Journal of Sustainable Development in Africa (Volume 11, No.1, 2009)

ISSN: 1520-5509

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BUSH ENCROACHMENT IN ZIMBABWE: A PRELIMINARY OBSERVATION ON SOIL PROPERTIES

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ABSTRACT

Vegetation structure and composition are closely linked to soil type in the savannas. A study was carried out to compare soil characteristics associated with bush encroachment and those of the adjacent savanna woodland. The objective of this study was to determine if bush encroachment is related to particular soil properties. Soil profiles were described and samples collected by major morphologic horizons. Bulk density and infiltration rates were determined. Samples were analyzed for soil organic carbon (C), cation exchange capacity (CEC), and total exchangeable bases (TEB). Results show very little differences in soil properties between bush encroachment and savanna woodland sites. Soil erosion was, however, more evident on bush encroachment sites compared to the savanna woodlands sites. From the results of this study we could not conclusively link soil properties to bush encroachment phenomena.

Keywords: Zimbabwe, bush encroachment, soil survey, savanna woodland, soil properties, vegetation structures

INTRODUCTION

The phenomenon of increasing woody plant abundance in the savannas, with accompanying changes in herbaceous cover and composition, is termed bush encroachment (Smit, 2004; Britz and Ward, 2007). Bush encroachment is accompanied by changes in tree to grass ratio, which is important in semi-arid savannas (Britz and Ward, 2007). Characteristically, bush encroachment leads to an increase in density of woody plants, often unpalatable to domestic livestock (Kraaij and Ward, 2006; Wiegand *et al*., 2006). The reasons for an increase in the abundance of woody plants in any vegetation type are diverse and complex (Smit, 2004). Increase in tree cover leads to reduced productivity and profitability of rangelands (Jacobs, 2000; Smit, 2004; Britz and Ward, 2007). Bush encroachment has been linked to ecosystem disturbances, such as by fire, overgrazing (Kraaij and Ward, 2006), and soil degradation (Dougill and Cox, 2007).

Bush encroachment in pasturelands is a distinctive type of secondary vegetation succession, which leads to an increase in woody biomass of the savanna ecosystem (Bond and van Wilgen, 1996; Scholes and Archer, 1997; Skowno *et al.*, 1999). The problem of bush encroachment is of global concern because it lowers carrying capacity and this reduces livestock production (Dean and Macdonald, 1994; Jacobs, 2000; Smit, 2004). In Africa, the main encroaching species are thorn trees (e.g. *Acacia karroo, A. reficiens, A. tortilis, A. mellifera,* and *Dichrostachys cinera)* (Kraaij and Ward, 2006). These species also tend to have very high levels of phenolic compounds (e.g. tannins) in their leaves, which reduce their digestibility to livestock and wildlife. The combination of thorniness and low digestibility of *Acacia* trees reduces their accessibility and natural value to consumers (Jacobs, 2000).

Understanding the ecology and functions of savanna ecosystems is critically important. Tropical savannas occupy approximately 65% of Africa, 60% of Australia, and 45% of South America, but still they are among the least understood terrestrial ecosystems (Huntley and Walker, 1982). Woody species significantly affect tropical grasslands and savannas in a number of ways. Several hypotheses have been proposed to explain the causes of bush encroachment but none of them have been found to be universally applicable (Dougill and Cox, 2007). A two-layer model, called Walter's two-layer hypothesis proposed by Walter (1954), cited in Britz and Ward (2007), is mainly used to explain the bush encroachment phenomenon. According to Walter's two-layer hypothesis, water is the limiting factor for both grassy and woody plants. Grasses use only top soil moisture, while woody plants use subsoil moisture (Wiegand *et al.,* 2006). In this model the balance between grass and bush production is determined by the relative availability of soil water and nutrients in different rooting zones (Dougill and Cox, 2007). Savanna grasses out-compete bush species for water and nutrients in the top soil layers, while woody species have the competitive advantage in the sub-soil. According to the two-layer model, cattle's grazing affects this balance by suppressing grass growth and promoting leaching to greater depth. This provides the opportunity for woody species to increase and for certain species to encroach (Britz and Ward, 2007) and, hence, the conclusion that bush encroachment is caused by the replacement of indigenous browsing animals by cattle and heavy livestock grazing (Skarpe; 1990, Hoffman and Ashwell, 2001; cited in Britz and Ward, 2007). Recent studies reveal that Walter's model is no longer sufficient to explain the bush encroachment process (Ward, 2005; Wiegand *et al*., 2006; Dougill and Cox, 2007). Ward (2005) argues that rooting niche separation cannot be an explanation for the initiation of bush encroachment because young trees use the same subsurface soil layer as grasses in the early stages of growth. He further states that overgrazing in combination with rooting niche separation is not a prerequisite for bush encroachment because bush encroachment sometimes occurs on soils too shallow to allow for root separation. Simulation and field studies have also disputed that rooting-niche separation is the sole mechanism explaining tree-grass coexistence (Wiegand *et al.*, 2006).

Several new hypotheses have been proposed as a consequence of the inadequacy of the two-layer model and the hypothesis that overgrazing is the cause of woody plant encroachment. Alternative hypotheses were proposed by Ward (2005) and Wiegand *et al*., (2007). In his review, Ward (2005) cited disturbance models developed by Higgins *et al.* (2000) that can be used to explain tree-grass coexistence in the savannas. Higgins *et al*. (2000) hypothesized that grass-tree coexistence is driven by the limited opportunities for tree seedlings to escape both drought and the flame zone into the adult stage. By this hypothesis bush encroachment occurs due to increased tree recruitment caused by reductions in grass standing crop and, hence, fire intensity. They predict that rainfall-driven variation in recruitment is more important in arid savannas, where fires are less intense and more frequent. Ward (2005) further cited another disturbance-based model that focuses on the role of fire (and its interaction with herbivory). The model by Langevelde *et al*. (2003) proposed that there is a positive feedback between fuel load (grass biomass) and fire intensity. Increased levels of grazing reduce fuel load, making fires less intense and, thus, less damaging to trees. This leads to an increase in woody vegetation and a switch from an open savanna to woodland. Browsers may enhance the effect of fire on trees because they reduce woody biomass. Indirectly, grass biomass is increased (assuming that there is strong competition between trees and grasses).

As a consequence of increased fuel load (because there is more grass), fires are more intense and, consequently, more biomass is removed by fire. The ecosystem then switches from one dominated by trees to a mixture of trees and grasses. This model, like any other has its weaknesses (see Ward, 2005). Wiegand *et al*. (2006) have hypothesized that bush encroachment in many semi-arid environments is a natural phenomenon occurring in ecological systems governed by patch-dynamic processes. Wiegand *et al*. (2007) hypothesized that any forms of disturbance (e.g. grazing or fire) create space, making water and nutrients available for tree germination. Under low soil nitrogen conditions, the nitrogen-fixing trees have a competitive advantage over other plants and, given enough rainfall, may germinate *en masse* in these patches created by the disturbances. Ward (2005) argues that in order to understand the causes of bush encroachment, we need mechanistic models to guide us and multi-factorial experiments in order to determine the interactions among causal factors.

Topography, soil structural properties, soil moisture, and nutrients all contribute to the tree-grass dynamics within savanna systems, but the specific factors involved in determining the tree-to-grass ratio and bush encroachment are not well understood (Ward, 2005; Britz and Ward, 2007). Scholes (1991) cited in Smit (2004) reported that nutrients, such as nitrates, phosphorus, a series of anions and cations, and various trace elements, are essential to the nutrition of plants, and acts as determinants of the composition, structure, and productivity of vegetation. Britz and Ward (2007) reported that soil texture is a crucial determinant of the tree-to-grass ratio due to its effects on plant growth, soil moisture, nutrient presence, and availability. Kraaij and Ward (2006) also noted that, in addition to nutrients and moisture, fire and herbivory play important roles in tree-grass dynamics in the savannas. The relationships between bush encroachment and soil properties have not been established in Zimbabwe.

This study was formulated as part of a major research project designed to study the ecology of the Shangani Ranches in Zimbabwe (Mzezewa *et al*., 2003). The objective of this study was to determine if bush encroachment is related to particular soil properties. To do this, we determined bulk density and infiltration rates and analyzed soil organic carbon (C), cation exchange capacity (CEC), and total exchangeable bases (TEB) on two sites experiencing bush encroachment and compared these properties from adjacent undisturbed savanna woodlands. The results from this investigation will contribute to a better overall understanding of the bush encroachment process.

MATERIALS AND METHODS

Study Area

The study was conducted in the Bulawayo Syndicate Block and Shangani Farm North of the Shangani Ranches (19˚30'S-20˚00'S, 29˚00'E-29˚30'E), situated about 340 km southwest of Harare, Zimbabwe. The altitude is about 1340 m asl. Other geographical details of the site are described in Mzezewa *et al.*, (2003). Two sites affected by bush encroachment were selected for this study. Immediately adjacent to these sites, relatively undisturbed savanna woodlands were selected as controls. Site I is located in the Shangani Farm North, while site II, in the Bulawayo Syndicate Block, is 12 km to the northwest. The study areas are used as paddocks for cattle and wildlife ranching.

The study area lies in agro-ecological Region IV, characterized by a semi-arid climate with a mean annual rainfall of 400-500 mm (Vincent and Thomas, 1960). The area experiences high temperatures, high evaporation rates, and moisture deficits (Mzezewa *et al*., 2000). Soils on study sites are developed on gneissic granite parent material (Nyamwanza and Mzezewa, 1997). The soils are generally shallow with a sandy texture on the surface and medium textures at depth. Gravelly soil layers and quartz stonelines are common features.

Vegetation on sites affected by bush encroachment was dominated by thorny thickets of *A. karroo* with scattered *Albizia amara* subsp. *sericocephala* and occasional *Euclea divinorum*. Both sites were virtually devoid of grasses and signs of severe sheet erosion were evident. Sites free of bush encroachment consisted of an open mixed woodland of *Colophospermum mopane*, *Sclerocarya birrea* subsp. *caffra*, *Combretum apiculatum* and some tall *Hyperrhenia* grass species.

Soil Sampling

A series of augering was done along transects in encroached and control areas on both sites to establish representative (modal) soil types. Soil profiles were dug to the parent rock on representative auger holes and described by standard methods (Soil Survey Staff, 1990). Samples were collected by morphologic horizon following international standards (Soil Survey Staff, 1990). Soil color was classified according to the Munsell color notation (Munsell Color, 2000). Soil samples for bulk density analysis were taken using cores of 7 cm diameter and 5.2 cm depth ($200cm^3$), following the method of Blake (1965). Triplicate core samples were taken from the middle of demarcated horizons.

Infiltration Tests

Infiltration measurements were conducted on representative soil profiles from sites experiencing bush encroachment and in adjacent savanna woodland (sites I and II). The method used was adapted from Landon (1984). Standard double ring infiltrometers with three diameter combinations (inner/outer = 28cm/53cm, 30cm/55cm, or 32cm/57cm) and a height of 25 cm were used. The infiltrometers were simultaneously driven (to a depth of about 10 cm) into the soil using a soft nylon hammer. The rings were simultaneously filled with water (to a height of 12 cm) and water intake readings were taken from the inner ring at set time intervals. For the first 5 minutes, readings were recorded every 30 seconds. After the first 5 to 10 minutes of infiltration, readings were taken at 1 minute intervals. Readings were later taken every 5 or 10 minute intervals depending on the rate of the infiltration. The experiment was stopped after 4 hours when the infiltration process had stabilized. Cumulative infiltrations over the entire measurement period were calculated from the depth recordings.

Soil Analyses

Bulk Density

Cores were used for the determination of bulk density (Blake and Hartge, 1986). A sharpened, open-ended cylindrical metal container was carefully pushed into the soil until the level of the ring was flush with the soil surface. The core was then carefully extracted, the soil trimmed away until flush with the ends of the container. The ends of the container were covered with lids and taken back to the laboratory. In the laboratory, the core plus soil were oven-dried at 110 ^{o}C for 24 hours and the soil was then re-weighed. The volume of the core was determined. The bulk density was calculated by dividing the oven dry mass of soil by the total volume of the core.

Soil pH and Texture

All data refer to the fine-earth fraction passing a 2 mm round hole sieve. Each 15-g soil sample was weighed into a 200-ml jar to which 75 ml of 0.1M $CaCl_2$ was added. The mixture was mechanically shaken for 30 min and pH was determined using a digital pH meter (Orion 701). Clay (<0.002mm) and silt (0.02-0.002mm) were determined by the hydrometer method (Bouyocos, 1965); coarse sand (2.0-0.5mm), medium sand (0.5-0.2mm), and fine sand (0.2-0.02mm) were separated by sieving**.** Soil textural classes were based on Thompson and Purves (1978).

Soil Organic Carbon

Organic C was determined using the Wakely-Black procedure (Nelson and Sommers, 1982). Although this procedure has been reported to give variable recovery of organic C (Nelson and Sommers, 1982) it is widely used in Zimbabwe where soil organic C content in most soils is less than 1% (Mugwira *et al.*, 1992). A 0.5 g sample of air-dried soil, ground to pass through a 0.05 mm sieve, was weighed into a 350 ml flask. A 5 ml aliquot of 166 mM potassium dichromate and 10 ml concentrated sulphuric acid were added to the soil. The suspension was swirled and left to stand for 30 min. A 25 ml aliquot of distilled water was then added to the suspension before it was transferred into a 50 ml centrifuge tube. The suspension was centrifuged for 15 min at 2000 rpm and carbon was determined as the absorbance of the supernatant solution in a 10-mm optical cell at 600 nm wavelength.

Cation Exchange Capacity (CEC) and Exchangeable Bases

Exchangeable cations were determined in 1 M ammonium acetate (pH 7) extract, and cation exchange capacity was determined by removal of ammonium ions by distillation following this extraction and washing with 96% alcohol (Rhodes, 1982). Ca and Mg were determined in the extract by atomic absorption spectroscopy (Pye Unicam SP9) and sodium and potassium by flame emission spectroscopy (Varian AA-1275).

RESULTS

Soil Morphological Properties

The soil morphological features on site I, both in the bush encroachment and savanna woodland pedons, were generally similar. However, the A horizon of the bush encroachment pedon was thinner than the A horizon in the savanna woodland pedon. This may be a sign that soils under bush encroachment were subjected to soil erosion prior to encroachment (Lal, 1990). Surface soil texture was sandy loam over sandy clays. The change in clay (<2 μm) content from surface to subsoils represented more than fifty percent (Table 1). Thus, an argilic horizon (Bt) was present in both soil profiles below a thin A horizon.

A special feature of both profiles on site I was a stoneline commencing at a depth of about 36 cm and 80 cm, on bush encroachment and savanna woodland pedons, respectively.

Massive soil structure was typical on the surface horizons of both profiles. Structure in the subsoil horizons of both profiles was generally weak to moderate subangular blocky. Surface colors generally ranged from yellowish brown (10YR 4/4) to dark yellowish brown (10YR 3/4). Subsoil colors were dark brown (7.5YR 4/4) and strong brown (7.YR 4/6) (Table 1). Soils on site I exhibited a duplex soil morphology. Based on morphology and laboratory data, pedons were classified as kandic Paleustalfs (Soil Survey Staff, 1990) and belong to the Fersiallitic group (5G) of the Zimbabwe system of soil classification (Thompson and Purves, 1978; Nyamapfene, 1991).

Soil profiles on site II were also generally similar, being clay loams over clays (Table 2). Like on site I, the A horizon in the bush encroachment pedon was progressively thinner than that in the savanna woodland. Both soil profiles on site II had higher silt (53-2μm) compared to the profiles on site I. The profiles on site II had a gravelly soil layer starting at a depth of about 67cm and 64cm, in bush encroachment and savanna woodland pedons, respectively. These layers were not sampled for physical and chemical analyses. Another striking difference was the gradual changes of clay with depth on profiles on site II, whereas the change was abrupt on the soil profiles on site I leading to the formation of argillic horizons. Soil structure was generally weak medium subangular blocky in surface horizons over gravelly subsoils. Colors in the surface horizons ranged from red (2.5YR 4/6) to reddish brown (5YR 4/4). Subsoils were dark red (2.5YR 3/6) and reddish brown (5YR 3/6). Based on morphology and laboratory analyses, these soils can be classified as typic Kandiustalfs (Soil Survey Staff, 1990) and belong to the Fersialllitic group (5G) of the Zimbabwe system of soil classification (Thompson and Purves, 1978; Nyamapfene, 1991).

Bulk Density

Bulk density was observed to increase from surface to subsoil horizons for all sites (Tables 2 and 3). This is the expected trend in normal soils (Campbell *et al.*, 1998; Rimmer, 1982). Bulk density in areas with bush encroachment was slightly higher than that in savanna woodland for both sites. High bulk densities (>1600 kg m^{-3}) were observed in this study. Bulk density in the bush encroachment pedon was relatively higher on site II compared to site I, while the opposite was observed in savanna woodland pedons.

Infiltration Rate

Infiltration rates were initially high on all pedons and progressively approached final infiltration rates or infiltration capacity of soils. Final infiltration rate in the bush encroachment pedon differed slightly from that in the savanna woodland pedon at site I. Final infiltration rates of 0.07 and 0.08 cm min^{-1} were recorded in the savanna woodland and bush encroachment pedons, respectively (Figure 1). Similar trends were observed in site II (Figure 2). Infiltration capacity of the savanna woodland pedon was 0.08 cm min^{-1} and that of the bush encroachment pedon was consistently lower at 0.03 cm min^{-1}.

Soil Chemical Properties

The pH of surface horizons (Tables 2 and 3) ranged from very strongly to strongly acid (4.3 to 4.9) (Thompson and Purves, 1978). This pH was generally 0.3 to 0.4 units lower than the underlying horizon at site I for the pedon pair. There was no consistence in pH trends on site II in both pedons.

Soil organic C was mostly below 1% on site I. Organic C was highest in the surface and ranged from 0.48 to 0.98% for all horizons at site I (Table 2) and increased from surface to subsoils in both pedons with the savanna woodland showing slightly higher organic C contents per horizon compared to the bush encroachment pedon. Organic C ranged from 1.17 to 2.33% in all horizons on site II and showed no systematic distribution in the profiles. However, the surface horizon in the savanna woodland showed higher organic C compared to the equivalent horizon in the bush encroachment pedon. Of note was a peak in organic C with levels of 2.33 and 2.01% in the bush encroachment and savanna woodland pedons, respectively. This peak in organic C coincided with a peak in clay content in the corresponding horizons.

Total exchangeable bases (TEB) (Table 2) ranged between 4.0 and 7.8 cmol kg^{-1} in all horizons and increased with depth on site I. Exchangeable base concentration was slightly higher in the surface of the savanna woodland pedon compared to the bush encroachment pedon. The trend was reversed in the subsoil horizons. TEB ranged between 7.8 and 17.6 cmol kg^{-1} for all horizons on site II (Table 3) and increased with depth. The difference in exchangeable bases in the surface horizons between the bush encroachment and savanna woodland pedons was marginal, with the savanna woodland pedon having a TEB concentration of 1.1 cmol kg^{-1} higher than the bush encroachment pedon. However, the corresponding subsoil horizons showed the opposite trend. TEB tended to increase with clay content in all pedons.

Generally all pedons had CEC <20 cmol kg^{-1} and followed a similar pattern to TEB. CEC values tended to be slightly higher in the surface horizon of a savanna woodland pedon than bush encroachment pedon on site I. This trend seemed to be reversed on site II.

DISCUSSION

The A horizons of soils in areas with bush encroachment were 4 to 7 cm thinner than the soils in the savanna woodland. This difference can be attributed to be soil lost via erosion and could amount to huge losses when converted to soil loss per hectare (Burt *et al.,* 2001). This may also suggest the inherent fragility of the soils in the bush encroachment area. High soil erodibility is associated with poor soil organic matter (Lal, 1990). Truncation of the A horizon decreases effective rooting depth and has secondary effects on available water holding capacity and soil fertility (Lal, 1999). Large differences in soil fertility status have a considerable impact on plant structure and growth potential (MET, 2007)

Soil organic matter is a key component in any ecosystem and any variation in its abundance and nature may have profound effects on soil processes. Loss of organic material leads to poor soil structure, a decline in water infiltration, water retention capacity, and soil fertility (Snyman, 1999). High bulk densities (>1600 kg m^{-3}) were recorded in this study. Comparable results were reported in the previous study (Mzezewa *et al*., 2003). Bulk density values in this study are much higher compared to the values recorded on Zimbabwean agricultural soils (Burt et *al*., 2001). The increase in soil bulk density with depth was negatively correlated with soil organic C. Low organic C levels in the surface horizons of the bush encroachment pedons is likely to result in high bulk densities compared to the savanna woodland pedons, although the difference tended to be small in this case. Soil bulk density is a function of soil organic matter (Xiao-Gang *et al*., 2007).

It has been reported that organic matter makes soil more resistant to compaction (Arridson, 1998). However, soil organic matter levels are generally low under this environment (less than 1% on average).

Mlambo *et al*. (2005) reported soil organic C values of 0.84%, 86%, and 0.96% outside small canopy, medium canopy, and large canopy of *C. mopane*, respectively, under similar environment in Zimbabwe. Snyman (1999) and Britz and Ward (2007) reported similar results in South African rangelands. Belsky (1994) reported that the soils located below tree crowns have significantly higher concentrations of organic matter, reduced bulk density, and increased water infiltration than open grasslands. Even though open areas away from tree canopies were sampled in the present study, tree canopy effect cannot be ruled out. Soil organic C levels in both pedons on site II were slightly higher than those at site I. This can be attributed to higher clay percentage in the profiles on site II. It has been reported in other studies that clay protects the organic matter from mineralization and/or eluviation (Campbell *et al.*, 1998).

The apparent non-systematic distribution of organic C in the profiles of both pedons on site II could be due to the mixing of soils by termites, whose activity was evident in the soil profiles at this site. Campbell *et al.* (1998) reported that termites are an important part of the soil ecosystem because of their effect on decomposition rates and their redistribution of organic matter and soil nutrients. The accumulation of organic C in the topsoil horizons can be attributed to the relative immobility of organic C in the clayey soils.

The bush encroachment pedon had a marginally lower final infiltration rate compared to the savanna woodland pedon at both sites. This observation is similar to that reported by Engels (1999) who concluded that soil compaction has important hydrologic implications in terms of its contribution to reduced plant growth, reduced infiltration rates, and increased run-off potentials. Several rangeland studies have shown that soil bulk density is negatively correlated with infiltration capacity and positively correlated with surface runoff (Liacos, 1962; Dennis *et al*., 2002).

The soils were characterised by low pH, low TEB, and low CEC. All these factors account for low inherent fertility of the soils. Potassium, in particular, will undergo rapid leaching in such soils (Young, 1976). There was very little difference in exchangeable bases and CEC on both pedons on site I. This could be due to little difference in the clay contents and soil organic matter, both of which are responsible for the major part of the CEC and also important for sustaining a reservoir of mineralizable nutrients. The slight increase in CEC and TEB on both pedons at site II can be attributed to an increase in clay content and soil organic C at this site compared to site I. Organic matter has a positive effect on CEC (Tisdale *et al*., 1990) It is also postulated that most of the exchangeable bases are taken up through soil-plant transfer since the study sites are used as paddocks all year round. Work cited in Snyman (1999) indicates that in semi-arid ecosystems, most of the plant nutrients are located near the soil surface where they are vulnerable to loss by grazing-induced sheet erosion.

Similar studies elsewhere reveal that soil characteristics on bush encroachment and savanna woodland are not significantly different. In the Kalahari, Dougill, and Cox (2007) compared soil properties in the control area and the bush encroached zone and concluded that there was no significant difference in surface or subsurface moisture levels between the bush encroached zone and the control. Similar comparisons using data for field capacity, bulk density, soil organic matter, and hydraulic conductivity also indicated no significant differences in hydraulic properties between the two sites. Although inorganic nitrogen and phosphorus were not determined in this study, research elsewhere has shown that plant variables are more sensitive to soil physical properties than to soil chemical properties (Rezaei *et al*., 2006) while studies by Belsky (1994) indicated that soil N, but not P or K, limited growth in open grasslands.

CONCLUSIONS

This study showed that soils in bush encroachment pedons were slightly eroded, had slightly higher bulk density, and marginally lower infiltration rates compared to the savanna woodland pedons. Organic C showed similar trends. Similarly, exchangeable bases and CEC showed little variation between sites. Research elsewhere (Dougill and Cox, 2007) proved that soil properties on bush encroachment were not significantly different from the control. In this study, we observed minor differences between soil properties on bush encroachment and the undisturbed savanna woodland. Results from this study could suggest that the relationships between soil properties and bush encroachment may be complex and needs to be explored further. This could suggest that it may be necessary to further test and re-evaluate models that incorporate a relationship between vegetation structure and soil properties across various geographic areas.

Acknowledgements

The authors wish to thank Debshan (Pvt) Ltd for funding this study. We would like to acknowledge the assistance by Shangani Ranch managers for making this study possible. Help and expertise offered by the field and laboratory staff at The Chemistry and Soil Research Institute, AREX, Zimbabwe, is appreciated.

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Table 1: Selected Morphological Properties of Paired Pedons:

		Horizon	Depth (cm)	Texture[a]	Structure[b]	Colour[c]
	Bush encroachment	A	0-15	SaL	massive	10YR 4/4
		Bt1	15-36	SaC	2 msab	7.5YR 4/4
		Bt2	36-58	SaC	2 msab	5YR 3/4
		C	58-105	-	-	-
SITE I	Savanna woodland	A	0-19	SaL	massive	10YR 3/4
		Bt1	19-42	SaCL	1 msab	7.5YR 4/6
		Bt2	42-80	SaCL	1 msab	7.5YR 3/6
		C	80-110	-	-	-
	Bush encroachment	A	0-16	SaCL	2 msab	2.5YR 4/6
		B1	16-42	C	2 msab	2.5 YR 3/6
		B2	42-67	C	1 msab	2.5 YR 3/6
		C	67-95	-	-	
SITE II						
	Savanna woodland	A	0-23	C	2 msab	5YR 4/4
		B1	23-40	C	2 msab	5YR 3/6
		B2	40-64	C	2 msab	5YR 3/6
		C	64-110	-	-	-

[a]Texture: C=clay, SaL=sandy loam; SaCL=sandy clay loam; SaC=sandy clay

[b]Structure: 1=weak; 2=moderate; m=medium; sab=subangular blocky

[c]Colour: Munsell colour notation listed by hue, value, and chroma

- gravelly layer not sampled

Table 2: Selected Physical and Chemical Properties of Paired Pedons (Standard Error): Site I

Site	Depth (cm)	Percentage C.S	m.S	f.S.	silt	clay		Bulk density (kgm^{-3})	pH	Organic C (%)	TEB ($cmol_ckg^{-1}$)	CEC ($cmol_ckg^{-1}$)
Bush encroachment	0-15	14	24	44	7	11		1700(3)	4.3	0.68	4.0	4.0
	15-36	18	18	30	8	26		1690(9)	4.6	0.60	8.2	8.8
	36-58	-	-	-	-	-		-	-	-	-	-
	58-105	-	-	-	-	-		-	-	-	-	-
Savanna woodland	0-19	19	21	34	10	16	13	1660(1)	4.4	0.98	6.6	6.8
	19-42	13	28	10	36		11	1660(0)	4.7	0.67	7.1	13.3
	42-80	12	22	11	44			1680(3)	5.1	0.48	7.8	15.0
	80-110	-	-	-	-	-		-	-	-	-	-

CEC- cation exchange capacity expressed in $cmoles_c$ (+)kg^{-1} of soil

F.S.=Fine grained sand; M.S.=medium grained sand; C.S.= coarse grained sand

- gravelly layer not sampled

Table 3: Selected Physical and Chemical Properties of Paired Pedons (Standard Error): Site II

Site	Depth (cm)	Percentage C.S	m.S	f.S.	silt	clay	Bulk density (kgm^{-3})	pH	Organic C (%)	TEB ($cmol_ckg^{-1}$)	CEC ($cmol_ckg^{-1}$)
Bush encroachment	0-16	4	6	43	24	23	1800(4)	4.9	0.81	7.8	12.9
	16-42	4	4	33	22	37	1820(0)	4.8	2.33	14.8	28.4
	42-67	10	8	32	21	29	1822(0)	4.9	1.56	17.6	18.2
	67-95	-	-	-	-		-	-	-	-	-
Savanna woodland	0-23	3	5	35	20	37	1570(8)	4.5	1.17	8.9	12.6
	23-40	4	4	30	18	44	1590(4)	4.5	2.01	10.2	13.6
	40-64	7	5	24	18	46	1610(7)	4.9	1.40	15.7	17.4
	40-110	-	-	-	-		-	-	-	-	-

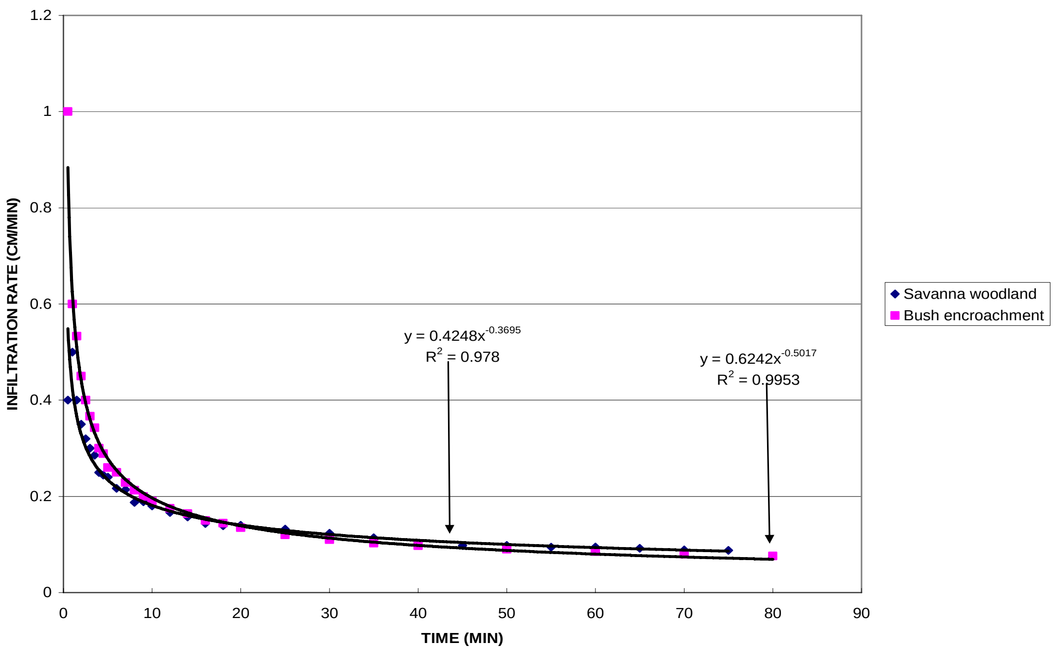

Figure 1 Infiltration rate on site

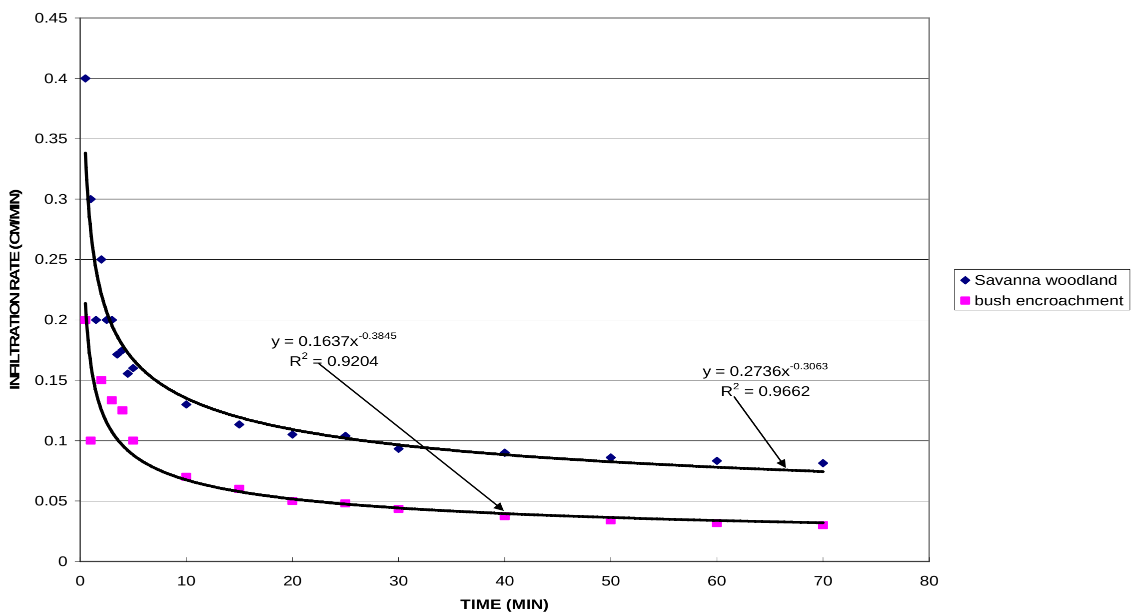

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Figure 2: Infiltration Rate on Site II