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Soil organic carbon management for sustainable land use in Sudano-Sahelian West Africa

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Abstract

Judged by their negative nutrient balances, low soil cover and low productivity, the predominant agro-pastoral farming systems in the Sudano-Sahelian zone of West Africa are highly unsustainable for crop production intensification. With kaolinite as the main clay type, the cation exchange capacity of the soils in this region, often less than 1 $cmol_c$ kg^{-1}soil, depends heavily on the organic carbon (Corg) content. However, due to low carbon sequestration and to the microbe, termite and temperature-induced rapid turnover rates of organic material in the present land-use systems, Corg contents of the topsoil are very low, ranging between 1 and 8 g kg^{-1} in most soils. For sustainable food production, the availability of phosphorus (P) and nitrogen (N) has to be increased considerably in combination with an improvement in soil physical properties. Therefore, the adoption of innovative management options that help to stop or even reverse the decline in Corg typically observed after cultivating bush or rangeland is of utmost importance. To maintain food production for a rapidly growing population, targeted applications of mineral fertilisers and the effective recycling of organic amendments as crop residues and manure are essential. Any increase in soil cover has large effects in reducing topsoil erosion by wind and water and favours the accumulation of wind-blown dust high in bases which in turn improves P availability. In the future decision support systems, based on GIS, modelling and simulation should be used to combine (i) available fertiliser response data from on-station and on-farm research, (ii) results on soil productivity restoration with the application of mineral and organic amendments and (iii) our present understanding of the cause-effect relationships governing the prevailing soil degradation processes. This will help to predict the effectiveness of regionally differentiated soil fertility management approaches to maintain or even increase soil Corg levels.

Introduction

The Sudano-Sahelian zone of West Africa (SSWA) is the home of the world's poorest people, 90% of whom live in villages and gain their livelihood from subsistence agriculture. The ongoing predominance of subsistence agriculture with limited access to market, and with very low levels of external inputs of mineral fertilisers and highly negative nutrient balances (Stoorvogel and Smaling, 1990) leads to a stagnation of agricultural productivity. However, the rather general lack of adoption of so called 'green revolution technologies' by farmers in SSWA is not only the consequence of inappropriate policies that favour urban populations at the expense of the rural sector but also of a very particular agricultural resource base.

Poor native soil fertility, low and erratic rainfall, high soil and air temperatures, surface crusting, low water-holding capacities and recurrent droughts are the main abiotic constraints to plant growth. Across the cultivated zones average rainfall varies from 300 to 800 mm and the ratio of annual rainfall to annual potential evapo-transpiration from 0.20 to 0.65. This zone is represented as the semiarid zones in Figure 1. Annual potential evapo-transpiration in SSWA is often over 1000 mm, higher than in Tropical Australia at

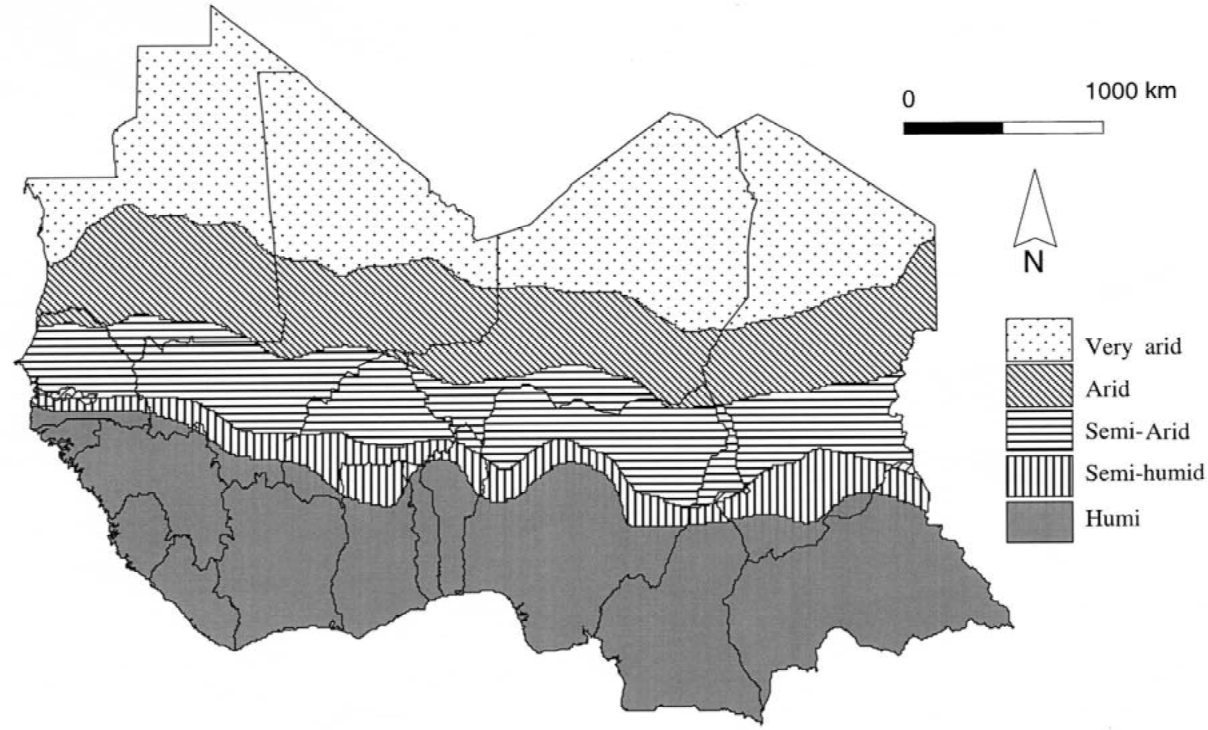

Figure 1. Agro-climatic zones in Sudano Sahelian West Africa (SSWA).

the same total amount of rainfall (Breman, 1998). The aridity of the climate means that the contribution of perennial species to the annual plant production, even in the case of undisturbed vegetation, is lower than elsewhere in the world at the same amount of annual rainfall. High soil temperatures, often exceeding 45 °C, can prevent crop establishment. Early season sand blasting caused by wind erosion further hampers seedling growth and rapid soil coverage with plants. Still, in the Sudano-Sahelian area, above 300 mm annual precipitation, primary and crop production are more limited by nutrients, phosphorus (P) before nitrogen (N), than by water or the adverse bio-physical conditions (Penning de Vries and Djitèye, 1982). The dominance of nutrient limitation over water is such that the vegetation uses only 10 – 15% of the average rainfall (Breman and de Ridder, 1991). The rest is lost by evaporation, run-off and leaching. The breakdown of these systems with population growth requires alternative approaches at higher levels of external inputs to increase the productivity of agricultural land. The effects of the application of organic materials such as crop residues (CR) and manure on the recycling of plant nutrients, on soil coverage and soil erosion and on the overall C balance of the agro-pastoral systems

Table 1. Correlation (r) between selected soil (0–20 cm) fertility parameters and average annual rainfall (n = 31)

	Ca	CEC	Corg	Total N	Clay	Rainfall
pH KCl	0.62***[a]	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***
Corg				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.

are well documented (Bationo et al., 1995; Buerkert et al., 1996; Padwick, 1983). However, much less is known about the effects of management practices on the Corg status of West African soils and how these may differ with soil type and climate. To this end, this paper will first discuss the status of Corg in the soils of the region and its annual losses in different management systems. Subsequently it will address the effects of organic amendments on soil properties and soil conservation. The last section will conclude by suggestions avenues for action and future research to contribute to a more sustainable land-use in this zone.

Role of soil organic carbon and its fate as affected by management practises

The concentration of organic carbon in the topsoil reported to average 12 mg kg^{-1} for the forest zone, 7 mg kg^{-1} for the Guinean zone, 4 mg kg^{-1} in the Sudanian zone and 2 mg kg^{-1} for the Sahel under the conditions of an undisturbed climax vegetation (Breman, 1998) is of utmost importance for the maintenance of soil productivity and was traditionally guaranteed through regular fallow periods. The soils in the Sudano-Sahelian zone are inherently low in Corg. These reflect the low shoot and root growth of crops and natural vegetation but also the rapid turnover rates of organic material with high soil temperature and microfauna, particularly termites. In a survey of 31 millet producing soils, Manu et al. (1991) found an average soil Corg content of 7.6 g kg^{-1} with a range from 0.8 to 29.4 g kg^{-1}. The data also showed that these Corg contents were highly correlated with total N (r = 0.97; Table 1) which indicates that in the predominant agro-pastoral systems without the application of mineral N fertilisers, N nutrition of crops largely depend on the maintenance of soil Corg levels. The effect of rainfall on turnover rates of Corg through higher biomass production, coupled with higher decay rates is reflected in the statistically significant but absolutely low correlation between rainfall and Corg (r = 0.42).

The importance of soil textural (clay and silt) properties for the Corg content of soils was stressed repeatedly as clays are an important component in the direct stabilisation of organic molecules and microorganisms (Amato and Ladd, 1992; Greenland and Nye, 1959; Feller et al., 1992). Thus, Feller et al. (1992) reported that independently of climatic variations such as precipitation, temperature and duration of the dry season Corg increased between 600 and 3000 mm annual rainfall with the clay and silt contents of low activity clay soils. Therefore, small variations in topsoil texture at the field or watershed level could have large effects on Corg. In this context, a survey of West African soils (Manu et al., 1991) indicated that for the soils investigated cation exchange capacity (CEC) depended more directly on Corg (r = 0.86) than on the soils' clay content (r = 0.46). De Ridder and Van Keulen (1990) found that a difference of 1 g kg^{-1} in Corg resulted in a difference of 0.25 cmol kg^{-1} for soil CEC. As a key determinant of soil productivity the maintenance of Corg levels must therefore be an important goal of farmers and researchers.

There is much evidence for a rapid decline of Corg levels with continuous cultivation of crops in SSWA (Bationo et al., 1995). For the sandy soils, average annual losses in Corg, 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, with an average of 2% much lower (Pieri, 1989; Table 2). Topsoil erosion may lead to significant increases in annual Corg losses such as from 2% to 6.3% at the Centre de Formation des Jeunes Agriculteurs (CFJA) in Burkina Faso (Table 2). However, such declines are site-specific and heavily depend on management practises such as the choice of the cropping system, soil tillage and the application of mineral and organic soil amendments. Data from Chad show that crop rotation and fallow management can minimise Corg losses. Thus, k-values in cotton-cereal rotations were 2.4%, lower than the 2.8% continuous cotton system. Also four years of fallow after 16 years of cultivation had led to large increases in Corg and a reduction of annual Corg losses to 0.5%. Data from a rotation trial at Sadoré in the Sahel revealed significant effects of crop rotation on soil Corg contents. After five years, Corg 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 Corg kg^{-1} (Bationo, unpublished data). The higher Corg level in the cowpea system was at least partly due to the falling of leaves from the legume crop.

At Nioro-du-Rip in Senegal without mineral fertiliser application, soil tillage increased annual the rate of annual Corg losses k from 3.8% to 5.2% (Table 2), whereas with mineral fertilisers at Sefa, Corg values increased from 3.8 g kg^{-1} with manual tillage to 64 mg kg^{-1} with deep tillage (Pieri, 1989). The effects of mineral fertiliser application on Corg seem to depend on the type of fertiliser used. While annual N application at 100 kg ha^{-1} was found to cause an N flush from decomposing organic matter of between 300 and 400 kg N ha^{-1} through an increase in biological activity, regular NPK applications were reported to reduce the depletion of Corg (Pieri, 1989). Similarly at Nioro-du-Rip in Senegal, annual Corg losses declined from 5.2% without NPK to 3.9% with NPK (Table 2). On the other hand fertiliser effects on crop growth may also be affected by a soil's Corg level. Berger et al. (1987) reported from the Northern Guinean zone that crop responses to chemical fertilisers ceased below 3.5 mg Corg kg^{-1}. On sandy Sahelian soils, however, Bationo et al. (1998) reported a very strong response to

Table 2. 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)	
				Number of 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.

mineral fertilisers with Corg contents as low as 1.7 mg kg^{-1}. There is still not a clear scientific explanation for this discrepancy.

The effects of surface mulched cereal stover (CR) on Corg levels are contradictory (Bationo et al., 1995). Through the stimulation of microbial activity, CR application can lead to a depletion of Corg. At a Sahelian site, soil respiration at millet harvest was found to be 2.7 mg C kg^{-1} d^{-1} in plots mulched with 4 t CR ha^{-1} compared to 1.5 mg C kg^{-1} d^{-1} in unmulched control plots. Average Corg mineralisation was more than twice as high in mulched plots than in unmulched plots (Bationo et al., 1999). At Saria in Burkina Faso, annual Corg losses increased from 1.9% without CR application to 2.2% with CR mulching. Similar increases in Corg losses were also reported from Bambey in Senegal (Table 2).

Nevertheless, these data are challenged by the results of a mulching experiment conducted from 1995 to 1998 at eight sites in SSWA from 510 to 1300 mm annual average rainfall and clay contents between 2% and 20%. They showed that with yearly CR mulching at 2000 kg CR ha^{-1} Corg levels declined much less than at a mulch rate of 500 kg CR ha^{-1} (Buerkert et al., 1999a).

Effects of crop residues and manure on soil productivity, fertiliser use efficiency and soil properties in a long term crop residue and fertilizers management trials conducted at Sadore (Niger) from 1984 to 1996. A slow-down of Corg from pre-cultivation levels has been found. In this trial CR mulch at 2 t ha^{-1} and

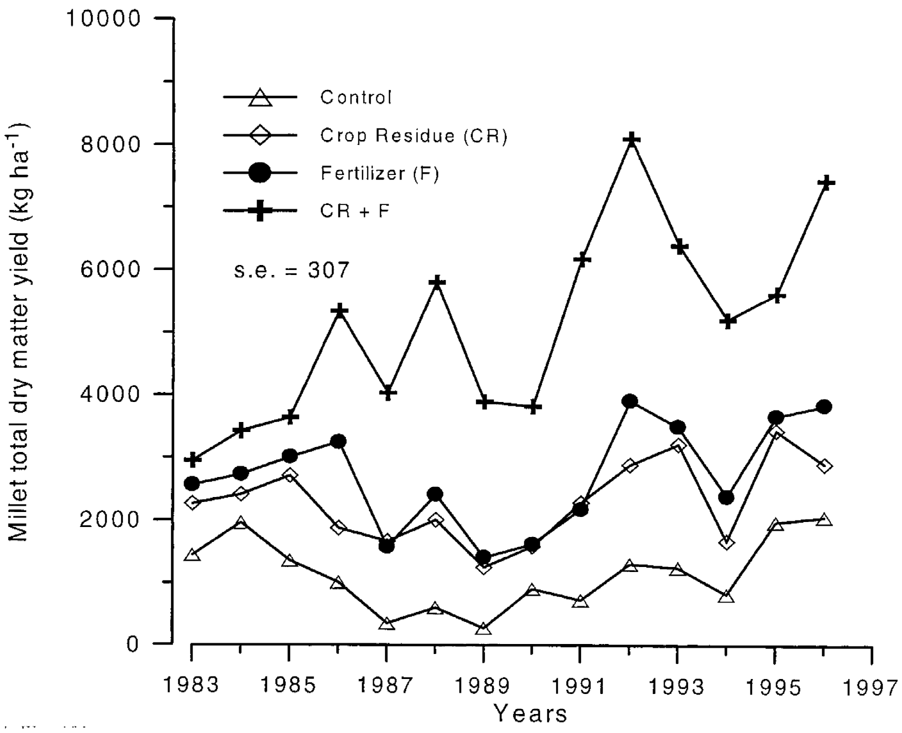

Figure 2. Pearl millet total dry matter yield as affected by different management practices over years. Source: Bationo et al. (1998).

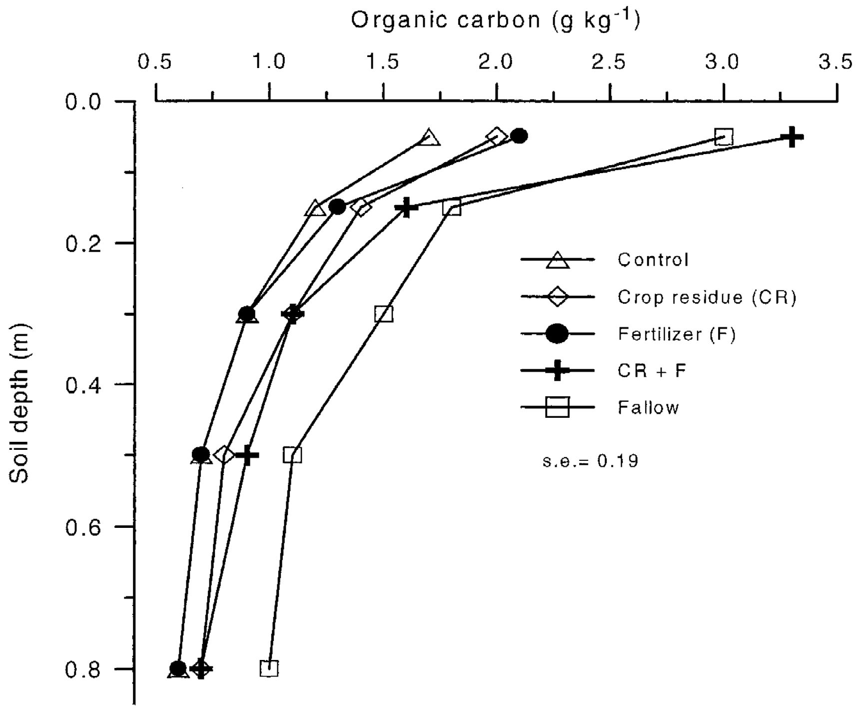

Figure 3. Soil organic carbon (Corg) as affected by soil depth and management practices. Sadoré, Niger, rainy season, 1996.

Table 3. Increase in incremental millet grain and stover yield due to fertiliser application

Zone	Year	Treatment	Fertiliser effect	
			Grain	Stover
			kg per kg P applied	
Sahelian zone (Sadoré)	1983	CR	-	-
		Fertiliser	59[1]	NA
		CR + Fertiliser	72[2]	NA
	1984	CR	-	-
		Fertiliser	34	21
		CR + Fertiliser	14	31
	1985	CR	-	-
		Fertiliser	67	188
		CR + Fertiliser	137	427
	1986	CR	-	-
		Fertiliser	57	184
		CR + Fertiliser	112	359
Sudanian zone (Tara)	1990	CR	-	-
		Fertiliser	81	103
		CR + Fertiliser	87	124
	1991	CR	-	-
		Fertiliser	51	108
		CR + Fertiliser	44	115
	1992	CR	-	-
		Fertiliser	40	83
		CR + Fertiliser	40	90

1. Calculated as (yield fertiliser - yield control) / P applied.
2. Calculated as (yield CR + fertiliser - yield control) / P applied.
NA = not available.
Source: Bationo et al., 1995

the annual application of 13 kg P ha^{-1} as SSP plus 30 kg N ha^{-1} as CAN led to similar TDM increases and to large additive effects (Figure 2). Levels of Corg were with 1.7 g kg^{-1} at 0.1 m lowest in unmulched control plots and with 3.3 g kg^{-1} highest in the topsoil of plots with the combined application of 4 t CR ha^{-1} and mineral fertilisers. However, even in plots with both amendments combined Corg levels were, except for the surface soil, lower than in an adjacent fallow (Figure 3).

Numerous research reports showed large crop yield increases as a consequence of organic amendments in the Sahelian zone of West Africa (Abdullahi and Lombin, 1978; Bationo et al., 1993, 1998; Evéquoz et al., 1998; Pieri, 1986, 1989). Bationo et al. (1995) reported from an experiment carried out in 1985 on a sandy soil at Sadoré, Niger that grain yield of pearl millet (*Pennisetum glaucum* L.) after a number of years had declined to only 160 kg ha^{-1} in unmulched and unfertilised control plots. However, grain yields could be increased to 770 kg ha^{-1} with a mulch application of 2 t CR ha^{-1} and to 1030 kg ha^{-1} with 13 kg P as SSP plus 30 kg N ha^{-1}. The combination of CR and mineral fertilisers resulted in a grain yield of 1940 kg ha^{-1}. Comparative data of P fertiliser use efficiency (FUE) with and without CR mulch application in the Sahel and the Sudanian zone underline the additive effects of both soil amendments (Table 3).

For the Sudanian zone, all available reports show a much smaller or even negative effect of the same rate of CR mulch on crop yields (Bationo et al., 1995; Sedogo, 1993). These differences in CR effects on crop growth between the Sahelian and Sudanian zone of West Africa may at least be partially explained by the effects of CR mulch on soil chemical and physical properties. In the Sahel with its early season sand storms, CR have been shown to increase soil P availability (Kretzschmar et al., 1991), cause better root growth (Hafner et al., 1993), improve potassium (K) nutrition (Rebafka et al., 1994), protect young seedlings against soil coverage during sand storms (Michels et al., 1995), increase water availability (Buerkert et al., 1999b), and reduce soil surface resistance by 65% (Buerkert and Stern, 1995) and topsoil temperature by over 4 °C (Buerkert et al., 1999b). In the Sudanian zone, in contrast, with its lower overall temperatures, higher rainfall, heavier soils and more rapid decomposition rates of organic materials, these effects of mulching on soil chemical properties have been found to be much weaker (Buerkert et al., 1999a).

The effects of mineral fertiliser application on pH, exchangeable bases and P sorption seem, at least on the weakly buffered Sahelian soils, too strongly depend on CR recycling. Without CR mulching pH levels in the topsoil of plots to which N and P were applied over 14 years were considerably lower than unmulched control plots. The increased mulch material produced in plots with mineral fertilisers led, if recycled, to a large rise in respective pH values throughout the upper 0.3 m (Figure 4). Similar effects of mineral fertilisers and CR were also measured on exchangeable bases (Figure 5). This trial also revealed that maximum P sorption in the topsoil as calculated by the Langmuir equation, declined from 91 mg P kg^{-1} in unmulched control plots without P fertilisers to 54 mg P kg with P application and to 37 mg P kg^{-1} with the additional application of 4 t CR ha^{-1} (Figure 6). From incubation studies under controlled conditions Kretzschmar et al. (1991) concluded that such increases in P availability after CR application were due to a complexation of iron and aluminium by organic acids.

On the nutrient poor West African soils, manure, the second farm-available soil amendment, can sub-

Table 4. Results of manuring experiments at three sites in semi-arid West Africa

A: Manure only

Location	Amount of manure applied ($t\ ha^{-1}$)	Crop	Crop response[a] (kg of DM t^{-1} manure) Grain	Stover
M'Pesoba, Mali	10	Sorghum	35[b]	n.s.
Saria, Burkina Faso	10	Sorghum	58	n.s.
Sadore, Niger 1987	5	Pearl millet	38	178
	20	Pearl millet	34	106

B: Manure with inorganic fertiliser

Location	Amount of		Crop	Crop response[a] (kg of DM t^{-1} manure)	
	Manure ($t\ ha^{-1}$)	Fertiliser ($kg\ ha^{-1}$)		Grain	Stover
M'Pesoba, Mali	5	NPK: 8-20-0	Sorghum	90[c]	n.s.
Saria, Burkina Faso	10	Urea N: 60	Sorghum	80	n.s.
Sadoré, Niger					
1987	5	SSP P: 8.7	Pearl millet	82	192
1987	20	SSP P: 17.5	Pearl millet	32	84

[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 rotation involving cotton-sorghum-groundnut-sorghum. Manure was applied in the first year.
[c] Estimated from visual intrapolation of graph.
n.s. = not specified.
Source: Williams et al., 1995

stantially enhance crop yields. For Niger, McIntire et al. (1992) reported grain yield increases between 15 and 86 kg for millet and between 14 and 27 kg for groundnut per ton of applied manure. Similar manure effects have been reported from other Sahelian countries (Table 4). However, given the large variation in the nutrient concentrations of the manure types applied, comparisons between results from different experiments should be made with great care (Table 5).

In general livestock can have significant effects on the maintenance of Corg levels in cropland, but cattle also is an important consumer and vector of organic materials and mineral nutrients from rangeland to manured fields. Recent data from village level studies the Sahel indicate that 46% of the grazed dry matter are either stored in the body mass of cattle and eventually transported to coastal slaughter houses or voided in the process of rumination and respiration (Buerkert and Hiernaux, 1998; Hiernaux et al., 1997).

Adapted approaches to maintain organic matter and soil productivity

In SSWA crop residues as surface mulch can play an important role in the maintenance of Corg levels and productivity of the prevailing acid soils through the recycling of mineral nutrients, increases in fertiliser use efficiency and a decrease in soil erosion effects on soil chemical, physical and biological properties. However, organic materials available for surface mulching are scarce given the low overall production levels of biomass in the region and their multiple competitive uses as fodder, construction materials and cooking fuel (Lamers and Feil, 1993). The quantities of CR found on-farm at the beginning of the rainy season range between 0 and 500 kg ha^{-1}. McIntire and Fussel (1986) reported that on farmers' fields in the Sahel average grain yields were 236 kg ha^{-1} and mean CR yields barely reached 1300 kg ha^{-1}. 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 cropping season, but at the onset of the rains in

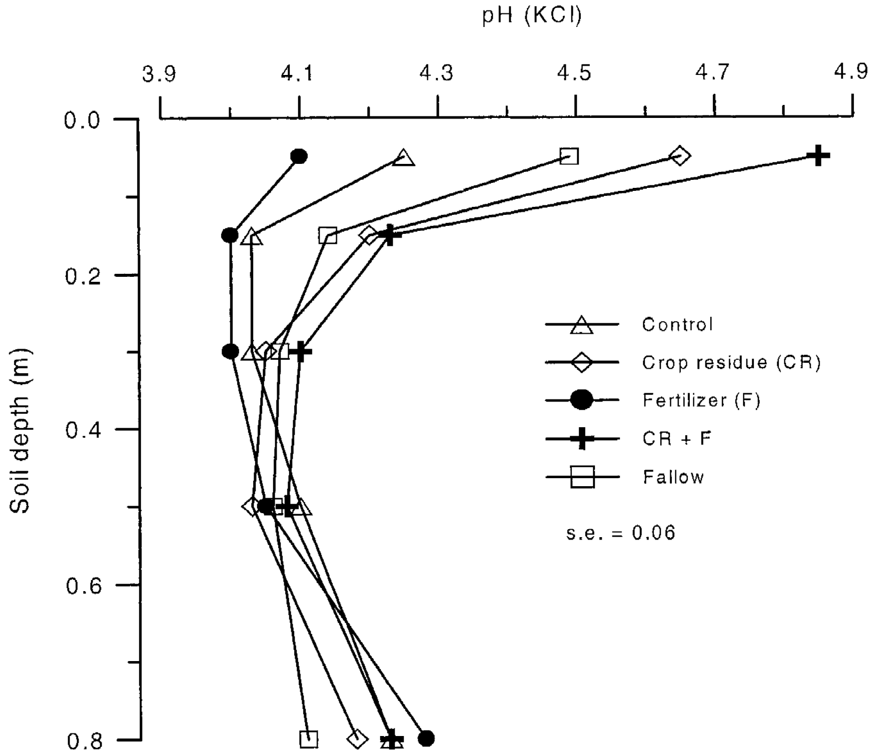

Figure 4. Soil pH as affected by soil depth and management practices. Sadoré, Niger, rainy season, 1996.

Table 5. Nutrient composition of manure at selected sites in semi-arid West Africa

Location and type of manure	Nutrient composition (%)		
	N	P	K
Saria, Burkina Faso			
Farm yard manure	1.5 – 2.5	0.09 – 0.11	1.3 – 3.7
Northern Burkina Faso			
Cattle manure	1.28	0.11	0.46
Small ruminant manure	2.20	0.12	0.73
Senegal			
Fresh cattle dung	1.44	0.35	0.58
Dry cattle dung	0.89	0.13	0.25
Niger			
Cattle manure	1.2 – 1.7	0.15 – 0.21	-
Sheep manure	1.0 – 2.2	0.13 – 0.27	-

Williams et al., 1995

the following year barely 250 kg ha^{-1} remained for mulching. Powell et al. (1987) showed that at least 50% of these large on-farm disappearance rates of millet stover could be attributed to livestock grazing. This included a complete loss of millet leaves.

Animal manure has a similar role as residue mulching for the maintenance of soil productivity but depending on rangeland productivity, it will require between 10 and 40 ha of dry season grazing land and between 3 and 10 ha of rangeland of wet season grazing to maintain yields on one hectare of cropland (Fernandez-Rivera et al., 1995). The potential of manure to maintain soil Corg levels and sustain crop production is thus limited by the number of animals available and the size and quality of the rangeland.

At the systems level, the maintenance of Corg levels in the soils of SSWA will largely depend on an increase in C fixation by plants. Given the strong limitation of plant growth by the low availability of mineral nutrients, a yield-effective application of mineral fertilisers is crucial. It would not only allow large increases in crop production and the amount of by-products but also to improve soil coverage by forage grasses and weeds. Both help to boost the overall productivity of the integrated crop-livestock systems with their multiple short-cuts in organic mater and nutrient cycles via animals. The use of locally available 'soft' rock phosphates suitable for direct application as soil amendment (McClellan and Notholt, 1986) may be

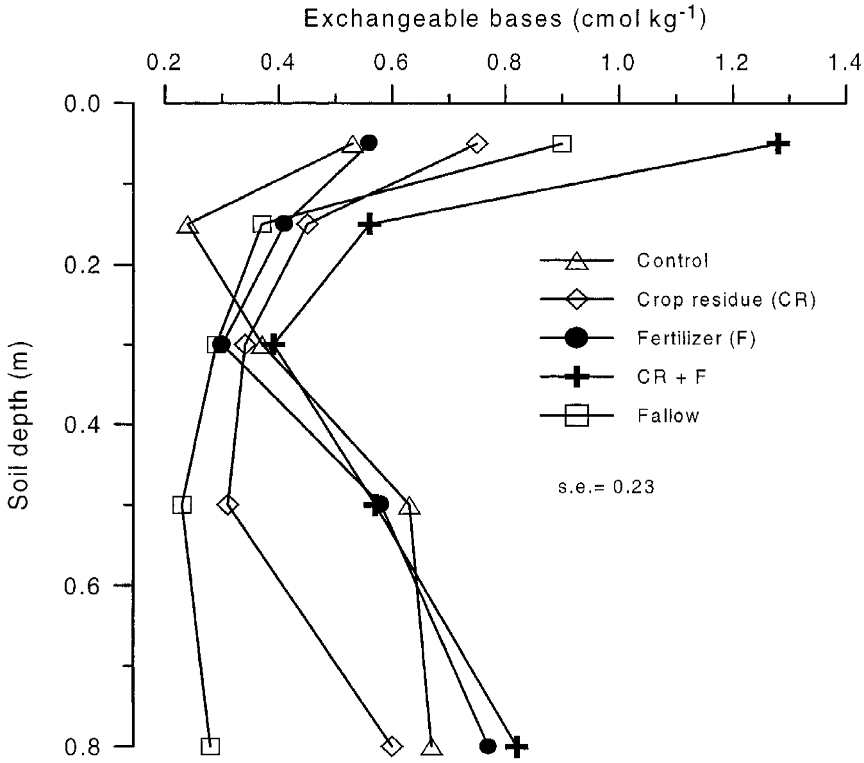

Figure 5. Exchangeable bases as affected by soil depth and management practices. Sadoré, Niger, rainy season, 1996.

Table 6. 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	With urine		Without urine	
		Grain yield	Total biomass	Grain yield	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

s.e.m. = standard error of the mean.
Adapted from Powell et al., 1998

cost-effective with high rainfall and on sites with a soil pH < 4.3. Under those conditions Bationo et al. (1990) found 'Tahoua' (Niger) rock 76% as effective as SSP in increasing millet yields. A low cost alternative, the placement of 4 kg P ha^{-1} as ground NPK (15-15-15) with the seed at sowing or shortly thereafter was shown to cause average TDM increases in millet, sorghum, maize, cowpea and groundnut of 70% for cereals and 74% for legumes at eight sites in West Africa (Buerkert and Hiernaux, 1998). The same au-

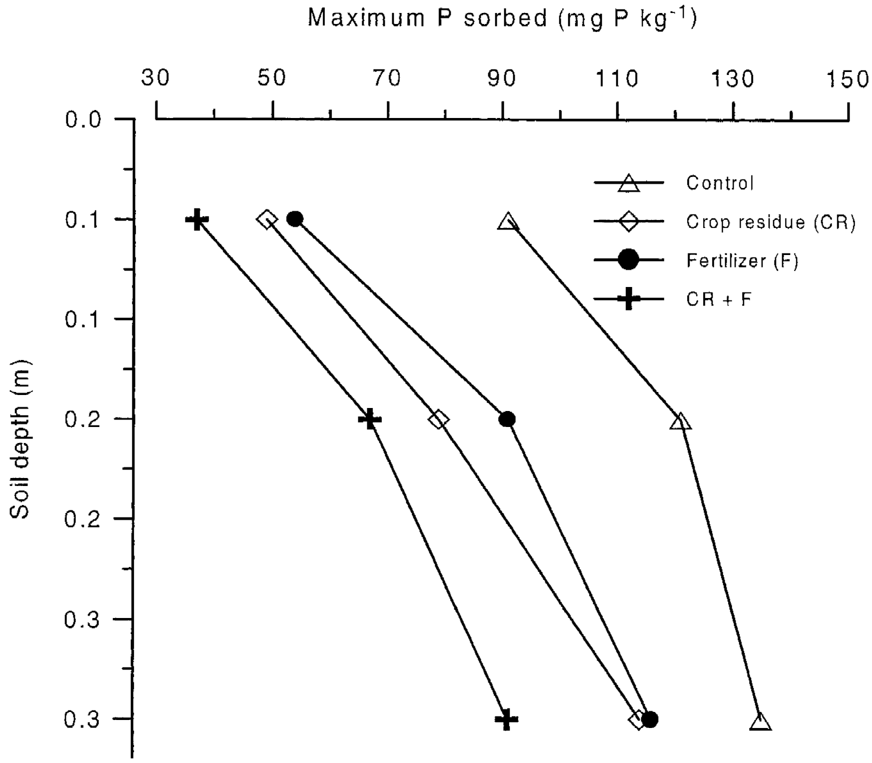

Figure 6. Maximum phosphorus sorbed as affected by soil depth and management practices, Sadoré, Niger, 1999.

thors also showed that after three years, TDM yields of cereals and legumes were doubled with either annual applications of 13 kg P ha^{-1} as SSP, or the combination of 39 kg P ha^{-1} applied once every three years as rock phosphate plus annual placed NPK application, or the combination of 130 kg P ha^{-1} applied once every ten years as rock phosphate plus annual placed NPK application. Phosphorus use efficiency (PUE), expressed as average increase in total dry matter of crops per kg of P applied, was almost twice as high for placed NPK at 4 kg P ha^{-1} as for broadcast SSP at 13 kg P ha^{-1}. Lowest PUE values were obtained for rock phosphate treatments with or without NPK placement. In 1998, on-farm trials conducted with 250 farmers in three regions of Niger confirmed these yield increases with placed NPK application and showed that this simple technique was particularly attractive to farmers given a reduction in their investment costs by about 70% compared to broadcast application of SSP or NPK fertiliser at 13 kg P ha^{-1}.

While it is clear that more basic research is still needed to increase our knowledge about the role and quality of organic matter in Sudano-Sahelian soils and how both are affected by management practices, the increased use of GIS based decision support systems should have an even higher priority. Together with more locally adapted crop growth simulation models, this would facilitate the definition of 'recommendation domains' for effective strategies to maintain Corg levels and subsequent soil productivity under the diverse agro-ecological conditions of SSWA. It would also allow to move away from the analysis of site-specific results to a more detailed understanding of principles governing sustainable production systems. To be adopted at the farm level, however, any innovation must meet the multiple goals of local farmers, and particularly their desire to increase short-term income and reduce risk. This will remain a major challenge for researchers and policy-makers alike.

Future research needs to examine the cause-effect relationships governing the critical levels of organic matter at farm level in order to establish accurate critical levels for the different soil types and climate in the SSWA. Legumes component in mixed cropping systems to enhance soil fertility, boast subsequent crop yields, and provide high quality feed for livestock is a priority area that needs further investigation. Another important area for future research is the relationship between soil organic matter and soil physical characteristics, and the role of agro-forestry in soil organic carbon turnover. Since most of the data reported in this paper were collected from on-station experiments, future research needs to take into account farmers' practices and socio-economics conditions.

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