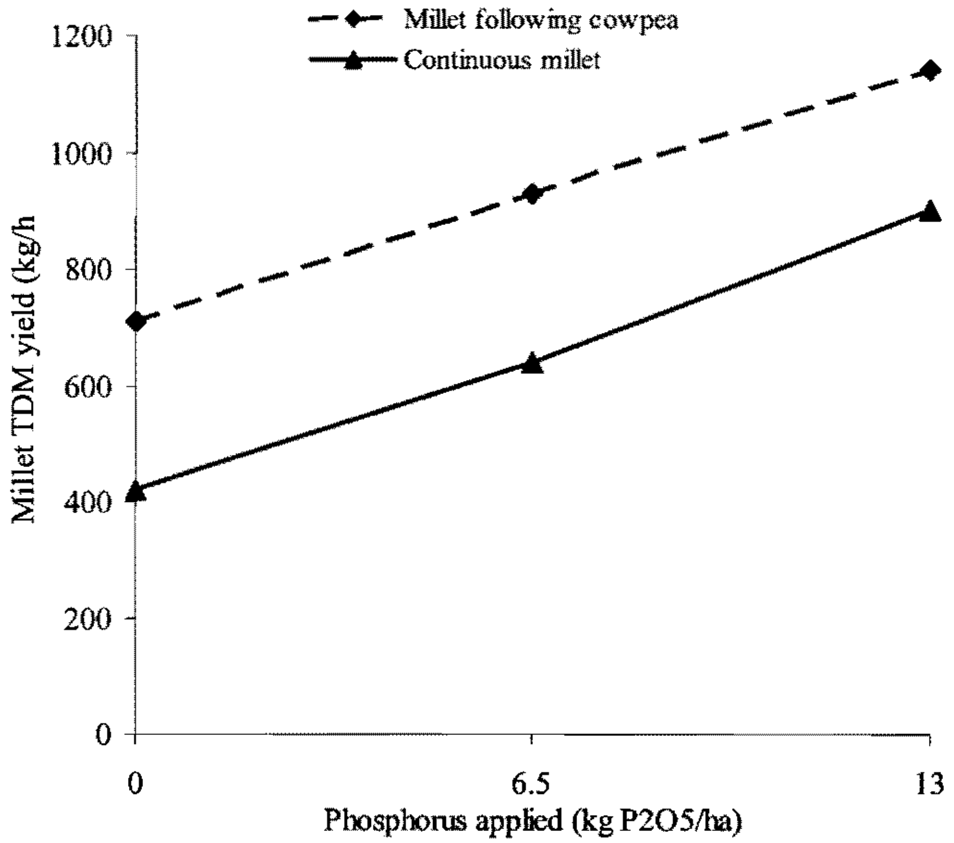
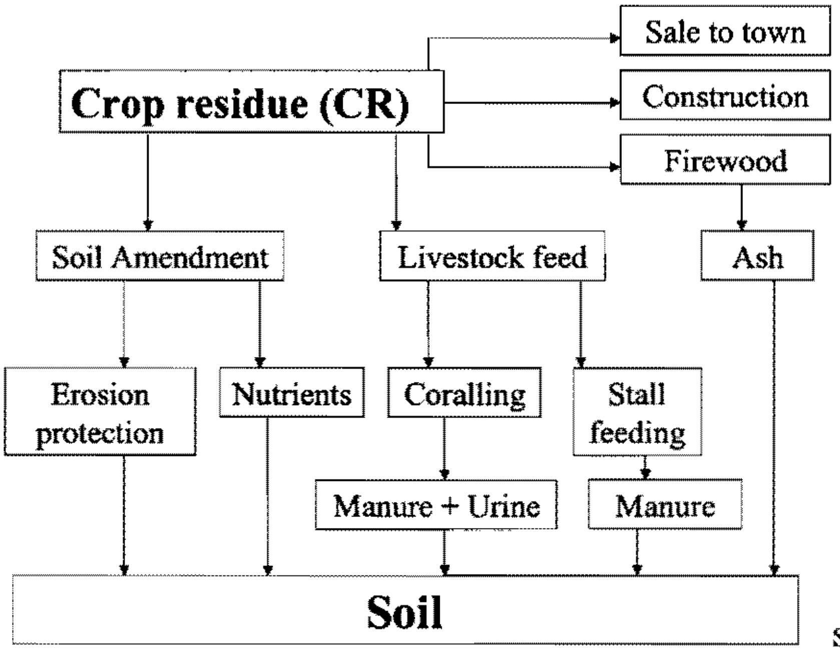


Figure 15: Effect of P fertilization and rotation on millet total dry matter yield

Figure 16 gives a schematic representation of the different uses of crop residues. Traditionally, many farmers burn whatever is left of their crop residue once their needs for fuel, animal feed, or housing and fencing material have 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.



Source: Bationo et al., 1995

Figure 16: The competing uses of crop residues in the West Africa Semi Arid Tropics

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 5t ha^{-1} every two years. However, the competition with other uses was not accounted for in this study. Lompo (1983) found in that zone upto 90% of crop residue is burned for cooking. This practise results in considerable loss of carbon and nutrients such as nitrogen and sulfur. Charreau and Poulain (1964) reported that 20 to 40kg N ha^{-1} and 5 to 10 kg S ha^{-1} are lost by burning crop residues. Other negative effects might be temporal changes in the population of micro organisms in the upper soil layers, particularly rhizobia , 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.

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 2t ha^{-1} (Rebafka et al., 1994). However, McIntire and Fussell (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.

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 to 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 intake from crop residues and up to 80% during periods of fodder shortage. 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). 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 (**Figure** 16) the increased 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 2.5kg N and 0.6 kg P per hectare of cropland. Although the manure rates applied are between 5 and 20t 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) Future research challenge with emphasis on organic matter quantity and quality

The complementarity 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. 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. Future research should alleviate 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.

In the decision support system for organic matter management, recommendation for appropriate use of organic material was made based on their resource quality, expressed as a function of N, polyphenol and lignin content (**Figure 17a**). The fertilizer equivalency of the different organic material can be predicted by the N content and the polyphenol contents (**Figure** 18). Applications of high quality organic materials enhance quick transformation into labile SOM fractions and improve nutrient supply and availability (Vanlauwe, 2004; Nandwa, 2001). The impact of organic resource quality on SOC is less clear. Roose and Barthes (2001) noted that the application of easily mineralizable manure was not sufficient to increase SOC levels. Low quality organic resources, which show limited increases in crop growth, contain substantial amounts of soluble polyphenols and lignins that may affect the longer-term decomposition dynamics and contribute to build up of SOC (Vanlauwe, 2004) necessary in the improvement of soil structure, aggregate stability (Six et al., 2002) and soil water buffering (Nandwa, 2001). Additionally, these resources have a positive impact on the environmental service functions of the soil resource (Vanlauwe, 2004).

Future research will therefore need 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. A recent hypothesis being tested is focusing on the linkage between resource quality, aggregate turnover, N use efficiency and C cycling across soil textures and climates (**Figure** 17 a and b). In natural ecosystems, nutrient limitation induces a slow aggregate turnover, which leads to a C sequestration and reinforces the nutrient limited environment. In intensively managed agroecosystems, aggregate turnover is fast due to high N availability and disturbance leading to high N and carbon losses. The combined use of organic resources of intermediate quality and mineral resources under this hypothesis may result in an optimal balance between N and C stabilization versus N availability for plants.

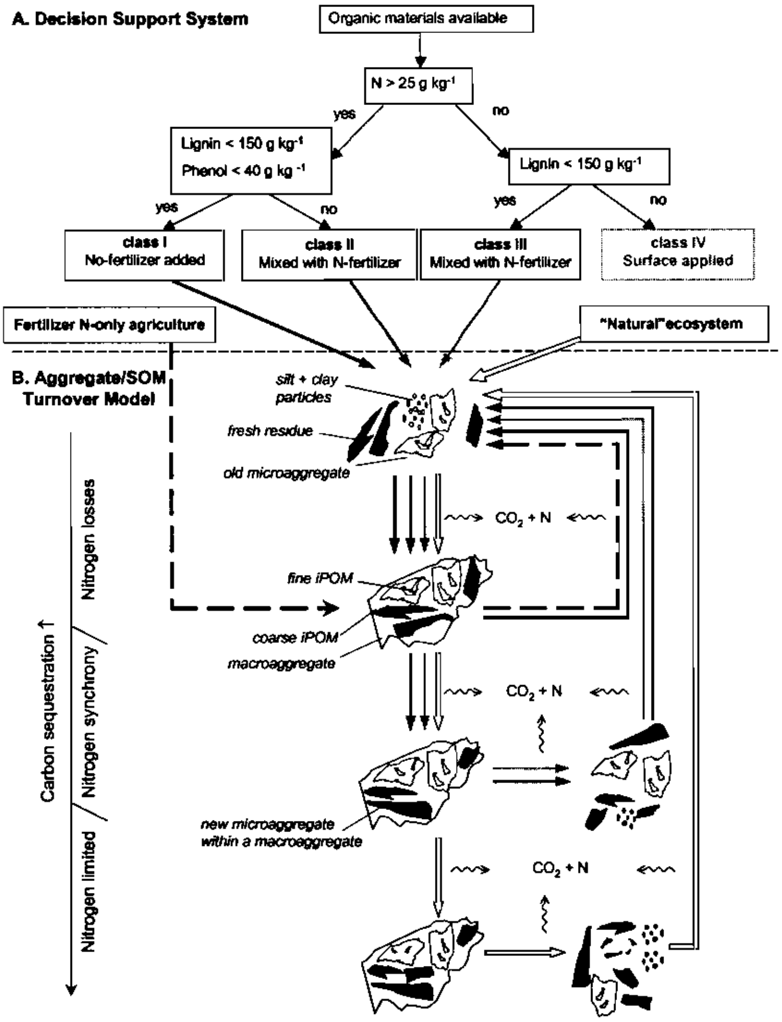


Figure 17. The decision support system for organic matter management and SOM turnover (Source: Palm et al., 2001; Six et al., 2000)

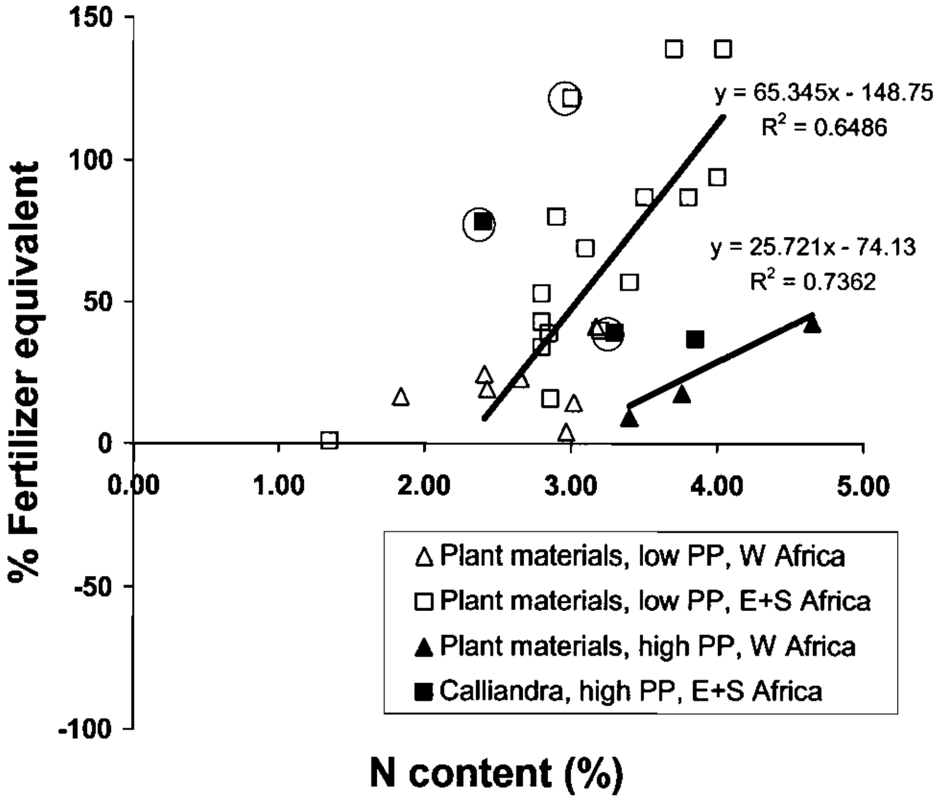


Figure 18. Fertilizer equivalency for different organic materials

(Source: Vanlauwe et al., 2002)

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