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Effect of bush encroachment on vertical soil organic carbon distribution in a clay loam soil in Shangani Ranches, Zimbabwe

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Abstract

Determination of vertical soil organic carbon (SOC) is essential for assessment of carbon sequestration in ecosystems. A study was conducted in Shangani Ranches to compare SOC distribution and assess carbon sequestration potential of undisturbed savanna woodland and bush encroachment ecosystems on a granitic clay loam soil. The SOC was determined at 0-15, 16-30 and 31-45cm depth ranges for the five replicate profiles assessed in the two ecosystems. Both ecosystems exhibited an exponential decrease (r^2=0.87) in SOC pool with soil depth. The average SOC pool ranged from 24 Mg ha^{-1} (31-45cm layer) to 42 Mg ha^{-1} (surface) for the savanna ecosystem, whilst the corresponding range for the bush encroachment ecosystem was 17 Mg ha^{-1} to 37 Mg ha^{-1}. The surface SOC pool was insignificantly higher ($P>0.05$) in the savanna woodland than the bush encroachment ecosystem. In the16-30 cm layer, the bush encroachment ecosystem had a significantly higher ($P<0.05$) SOC pool than the savanna woodland whilst the 31-45cm layer had the reverse scenario. Overally, the savanna woodland significantly stored 2.42 Mg ha^{-1} more ($P<0.05$) SOC than the bush encroachment ecosystem in the top 45cm of the soil. Secondary vegetation succession in Shangani ranches was attributed to the differences in SOC allocations in the soil horizons. This study established an abnormal trend in SOC distribution, such that the shrub-dominated ecosystem had lower SOC in deeper soil horizons compared to the tree dominated system (savanna woodland). The savanna woodland was found to have more potential to sequester carbon than the bush encroachment ecosystem.

Key words: bush encroachment, carbon sequestration, ecosystem, organic carbon, savanna

Introduction

Historical accounts, photographic records and quantitative studies have demonstrated extensive invasion of grasslands by woody plant species and increase in woody plant density in savannas over the past 200 years (Burrows, 1999). Gifford and Howden (1999), cited by Burrows (1999), described woody plant thickening in grazed rangelands (bush encroachment) as an example of the more general phenomenon of vegetation recovery and succession that either follows episodic ecosystem disturbance events, or is associated with certain protracted disturbances in many woody ecosystems. Bush encroachment is a special type of secondary vegetation succession, which leads to an increase in woody biomass of the savanna ecosystems (Scholes and Archer, 1977; Bond and van Wilgen, 1996; Skowno et al. 1999).

Changes in vegetation structure (thickening) lead to changes in carbon stocks and rate of enrichment of atmospheric CO_2. Scholes and Hall (1996) reported that increased tree cover in savannas could be contributing a worldwide sink of 2 Tg C/yr (or 2×10^{12} C/yr). Burrows (1999) quoted Burrows et al. (1998) as estimating that vegetation thickening in the state of Queensland, Australia, provides a sink in excess of 27 Tg C/yr above ground. Below ground was estimated to account for a further 9 Tg C/yr. Fearnside and Guimares (1996) reported that carbon fluxes resulting from thickening of savannas are less obvious.

It is accepted as a general rule that below ground biomass flux is proportionate to that above ground, in line with community root: shoot ratios (Nihlgard, 1972). Johnson et al. (1996), basing on empirical model, indicated a 40% increase in C storage over 40 years in a landscape originally occupied by cultivated fields as both herbaceous succession and forest encroachment occurred.

In terrestrial ecosystems, carbon sequestration (removal of carbon from atmosphere) is achieved through plant photosynthesis which incorporates atmospheric carbon (CO_2) into biomass. Vegetation therefore acts as a major CO_2 sink. Vangen et al. (2005) reported high attainable rates of carbon sequestration in the range of 0.1 to 5.3MgCha^{-1} yr^{-1} in natural and improved fallow systems of Sub-Saharan Africa. Hence, there is a high potential to mitigate global warming in this region.

Estimating potential C sequestration is more difficult for rangelands than for cultivated croplands. Rangelands include a wide diversity of plant communities, soils and landscapes. Furthermore, ecosystem responses are complex because management practices may include shifts in plant communities that may, over time, exert secondary effects on C storage (Schuman et al., 2002).

Soils are the largest pool of terrestrial carbon in the biosphere, storing more C than is contained in plants and the atmosphere combined (Schlesinger, 1997). Jobbagy and Jackson (2000) indicated that patterns and controls of soil organic carbon (SOC) storage are critical for our understanding of the biosphere, given the importance of SOC for ecosystem processes and the feedback of this pool to atmospheric composition and the rate of climate change. The aspect of SOC pool and its vertical distribution in the soil and accompanying relationships with climate and vegetation is poorly understood (Jobbagy and Jackson, 2000). They further showed that plant functional types affected the vertical distribution of SOC. The percentage of SOC in the top 20 cm (relative to the first metre) averaged 33%, 42%, and 50% for shrublands, grasslands and forests, respectively. Globally, the relative distribution of SOC with soil depth had a slightly stronger association with vegetation than with climate. In a study carried out on reclaimed mine soil; SOC sequestration potential is more for pasture than forest systems. Information on restoration of drastically disturbed mine soils show restoration potential of 25 to 35 Mg C ha^{-1} over a 25-year period (Akala and Lal, 2001).

Modern techniques provide accurate, reliable, easily verifiable and inexpensive methodologies to document vegetation thickening and its contribution to carbon sinks for the above ground component (Burrows, 1999). The below ground biomass which contributes to SOC enhancement and sequestration is little understood. The aim of this paper is to present preliminary findings on SOC distribution patterns in a clay loam soil experiencing bush encroachment in a semi-arid savanna.

Methods and materials

Site description and sampling

Measurements of SOC distribution with depth were done in 2002 in the Shangani Ranches, situated about 340 km south west of Harare, Zimbabwe. The study area lies in agro-ecological Region IV, which experiences semi-arid climate and 400 to 500 mm of annual rainfall (Vincent and Thomas, 1960). The area experiences high temperatures, high evaporation rates and moisture deficits (Mzezewa et al., 2000). The site selected for the study is experiencing bush encroachment being invaded by *Acacia karoo*. Sheet erosion was evident. Immediately adjacent to the bush encroachment site, relatively undisturbed open savanna woodlands dominated by *Colphospermum mopane*, *Schlerocarya birrea subsp. Cafra* and *hyperhenia* grass species, was selected as control. Predominant soils of the area are clay loams developed on gneissic granite (Nyamwanza and Mzezewa, 1997) and are classified as typic kandiustalfs (Soil Survey, 1990). Selected properties of the studied soil are shown in Table 1. The study areas are used as paddocks for cattle and wildlife ranching.

Table 1. Selected properties of the studied soil.

Depth (Cm)	Clay	silt	sand	pH	CEC	TEB
		%			(cmol$_c$.kg^{-1})	
0-15	23	24	53	4.9	12.9	7.8
15-30	37	22	41	4.8	28.4	14.8
30-45	29	21	42	4.9	18.2	17.6

Five replicate pits were dug on each treatment after systematic augering. Soil samples were obtained for 0-15, 16-30 and 31-45 cm-depths from the profiles. A total of three sub samples were obtained for each depth and composited.

Soil analysis

Clods were broken down by hand and identified stones and plant debris removed.

The samples were air dried under shade and then passed through a 2mm-sieve. For SOC, a 0.5-g sample air dried soil was ground to pass through 0.05-mm sieve prior to determination by the Walkely and Black method (Nelson and Sommers, 1986). Soil texture was determined by the Bouyocos (1965) hydrometer method. Soil pH was determined by weighing a 15-g soil sample in a 200-ml honey jar to which 75 ml 0.1 M $CaCl_2$ were added. The mixture was shaken mechanically for 30 minutes and pH was determined using a digital pH meter (Model: Orion 701). The pH meter was calibrated using pH 4 and 7 buffer solutions. Exchangeable cations were determined in 1 M ammonium acetate (pH 7) extract, and cation exchange capacity (CEC) was determined by removal of ammonium ions by distillation (Rhodes, 1982) following this extraction and washing with 96 % alcohol. Calcium and Magnesium were determined in the extract by atomic absorption spectroscopy (Pye Unican SP9) and sodium and potassium by flame emission spectroscopy (Varian AA-1275). Results of analysis are shown in Table 1. Soil bulk density was determined by the core method (Black and Hartge, 1986) and corrected for gravel content assuming the particle density of 2.65 Mg m^{-3} (Akala and Lal, 1999). The SOC content for 0 to 45-cm depth was calculated. It was difficult to obtain samples below the depth of 45 cm because of the large concentration of stones and gravel. Most roots were confined to the top 45 cm layer. The SOC pool was computed on a volume basis by multiplying C content (as fraction) with soil bulk density and sample depth using the following equation (Lal et al., 1998; cited by Akala and Lal, 1999)

$$\text{Mg C ha}^{-1} = \text{C x corrected }_b\ (\text{Mg m}^{-3}) \text{ x sample depth (m) x } 10^4\ \text{m}^2\text{ha}^{-1}$$

where $_b$ is soil bulk density

Differences in SOC between the two systems in each depth range were assessed by using a paired t-test (at $P<0.05$).

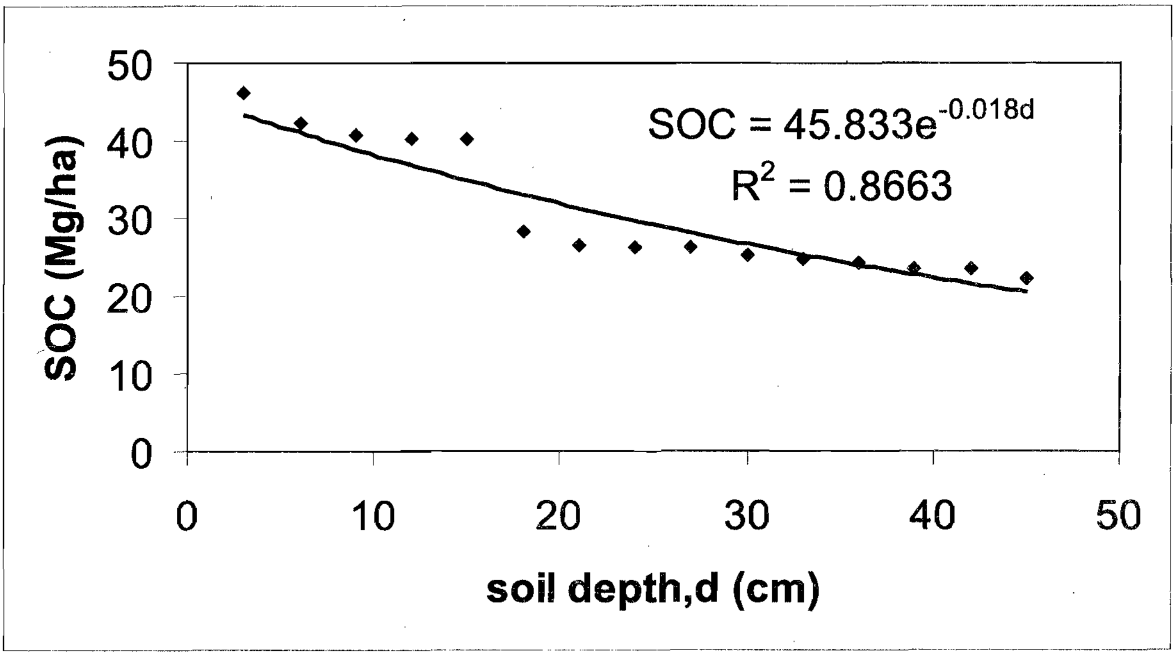
Results

There was a decrease in the SOC content from surface soil horizons to sub soils in both bush encroachment and savanna woodland systems (Table 2). The decrease of SOC pool with depth in the 0-45cm-soil layer is exponential (Figs 1 and 2), with the bush encroachment system exhibiting a stronger relationship (r^2=0.8685) than the savanna system (r^2=0.8663) though the relationships were not significantly ($p>0.05$) different.

Table 2. Distribution of mean SOC pool (S.E.) by depth for the two ecosystems (Mg ha^{-1})

Treatment (system)	Depth (cm)		
	0-15	15-30	30-45
Bush encroachment	37.20(0.49)	30.86(0.77)	16.90 (0.27)
Savanna woodland	41.98(1.15)	26.54(0.51)	23.66(0.43)

Significance	ns	*	*



* significant at(P<0.05), ns not significant

Figure 1: Variation of SOC pool with depth in the savanna woodland ecosystem.

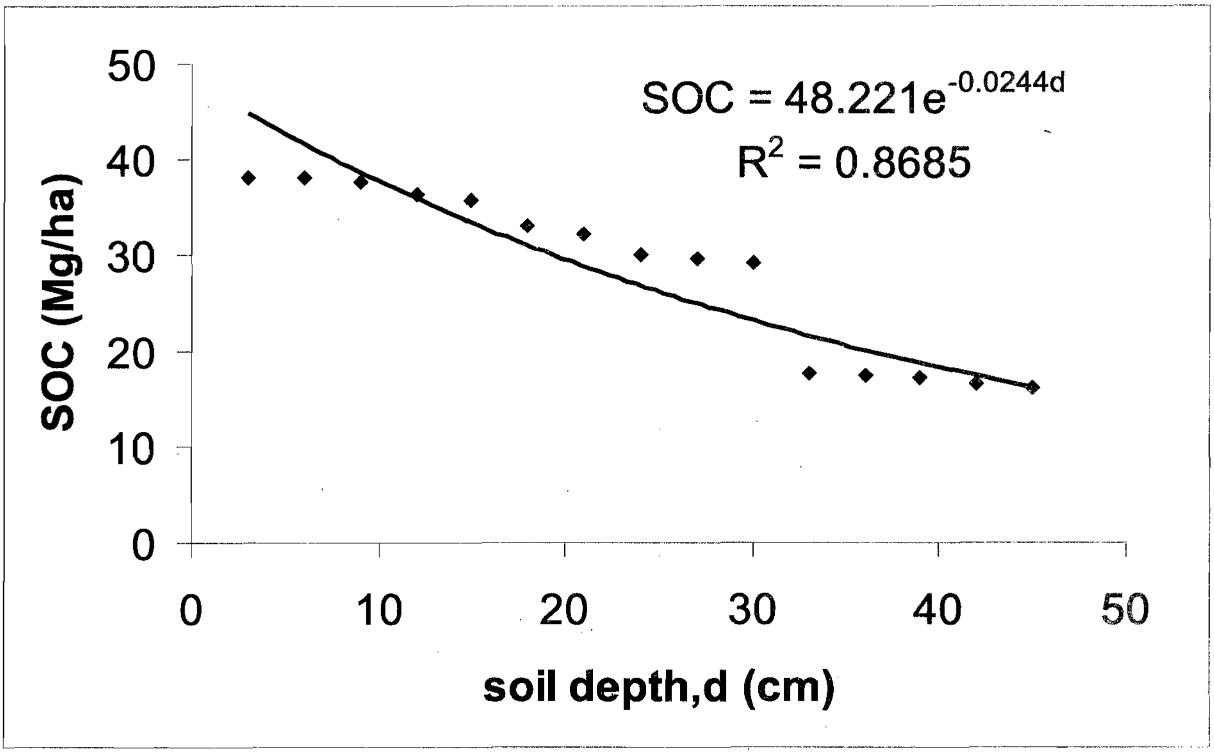


Figure 2: Variation of SOC with depth in the bush encroachment ecosystem.

Table 2 shows SOC storage of about 37, 31 and 17 Mg ha^{-1} in the 0-15, 16-30 and 31-45 cm depth, respectively, for the bush encroachment system whilst the savanna woodland system had 42, 27 and 24 Mg ha^{-1}in 0-15, 16-30 and 31-45 cm depth, respectively. Similar distribution patterns were observed elsewhere (Jobbagy and Jackson, 2000; Mehdi et al., 2001; Schuman et al., 2002). SOC storage in the 0-15 cm depth in the savanna woodland system compared to the bush encroachment system was not significantly different ($p>0.05$).

Table 3. Mean SOC pool (Mg ha^{-1}) from 0-45cm in the two ecosystems

Treatment	Mean	SE of mean	Significance
Bush encroachment	28.31	2.29	*
Savanna woodland	30.73	2.19	
* significant at ($P<0.05$)			

SOC was significantly higher ($p<0.05$) in the bush encroachment system compared to the savanna woodland system, in the 16-30 cm depth. The reverse was observed in the 31-45 cm depth in which SOC storage was significantly higher ($p<0.05$) in the savanna woodland system compared to the bush encroachment system. The overall SOC pool was significantly higher ($P<0.05$) in the savanna woodland system compared to the bush encroachment system (Table 3).

The savanna system stored 2.42 Mg ha^{-1} more SOC than the bush encroachment system.

Discussion

Soil carbon content, chemistry and distribution may change following shifts in dominant plant life form because plant life forms differ in litter chemistry and patterns of detrital input (Gill and Burke, 1999). The observed trend in SOC distribution with depth has been reported previously. Schuman et al. (2002) indicated that soil organic carbon in many rangeland ecosystems is concentrated at the soil surface. Hilnski (2001) described the vertical distribution of SOC as a function, which decays exponentially with depth. Root distribution affects the vertical placement of C in the soil, and above- and below ground allocation affects the relative amount of C that eventually falls to the soil surface from shoots (Estanban et al., 2000). The replacement of savanna woodland by the *Acacia karroo* shrubs at this site was postulated to account for the differences in SOC allocations in the different soil horizons. Tree species vary in amount of aboveground, litter quantity inputs, litter quality inputs and root production (Rhodes et al., 2003). The differences among species affect decomposition rate, soil mineralization and ultimate soil C storage. Livestock waste matter also significantly affects nutrient cycling and relocation in grazing systems (Schuman et al., 2002). In a global review of root distributions, grasses had the shallowest root profiles, trees were intermediate,and shrubs had the deepest profiles (Jackson et al., 1996). However, this study indicated a reversed order in which the shrub-dominated ecosystem (bush encroachment) had lower SOC in deeper soil horizons compared to the tree-dominated system (savanna woodland). This could be due to higher relative above ground C allocation for shrubs than for trees. Table 3 shows that SOC sequestration potential is more in the savanna woodland system compared to the bush encroachment system. The SOC storage in the two systems is however much higher compared to the global average in similar vegetation systems (Jobbagy and Jackson, 2000) much lower compared to perennial bioenergy crops (Mehdi et al., 2001) and is comparable to a mine soil under forest (Akala and Lal, 1999)

Conclusions

Because of the importance of carbon dioxide as a greenhouse gas, any changes in the ecosystem that tend to affect carbon fluxes have implications on climate change. This work suggests that changes in vegetation control vertical SOC distribution patterns.

The savanna woodland has a higher potential to sequester SOC compared to the bush encroachment system.

Future work may focus in the following areas: (i) investigation of many sites over a wider geographical area because the results may be site- or species-specific and (ii) Root biomass distribution studies will help explain differences in C allocation in the soil horizons.

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