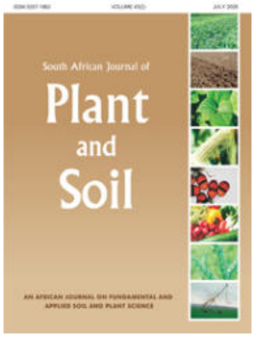

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An assessment of soil properties in sites dominated by different encroacher bush species in the Kalahari Sands Plateau of Namibia

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The increasing proliferation of native encroacher bush species is evident, although the underlying drivers of their expansion remain unclear. This study assessed the soil properties in sites dominated by *Senegalia mellifera*, *Dichrostachys cinerea* and *Terminalia sericea* in the Kalahari Sands Plateau of Namibia. Four soil samples (0–30 cm depth) were collected per plot and composited for laboratory analysis, while temperature and moisture measurements were recorded *in situ*. The results showed differences in soil chemical properties between sites dominated by different encroacher bush species, while sodium remained constant. Although chemical properties varied across the farms, soil moisture and temperature remained uniform. Soil texture also differed across sites dominated by encroacher bush species, while clay remained uniform. The soil texture differed across the three farms. The study found no uniform pattern in soils from sites dominated by different encroacher species, although *Terminalia sericea*-dominated sites had the poorest soil quality. It is therefore recommended to consider soil properties and dominant woody species in specific areas when assessing the impacts of woody species on rangeland ecosystems, as they influence herbaceous species composition.

Keywords: bush encroachment, encroaching species, organic matter, soil fertility, soil property

Introduction

Rangelands serve an important economic and ecological function globally, because they are comprised of different woody vegetation that may have beneficial and detrimental effects on the environment (Hyvärinen et al. 2019). The encroachment of savannas and semi-arid rangelands by woody plant species over the years has converted them into shrublands (O'Connor et al. 2014; Stevens et al. 2017) and is globally recognised as a form of rangeland degradation (De Klerk 2004; Eldridge et al. 2011; Belayneh and Tessema 2017). Bush encroachment threatens the service supply (i.e. water table recharge and nutrient supply), grazing capacity and biodiversity of savanna ecosystems (Archer et al. 2017; Yassin 2019). An estimated area of 30 to 45 million hectares of Namibia is bush-encroached (SAIEA 2015). However the causal factors are poorly understood and some of the factors linked to bush encroachment include climate change, increased atmospheric CO_2 concentration, overgrazing and suppression of fires (Archer et al. 2017; Belayneh and Tessema 2017; Yassin 2019).

Numerous studies revealed that various woody species, due to species-specific traits, can influence the soil environment in different ways (Collins et al. 2020; Zeng et al. 2020; Gebirehiwot et al. 2022). In terms of nutrient supplementation, many studies have shown that woody plants create fertile patches underneath their canopies in arid ecosystems (Tongway and Ludwig 1996; Gedda 2003; Ward et al. 2017).

The majority of the studies that assessed the impact of woody plant encroachment on the properties of soil only compared paired non-encroached and encroached areas (Belayneh and Tessema 2017; Kimaro et al. 2019; Xiang et al. 2019). Consequently, the effect of individual encroacher woody species on soil properties remains poorly understood. Therefore, understanding the variation in soil properties across different sites could provide insights into the factors that influence the proliferation of different encroacher woody species and key information for rangeland management practices (Mussa et al. 2016a). This study hypothesised that (1) soils from sites dominated by different encroacher bush species vary in their chemical properties, and (2) soils from sites dominated by different encroacher bush species vary in their physical properties. To assess differences in soil properties and test the associated hypotheses, sites dominated by three encroacher bush species were surveyed on Kalahari sands substrates. The study focused on *Senegalia mellifera*, *Dichrostachys cinerea* and *Terminalia sericea*. Hence, the objective of this study was to assess variations in soil chemical and physical properties among sites dominated by these species in the Kalahari Sands Plateau of Namibia.

Materials and methods

Study area

The study was conducted at Okahambo Farm in Omaheke Region, Blystoom Farm in Otjozondjupa Region, and Ghaub Nature Reserve Farm in Oshikoto Region. All farms are located on the Kalahari Sands Plateau of Namibia (Figure 1).

Site selection

Three farms, Blystroom, Ghaub Nature Reserve and Okahambo, were selected for this study, which formed part of the Enhancing Rangeland through Bush Control and Sustainable Intensification to Combat Climate Change and Improve Livelihoods (RIBS) project in the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL 2.0) Programme. These farms were mainly selected for the study because they were on the Kalahari Sands Plateau and each had specific field sites (i.e. a field site was defined as an area on a farm dominated by a particular encroacher bush species) dominated by three encroacher bush species, i.e. *Senegalia mellifera*, *Dichrostachys cinerea* and *Terminalia sericea* (Table 1). The selection was also based on the willingness of farmers to participate in the study. The selected field sites were homogeneously dominated by the desired encroacher bush species. Moreover, the sites had no to very few protected woody species, and woody plant species whose basal diameter was more than 18 cm above the basal swelling of the main stem.

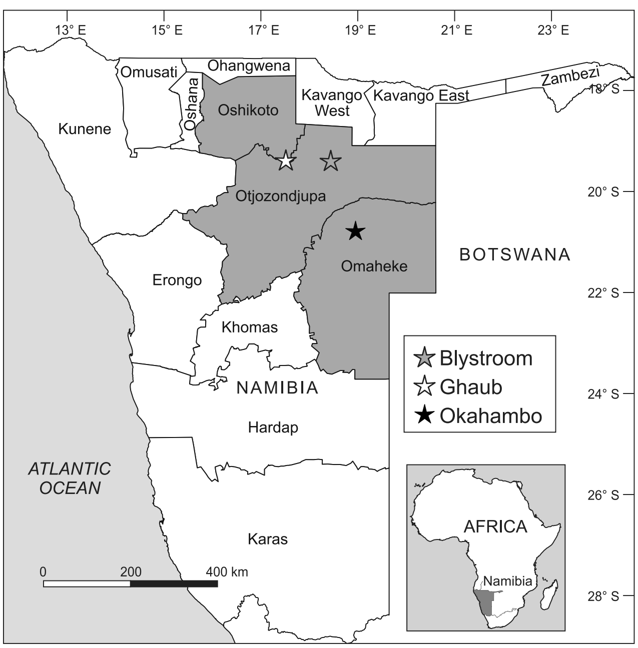

Figure 1: Location of the Okahambo, Blystoom and Ghaub Nature Reserve farms in Namibia

Description of encroaching bush species

Terminalia sericea is a deciduous tree or sometimes shrub with a rounded to flattish crown, growing up to 8 m tall. It has an erect stem with conspicuously layered branches that are often horizontal. It is commonly known as silver cluster-leaf and belongs to the Combretaceae family (Mannheimer and Curtis 2018). It has simple leaves that are spirally arranged and cluster towards the ends of branchlets, pale silvery-green in colour with silky hairs. The inflorescence is an axillary spike (up to 70 mm long) and the flowers are small, cream–pale yellow with an unpleasant odour occurring mainly from October to December. The fruit is single-winged, ovate, single-seeded and changes from yellow to brown to pinkish-brown as it matures (Mannheimer and Curtis 2018). *Terminalia sericea* is endemic to Africa, extending from Tanzania southward to South Africa. Although it is often one of the dominant species in mixed woodland, *Terminalia sericea* is restricted mainly to sandy areas and occurs in various savanna types and dry woodland. In Namibia, it is mostly found in the north-eastern and central-eastern parts of Namibia (Mannheimer and Curtis 2018).

Dichrostachys cinerea is a thicket-forming small tree or deciduous shrub that can grow to a height of 7 m. It is commonly known as sickle-bush and belongs to the Fabaceae family (Mannheimer and Curtis 2018). It has young, downy branchlets and lateral branches that are straight, spinous and sturdy with a sharp tip. The leaves are alternate, bipinnately compound, with both surfaces pale green and hairless above. The inflorescence is a bicoloured hanging axillary spike that has pink basal flowers (varying from white to purple) with staminoides and the remainder are yellow. The tree is bisexual and flowers from October to January, and its fruit is a cluster of dark brown contorted pods that do not split when mature (Mannheimer and Curtis 2018). It is native to Africa and *Dichrostachys cinerea* is widely spread in a variety of habitats across the central and northern parts of Namibia (Mannheimer and Curtis 2018).

Senegalia mellifera, formerly known as *Acacia mellifera*, subsp. *detinens* is a thicket-forming, much-branched, V-shaped deciduous shrub or single-stemmed tree with a rounded crown that can grow up to 8 m high. It is commonly known as black-thorn acacia and belongs to the Fabaceae family (Mannheimer and Curtis 2018). It has strongly curved thorns paired at nodes and shiny with a black and grey base. The leaves are bipinnately compound, spirally arranged and hairless to downy. The inflorescence is a short spherical spike and the flowers are white to cream-coloured, although specimens with deep pink flowers have been recorded from several localities. They are sweetly scented and flower mainly from August to October, but sometimes later in the season also just before the leaves appear. The fruit is a flattened, thin and oblong pod that is straw-coloured to

Table 1: Description of the study area. Sources: Katjiua and Ward (2006), Van Oudshoorn (2012), Strohbach (2014), Mendelsohn et al. (2022), Hiangoro et al. (2026). AMEL, *Senegalia mellifera*; DCIN, *Dichrostachys cinerea*; TSER, *Terminalia sericea*

Study site	Blystroom	Okahambo	Ghaub
Biome	Tree-and-shrub savanna	Tree-and-shrub savanna	Tree-and-shrub savanna
Vegetation type	Northern Kalahari	Central Kalahari	Krastveld
Soils	Mollic Leptosols	Ferralic Arenosols	Mollic Leptosols
Dominant structure	Broadleaved woodlands	Open acacia woodlands	Mixed woodlands
Landscape	Kalahari Sandveld	Kalahari Sandveld and Khomas Hochland plateau	Kalahari Sandveld
Altitude (m)	1 200–1 400	1 400–1 600	1 600–2 000
Temperature range (°C)	20–22	20–22	20–22
Annual rainfall (mm)	450–500	400–450	550–600
Location	19°51′77″ S, 18°67′71″ E	20°85′10″ S, 19°23′65″ E	19°28′16″ S, 17°44′59″ E
Major plant species	*Terminalia sericea*, *Dichrostachys cinerea*, *Senegalia mellifera*, *Combretum collinum* (trees); *Aristida stipitata*, *Stipagrostis uniplumis* (grasses)	*Dichrostachys cinerea*, *Senegalia mellifera*, *Croton gratissimus*, *Terminalia sericea* (trees); *Aristida stipitata*, *Stipagrostis uniplumis* (grasses)	*Dichrostachys cinerea*, *Terminalia sericea*, *Senegalia mellifera* (trees); *Stipagrostis uniplumis*, *Eragrostis trichophora* (grasses)
Land use	Livestock farming and cultivated pastures	Sustains herds of cattle, sheep and goats	Livestock and game farming and crop cultivation
Plant density (plants ha^{-1})	8 333	12 469	7 963
Distance between plots			
AMEL site (km)	4.5	1.35	2.6
DCIN site (km)	1.8	0.45	0.5
TSER site (km)	0.62	0.18	0.54
Distance between sites (km)	4.1	3	6

pale brown with the apex drawn out. It splits open when mature releasing 7–10 seeds per pod (Mannheimer and Curtis 2018). *Senegalia mellifera* is widespread throughout Africa and throughout Namibia (Mannheimer and Curtis 2018).

Experimental design and layout

The study used a split-plot design with the farm as the whole-plot factor, which had three subplots dominated by encroacher bush species, viz. *S. mellifera*, *D. cinerea* and *T. sericea*, that were randomly selected. Three individual plots (10 m × 10 m) were randomly set up at each of the three field sites by driving four metal corner posts of 1.8 m length into the ground at a depth of 60 cm (Figure 2). The four corners were used to fence off each plot separately and to prevent it from being grazed by livestock and wildlife. A 1-m-wide entrance was erected into one fenced side of the square to allow researchers access onto the plot for soil assessment.

Different dominant encroacher bush species were selected three times at each field site per farm. Hence, a total of nine plots were constructed at each farm, resulting in a total of three plots per woody species per farm. The Global Positioning System (GPS) coordinates were recorded at the entrance of each plot before data collection. The soil sample data collection was conducted towards the end of the wet season (April–May) in 2023.

Soil sampling

The soil samples were collected from four standardised locations within the buffer belt around each plot, starting at the northern-most side (labelled "N") and proceeding clockwise (Figure 2). The soil was excavated using a spade to dig a hole of 20 cm × 20 cm and at a depth of 30 cm. Four holes were dug in each plot halfway along the side

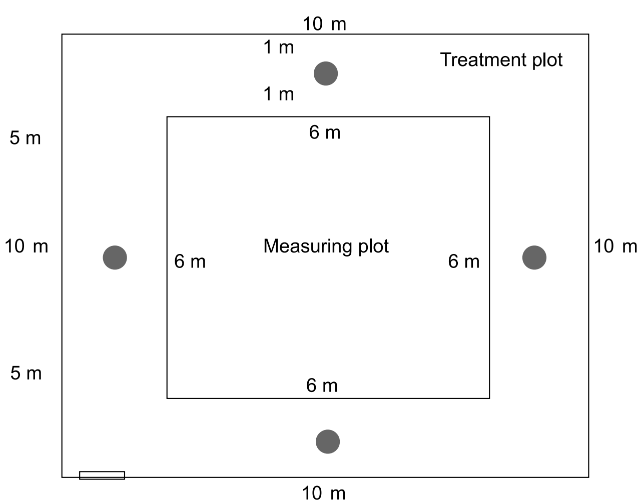

Figure 2: The soil sampling locations per plot

and halfway into the buffer zone (Figure 2), and the soil samples (i.e. a composite soil sample from a depth of 0–30 cm) were placed in zip-lock bags. At each of the four holes the excavated soil was uniformly mixed and a 500 g sample was collected. The soil samples were pooled to get a composite sample of 500 g for each plot, which was submitted for soil analysis at the Soil Analytical Laboratory in Windhoek, Namibia. The moisture and temperature readings were recorded *in situ* using a Takeme-10EC portable sensor at depths of 2, 10, 20 and 30 cm, respectively. The readings at each depth were replicated three times, resulting in 12 readings per hole and 48 readings per plot.

Soil sample preparation and chemical analysis

Before analysis, the soil samples were air-dried and ground to pass through a 2-mm mesh sieve, and stored at low humidity to avoid alteration of the electrical conductivity. As per the project requirements, the soil samples were analysed for pH and the extractable soil cations calcium (Ca), sodium (Na), magnesium (Mg), potassium (K) and phosphorus (P). In addition, the samples were analysed for electrical conductivity (EC), total nitrogen (TN), organic carbon (OC) and organic matter (OM).

For the pH, the water was prepared by weighing approximately 30.00 g of soil sample (<2 mm) into a 120 ml plastic beaker and adding 75 ml of reagent-grade water. This mixture was blended for about 20 s on three different occasions during a period of 1 h and then tested for pH using electrodes (Hendershot et al. 1993).

The soil cations were extracted following procedures outlined by the Soil Science Society of South Africa (1990) using 1 M ammonium acetate at a pH of 7. Approximately 5.00 g of air-dried <2 mm soil sample was weighed into an acid-rinsed 125 ml brown plastic bottle, and 50 ml of 1 M ammonium acetate (pH 7.0) solution was added. This was agitated on a reciprocating agitator for 30 min and allowed to rest for a few minutes before being filtered into acid-rinsed collecting glass bottles. It was refrigerated overnight. Thereafter, 20 ml filtrate and 1 ml of 65% nitric acid solution were added to an ICP vial. The Na and K concentrations were determined by atomic emission spectrophotometry (Kirchhoff and Bunsen 1860), while atomic adsorption spectroscopy developed by Walsh (1955) was used to determine Ca and Mg. The soil texture (particle size) analysis was performed using the pipette method to disperse the sample by shaking it with sodium hexametaphosphate or sodium carbonate solution.

The silt and clay-sized particles were isolated by collecting samples from a depth of 6 cm at intervals established according to Stokes' Law of Sedimentation. The sand was isolated using a wet sieving process through a 53-micron sieve (Miller and Miller 1987). The EC was determined according to the procedure outlined by van Reeuwijk (2002). Available P was determined using the Bray 1 method (Bray and Kurtz 1945). Organic carbon (OC) was determined on samples that were first ground to pass through a 0.5-mm sieve using the Walkley–Black wet oxidation method (Okalebo et al. 2002). The OC was analysed by wet oxidation with potassium dichromate ($K_2Cr_2O_7$) in a sulfuric acid medium (Okalebo et al. 2002). Percent OM content was estimated by multiplying the value of percent OC by the conversion factor of 1.724 (Okalebo et al. 2002). Total nitrogen was analyed using the Kjeldahl digestion, distillation and titration method by oxidising the OM in concentrated sulfuric acid solution (0.1 N H_2SO_4) (Black 1965).

Data analysis

All data were analysed using the computer software SPSS version 29.0 (IBM Corporation, Armonk, NY, USA). The data were subjected to a split-plot analysis of variance, under a general linear model framework, to test the variation in soil physical and chemical properties of sites encroached by different bush species and across the farms. Data were checked for normality using the Shapiro–Wilk test and transformed where necessary; homogeneity of variance was confirmed using Levene's test. Where the *F*-test was significant, Tukey's honestly significant difference test was used to compare means. When assumptions were violated and none of the transformations were satisfactory, a Kruskal–Wallis test was used, and means that differed significantly were compared using Dunn's test. Differences were considered significant at $p < 0.05$.

The statistical model used was:

$$Y_{ijkl} = \mu + F_i + W_{k(i)} + S_j + SF_{ij} + e_{ijkl}$$

where Y_{ijkl} is the dependent variable (i.e. pH, EC, TN, OC, OM, P, Ca, Mg, Na, K, temperature, moisture, soil texture, etc.); µ is the overall mean; F_i is the effect of farm (i = Blystroom, Ghaub and Okahambo; the whole-plot factor); $W_{k(i)}$ is the whole-plot error; S_j is the effect of dominant encroacher bush species (j = *Senegalia mellifera*, *Dichrostachys cinerea* and *Terminalia sericea*; the subplot factor); SF_{ij} is the interaction effect between the *i*th encroacher bush species and the *j*th farm; and e_{ijkl} is the random component explaining variation among plots of the same species (the subplot error).

Results

Soil chemical properties

Soil pH(H_20)

The pH was higher ($p < 0.05$) in soils from *S. mellifera*-dominated sites compared to *D. cinerea*- and *T. sericea*-dominated sites, which did not differ ($p > 0.05$) (Table 2). Moreover, soils from Ghaub farm had a higher pH compared to Blystroom and Okahambo, which did not differ ($p > 0.05$) amongst each other (Table 3). Additionally, the soil pH showed no farm x species interaction effects ($p > 0.05$).

Electrical conductivity

Electrical conductivity was different between soils collected from sites dominated by different encroacher bush species. The EC was higher in soils from *S. mellifera*-dominated sites compared to *D. cinerea* and *T. sericea* dominated sites, though the EC was higher in soils from sites dominated by *D. cinerea* ($p < 0.05$) than in *T. sericea*

Table 2: Soil chemical properties at sites dominated by different encroacher bush species. Means with different lowercase superscript letters differ at $p < 0.05$. AMEL, *Senegalia mellifera*; DCIN, *Dichrostachys cinerea*; TSER, *Terminalia sericea*; SEM, standard error of mean; S, dominant species; S × F, the effects of the interaction between the dominant species and farm

Soil properties	Species			*p*-value		
	AMEL	DCIN	TSER	SEM	S	S × F
pH (H_2O) (2:5, w/v)	6.82^{a}	6.09^{b}	5.74^{b}	0.209	<0.001	0.097
Electrical conductivity (mS m^{-1})	17.69^{a}	8.86^{b}	2.85^{c}	2.004	<0.001	<0.001
Organic carbon (% m/m C)	0.92^{a}	0.79^{b}	0.27^{c}	0.087	<0.001	<0.001
Organic matter (% m/m OM)	1.58^{a}	1.36^{a}	0.48^{b}	0.132	<0.001	<0.001
Total nitrogen (mg N kg^{-1})	$1\,802.78^{a}$	$1\,753.89^{a}$	$1\,456.78^{b}$	129.975	0.043	0.059
Exchangeable phosphorus (mg P kg^{-1})	4.73^{a}	3.29^{b}	2.51^{b}	0.657	0.016	0.100
Exchangeable potassium (mg K kg^{-1})	149.89^{a}	103.89^{a}	44.56^{b}	25.472	0.005	0.371
Exchangeable sodium (mg Na kg^{-1})	4.72	4.98	6.91	1.936	0.489	0.343
Exchangeable magnesium (mg Mg kg^{-1})	229.00^{a}	131.33^{b}	61.33^{c}	36.332	0.002	0.137
Exchangeable calcium (mg Ca kg^{-1})	$1\,294.44^{a}$	527.22^{b}	151.78^{c}	172.363	<0.001	<0.001

dominated sites (Table 2). In addition, soils from Ghaub farm had a higher EC than Blystroom and Okahambo farms, which did not differ ($p > 0.05$) amongst each other (Table 3). Moreover, the interaction of farm and dominant encroacher bush species also had an effect ($p < 0.05$) on the soil EC.

Organic carbon

The OC content was higher ($p < 0.05$) in soils from *S. mellifera-dominated* sites compared to *D. cinerea*- and *T. sericea*-dominated sites, although the OC was higher in soils from sites dominated by *D. cinerea* ($p < 0.05$) than in *T. sericea* sites (Table 2). Additionally, Ghaub farm had soils with a higher ($p < 0.05$) OC content than Blystroom and Okahambo farms, which did not differ ($p > 0.05$) amongst each other (Table 3). However, the interaction of farm and dominant encroacher bush species influenced the soil OC content ($p < 0.05$).

Organic matter

The OM content of soils from *S. mellifera*- and *D. cinerea*-dominated sites was not different ($p > 0.05$), but the OM content from both sites was higher ($p < 0.05$) than that of soils from *T. sericea*-dominated sites (Table 2). The Ghaub farm had soils with a higher ($p < 0.05$) OM content than the Blystroom and Okahambo farms, which did not differ ($p > 0.05$) between each other (Table 3). However, the interaction of farm and dominant encroacher bush species influenced the soil OM content ($p < 0.05$).

Total nitrogen

The TN content of soils from *S. mellifera*- and *D. cinerea*-dominated sites was not different ($p > 0.05$), but the TN content from both sites was higher ($p < 0.05$) than that of soils from *T. sericea*-dominated sites (Table 2). The TN content was higher ($p < 0.05$) in the soils of Ghaub farm than the soils of Blystroom and Okahambo farms, which did not differ ($p > 0.05$) between each other (Table 3). The interaction of farm and dominant encroacher bush species did not influence the soil TN content ($p > 0.05$).

Exchangeable phosphorus

The P content of soils from *S. mellifera*- and *D. cinerea*-dominated sites was not different ($p > 0.05$), but the P content from the *S. mellifera*-dominated site was higher than that of soils from *T. sericea*-dominated sites (Table 2). However, the P content of soils from the *T. sericea*-dominated sites was similar to that of soils collected from *D. cinerea*-dominated sites ($p > 0.05$) (Table 2). The P content of soils collected across the three farms was not different ($p > 0.05$) (Table 3). Moreover, the interaction of farm and dominant encroacher bush species did not influence the soil P content ($p > 0.05$).

Exchangeable potassium

The K content of soils from *S. mellifera*- and *D. cinerea*-dominated sites was not different ($p > 0.05$), but the K

Table 3: Chemical properties of soil collected from *the* Okahambo, Blystoom and Ghaub farms. Means with different lowercase superscript letters differ at $p < 0.05$. SEM, Standard error of the mean

Soil properties	Farm				
	Okahambo	Blystroom	Ghaub	SEM	*p*-value
pH (H_2O) (2:5, w/v)	5.78^{b}	5.96^{b}	6.91^{a}	0.209	<0.001
Electrical conductivity (mS m^{-1})	2.94^{b}	4.96^{b}	21.52^{a}	2.004	<0.001
Organic carbon (% m/m C)	0.19^{b}	0.36^{b}	1.43^{a}	0.087	<0.001
Organic matter (% m/m OM)	0.33^{b}	0.58^{b}	2.50^{a}	0.132	<0.001
Total nitrogen (mg N kg^{-1})	$1\,224.56^{b}$	$1\,236.56^{b}$	$2\,552.33^{a}$	129.975	<0.001
Exchangeable phosphorus (mg P kg^{-1})	2.54	3.82	4.18	0.657	0.065
Exchangeable potassium (mg K kg^{-1})	82.67^{b}	71.67^{b}	144.00^{a}	25.472	0.031
Exchangeable sodium (mg Na kg^{-1})	4.87^{ab}	3.18^{b}	8.58^{a}	1.936	0.045
Exchangeable magnesium (mg Mg kg^{-1})	68.22^{b}	156.78^{a}	196.67^{a}	36.332	0.012
Exchangeable calcium (mg Ca kg^{-1})	159.89^{b}	289.67^{b}	$1\,523.89^{a}$	172.363	<0.001

content from both sites was higher than the K content in soils from *T. sericea*-dominated sites (Table 2). Ghaub farm had soils with a higher ($p < 0.05$) K content than the Blystroom and Okahambo farms, which did not differ ($p > 0.05$) from each other (Table 3). The interaction of farm and dominant encroacher woody species did not influence the soil K content ($p > 0.05$).

Exchangeable sodium

The Na content of soils sampled from sites dominated by different encroacher bush species did not differ ($p > 0.05$) (Table 2). However, the Na content of soils differed ($p < 0.05$) across all three farms (Table 3). The Na content of the soils from Ghaub and Okahambo farms did not differ ($p > 0.05$), although Ghaub had a higher Na content than Blystroom farm. The soil Na content showed an interaction effect between farm and dominant encroacher bush species ($p < 0.05$).

Exchangeable magnesium

There was a difference ($p < 0.05$) in the Mg content of soils sampled from sites dominated by different encroacher bush species. The Mg content was higher in soils from *S. mellifera*-dominated sites compared to *D. cinerea*-dominated sites, and the Mg content from both sites was higher ($p < 0.05$) than that of the soils from *T. sericea*-dominated sites (Table 2). The Mg content was higher ($p < 0.05$) in the soils of the Ghaub farm than in the soils of the Blystroom and Okahambo farms, which did not differ ($p > 0.05$) from each other (Table 3). The interaction of farm and dominant encroacher bush species did not influence the soil Mg content ($p < 0.05$).

Exchangeable calcium

Soils from *S. mellifera*-dominated sites had higher Ca content ($p < 0.05$) than those from *D. cinerea*-dominated sites, which in turn had higher Ca levels than soils from *T. sericea*-dominated sites (Table 2). In addition, soils from the Ghaub farm had a higher Ca content than the Blystroom and Okahambo farms, which did not differ ($p > 0.05$) from each other (Table 3). However, the interaction of farm and dominant encroacher bush species had an effect ($p < 0.05$) on the soil Ca content.

Correlation analysis

The strength and significance of the correlations among soil chemical properties is shown in Figure 3 (i.e. red indicates a strong positive correlation while blue indicates a strong negative correlation, and an asterisk indicates correlations that were significant). The correlation heatmap shows that OC, OM, and TN formed a tight cluster ($r = 0.88$–1.0). In addition, pH strongly correlates with Conductivity ($r = 0.89$), Calcium ($r = 0.81$), and Potassium ($r = 0.77$). However, Sodium shows a weak correlation overall ($r < 0.41$), while Phosphorus moderately links to pH cluster ($r = 0.52$–0.69) but dissociates from organic nutrients ($r = 0.41$–0.60) (Figure 3).

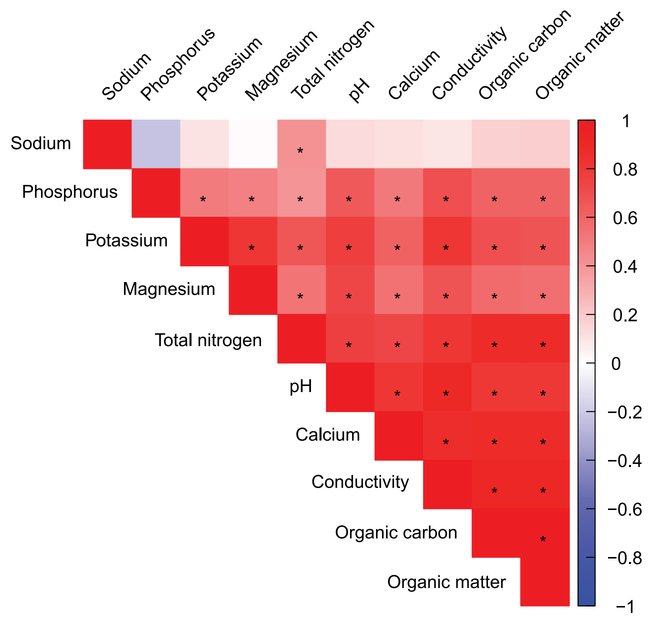

Figure 3: Correlation heatmap of soil chemical properties

Soil physical properties

Soil moisture

The soil moisture content of sites dominated by different encroacher bush species did not differ ($p > 0.05$) at all soil depths (Figure 4). Additionally, the soil moisture content was not different ($p > 0.05$) across the three farms at all soil depths (Figure 6). Moreover, the interaction of farm and dominant encroacher bush species did not influence the soil moisture content ($p > 0.05$).

Soil temperature

The soil temperatures in sites dominated by different encroacher bush species did not differ ($p > 0.05$) at all depths (Figure 5). There was also no difference ($p > 0.05$) in the soil temperatures across different farms at all soil depths (Figure 7). Moreover, the interaction of farms and

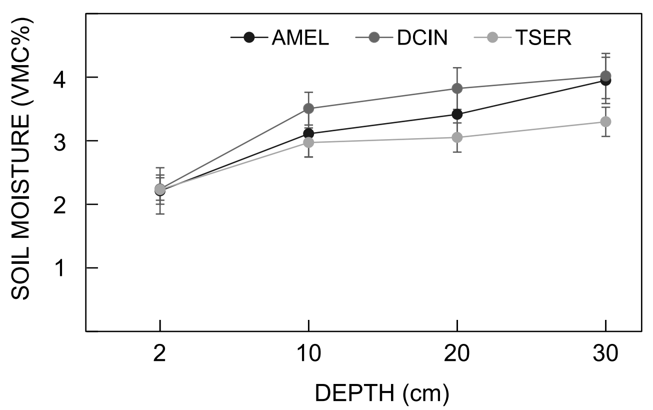

Figure 4: Soil moisture content of soil from sites dominated by different encroacher woody species at various depths. AMEL, *Senegalia mellifera*; DCIN, *Dichrostachys cinerea*; TSER, *Terminalia sericea*

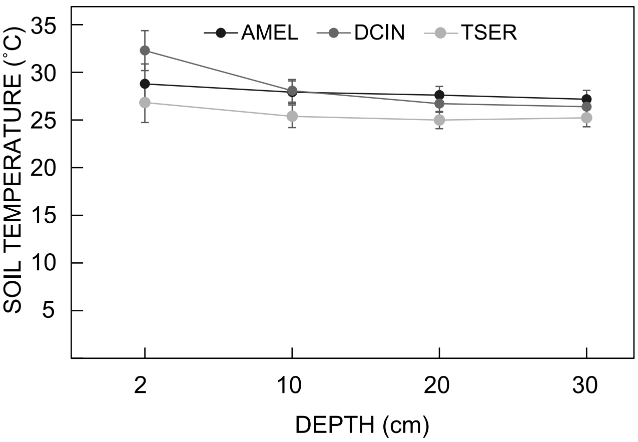

Figure 5: Soil temperatures at sites dominated by different encroacher woody species. AMEL, *Senegalia mellifera*; DCIN, *Dichrostachys cinerea*; TSER, *Terminalia sericea*

dominant encroacher bush species did not influence soil temperatures ($p > 0.05$).

Soil texture

Sand

The percentage of sand in soils from sites dominated by *T. sericea* and *D. cinerea* did not differ ($p > 0.05$), though both sites had higher sand content ($p < 0.05$) than soils from *S. mellifera*-dominated sites (Table 4). However, soil samples from the Blystroom and Okahambo farms did not differ in percentage of sand content, but both farms had higher ($p < 0.05$) percentage sand in their soils compared to the Ghaub farm (Table 5). Additionally, the interaction of farm and dominant encroacher bush species influenced ($p > 0.05$) the sand content in the soil.

Silt

The percentage silt in soil sampled from sites dominated by *S. mellifera* and *D. cinerea* showed no difference ($p > 0.05$), but the silt percentage in soils dominated by *S. mellifera* differed ($p < 0.05$) from those of the *T. sericea*-dominated

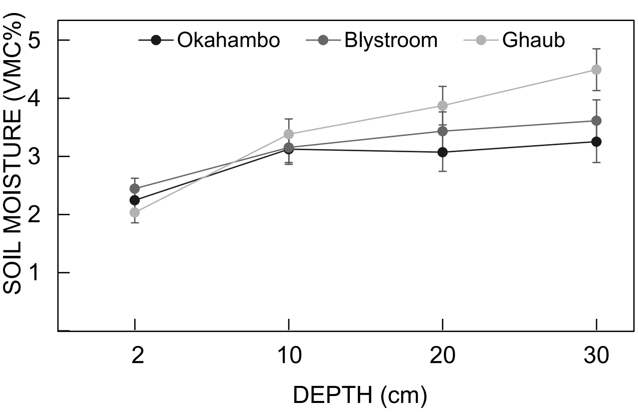

Figure 6: Soil moisture content at various soil depths across the Okahambo, Blystoom and Ghaub Nature Reserve farms

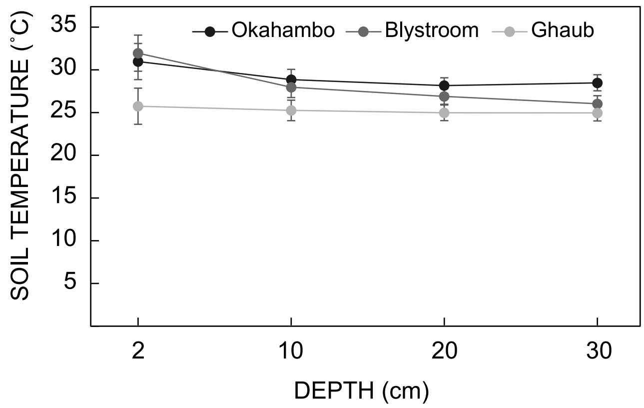

Figure 7: Soil temperatures across the Okahambo, Blystoom and Ghaub Nature Reserve farms

sites (Table 4). In addition, the silt percentage of the soils of Ghaub farm was higher than in the soils of Blystroom and Okahambo farms, which did not differ ($p > 0.05$) (Table 5). Additionally, the interaction between farms and dominant encroacher bush species did not influence ($p > 0.05$) the silt percentage in the soils.

Clay

The clay percentage of the soil sampled from sites dominated by different encroacher bush species did not vary ($p > 0.05$) (Table 4). However, the soil of Ghaub farm had a higher clay content than the soil at the Blystroom and Okahambo farms, which did not differ ($p > 0.05$) (Table 5). Additionally, the interaction between farms and encroacher bush species showed no effect of the soil clay content ($p > 0.05$).

Discussion

Soil chemical properties

The differences in pH and EC of soils collected from sites dominated by different encroacher bush species could be attributed to differences in grazing pressure and the type of encroacher species dominating particular areas. This result is consistent with studies conducted in South Africa, Ethiopia and China, which demonstrated that grazing pressure affects soil pH, with exclusion leading to acidification (Fenetahun et al. 2021; Hong et al. 2021). The variation in soil pH and EC observed across sites dominated by different encroacher bush species is consistent with the findings of Megersa and Worku (2018) and Malan et al. (2021), who reported that soils associated with different woody species exhibit differing pH values. This result is also comparable with the findings of Malan et al. (2021), who reported that soil EC varied among sites depending on the dominant woody species, with higher EC values recorded in *S. mellifera*-dominated sites, while no significant difference was observed between sites dominated by *D. cinerea* and *Vachellia karoo*. The soil pH values recorded in the current study were within the same range of those reported by Tokozwayo et al. (2021) for moderately to densely encroached areas (pH 5–7).

Table 4: Texture of soil collected from sites dominated by different encroacher bush species. Means with different letters differ at $p < 0.05$. AMEL, *Senegalia mellifera*; DCIN, *Dichrostachys cinerea*; TSER, *Terminalia sericea*; S, dominant species; S × F, the effects of the interactions between dominant species and farm.

	Species			*p*-values		
Soil texture	AMEL	DCIN	TSER	SEM	S	S × F
Sand (%)	82.16^{b}	87.05^{a}	90.28^{a}	1.590	<0.001	0.038
Silt (%)	10.34^{a}	6.99^{ab}	4.26^{b}	2.024	0.034	0.132
Clay (%)	7.62	6.52	5.38	1.179	0.205	0.640

The variation in pH across farms could be closely associated with differences in plant densities. This would agree with Tokozwayo et al. (2021), who found less-acidic soils under dense woody plant covers. Moreover, such differences in soil pH could be attributed to the effect of litter quality, as litter from different bush species varies in chemical and resultant properties. Litter rich in base cations tends to increase or maintain higher soil pH (alkaline), while litter with more acidic compounds or higher carbon: nitrogen ratios can lower the soil pH (Mueller et al. 2015; Desie et al. 2020). Furthermore, species from the *Vachellia* and *Senegalia* genera are reported to produce leaf litter that can positively increase soil pH (Hagos and Smit 2005). The strong positive correlations between pH and EC, Ca and K point to a dominant soil chemistry control related to base saturation and alkalinity. In savannas and southern African rangelands, pH is a key factor as it influences cation exchange, nutrient availability and the accumulation of salts (Malongweni and Van Tol 2022). Typically, higher pH levels ranging from neutral to alkaline tend to increase EC due to elevated concentrations of soluble salts, such as Ca and K, thereby enhancing base saturation (Malongweni and Van Tol 2022). However, EC values reported in the current study were lower than those reported by Megersa and Worku (2018). The present study revealed a significant difference that could be attributed to the low clay and silt contents, as soils with higher silt and clay hold more exchangeable cations and retain more moisture, thus enhancing ion concentration and EC (Regassa et al. 2023). The reduced EC could be accelerated by root actions such as penetration, which enhances water infiltration into the soil. This causes salts to drain out and thus reduces the EC value (Megersa and Worku 2018). The findings of the current study contrast with the study by Megersa and Worku (2018), who reported no variation among woody species. The same study, however, noted lower EC values under *Vachellia oerfota* (*Acacia nubica*) and higher values under *Prosopis juliflora*.

The OC values in the current study were lower than those reported by Tokozwayo et al. (2021) for moderately and densely encroached areas. Moreover, the current study is consistent with the previous study by Malan et al. (2021), which found differences in soil OC and OM contents of sites dominated by different bush species and nitrogen-fixing encroacher species that had higher contents. The elevated soil OC and OM levels in this study could be attributed to the accumulation of decomposed plant materials, which may have transformed into soil OM and soil OC during the decomposition processes (Malan et al. 2021; Smet and Ward 2005). The soil OM is vital for rangeland woody species productivity, and it is known to improve soil structure, nutrient release and water-holding capacity (Abdallah et al. 2012). Differences in soil OC and OM content could also be attributed to factors that influence OM accumulation, that is, the quantity and quality of litter and rainfall (Tokozwayo et al. 2021). In addition, it could also be associated with differences in plant densities across the different sites. The current study disagrees with Megersa and Worku (2018), who revealed a positive correlation between OC and TN. Moreover, tight clustering suggests that OC, OM and TN are influenced by similar underlying factors, such as bush encroachment and grazing intensity. This relationship can be attributed to their common origin from the same pool of plant litter and microbial biomass, with their cycling governed by similar factors, including vegetation cover, rainfall and management practices such as grazing (Du Preez et al. 2011). Consequently, this suggests a synchronisation of the carbon and nitrogen cycles, among other interactions.

The current study had similar nitrogen contents at sites dominated by different encroacher bush species, although the TN differed across the three farms, with such differences attributed to variations in bush density. Soil nitrogen is reported to increase with the increase in bush densities (Tokozwayo 2016). However, differences could also be associated with varying pH values, as soils with a pH between 5 and 7 generally contain higher nitrogen concentrations. This pH range enhances microbial activities and supports nitrogen fixation (Mojiri et al. 2012; Tokozwayo 2016). This study contrasts with the findings of

Table 5: Texture of soil collected from the Okahambo, Blystoom and Ghaub farms. Means with different lowercase superscript letters differ at $p < 0.05$. SEM, standard error of the mean

	Farm				
Soil texture	Okahambo	Blystroom	Ghaub	SEM	*p*-value
Sand (%)	93.78^{a}	94.27^{a}	71.44^{b}	1.590	<.001
Silt (%)	1.40^{b}	1.99^{b}	18.20^{a}	2.024	<.001
Clay (%)	4.98^{b}	4.12^{b}	10.42^{a}	1.179	<.001

Malan et al. (2021), who reported higher soil TN under *S. mellifera* encroachment, while soils beneath *D. cinerea* and *Vachellia karroo* showed no significant differences. Moreover, Megersa and Worku (2018) reported that soils from areas dominated by different encroacher bush species varied in their TN content. On the contrary, the TN contents reported in the current study were higher than those reported by Malan et al. (2021) and Megersa and Worku (2018).

In the current study, P and K concentrations were higher in sites dominated by nitrogen-fixing encroacher bush species, i.e. *S. mellifera* and *D. cinerea*, compared to *T. sericea*-dominated sites. The differences in P and K between these sites could be attributed to the diverse mechanisms that might have influenced cations, such as variations in cation uptake, litter production and nitrogen fixation (Malan et al. 2021; Mussa et al. 2016b). Differences in P could also be associated with the parent materials of savanna soils (Malan et al. 2021) and attributed to the differences in the density of bush-encroached areas (Tokozwayo et al. 2021). Additionally, differences could be due to variation in the actual uptake of available P and production of litter with a high concentration of organic acids, as these are mechanisms by which plant species influence the accessible P (Finzi et al. 1998). The findings of the current study were consistent with other studies that revealed that soil exchangeable K is positively affected in soils of bush-encroached sites, which are influenced by different woody species (Malan et al. 2021; Megersa and Worku 2018). In contrast, Tokozwayo et al. (2021) reported that K concentrations showed no clear trend across varying degrees of encroachment. Furthermore, only approximately 1%–2% of total K is readily available for plant uptake, while the majority remains in forms that are inaccessible to plants (Sidhu et al. 2024). The P and K values reported in this study were lower than those reported by Tokozwayo et al. (2021), but similar to Malan et al. (2021) who reported higher cation concentrations underneath *S. mellifera* and *D. cinerea* bushes. However, this study found that, despite uniformity in the Na content, P and K contents differed across sites dominated by different encroacher bush species.

The difference in soil exchangeable Ca and Mg across sites dominated by different encroacher bush species could be attributed to various influences of cations, which include specific variation in cation uptake, litter production and nitrogen fixation (Malan et al. 2021; Mussa et al. 2016b). The findings of the current study were consistent with other studies that revealed that soil exchangeable Ca and Mg are positively affected in soils of encroached sites and influenced by different woody plant species (Malan et al. 2021; Megersa and Worku 2018). In the current study, exchangeable Na in sites dominated by different encroacher bush species was not greatly influenced, which contradicts the findings reported by Megersa and Worku (2018) and Malan et al. (2021), who found higher exchangeable Na in sites encroached by *S. mellifera*.

Soil physical properties

Woody plants influence water availability through mechanisms that include infiltration, transpiration, interception and litter mulch (Sheil and Tobella 2020). However, based on encroacher bush species-specific influences, the current study found no difference in the moisture and temperature content of soil from sites dominated by different encroacher woody plant species. Therefore, this implies that sites dominated by different encroacher bush species had uniform soil moisture contents. This could be because there was no variation in other soil properties, such as soil structure, which could be key determinants of soil moisture (Gwak and Kim 2017; Zhao and Ming 2018). These findings contradict those of Gusha (2015), who found higher soil moisture content in a homogenous vegetation unit dominated by thicket compared to sparsely encroached and grassland units. The lack of variation in soil moisture on sites dominated by different encroacher bush species could be explained by environmental stimuli responses. Plants of the same species can develop different rooting systems in response to specific environmental stimuli, such as soil moisture (Bhattachan et al. 2012; Zanetti et al. 2015). Moreover, different woody species can also respond to hydrotropism stimuli with their lateral roots (Guevara and Giordano 2015). Therefore, if the stimuli are similar, it can result in different species responding in the same way and could subsequently cause them to have unvarying effects on physical properties, such as soil moisture. The low soil moisture across all sites and farms could be due to altered rainfall redistribution caused by vegetation. This is consistent with Chapman and Reiss (1999), who further attributed low soil moisture to evapotranspiration, water uptake and increased infiltration due to root growth.

Soil temperature affects plant growth, nutrient availability, OM decomposition and gas exchange between the soil and the atmosphere (Lehnert 2014; Onwuka 2018). The current study showed no difference in soil temperatures of sites dominated by different encroacher bush species and across three farms. This could be because there was no difference in the soil moisture content, which plays a crucial role in influencing the variation in soil temperature. As soil moisture decreases under the extraction of encroacher species, the evaporative cooling is reduced and consequently the soil temperature increases, with this effect being more pronounced in grasslands compared to areas under woody plant canopies (Lozano-Parra et al. 2018).

The soil texture differed across sites dominated by different encroacher bush species. These findings were consistent with those of Malan et al. (2021), who found that soil texture was significantly positively affected by the woody plant species, with sites encroached by *S. mellifera* showing the strongest positive effect. Megersa and Worku (2018) also observed that sand was more affected by woody plant species than the clay soil. The current study also found a significant difference in the soil texture (sand, silt and clay contents) of soil from different farms. The differences in soil texture could be due to factors such as disparity in the bush invasion rates across the farms. The findings of the current study concurred with the study of Eshete et al. (2020), who found that soil texture differed across different sites, which could be associated with the invasion rate of the bush. This was supported by Agena et al. (2014), who pointed out that the variance in soil texture across different farms could also be attributed to the transformation in soil parent materials.

Conclusion

Based on the observed differences in soil chemical properties (pH, EC, OC, OM, TN, P, Ca, Mg and K) between sites dominated by *S. mellifera*, *D. cinerea* and *T. sericea*, the study shows that habitats dominated by different types of encroacher bush species have varying soil chemical properties. These differences in soil chemical properties could be influenced by which encroacher species would most likely proliferate in a certain area. However, there was no difference in the Na content of soils from sites dominated by different bush species, thus highlighting the fact that different encroacher bush species did not result in universal effects on soil chemical properties. Moreover, the study found a significant difference in soil chemical properties (pH, EC, TN, OC, OM, Na, Ca, Mg and K) across the three farms. However, the study did not find differences in soil moisture and temperature for sites dominated by three encroacher bush species. The silt and sand percentages differed across sites dominated by encroacher species, while the clay percentage remained uniform. Soil texture was the only physical property that differed across the three farms. The findings of the current study indicate that soils from sites dominated by *T. sericea* displayed the poorest overall soil quality. These soils were marked by high pH and Na levels, coupled with low contents of all other chemical properties, as well as reduced moisture, temperature, silt and clay contents. Therefore, the study concludes and recommends that it is imperative to consider soil properties and types of encroacher bush species that dominate specific areas when evaluating the impacts of woody plants on rangeland ecosystems. This is important because the soil properties can affect the herbaceous species present and their biomass.

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Data availability — Upon reasonable request, all or part of the research data collected and analysed for this manuscript will be made available.

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Ethics approval — The study used soil samples collected from different sites dominated by different encroacher bush species, and the University of Namibia's ethical standards were followed to ensure that no negligent soil disturbances occurred during soil sampling. The Ethical Clearance Certificate Number NEC027 was obtained from the University Ethics Committee before the commencement of the research study. This was not a clinical trial study but rather an assessment of rangeland's conditions where an ethics declaration was not applicable.

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