Long-term impacts of season of grazing on soil carbon sequestration and selected soil properties in the arid Eastern Cape, South Africa

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Abstract

Background and Aims: The karoo biomes of South Africa are major feed resources, yet soil nutrient depletion and degradation is a major problem. The objective of this study was to assess impacts of long-term (>75 years) grazing during spring (SPG), summer (SUG), winter (WG) and exclosure (non-grazed control) treatments on soil nutrients, penetration resistance and infiltration tests.

Methods: A soil sampling campaign was carried out to collect soil to a depth of 60 cm to analyse bulk density, soil physical and chemical parameters as well as soil compaction and infiltration.

Results: Generally, grazing treatments reduced soil organic C (SOC) stocks and C:N ratios, and modified soil properties. There was higher SOC stock (0.128 Mg ha^{-1} yr^{-1}) in the exclosure than in the SPG (0.096 Mg ha^{-1} yr^{-1}), SUG (0.099 Mg ha^{-1} yr^{-1}) and WG (0.105 Mg ha^{-1} yr^{-1}). The C:N ratios exhibited similar pattern to that of C. From the grazing treatments, the WG demonstrated 7 to 10% additional SOC stock over the SPG and SUG, respectively.

Conclusions: Short period animal exclusion could be an option to be considered to improve plant nutrients in sandy soils of South Africa. However, this may require a policy environment which supports stock exclusion from such areas vulnerable to land degradation, nutrient and C losses by grazing-induced vegetation and landscape changes.

Key words: Arid ecosystem; Exclosure; Grazing season; Organic matter; Soil organic carbon; Total Nitrogen

Introduction

The karoo biomes of South Africa are major feed resources for livestock farming. In the arid to semi-arid environments of the country, more than 75% of the land is used for livestock production (Smet and Ward 2006) and is a foundation for the country's dairy, beef and wool industries (Du Preez et al. 2011). South African soils are generally characterized by low SOC contents due to extreme variability in rainfall and land deterioration (Koetze et al. 2013), vegetation removal by stock and/or burning, variability in soil types and climate variability (Du Preez et al. 2011). In such arid regions, rangeland management and protection from degradation is of utmost importance to improve soil organic matter, and thereby the SOC storage.

In many ecosystems, livestock grazing has been shown to affect plant diversity, soil C, total nitrogen (N), and ecosystems functioning (Franzluebbers 2005). However, the effect of grazing on C and N stock has been variably documented in the literature. Grazing management practices have been shown to increase soil C (Reeder et al. 2004) and N concentrations (Liu et al. 2012), have no effects (Barger et al. 2004) and decrease soil C (McSherry and Ritchie 2013) and N levels (Steffens et al. 2008). This variation is due to the variation in climate, soil type and landscape management (Lal 2002) and type of plant community (Ampleman et al. 2014).

In the vast arid karoo biomes of South Africa, like most other African countries, little is known about impacts of long-term grazing strategies on soil C dynamics, as grazing practices would shed light on soil C dynamics in these ecosystems, resulting in alteration of the physical and chemical characteristics of soils. There is limited information on factors controlling the spatial and temporal variability of SOC stocks through C decomposition and dynamics, and other soil properties under different grazing managements (Kotze et al. 2013). Although season and frequency of grazing are factors manipulated to achieve desired management goals in grazing lands (Evans et al. 2012), little has been documented about the long-term effects of seasonal grazing management on C and N dynamics in the arid karoo biome of South Africa. Moreover, due to multifaceted interactions between C and N in a karoo ecosystem, grazer effect on SOC is highly context-specific (McSherry and Ritchie 2013) and site-specific information is essential for various management scenarios (Derner and Schuman 2007; Du Preez et al. 2011).

The aim of this study was to assess impacts of long-term seasonal grazing management and exclosure (non-grazed control) on soil C, N and other soil parameters. We hypothesized that long-term seasonal grazing managements would not have a significant effect on soil C and N contents and other soil properties compared to exclosure, but would have an additional benefit in terms of sustainable animal production and ecosystem services.

Materials and methods

Study site description

This study was conducted at the long-term experimental site of Grootfontein Agricultural Development Institute, Eastern Cape, South Africa. The study site is 122.4 ha and located at latitude 31^{o} 22`E, longitude 24$^{o}$ 45`N, with an altitude of 1260 m above sea level. The area lies within 100 to 500 mm rainfall regions (arid zone), with higher coefficient of variation (>40%) as rainfall decreases. The long-term mean annual and median rainfall is 370.2 and 359 mm, respectively. The rainfall (southern hemisphere seasons) distribution is 15% in spring (September-October), 30% in summer (October-March), 50% in autumn (April to May) and 5% in winter (June-August) (Fig 1). The average January temperature is 20.9^{o}C while the average July temperature is 7.9^{o}C.

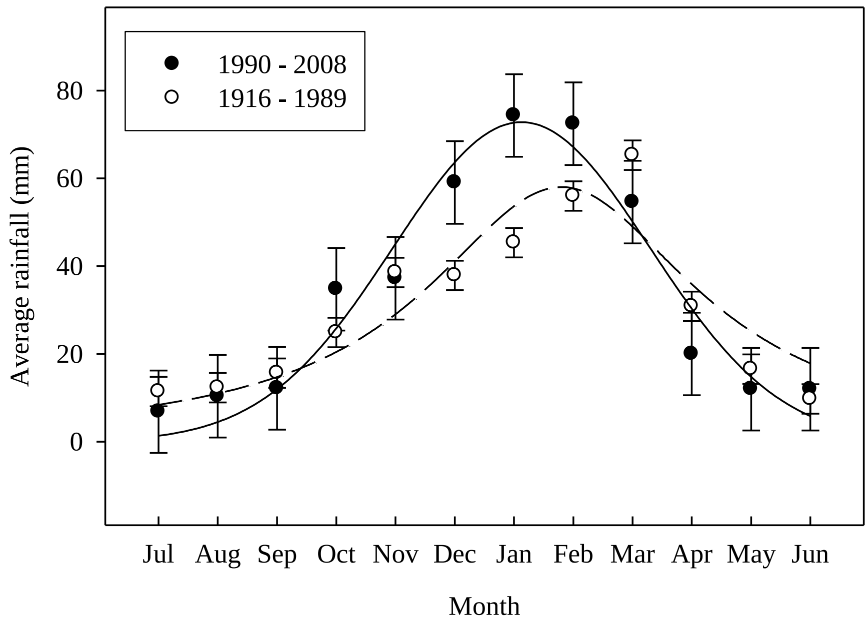


Fig 1 Recent (1990-2014) and earlier (1916-1989) average monthly rainfall in the arid Eastern Cape, South Africa. Lines are Gaussian regressions for 1990-2014 (solid) and 1916-1989 (dashed). Bars represent standard errors.

Karoo biome is a grassy, shrub land, the third largest biome in South Africa, covering about 20.5% of the land area. The geology underlying the biome is varied, as the distribution of this biome is determined primarily by rainfall. Climatologically and biologically the Karoo is a heterogeneous and ecotonal region. It is an ideal biome for sheep and goat production; in the main river valleys, people also farm olives, citrus and deciduous fruit. Grass species such as *Aristida diffusa (*Iron grass*), Eragrostis curvula (*Love grass*) and Hyparrhenia hirla* (Thatch grass) have increased in the SPG and SUG treatments. Summer grazing rapidly increased the relative abundance of dwarf shrubs over the study years. Most of the grasses are of the C-4 type and, like the shrubs, are deciduous in response to rainfall events. On the other hand, grass species such as *Themeda triandra* (Red grass), *Sporobolus fimbriatus* (Drop seed grass), *Digitaria eriantha* (Finger grass) and *Cymbopogon plurinodis* (Turpentine grass) were commonly found in the WG and exclosure treatments (Du Toit 2010; 2011).

The predominant soil type, over 80% of the karoo area, is a lime-rich, weakly developed shallow (<30 cm) soil over rock. Generally the soils of the study site are of the Shigalo series, aridisols (Soil Survey Staff, 1999), categorized under textural class sandy clay loam. Although less than 5% of rain reaches the rivers, the high erodability of soils poses a major problem where overgrazing occurs. The soil color of the study site was identified as 7.5YR, 5YR, 10YR and 5YR in the SPG, SUG, WG and exclosure, respectively.

Merino wethers grazed the treatments at a stocking rate of 2.35 animals ha^{-1}, with individuals being replaced with young animals after three to four years. Animals were allowed during day hours (9:00 am to 5:00 pm) free grazing on velds, and were not supplemented with any other feeds throughout the study period, because the initial objective of the study was to evaluate wool yield and animal performance of growing sheep under veld conditions. Except minimal and localized dung and faeces (estimated to be less than 3 kg N ha^{-1} yr^{-1}) returned to the soil in grazing treatments, chemical fertilizers were not applied on the veld during the study period. The study started in 1934 and terminated in 2010/2011; soil samples were taken between May and November, 2012.

Sampling design and procedure

The study site consists of various grazing season treatments including spring (SPG, August-December), summer (SUG, December to April), winter grazing (WG, April to August) (grazing for about 75 years) and exclosure, which has not been grazed for more than 75 years. The plots were laid out in parallel rectangular strips (width/ length ratio of approximately 1:10) of 25.5 ha (seasonal treatments) and 3.4 ha (exclosure) along the gentle sloping mixed karoo veld. Five parallel transects, 100 m apart and perpendicular to the long axis of each plot, were delineated. Soil samples, at least 15 m from the edge of the plots, were collected every 20 m along each transect (Fig 2).

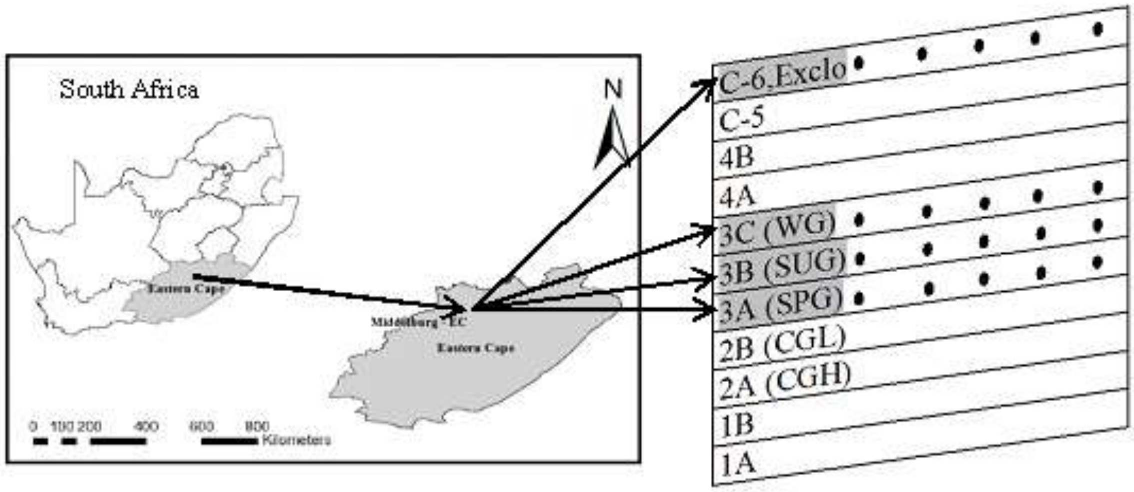


Fig 2 Treatment sites, their relative positions and experimental layout of long-term grazing study site in the arid Eastern Cape, South Africa. Closed small circles are sampling points: SPG (spring grazing), SUG (summer grazing), WG (winter grazing) and C-6, Exclo (Camp-6, exclosure), CGL, continuous grazing at light stocking rate; CGH, continuous grazing at heavy stocking rate

To determine C, N, soil texture and soil chemistry, soil was sampled until 60 cm depth in 10 cm steps (0-10, 10-20, 20-30 cm), and 30-60 cm (pooled due to bedrocks below 30 cm depths in some plots). Five samples were taken from each sampling sub-plot for grazing treatments and three sampling sub-plot for exclosure along transects, and a total of 496 soil samples were collected. For each transect, samples were pooled per layer and mixed to make a single homogenous soil sample per layer. To determine bulk density, undisturbed soil cores (5.8 cm diameter) were collected using a core sampler with the same sampling procedure as on the transects. Soil water contents were measured from bulk density soil core samples. Soil penetration resistance was measured at 1 cm intervals down to a depth of 60 cm using a Rimik™ CP20, with a total of 2800 readings being taken: 747 from the SPG, 776 from the SUG, 862 from the WG and 415 from the exclosure. Infiltration rate readings (n=150) were collected at every ten minutes over the period of an hour, using a mini double ring infiltrometer (15 cm inner and 30 cm outer diameters) until it reached a steady state.

Soil sample preparation and analysis

Bulk density was determined on intact soil cores by drying the soil at 105°C for 24 h and dividing the oven dry mass by the volume of core sampler. Soil particle sizes were analysed using wet-sieving and sedimentation method following the standard procedure of The Non-Affiliated Soil Analysis Work Committee (1990). The samples were air dried and ground to pass through a 150-µm screen and analysed for total C and N using a Carlo Erba NA1500 C/N analyzer (Carlo Erba Strumentazione, Milan, Italy). All other chemical analyses were undertaken in duplicate following the procedure of The Non-Affiliated Soil Analysis Work Committee (1990): pH (1:2.5 soil to water suspension), exchangeable Ca, K, Mg and Na (1 mole dm^{-3} NH_4OAC at pH 7). Since SOC content varied along the soil depths due to differences in bulk density at different soil profiles, SOC stock (g cm^{-2}) and total N (TN) stock (g cm^{-2}) were estimated after Bagchi and Mark (2010) as follows:

$$SOC = \sum_{i=1}^{n} D_i \rho_i SOC_i$$

$$TN = \sum_{i=1}^{n} D_i \rho_i TN_i$$

Where SOC is soil organic C stock (Mg ha^{-1}) and TN is total N stock (Mg ha^{-1}); i is the number of soil layers,(i=1, 2, 3 and 4); D_i is the depth interval (cm); ρ_i is the bulk density (g cm^{-3}) in the soil layer i; SOC_i is the mean SOC content (%) in the soil layer i; N_i is the mean N content (%) in the soil layer i.

Statistical analysis

All analyses were tested for normality using the UNIVARIATE procedure of SAS (SAS Institute 2008). The effects of grazing management, soil depth and their interactions on soil C, N, C:N ratio and other soil parameters were examined using analysis of variance with the MIXED model (PROC MIXED SAS Institute Inc. 2008). Grazing management, soil depth, and their interactions were fixed effects, while transect and transect by grazing management were random effects. Where necessary, the data were transformed using the logarithmic transformation. When treatment effects were significant ($P < 0.05$), the means were separated using Tukey's tests. Pearson correlations were used to analyse the trends of soil parameters (PROC CORR SAS Institute Inc. 2008).

Results

Season of grazing on soil C and N storage

Our results indicated that long-term (about 75 years) cumulative effect of grazing management on soil C and N varied considerably (Table 1). For all treatments and individual soil core, the C content ranged from 0.19 to 1.12% (mean: 0.51), while N content ranged from 0.02 to 0.14% (mean: 0.06) and C:N ratios from 3.70 to 17.16. Season of grazing influenced soil C contents and C:N ratios, with the lowest values being found in the

SPG. There was higher ($F_{3,281}$=9.826, $P < 0.001$) C content in the exclosure than in the grazing treatments while the differences for C:N ratios were only marginally significant ($F_{3,281}$=2.600, P=0.053). The interaction effect of grazing management-by-soil depth on C contents was only marginally significant ($F_{9,281}$=0.877, P=0.048).

The C and N stocks and C:N ratios demonstrated great variations depending on management practices and soil depths (Fig 3). There was higher C stock ($F_{3,281}$=12.982, $P < 0.001$) and C:N ratios ($F_{3,281}$=6.975, $P < 0.001$) in the exclosure than grazing treatments, suggesting that C storage in dry lands could be improved by livestock exclusion. Among the grazing treatments, the C stock was 7 and 10% higher in the WG than in the SPG and SUG, respectively. The N stock differences between the grazing treatments and exclosure was in the range of 6%. Generally, the WG practices resulted in higher C stocks as mature vegetation were resistant to grazing pressure and trampling by sheep was less due to low moisture in the soil.

Table 1 Soil organic C (SOC) and total N contents (%) and C:N ratios (mean ± SEM) as influenced by grazing management (SPG, SUG, WG and exclosure) and soil depths (0-10, 10-20, 20-30 and 30-60 cm) in the arid Eastern Cape, South Africa

Fixed effects	Soil parameters		
	SOC	Total N	C:N
Grazing management (GM)	***	NS	*
SPG	0.48 ± 0.015[c]	0.057 ± 0.02	8.50 ± 0.22[b]
SUG	0.47 ± 0.015[c]	0.058 ± 0.02	8.57 ± 0.23[b]
WG	0.52 ± 0.015[b]	0.060 ± 0.02	8.71 ± 0.24[b]
Exclosure	0.62 ± 0.02[a]	0.064 ± 0.03	9.83 ± 0.30[a]
F-test	9.826	1.850	2.600
P-value	<0.001	0.139	0.053
Soil depth (cm)	***	**	***
0-10	0.534 ± 0.013[a]	0.054 ± 0.002[b]	10.05 ± 0.21[a]
10-20	0.540 ± 0.013[a]	0.058 ± 0.002[b]	7.76 ± 0.22[c]
20-30	0.538 ± 0.014[a]	0.073 ± 0.002[a]	8.32 ± 0.22[b]
30-60	0.415 ± 0.015[b]	0.050 ± 0.002[c]	8.67 ± 0.40[b]
0-60	0.529 ± 0.026[a]	0.061 ± 0.003[b]	8.67 ± 0.40[b]
F-test	11.261	20.566	15.795
P-value	<0.001	<0.001	<0.001
GM *soil depth	*	NS	NS
F-test	0.877	2.108	1.515
P-value	0.048	0.107	0.08

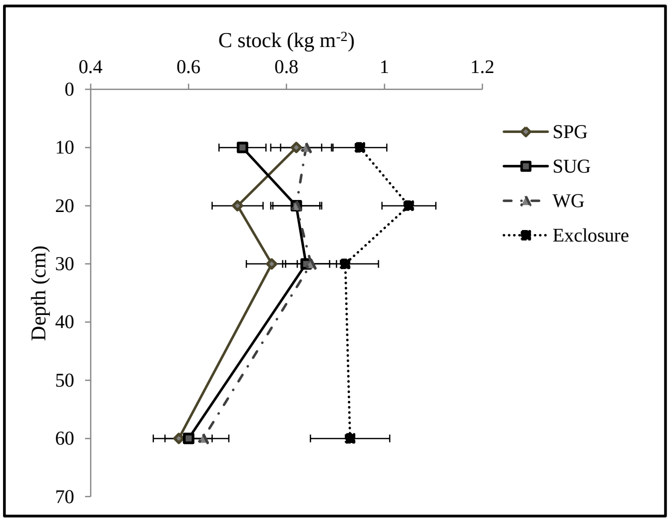
Mean values in each column for each parameter followed by different letters are statistically different at $P < 0.05$.

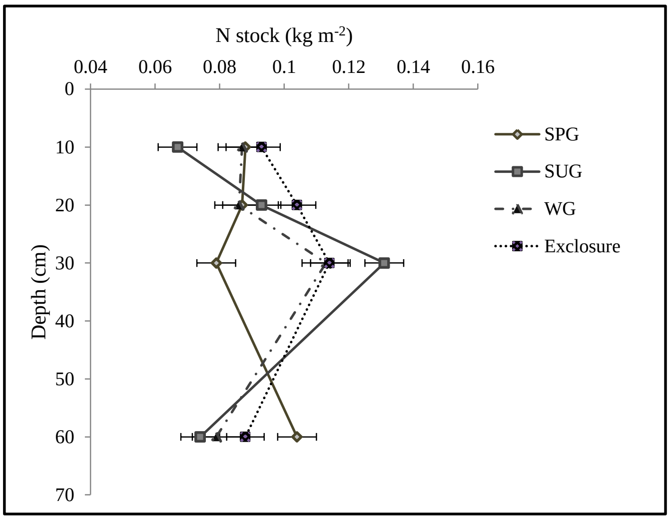
NS, $P > 0.05$; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$, SEM=standard error mean

Distribution of C and N storage in different soil layers

Seasonal grazing demonstrated clearly visible and consistent effects on C and N contents along the soil layers (Table 1). Generally, the C and N contents and C:N ratio was higher in the top 0-30 cm soil layer but tended to decrease with depth. The C content in the top soil layers (0-10, 10-20 and 20-30 cm) was higher ($F_{3,281}$=11.261, $P < 0.001$) than 30-60 cm. Similarly, the N content at 20-30 cm soil layers was higher ($F_{3,281}$=20.566, $P < 0.001$) compared to other soil layers. At the same time, the N content at 0-10 and 10-20 was higher than 30-60 cm soil layer. The higher proportion of C (63.1%) and N (78.7%) in the top 0-30 cm, where litter turnover is usually high, signifies that C and N in the karoo biome are vulnerable to losses through C oxidation, ammonia volatilization, N mineralization and runoff. There was higher C:N ratios ($F_{3,281}$=15.795, $P < 0.001$) in the top 0-10 cm than 30-60 cm soil layer, but it was the least (7.76) at 10-20 cm.

Soil C and N stocks, and C:N ratios were generally higher in the top 0-30 cm layers, where soil organic matter is usually high, due to plant residue and litter cover (Fig 3). We found increased ($F_{3,281}$=7.642, $P < 0.001$) C stock in the top soil layers, which was higher by 24.1, 26.1 and 28.7% at 0-10, 10-20 and 20-30 cm, respectively, compared to 30-60 cm soil layer. The N stock ($F_{3,281}$=22.888, $P < 0.001$) and C:N ratios ($F_{3,281}$=23.333, $P < 0.001$) differed at each soil layer, suggesting great variations at different soil layers. The highest N stock (0.12 kg m^{-2}) was found at 20-30 cm while the least (0.08 kg m^{-2}) at 30-60 cm soil layer. Likewise, the highest (10.1) C:N ratios was found at 0-10 cm while the least (7.7) at 20-30 cm. Grazing management-by-soil depths interaction was significant on N stock ($F_{9,281}$=2.434, $P < 0.01$) and C:N ratios ($F_{9,281}$=2.389, $P < 0.05$). Livestock exclusion increased N and C:N ratios, but decreased at soil layers >30 cm depths (Fig 3).





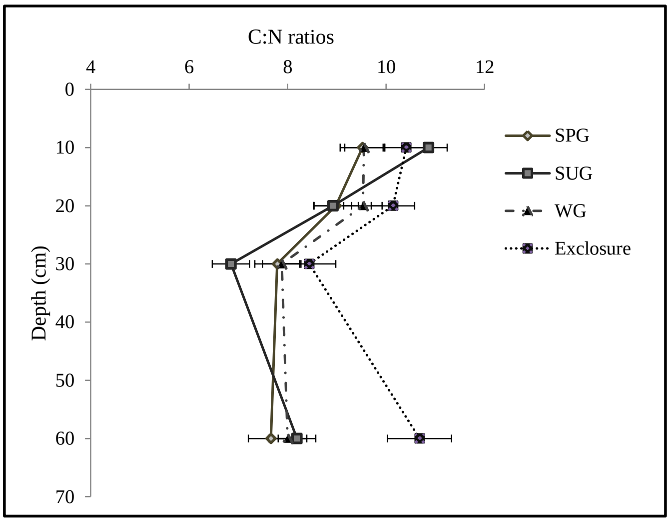


Fig 3 C and N stocks (kg m^{-2}), C:N ratios as affected by grazing in spring (SPG), summer (SUG) and winter (WG) and exclosure in the arid Eastern Cape, South Africa. Bars represent the standard error of the mean

Soil physical parameters

Grazing management practices were shown to influence the clay content ($F_{3,71}$=6.945, P < 0.001) while they had non-significant (P > 0.05) effect on silt and sand contents (Table 2). Clay content was 48% lower in the exclosure than in the SPG, but it was 37% higher in the SUG than in the exclosure. We did not find evidences for differences in soil texture in different soil layers. However, the bulk density was lower (P < 0.05) in the exclosure and WG than in the SUG and SPG (Table 2). We found higher bulk densities when the paddocks grazed early in the growing season (spring) and summer. In the very surface soil, we found lower ($F_{3,71}$=1.413, P < 0.05) bulk density than at 10-20 and 20-30 cm soil layers. Likewise, the bulk density was lower (P < 0.01) at 10-20 and 20-30 cm than 30-60 cm. There was no significant effect of grazing management-by-soil depth interaction on soil physical parameters except for bulk density ($F_{3,71}$=3.025, P < 0.01) (Fig 4). Bulk density decreased in the WG and exclosure, but it increased at soil layers >10 cm.

Table 2 Selected soil physical properties (mean ± SEM) as influenced by grazing management (SPG, SUG, WG and exclosure) and soil depths (0-10, 10-20, 20-30 and 30-60 cm) in the arid Eastern Cape, South Africa

	Soil texture			
Fixed effects	Silt (%)	Clay (%)	Sand (%)	Bulk density (g cm^{-3})
Grazing management(GM)	NS	***	NS	*
SPG	10.8 ± 1.72	28.3 ± 1.65[a]	60.9 ± 1.80	1.55 ± 0.01[a]
SUG	10.1 ± 1.59	26.1 ± 1.53[a]	64.3 ± 1.66	1.56 ± 0.01[a]
WG	13.9 ± 1.69	20.1 ± 1.53[b]	66.0 ± 1.66	1.52 ± 0.01[b]
Exclosure	13.8 ± 2.10	19.1 ± 2.02[b]	64.6 ± 2.20	1.51 ± 0.02[b]
F-test	1.339	6.945	1.472	1.413
P-value	0.271	<0.001	0.232	0.025
Soil depth (cm)	NS	NS	NS	**
0-10	10.8 ± 1.59	22.8 ± 1.53	66.5 ± 1.66	1.50 ± 0.01[c]
10-20	14.0 ± 1.59	22.3 ± 1.52	63.8 ± 1.66	1.53 ± 0.01[b]
20-30	9.50 ± 1.86	25.7 ± 1.79	64.9 ± 1.95	1.55 ± 0.02[b]
30-60	14.4 ± 1.97	22.9 ± 1.89	60.7 ± 2.06	1.58 ± 0.02[a]
F-test	1.798	0.772	1.655	3.025
P-value	0.158	0.514	0.187	0.005
GM*depth	NS	NS	NS	**
F-test	1.390	0.370	1.532	3.025
P-value	0.215	0.945	0.160	0.005

Mean values in each column for each parameter followed by different letters are statistically different at *P < 0.05;* NS, *P > 0.05;*P < 0.05;**P < 0.01;***P < 0.001*. SEM=standard error mean

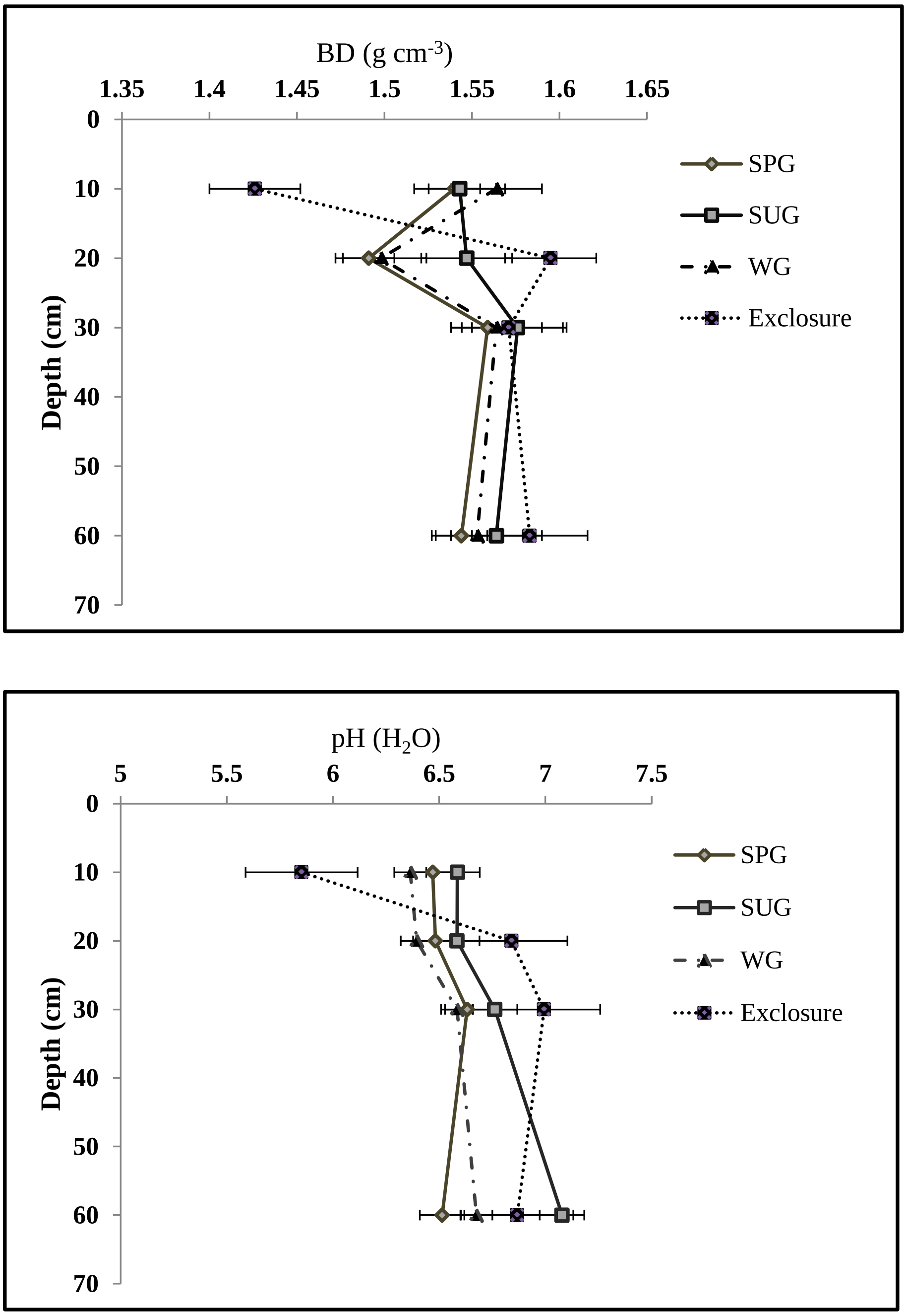


Fig 4 Bulk density**,** BD (g cm^{-3}) and pH (H_2O) as affected by grazing in spring (SPG), summer (SUG) and winter (WG) and exclosure in the arid Eastern Cape, South Africa. Bars represent the standard error of the mean

Soil chemistry

Effects of grazing management was evident on all soil chemical properties considered in this study (exchangeable Ca, K, and Na, CEC and pH) except the Mg content, which was only marginally significant ($F_{3,71}$=2.683, P=0.055) (Table 3). The exchangeable Ca, Mg, and pH generally increased along soil depth up until

30 cm with Mg content increment extending down to 60 cm depth. The Ca content was higher ($F_{3,71}$=15.432, P < 0.001) in the exclosure compared with the seasonal grazing. Conversely, the K content was lower ($F_{3,71}$=2.967, P < 0.05) in the exclosure and WG than in the SPG and SUG. Grazing at plant growing season (SUG) contributed to an increased (26 mg kg^{-1}) Na content compared to the SPG and exclosure while the Na in the WG was the least (13 mg kg^{-1}). Likewise, the pH value (6.75) was higher ($F_{3,71}$=4.153, P=0.01) in the SUG than other seasonal grazing, having the least (6.32) in the exclosure. Likewise, the highest ($F_{3,71}$=19.902, P < 0.001) CEC was found in the SUG while the least in the SPG (15.3 cmol kg^{-1})

Table 3 Selected soil chemical properties (mean ± SEM) as influenced by grazing management (SPG, SUG, WG and exclosure) and soil depths (0-10, 10-20, 20-30 and 30-60 cm) in the arid Eastern Cape, South Africa

	Exchangeable cations (mg kg^{-1})					
Fixed effects	Ca	K	Mg	Na	pH (H_2O)[a]	CEC(cmol kg^{-1})
Grazing management (GM)	***	*	NS	*	**	***
SPG	906± 79.9[b]	224 ± 15.4[a]	554 ± 48.9	17.3 ± 3.0[b]	6.53 ± 0.09[b]	15.3 ± 1.7[c]
SUG	858± 73.9[b]	234 ± 14.2[a]	659 ± 45.3	25.7 ± 2.8[a]	6.75 ± 0.08[a]	32.7 ± 1.6[a]
WG	728 ± 73.9[b]	197 ± 14.2[b]	527 ± 45.3	13.0 ± 2.8[c]	6.50 ± 0.08[b]	25.6 ± 1.6[b]
Exclosure	1496 ± 91.8[a]	172 ± 17.7[b]	468 ± 56.2	20.6 ± 3.4[b]	6.32 ± 0.10[c]	28.4 ± 1.96[b]
F-test	15.432	2.967	2.683	3.737	4.153	19.902
P-value	<0.001	0.039	0.055	0.016	0.01	<0.001
Soil depth (cm)	**	NS	**	NS	**	*
0-10	771 ± 73.9[b]	222 ± 14.2	417 ± 45.3[c]	16.9 ± 2.76	6.32 ± 0.08[b]	25.7 ± 1.6[b]
10-20	952 ± 73.9[b]	214 ± 14.2	525 ± 45.3[b]	18.7 ± 2.76	6.58 ± 0.08[ab]	22.4 ± 1.6[b]
20-30	1159 ± 79.8[a]	207 ± 15.4	628 ± 48.9[a]	18.5 ± 3.0	6.76 ± 0.09[a]	25.1 ± 1.7[b]
30-60	1106 ± 91.8[a]	184 ± 17.7	640 ± 56.2[a]	22.6 ± 3.4	6.46 ± 0.10[ab]	29.7 ± 1.96[a]
F-test	5.032	1.018	4.633	0.559	5.052	2.871
P-value	<0.004	0.391	0.006	0.664	0.004	0.044
GM*depth	NS	NS	NS	NS	***	NS
F-test	1.164	0.603	0.305	0.463	4.317	0.680
P-value	0.335	0.789	0.970	0.893	<0.001	0.723

[a]pH in water solution. Mean values in each column for each parameter followed by different letters are statistically different at $P < 0.05$; NS, P > 0.05;*$P < 0.05$;**$P < 0.01$;***$P < 0.001$. SEM=standard error mean

Except the K and Na, which showed insignificant variations (P > 0.05), other soil chemical parameters exhibited great variations along the soil layers (Table 3). In general, the K content showed a decreasing trend while Na increased as soil depth advanced. There were lower Ca ($F_{3,71}$=5.032, P < 0.01) and Mg ($F_{3,71}$=4.633, P < 0.01) at 0-10 and 10-20 cm than 20-30 and 30-60 cm soil layers. Conversely, the CEC was higher ($F_{3,71}$=2.871, P <

0.05) at 30-60 than 0-10, 10-20 and 20-30 cm soil layers. The pH showed an increasing trend as depth advanced. However, statistically it was higher ($F_{3,71}$=5.052, $P < 0.01$) only at 20-30 cm than 0-10 cm soil layer. There was a significant grazing-by-soil depth interaction ($F_{9,71}$=4.317, $P < 0.001$) on pH value (Table 3 and Fig 4). Soil pH increased in seasonal grazing, but it decreased at depths <10 cm.

Association between soil properties (pooled along soil layers)

Despite the difference in grazing management, soil C was strongly, positively correlated (r=0.944, $P < 0.01$) with N stock values along soil layers (Table 4), suggesting that factors influencing N stock could strongly affect the C stock as well. However, the C stock value was moderately correlated with the CEC (r=0.323, $P < 0.05$) and silt (r=0.250, $P < 0.05$) contents. There was positive, but weak correlation of C stock with the Ca, Mg and BD. On the other hand, the N stock was positively correlated with Mg (r=0.235, $P < 0.05$), CEC (r=0.297, $P < 0.05$) and BD (r=0.235, $P < 0.05$).

Soil penetration resistance

Grazing management practice caused variations in terms of soil compaction measured as penetration resistance of the soil at 1 ($F_{3,16}$=5.70, $P < 0.05$), 4 ($P < 0.05$), 5 ($F_{3,16}$=3.96, $P < 0.01$), 6 ($F_{3,16}$=6.28, $P < 0.01$), 7, 8, 9, and 10 cm depths ($F_{3,16}$=2.56, $P < 0.05$) (Fig 5, a). Generally, at the top 0-3 cm as well as 4-11 cm interval, the SUG had higher soil penetration resistance compared with other treatments. At 10-20 cm depth, there was consistently higher soil penetration resistance in the SUG treatment than in the SPG, although these differences were only marginally significant ($F_{3,16}$=2.49, $P < 0.10$) (Fig 5, b). The differences in terms of soil penetration disappeared at greater than 14 cm soil depth and resumed thereafter at depth 50-55 cm (Fig 5, d). However, due to the presence of rock outcrops and sometimes shallow parent material, measurements were not taken below 38 and sometimes 50 cm for the exclosure and WG treatments, respectively (Fig 5, c and d).

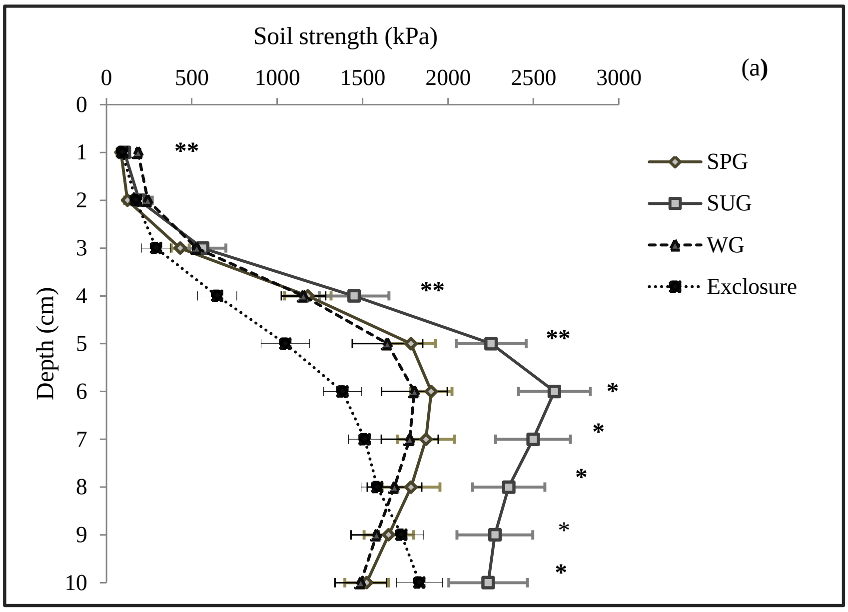
Table 4 Correlation coefficients (pooled across soil layers and grazing management) of soil parameters in the arid Eastern Cape, South Africa

	C	N	Ca	K	Mg	Na	CEC	pH	Silt	clay	Sand	BD
C		0.944**	0.197	−0.222	0.175	−0.181	0.323*	−0.048	0.250*	−0.189	−0.139	0.226
N			0.095	−0.216	0.235*	0.107	0.297*	0.007	0.162	−0.079	−0.151	0.235*
Ca				−0.111	0.268*	0.239*	0.082	0.178	0.109	−0.066	−0.013	−0.136
K					0.237*	−0.020	−0.109	0.033	−0.239*	0.170	0.108	0.142
Mg						0.635**	0.248*	0.337*	−0.193	0.285*	−0.081	0.102
Na							0.239*	0.219	−0.149	0.192	−0.050	−0.078
CEC								0.113	0.005	−0.119	0.089	0.163
pH									−0.131	0.083	0.031	0.232*
Silt										−0.492**	−0.538**	−0.083
Clay											−0.409**	0.083
Sand												−0.047
BD												

BD, bulk density

** Correlation is significant at the 0.01 level

* Correlation is significant at the 0.05 level


Soil strength (kPa)
0 500 1000 1500 2000 2500 3000
(a)
Depth (cm)
0 1 2 3 4 5 6 7 8 9 10
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*
*
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*
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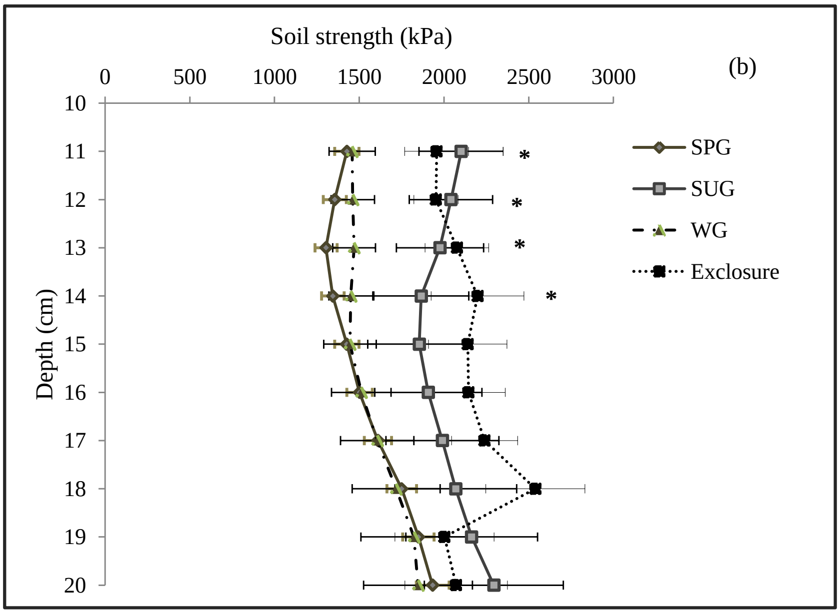
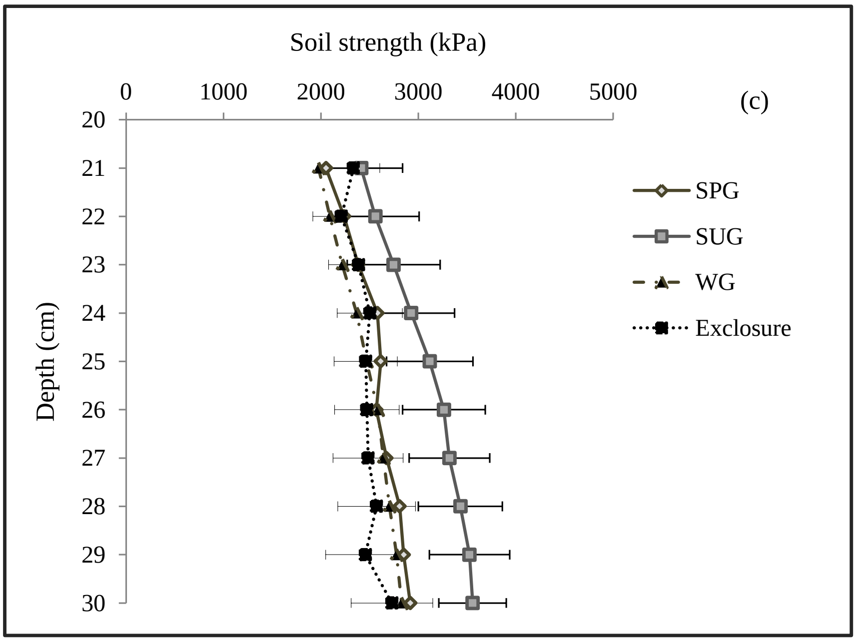
SPG
SUG
WG
Exclosure


Soil strength (kPa)
0 500 1000 1500 2000 2500 3000
(b)
Depth (cm)
10 11 12 13 14 15 16 17 18 19 20
*
*
*
*
SPG
SUG
WG
Exclosure



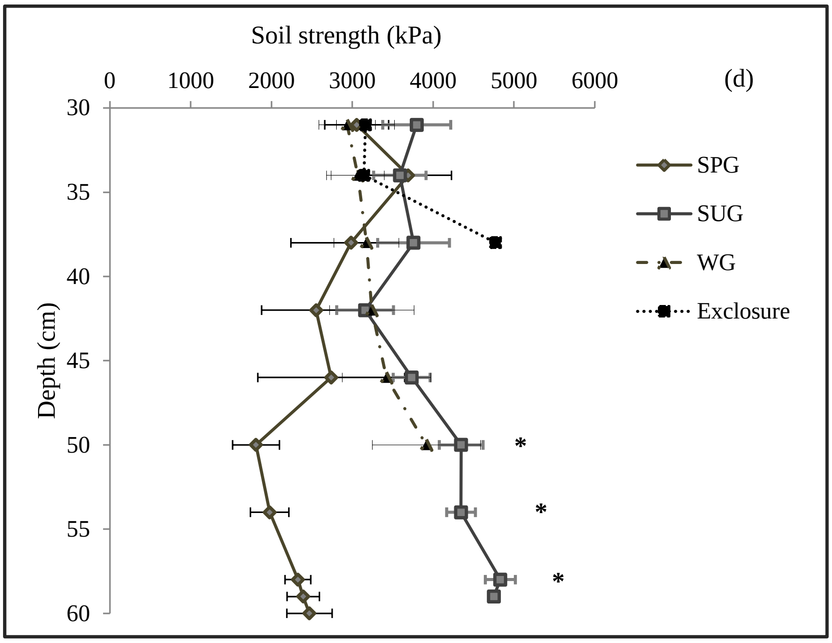


Fig 5 Soil penetration resistance in spring (SPG), summer (SUG) and winter (WG) grazing and exclosure at (a) 0-10 cm (b) 11-20 cm (c) 21-30 cm, (d) 31-60 cm depths in the Eastern Cape, South Africa

Bars represent the standard error of the mean. *$P < 0.05$; **$P < 0.01$position for Fig 5

Water infiltration rate and volumetric water content

Excessive soil moisture or rainfall can lead to nutrient loss through enhanced leaching or runoff, however, an optimal level of soil moisture is required to facilitate nutrient recycling processes in soil. The soil volumetric water content and water infiltration rate varied considerably in the soil layers (Fig 6). The exclosure and winter grazing increased infiltration rate while generally early wet (spring) and main rainy season (summer) grazing reduced water infiltration rate (Fig 6, a). The soil water content of the top soils in the WG (20.62%) and exclosure (23.98%) treatments was higher ($F_{3,14}$=4.61, P < 0.001) compared to the SPG (19.34 %) and SUG (19.91%) (Fig 6, b). Below 20 cm depth, the exclosure had consistently higher soil water content than grazing treatments. At the steady state, the exclosure and WG demonstrated marginally higher ($F_{2,12}$=3.86, P=0.051) infiltration rate compared with the SUG and SPG treatments.

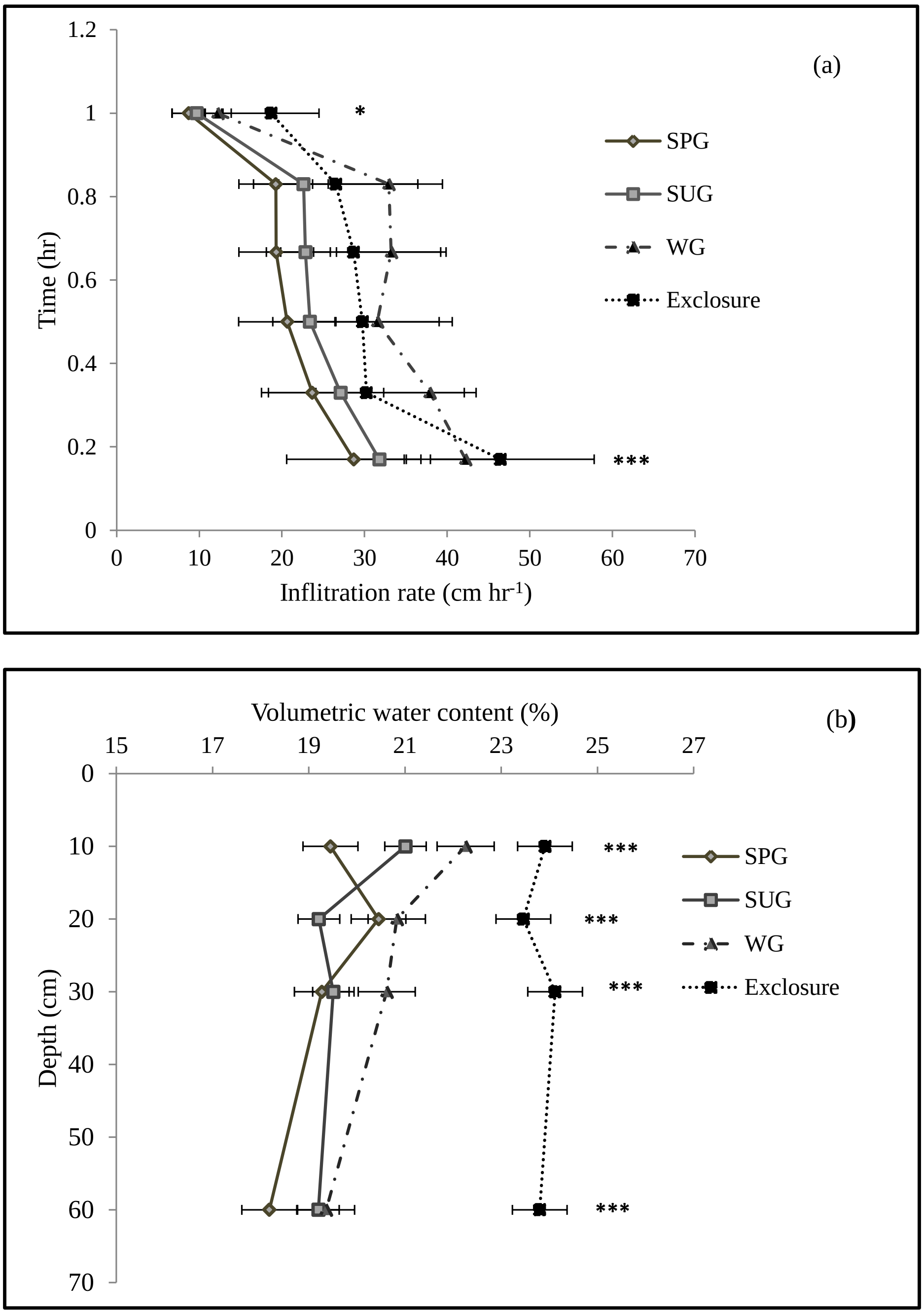


Fig 6 Soil volumetric water content (%; Fig 6a) and Water infiltration rate (cm hr^{-1}; Fig 6b) in spring (SPG), summer (SUG) and winter (WG) grazing, and exclosure treatments in the Eastern Cape, South Africa
Bars represent the standard error of the mean. $^{*}P$ < 0.05; $^{***}P$ < 0.001

Discussion

Influences of season of grazing on soil C and N storage

Our results indicated that long-term cumulative effects of seasonal grazing practices considerably influenced soil C and N stocks. The soil C and C:N ratios were consistently higher in the exclosure; and this signifies in cases with no disturbances in the long-term, C would be expected to increase until it reaches equilibration (Derner and Schuman 2007; Wilson et al. 2012). Consequently, more C (29.3-33.3%) was stored in the exclosure than in seasonal grazing, which was at a rate of 0.096-0.128 Mg ha^{-1} yr^{-1}, on average, for the entire period. The results are in the range (0.02-0.12 Mg ha^{-1} yr^{-1}) reported for arid rangelands (Lal 2000). The C and N stock obtained in this study is closer to the average for Africa (Beukes and Cowling 2003; Koetze et al. 2013) while smaller than reports elsewhere in the world (Evans et al. 2012; Liu et al. 2012).

Concerning grazing time our results show, that winter grazing (WG, 0.79 kg C m^{-2} compared to 0.96 kg C m^{-2} of the exclosure) seemed to be a good compromise having tangentially higher soil C stocks than the SPG (0.74 kg C m^{-2}) and SUG (0.72 kg C m^{-2}). This is partly associated with better soil condition and a soil surface covered by vegetation during the winter season providing root density and depth and increasing tolerance to drought (Cheng et al. 2011). The reduced C in the SPG and SUG treatments could be firstly, due to removal of aboveground plant biomass by animals early in the growing season. Secondly, reduced root growth in the presence of grazing might affect the rooting biomass contribution to the soil organic matter pool (Reeder et al. 2004; Briske et al. 2008; Liu et al. 2012). Reduced root allocation usually influences soil C inputs and also decreases N retention within the soil (Derner et al. 2006). Our results confirm the findings of Evans et al (2012) who reported reduced SOC when lands grazed during plant growing season (spring to summer) partly due to increased soil compaction. On the other hand, in the WG treatment vegetation was usually grazed after fully matured, and as a result plants were resistant to grazing pressure (Du Toit et al. 2011). The higher SOC concentration in the top soil layers is mainly attributed to the magnitude and proportion of fine root mass (Lal 2000; Derner et al. 2006) and litter accumulation (Liu et al. 2012). On contrary, Beukes and Cowling (2003) reported reduced SOC at the tops soils (0-10 cm) in non-selective grazing at high grazing intensity.

Estimating an annual C storage since last soil sampling (C difference divided by the 75 years), the C stock rate of the exclosure was in the range of 0.128 Mg C ha^{-1} yr^{-1} compared to 0.105 for WG, 0.099 for SUG and 0.096

Mg C ha^{-1} yr^{-1} for SPG, respectively. Livestock exclosure, as a method of land restoration increases C sequestration through higher above and below-ground biomass and species richness (Liu et al. 2012). The results agree with other reports (Cheng et al. 2011; Witt et al. 2011) that higher residues return from higher primary productivity contribute to an increased soil C and N stocks. With respect to grazing, the SOC storage varies depending on whether the grazing pressure exceeds the areas and/ or season's carrying capacity beyond a given threshold (Cheng et al. 2011). This threshold depends mainly on vegetation type, as C_4-dominated grasslands differ so strongly in their response of SOC to grazing (McSherry and Ritchie 2013).

The N stock in the exclosure was higher by 9.9-16.3% than seasonal grazing, and the majority (70%) of this stock was at the top soil layers. This could be due to a function of root distribution and hence senescence for long period of time. Grazers return significant proportions of ingested N through their faeces and urine (Oenema et al. 2005), which may increase N inputs under heavy grazing intensity. However, due to light grazing pressure in our study, the N differences associated with animal (sheep) faeces and urine leftovers, were only small (estimated to be less than 3 kg ha^{-1} yr^{-1}). According to Steffens et al (2008), the higher N in the livestock excluded site is due to the presence of accumulated aboveground and belowground biomass, plant litter and crop residues, which may have contributed to the higher soil organic matter, a reservoir of soil C and N (Pineiro et al. 2010). Nevertheless, our results confirm that in arid regions, a slightly higher C:N relationship can be maintained through livestock exclusion. Improvement in N provides the potential for C sequestration (Pineiro et al. 2010), land rehabilitation and restoration (Derner and Schuman 2007). Although grazing affected N through removal of aboveground biomass, regardless of these practices, there was higher N stock at the uppermost (0-30 cm) soil layers, implying that the amount and turnover of N in the top soils is usually high (Derner et al. 2006), and at the same time, vulnerable for losses through ammonia volatilization and run off.

Season of grazing effects on soil properties

Soil health in terms of physical and chemical properties depends mainly on plant and soil management practices. As a physical soil quality, bulk density and soil compaction are good indicators, because of the strong correlation with soil processes (Mikhailova et al. 2000; Murphy et al. 2004; Evans et al. 2012) including aggregate stability, microbial process, nutrient retention and/ or nutrient recycling (Neff et al. 2005) and C sequestration. The higher clay content in the SPG and SUG did not show a corresponding higher C and N stocks may be due to light textured clay (<35%) content. Such kinds of soils have inherent soil physical problems like hard setting, sodicity and low organic carbon levels (Chan et al. 2003). It may be due to a frequent disruption of aggregates by animals as soils were wet during the SPG and SUG grazing (Six et al. 2000). Contrary to our finding, Mcsherry and Ritchie (2013) reported positive effects of grazing on SOC at lower precipitation, finer soils with higher clay (>35%) content. For grazing exclosure, higher Ca and lower bulk densities were explained partly by higher rate of biomass recycling back to the soil leading to better macro porosity, and thus water holding capacity (Donkor et al. 2002; Witt et al. 2011). The absence of trampling by livestock lead to the formation of stable micro-aggregates in which SOC has been stabilized and sequestrated in the long-term (Six et al. 2000; Kotze et al. 2013). Indeed, exclosure showed higher CECs and nutrient retention compared to grazed treatments.

The increasing trend in Ca, Mg and CEC as soil depth advanced might be related to leaching of nutrients to lower layers due to the sandy dry land soils. In arid environments, due to limited biomass, livestock production affects SOC due to amount and composition of litter inputs to soil system, and in turn affects soil moisture and physical properties (Witt et al. 2011). Soil nutrients in the top soil layers could be modified by long-term seasonal grazing and/or exclosure. According to Derner et al (2006), the magnitude and distribution of fine root mass in the top soil profile is a principal driver mediating the effect of community composition in the biogeochemistry of grassland ecosystems.

Season of grazing on soil compaction and water infiltration

For seasonally grazed treatments, severe grazing on immature vegetation is often associated with higher soil compaction through animal trampling. For the karoo region, Beukes and Cowling (2003) reported that unlike early plant growing season grazing (spring), in winter grazing soils are less sealed and compacted, as lands covered by mature vegetation, similar to our finding. Similar effects have also been reported by others (Bouwman and Arts 2000; Donkor et al. 2002; Evans et al. 2012; Kotze et al. 2013). However, the extent of compaction is dependent on soil moisture, inherent soil particle distribution, soil type, stock class and stocking rate (Beukes and Cowling 2003). Other factors like spatial arrangement of grazing related to the distribution of water points (Kotze et al. 2013), landscape position and variability of inherent soil parent material may also contribute to the compaction of the soil.

From seasonal grazing treatments, winter grazing showed the lowest soil compaction mainly due to the reduced soil moisture content in winter because soil compaction is enhanced under optimal soil water conditions (Hamza and Anderson 2005). The freeze-thaw cycles during the winter season might have also contributed to lower compaction for grazing during the winter season (Donkor et al. 2002). This was also confirmed by higher water infiltration rate and soil moisture content in the WG, which is often associated with low surface runoff, probably due to an increase in soil organic matter which enhances porosity and water retention capacity. Enhanced soil moisture following long-term grazing exclusion has been reported previously (Witt et al. 2011). The implication is that land restoration through livestock exclusion is of the utmost importance because stock farming is practiced in the majority of South Africa (Du Preez et al. 2011; Kotze et al. 2013).

Conclusion

Our findings indicated that grazing reduced soil C stocks and C:N ratios, and altered the magnitude and allocation of soil nutrients. Grazing during spring and summer increased soil compaction while reduced water infiltration rate, nutrient and water retention and nutrient recycling. Long-term accumulation of soil organic matter in the exclosure, however, generally resulted in improved soil C content and C:N ratios as well as other soil nutrients. The exclosure and WG showed higher volumetric water content and infiltration rate. Among the grazing treatments, the WG is a promising alternative management option to optimize livestock production while managing soil nutrients and other ecosystem services and functions. The results suggest that stock exclusion (soil and vegetation resting time, 3-5 years) would be a viable management option to improve soil organic matter and critical nutrients in the sandy soils of arid regions. However, this may require a policy environment which supports stock exclusion from such areas vulnerable to land degradation, nutrient and soil C losses by grazing-induced vegetation and landscape changes.

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