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Potential of Soil Carbon Sequestration under Various Landuse in the Sub-humid and Semi-arid Savanna of Nigeria: Lessons from Long-term Experiments

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Abstract: The objective of this research is to use the opportunity of the long-term Cowdung (D), Nitrogen (N), Phosphorus (P) and Potassium (K) trial at Samaru and the improved pasture trial at Shika both in Zaria and the sand dune stabilization trial at Gidan Kaura near Illela in NW Nigeria to provide reliable estimates of the long-term soil C turnover in the semi-arid and sub-humid savannas of Nigeria and by extension, West Africa. After 45 years of the DNPK treatments, Soil Organic Carbon (SOC) content in the unamended soil (control) was still on a slight increase, as represented by an increase of 1.81 t C ha^{-1} or 10 g C m^{-2} yr^{-1} between 1977 and 1995. In the same period of 45 years, the use of continuous NPK application resulted in only slight increase in SOC (3%) over the unamended soil while manure with NPK gave 115% more SOC. The use of NPK between 1977 and 1995, a period of 18 years, improved SOC content from 4.95 to 7.30 t C ha^{-1}, giving a rate of 13 g C m^{-2} yr^{-1}. This rate is about 50% less the rate using manure alone and 75% less using manure with NPK. After 6 years of natural fallow, the unamended soils experienced a slight decrease in SOC content from 7.04 to 6.83 t C ha^{-1} representing about 3% reduction. Generally, the rate of SOC sequestration during the fallow period is approximately 400% more than the rates under continuous cultivation. The rate of carbon sequestration for plots receiving manure during cultivation is 24 g C m^{-2} yr^{-1} and this increased to 108 g C m^{-2} yr^{-1} during the fallow period. Improved pasture like *Brachiaria decumbens* has the potential to sequester about 20 t C ha^{-1} in 3 5 years or a rate of 825 g C m^{-2} yr^{-1} over the control. Despite the near natural conditions of the sand dune stabilization trial, SOC under shelter belt sequestered up to 39.09 t C ha^{-1} in 12 years of the trial. This value is about 16 times the SOC in the unstabilized sand dune (control). The rate of SOC accumulation in the shelter belt is about 305 g C m^{-2} yr^{-1} more than the control. The potential for SOC sequestration by the use of eucalyptus and neem trees In afforestation in NW Nigeria is between 23 and 305 g C m^{-2} yr^{-1} over the control. Under continuous cultivation, the potential for SOC sequestration is greatest when NPK is co-applied with manure giving a rate of 36 to 158 g C m^{-2} yr^{-1}.

Key words: Carbon sequestration, landuse, long-term experiments, savanna

Introduction

Carbon sequestration in soil organic matter is increasingly advocated as a potential 'win-win' strategy for reclaiming degraded lands, particularly in semi-arid regions of the developing world and mitigating global climate change (Lal *et al*., 1999; Batjes, 2001; FAO, 2001). It is argued that it has the

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potential to simultaneously improve local soil fertility, enhance crops yields, reduce poverty and increase the global carbon uptake through terrestrial sinks and thus, contribute to climate change mitigation (Rosenberg *et al*., 1999; Batjes, 2001; Lal, 2002).

Some scientists suggest that the highest potential for soil carbon sequestration (SCS) can be found in degraded lands especially in the semi-arid and sub-humid regions of the tropics (USGS, 2000; Follett *et al*., 2001). The degradation of cropland and pastures is most extensive in Africa and within Africa; the Sahelian ecosystem is one of the most vulnerable to land degradation (Oldeman *et al*., 1990; Thomas and Middleton, 1994). This region has been subjected to repeated periods of severe drought (Nicholson, 2001) and, climatic and human induced degradation (Ojima *et al*., 1993). Soils in this region are low in organic carbon (Bationo and Buerkert, 2001) and therefore, potentially could sequestered carbon. Two principal approaches for increasing terrestrial C sequestration are converting marginal land to grassland and forest and increasing productivity on crop and forest lands with residue management and application of technology. Of the many new technologies, novel fertilizers and soil amendments and use of Plant Growth Regulators (PGRs) have potentials to increase biomass production and hence enhance carbon sequestration in soils of the drylands (Metting *et al*., 1999). Long-term experiments have shown that in Senegal 4.5 t C ha^{-1} was obtained for continuously cultivated areas without manure input to 18 t C ha^{-1} for non-degraded savannas (Tiessen *et al*., 1998). Through improved management, soils in the semi-arid regions have been reported to sequester between 0.05 and 0.3 t C ha^{-1} yr^{-1} on croplands and 0.05 to 0.1 t C ha^{-1} yr^{-1} on grasslands and pastures (Lal, 1999). The potential for SCS lies in the low SOC and the vast degraded lands in this region.

Progress has been made in our understanding of the processes of soil C sequestration in recent times. However, many gaps still remain in our understanding of how the stocks and the quality of C evolve in different soils and under different management practices on the long run (Lal *et al*., 1997; Metting *et al*., 1999). Such knowledge gaps are more critical for tropical soils in Africa (Lal, 1999). Post and Kwon (2000) provided an extensive review of existing literature on the potential of SCS under different land uses but reports from Africa constituted less than 10%. Long-term agricultural experiments especially from other parts of the world, have been valuable for understanding soil carbon dynamics under agriculture. Additional long-term trials that address SOC dynamics under different land uses, especially from tropical Africa, would further enhance our understanding and increase our predictive capability over long time scales (Chaudhary *et al*., 1981; Perkins and Thomas, 1993; Michels *et al*., 1995). However, an important pre-requisite to taking advantage of the enormous potentials for SCS in tropical Africa is to know the carbon stocks of the semi-arid and sub-humid regions and their potentials for increase. The objective of this study use the opportunity of the long-term Cowdung, Nitrogen, Phosphorus and Potassium (DNPK) trial at Samaru and the improved pasture experiments at Shika, both in Zaria and the sand dune stabilization trial at Gidan Kaura near Illela in NW Nigeria to provide reliable estimates of the long-term soil C turnover in the semi-arid and sub-humid savannas of Nigeria and by extension, West Africa.

Materials and Methods

This report synthesizes the results of previous studies on the long-term experiments at Samaru and Shika, both in Zaria and Gidan Kaura near Illela, all in Nigeria (Fig. 1). Reports on the DNPK trial were obtained from Bache and Heathcote (1969), Moehansyah (1977), Agbenin and Goladi (1998) and Ogunwole and Ogunleye (2005). Ogunwole *et al*. (2004) provided information on the improved pasture trials at Shika while Raji *et al*. (2004) reported on the sand dune stabilization trial at Gidan Kaura. All these have been synthesized into the present study.

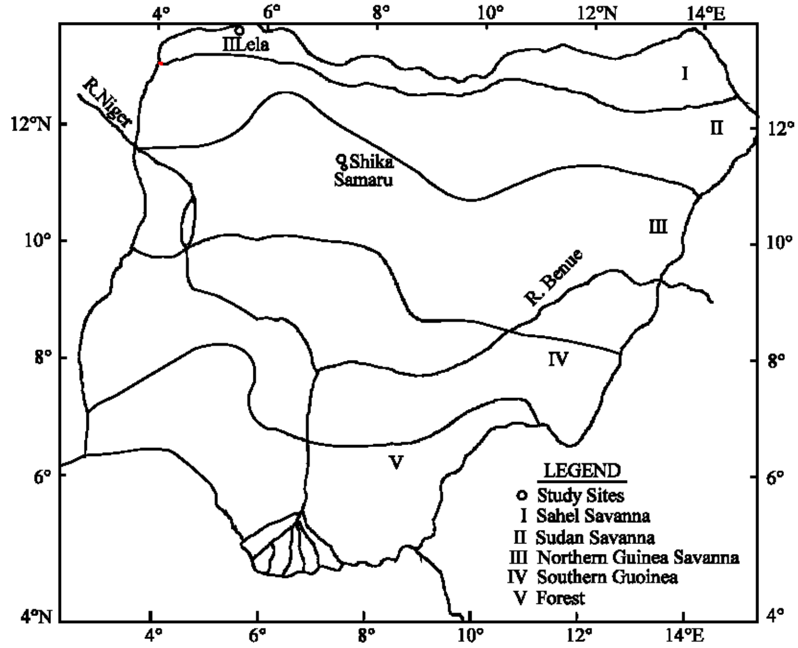

Fig. 1: Map of study site in Nigeria

The long-term DNPK trial started in 1950 and is the oldest organic and mineral fertilizer experiment in West Africa. In the first decade of the trial (1950-1960) cotton, sorghum and groundnut were cropped in rotation while between 1961 and 1970 cotton monoculture dominated. From 1976, a rotation of groundnut and maize became the predominant cropping pattern. Nitrogen was usually not applied whenever groundnut is grown as a sole crop. In 1967, lime was applied on a plot-by-plot basis depending on the actual lime requirement of each plot. Also, micronutrients [like zinc (Zn), molybdenum (Mo), boron (B) and copper (Cu)] were sprayed on the crop growing on the field in that same year. As a management practice, all crop residues and weeds, etc. are removed after crop is harvested and burnt in a nearby trench. This is to stimulate the prevalent farmers' practice of crop residue removal for livestock feeding and for fencing and roofing. The trial has been under natural fallow since 1997, which was the period Agbenin and Goladi (1998) and Ogunwole and Ogunleye (2005) sample the soils.

The DNPK trial is located at Samaru-Zaria (11°11'N, 07°38'E) in the sub-humid northern Guinea savanna at an altitude about 686 m above sea level. The climate is characterized by an annual rainfall of about 1065 mm, most of which fall in about 85 days between the months of May and September. The average temperature is 25°C with a monthly range from 22 to 29°C. The soils at Samaru have been classified as Typic Haplustalf (Ogunwole *et al*., 2001). The parent material is basement complex Precambrian rocks covered by aoelian deposits. Vegetation is largely that of the Guinea zone, which contains savanna woodland on more fertile soils and tree and shrubs on the poorer. Presently the natural vegetation is sparse but the land is cultivated to cereals and legumes. A summary of the site information is given in Table 1 while that of the management practices adopted in the last 54 years is presented in Table 2. Details could be found in Ogunwole and Ogunleye (2005).

Table 1: Description of the sampling sites

Parameter	Samaru-Shika-Zaria	Gidan Kaura-Illela
Location	11°11;N; 07°38'E	13°45'N, 5°05'E
Agroecological zone	Northern Guinea savanna	Sahel savanna
Long term mean rainfall	1065 mm	500 mm
Length of rainy season	130-160 days	65-80 days
Potential annual evaporation	1200-1500 mm	400-500 mm
Mean air temperature	24-26°C	27-29°C
Year of establishment	DNPK trial-1950 Pasture trial-1963	Sand dune trial-1986
Landuse/vegetation	Semi-permanent cultivation/ *Hyparrhenia* spp., *Andropogon* spp.	Shifting cultivation/ *Combretum nigricans*, *Anogeissus*
Soil classification	Typic Haplustalf	Ustic Quartzipsamment

Table 2: Description of the selected treatments at Samaru, Shika and Gidan Kaura

Treatments	Fertilizer/manure combination/description	Rates (kg ha^{-1})
A. DNPK Trial at IAR-ABU, Samaru-Zaria		
DNPK	Dung + nitrogen + phosphorus + potassium	D = 5000; N = 48-135; P = 18-54; K = 29-58
NPK	Nitrogen + phosphorus + potassium	N = 48-135; P = 18-54; K = 29-58
D	Dung	D = 5000
N	Nitrogen	N = 48-135
Control/check	Zero amendment	Zero
B. Improved pasture trial at NAPRI-ABU, Shika-Zaria		
Brachiaria decubens (BD)	Nitrogen + potassium + phosphorus	N = 40; K = 20 ; P = 20
Digitaria smutsii (DS)	Nitrogen + potassium + phosphorus	N = 40; K = 20 ; P = 20
Mixed grasses (MG)	Nitrogen + potassium + phosphorus	N = 40; K = 20 ; P = 20
C. Sand dune stabilization trial at Gidan Kaura-Illela		
Shelter belt	Neem (Azadirachta indica A. Juss), spaced 200m apart. Zero amendment	
Live fencing	Local shrub species as hedgerow, zero amendment	
Direct tree revegetation	Neem and eucalyptus randomly planted, zero amendment	
Direct tree revegetation facilitated	Neem and eucalyptus facilatated using Alcosob (a water absorbing polymer), zero amendment	
Control/check	Unstabilized, active sand dune, zero tree and amendment	

The long-term grass pasture experiment is located on the research fields of the National Animal Production Research Institute (NAPRI), Shika also in Zaria, Nigeria (latitude 11° 11'N and longitude 7° 38'E). Four adjacent fields of about 2.5 ha each, planted to *Brachiaria decumbens* (BD), *Digitaria smutsii* (DS) and a mixture of both grasses (MG) formed the three treatments. An adjacent plot under continuous cultivation to sorghum/millet serves as the control. The summary of the management practices on these fields is presented in Table 2 while details are available in Ogunwole *et al.* (2004). On the pasture fields at NAPRI, grazing is only allowed during the dry season while bale-ing is done immediately after the rains in November. From available records, the fields have never witnessed any fire outbreak since 1963 and have been continuously under the same planted pasture.

The long-term sand dune stabilization trial started in 1986 at Gidan Kaura, a village 25 km NE of Illela (13°45'N, 5°05'E, altitude 400 m) in the semi-arid to arid fringes of NW Nigeria. The total rainfall is about 500 mm with a pronounced dry season which lasts from October till June, while the wet season is characterized by frequent and torrential rains of relatively short duration. The monthly temperatures are lowest in December and January (13°C) during which a dust carrying desert wind blows from the northwest. Temperature is maxima in April (38°C), just before the advance of the rains from the south. Parent materials of the soils are the sand dunes which were deposited in the Pleistocene (Sombroek and Zonneveld, 1971). The soils have been classified as Ustic Quartzispamments (Raji *et al*., 1996). A summary of the treatments and management practices adopted between 1986 and 1998 (year of soil sampling) is presented in Table 2 while details could be found in Raji *et al*. (2004).

All the studies measured soil organic carbon by the wet combustion method of Walkey-Black (Allison, 1965) or the modified version (Nelson and Sommer, 1982). For the bulk density determination, the core ring method (Blake and Hartge, 1986) was used by all the reports. The use of bulk density was to allow the conversion of soil carbon values to area basis. Bulk density values reported by Ogunwole and Ogunleye (2005) for each treatment gives a comprehensive and detail information of the bulk density values not given by previous reports. It was therefore, used for all the calculations in this work. Goladi (1997) reported an average bulk density value of 1.53±0.2 Mg m^{-3} for all the DNPK experimental plots. This value is similar to the average value of 1.52 Mg m^{-3} obtained by Ogunwole and Ogunleye (2005). The average values are also slightly higher than the value obtained for the native site as reported by Goladi (1997) to be 1.51 Mg m^{-3}. Goladi (1997) attributed this slight difference to the fact that the effect of cultivation on bulk density of savanna soils is usually short-lived because bulk density quickly returns to the original value at the end of the growing season.

Results and Discussion

Soil Carbon Sequestration in Cropland

This study highlights the impact of long-term recommended practices on the quality of soils in the savanna agroecosystems. Important among the recommended management practices for SOC sequestration on cropland is residue incorporation. Soil organic carbon among the DNPK treatments ranged from 4.95 to 8.64 t C ha^{-1} in 1977 (Fig. 2). When compared with the control, this represents a decrease of 0.28 t C ha^{-1} with 27 years of continuous N fertilization (Table 3) but about 68% increase or 3.55 t C ha^{-1} under continuous manure application. This means that addition of manure as a soil fertility restoration practice for increased crop production, can also lead to increased sequestration of carbon. However the addition of mineral NPK fertilizer to manure did not improve soil C sequestration in these soils. After 45 years of the treatments, SOC content in the unamended soil (control) was still on a slight increase, as represented by an increase of 10 g C m^{-2} yr^{-1} between 1977 and 1997 (Fig. 2). Though the DNPK trials are similar to the Versailles experiment in France, except that the Versailles experiments are without a crop, the SOC content was reported to decrease

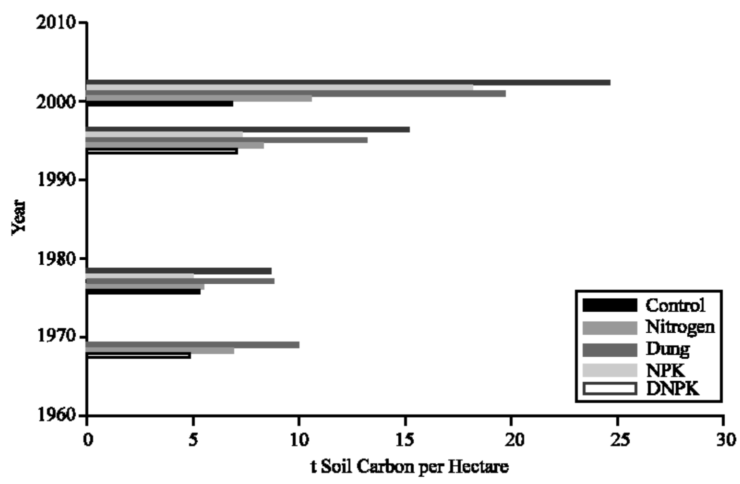

Fig. 2: Soil organic carbon turnover in the DNPK Plots at Sanaru

Table 3: Bulk density and organic carbon data for soils (0-15 cm) under long-term sand dune stabilization trail

Parameter	Bulk density Mg m^{-3}	g kg^{-1}	Organic carbon t soil C ha^{-1}	Rate of C change g C m^{-2} yr^{-1}
A. DNPK Trial at IAR-ABU, Samaru-Zaria (45 years)				
Control (no amendment)	1.34	3.50	7.04	-
N	1.35	4.10	8.30	126
D	1.54	5.70	13.17	613
NPK	1.57	3.10	7.30	26
DNPK	1.44	7.00	15.12	808
B. Sand dune stabilization trial at Gidan Kaura-Illela (12 years)				
Control (unstablised sand dune)	1.76	0.93	2.46	-
Live fencing	1.65	2.10	5.20	274
Direct revegetation facilitated	1.65	2.40	5.94	348
Shelter belt	1.57	16.60	39.09	3663
C. Improved pasture trial at NAPRI-ABU, Shika-Zaria (35 years)				
Continuous cultivation (control)	1.56	5.40	12.64	-
Brachiaria decumbens	1.66	8.39	20.89	825
Digitaria smutsii	1.75	5.48	14.39	175
Mixed grasses	1.66	5.53	13.77	113

by 50% in 50 years of treatment (FAO, 2001). In the same period of 45 years, the use of continuous NPK application resulted in only slight increase in SOC (3%) over the unamended soil while manure with NPK gave 115% more SOC. However, Halvorson *et al*. (1999) reported an increase in SOC from 15 Mg ha^{-1} for zero N fertilizer use to 17 Mg ha^{-1} for a 134 kg N ha^{-1} (13% increase) after 11 crops in Akron, Colorado. Application of farmyard manure resulted in doubling the SOC content in the Rothamsted long-term agronomic experiment (FAO, 2001). Continuous application of only N fertilizer also resulted in an increase of 1.26 t C ha^{-1} over the control.

The use of NPK between 1977 and 1995, a period of 18 years, improved SOC content from 4.95 to 7.30 t C ha^{-1}, giving a rate of 13 g C m^{-2} yr^{-1}. This rate is about 50% less the rate using manure alone and 75% less using manure with NPK (Table 3). The use of N fertilization alone for 18 years also resulted in an increase of about 2.83 t C ha^{-1} or 16 g C m^{-2} yr^{-1}. Drinkwater *et al*. (1998) obtained slightly lower values of 2.2 t C ha^{-1} in Pennsylvania in 15 years using chemical nitrogenous fertilizers. Crop residue management is another important method of sequestering C in soil and increasing the soil organic matter content. However, Drinkwater *et al*. (1998) have shown that manure application resulted in 5.5 times more SOC over rates from nitrogenous fertilizers compared with the 3 times SOC under legume-based rotation. This is because manure is a valuable source of SOC and it promotes the formation and stabilization of soil macroaggregates and particulate organic matter. In addition to this, manure is more resistant to microbial decomposition than plant residues. Gregorich *et al*. (1998) found that manured soils had large quantities of soluble carbon with a slower turnover rate than in control or fertilized plots. There is no doubt that the use of manure, on a long-term basis, improve soil C content when compared with other management options practiced within the sub-humid savanna of Nigeria. Results from the unamended soil also tend to indicate that the removal of crop residue for livestock feeding, a common practise in the study area, drive the system to a new steady state of about 6 t C ha^{-1} (Table 3). Using manure alone also result in doubling the SOC content when compared with the control and the use of NPK fertilization gives results similar to those obtained from the Rothamsted experiments (FAO, 2001). These results have shown that practices like manuring that enhance SCS will improve soil quality and reduce agricultural contribution to carbon dioxide emissions.

Natural Fallow/Improved Pasture Establishment after Continuous Cultivation.

Converting marginal cropland to either native grassland or improved pasture also tend to increase SOC and as such the overall quality of surface soils. The DNPK plots in Samaru have been under natural fallow since 1995 after 45 years of continuous cultivation. In 2001, after 6 years of natural fallow, the unamended soils experienced a slight decrease in SOC content from 7.04 to 6.83 t C ha^{-1} representing about 3% reduction. This result shows that the resilient power of the unamended soils (degraded) to self restoration is low under natural fallow. Research reports have shown varied role that fallow play in carbon sequestration in soils. However, Rasmussen (1998) identified the frequency of summer fallow to influence negatively the SOC content in the United State. Fallow plots which had received manure under cultivation had their SOC content increased from 13.17 to 19.64 t C ha^{-1}, an increase of 6.47 t C ha^{-1} in 6 years or 108 g C m^{-2} yr^{-1}. The highest increase in SOC content was obtained on plots previously receiving NPK. Increase in SOC of such plots was about 150% of the pre-fallow levels while plots receiving manure with NPK fertilizer sequestered up to 24.62 t C ha^{-1} (Fig. 2) from 15.12 t C ha^{-1} prior to the fallow period or 158 g C m^{-2} yr^{-1} (Table 3). Conant *et al.* (2001) reported that marginal lands in the United States under improved grassland have the potential to sequester about 50 g C m^{-2} yr^{-1}. Generally, the rate of SOC sequestration during the fallow period is approximately 400% more than the rates under continuous cultivation. The very high rates during the fallow periods could be attributed to the highly degraded nature of the soils since organic matter is normally harvested annually from the DNPK plots while under continuous cultivation. The carbon sequestration rate for plots receiving manure during cultivation is 24 g C m^{-2} yr^{-1} but increased to 108 g C m^{-2} yr^{-1} during the fallow period. The non-degraded soils receiving either inorganic fertilizers or manure or a combination of these, were more resilient in self-restoration under bush fallow.

With improved pasture, Brachiaria decumbens had the greatest potential of SOC sequestration of the three species screened in the sub-humid savanna of Nigeria. It sequestered about 20 t C ha^{-1} in 35 years or about 825 g C m^{-2} yr^{-1} over the control. This rate is several times the rate under natural fallow and multiple of the rate given by Post and Kwon (2000) (110 g C m^{-2} yr^{-1}) for the grassland Conservation Reserve program of the United State. However, Fisher *et al.* (1994) also reported between 800 and 1300 g C m^{-2} yr^{-1} increases in SOC when a native tropical savanna was replaced with productive, deep-rooting exotic grasses in the first 3-6 years. These facts suggest that improved or exotic grasses sequester SOC in multiples of rates under natural fallow and that longer time periods are required for pronounced increases in SOC under condition of low grass productivity. The change in SOC concentration may be caused by increased inputs obtained from increased production and as a result of fertilizer application. High carbon contributions have been reported from input from plant roots in grassland sites (Farage *et al.*, 2003). It is this high production of roots that provides potential to increase SOC in pastures.

Soil Carbon Sequestration in Forestlands

Afforestation is recognised as major sink for carbon but as well as accumulating carbon above ground, it can also make significant contributions to soil carbon even in drylands (Silver *et al.*, 2000; Lal *et al.*, 2003). However, management practices such as fertilization and liming, harvesting and site preparation and choice of appropriate species have beneficial impact on SOC sequestration (Hoover, 2003; Lal *et al.*, 2003). In the sand dune stabilization trials in Gidan Kaura, aside from the screening for appropriate tree species, no other management practice is carried out. Despite the near natural conditions of the trial, SOC under eucalyptus in shelter belt sequestered up to 39.09 t C ha^{-1} in 12 years of the trial. This value is about 16 times the SOC in the unstabilized sand dune (control) and gives SOC rate of accumulation of about 305 g C m^{-2} yr^{-1}. Post and Kwon (2000) also reported rates of up to 300 g Cm^{-2} yr^{-1} in a subtropical wet forest plantation. The rate of SOC accumulation in this semi-arid environment is however, greater than the 1150 g C m^{-2} reported by Bashkin and Binkley (1998) in the top 10 cm of soil under the same fast-growing eucalyptus trees after 12-13 years of growth in a wet tropical forest previously under sugar cane field. The rate of SOC mineralization is however, higher under wetter tropical conditions than dry semi-arid regions because of increased biological activities (Post and Kwon, 2000). The use of live fencing, a common practice around residential compounds in the semi-arid regions resulted in over 110% increase in SOC over their control (Table 3). However, when direct tree revegetation is facilitated by the use of a polymer that absorb water many times its own mass, the increase in SOC sequestration rate was 141% over the control. The potential for SOC sequestration by the use of eucalyptus and neem trees in afforestation in NW Nigeria is about 23 to 305 g C m^{-2} yr^{-1} over the control. These values would increase substantially if management practices such as fertilization are introduced. Fertilization is particularly important because most forest are N-limited (Magill and Aber, 2000; Post and Kwon, 2000).

Conclusions

The potentials of C sequestration in soils of the sub-humid and semi-arid savanna of Nigeria under different landuses indicate that there is a vast scope for enhancing soil carbon through the adoption of recommended management practices for the highly degraded lands of the savanna. While there is a dearth of data currently available to determine precisely the amount of SOC accumulation in large regions in Nigeria, the data from the long-term experiments could be used to investigate some aspects of carbon fluxes in the carbon cycles in the tropics. This present data shows that afforestation, without recommended soil management practices, using neem and eucalyptus could sequester up to 305 g C m^{-2} yr^{-1} in the semi-arid savanna while planted *Brachiaria decumbens* in the sub-humid savanna sequestered about 825 g C m^{-2} yr^{-1} over the control in 35 years of planting. Under continuous cultivation, the potential for SOC sequestration was greatest when NPK was co-applied with farmyard manure giving a rate of up to 158 g C m^{-2} yr^{-1}. Targeting these rates in the savanna ecosystems is therefore, feasible and would be at a modest cost since few recommended soil management practices were adopted. This study has shown that SCS rates were influenced primarily by management practices in the savanna. Due to the relatively high potential of SCS rates, manure application with NPK fertilizer, improved pasture management and agroforestry are potentially a substantial sink for SOC in the savanna.

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