

Soil carbon and nitrogen in five contrasting biomes of South Africa exposed to different land uses

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Accepted 12 November 2003

Stocks of soil C to a depth of 50 cm in untransformed, indigenous veld ranged from 21 t ha⁻¹ in karoo to 168 t ha⁻¹ in thicket and stocks of N ranged from 3.4 t ha⁻¹ in karoo to 12.8 t ha⁻¹ in grassland. Mean soil C in thicket (5.6%, 0-10 cm) was approximately five times greater than expected for a semi-arid region. Removal of vegetation due to cultivation, grazing or burning reduced soil C and N at all sites. Soil C under intact thicket was greater than at sites degraded by goats (71 vs 40 t ha⁻¹, 0-10 cm). Restoration of thicket could potentially sequester ~40 t C ha⁻¹. The sale of this sequestered carbon to the international market may make restoration of thousands of hectares of degraded thicket financially feasible. Soil C under plant cover was greater than in exposed soil in renosterveld (28 vs 15 t ha⁻¹) and in karoo (7 vs 5 t ha⁻¹). Parent material was also related to soil C content. In grassland, soil C was greater in dolerite-derived than sandstone-derived soils (54 vs 27 t ha⁻¹); and in bushveld it was greater in basalt-derived than granite-derived soils (28 vs 14 t ha⁻¹ in unburnt plots). Annual burning in bushveld reduced soil C, particularly at the surface. Soil C in the 0-1 cm layer of unburnt plots was 2 to 3 times greater than in burnt plots.

Keywords: land use, sequestration, soil carbon, soil nitrogen, South African biomes

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Introduction

The increase in atmospheric CO₂ and associated concerns of global warming have turned the world's attention towards the global C cycle (Lal, 2001). Sequestering C into biomass or soil could buy time to address the problem but the production of biomass in a mostly semi-arid country such as South Africa is limited by available water. Consequently stocks of soil C per unit area in South Africa are typically lower than in temperate, mesic regions (Du Preez & Snyman, 1993; Du Toit & Du Preez, 1995; Schulze, 2000). Soil with a cover of vegetation tends to have more C than exposed soil because plants recycle C and they may suppress mineralisation by releasing antibacterial exudates (Theron, 1951; 1963), and reduce mineralisation catalysed by wetting and drying of the soil (Birch, 1958) by shading and cooling and by intercepting rainfall. Removal of vegetation by ploughing, grazing, browsing or burning reduces soil organic matter. Declines in C due to cultivation have been recorded in grasslands of the highveld (Du Toit *et al.*, 1994; Nel *et al.*, 1996) but the extent to which land use affects soil C in other South African regions is largely unknown. In this paper, soil C is examined in five contrasting biomes and stocks of soil C under vegetation, in open, bare soils and in soils exposed to a variety of land use practices (including cultivation, livestock husbandry, pastures, forestry and veld burning) are compared.

Materials and methods

Study areas

The study sites (Figure 1) were named after the characteristic natural vegetation types for each area as defined by Low & Rebelo (1996) and included: West Coast Renosterveld (renosterveld), Central Nama Karoo (karoo); Xeric Succulent Thicket (thicket); Moist Upland Grassland (grassland); and Mixed Lowveld Bushveld (bushveld). A summary of geographic features including climate, vegetation, geology, soils,

and land uses is presented in Tables 1 and 2.

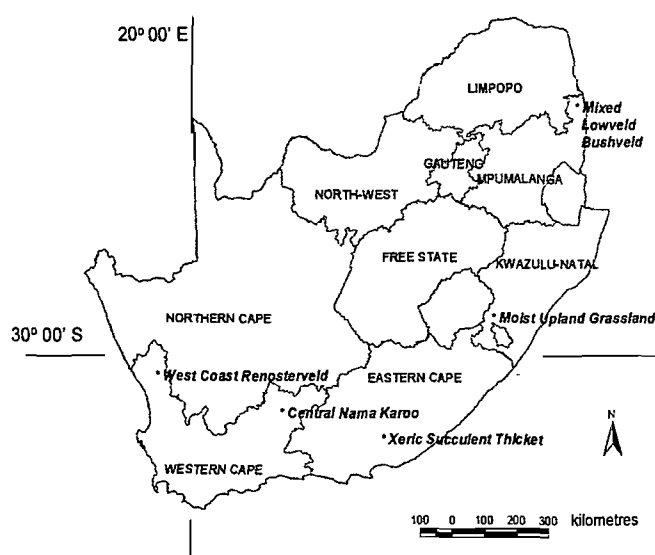


Figure 1 The location of the five study sites.

Sampling

Composite samples, comprising 15-20 subsamples, were taken at least 10 m apart with an auger to a depth of 10 cm as described below:

(a) **Renosterveld** - Dwyka sediment-derived soils were sampled from (i) open renosterveld i.e., on bare ground outside of bush clumps; (ii) below renosterbos bushes (*Elytropappus rhinocerotis* [L.f.] Less.); and (iii) old wheatlands planted to medic (*Medicago* spp.); and (iv) cultivated wheat fields. Dolerite-derived soils were sampled from (i) virgin veld and (ii) cultivated wheat fields. All sites were at least 500 m apart.

Table 1 Location, climate and vegetation of the study sites.

Site	Latitude	Longitude	Mean temp ^a	T. range ^b	MAP ^c	Elev ^d	Indigenous vegetation
Renosterveld	31°20' S	19°10' E	15.9	9.2-22.2	350	800	Bushes (e.g. <i>Elytropappus rhinocerotis</i>), geophyte spp. (Iridaceae) and grasses
Karoo	32°15' S	22°50' E	17.4	11.3-23.4	225	1100	Small bushes (e.g. <i>Pentzia incana</i>), grasses (e.g. <i>Stipagrostis</i> spp.)
Thicket	33°30' S	25°20' E	17.6	12.3-22.4	250-400	300-500	Dense thicket (~3 m tall), predominantly <i>Portulacaria afra</i>
Grassland	29°45' S	29°30' E	15.1	9.2-19.2	1050	1700	Dominated by grasses, but rich in non-graminoid species, especially Asteraceae
Bushveld	23°-25°S	30°-31° E	21.1-23.3	16-28	400-700	300-700	Savanna trees (e.g. <i>Acacia</i> , <i>Terminalia</i> , <i>Combretum</i> spp.) and grasses

^a Mean temp=mean annual temperature (°C), ^bT. range=range in mean monthly temperature (°C), ^cMAP=mean annual precipitation (mm), ^dElev.=elevation in metres above sea level. Schulze (1997).

Table 2 Geology, soil forms and land use at the study sites.

Site	Geology	Soil forms (SA classification) ^a	World Reference Base classification ^b	Land use
Renosterveld	Dwyka sediments (shale and tillite), Karoo dolerite	Sandy loams (Estcourt, Valsrivier, Glenrosa, Sterkspruit, Klappmuts, Swartland), clays (Arcadia, Shortlands and Augrabies)	Eutric Planosols, Hyperochric Rhodic Luvisols, Skeletic Lep-tosols & Albic Luvisols; Chromic, Grumic & Calcic Vertisols, Vertic Leptosols, Rhodi-Eutric Nitisols and Calcic Cambisols	Livestock (sheep), wheat, <i>Medicago</i> pas-tures, nature reserve, old lands
Karoo	Beaufort Group sedi-ments, Karoo dolerite	Sandy loams (e.g. Addo, Oakleaf, Augrabies, Prieska, Garies, Kimberley & Valsrivier)	Aridic Calcisols, Aridic Cambisols, Calcic Luvisols, Petric Calci-sols & Chromic Luvisols.	Stock/game farming: cattle, goats, sheep, springbuck (<i>Antidorcas marsupialis</i>)
Thicket	Bokkeveld & Uiten-hage sediments (shales, sandstones)	Loamy sands (e.g. Augrabies, Klappmuts, Val-srivier, Oakleaf & Glenrosa)	Calcic Cambisols, Calcic Luvisols, Rhodic Luvisols & Calcic Regosols	Goat farming transforms dense thicket into an open savanna, dominated by ephemeral grasses & forbs.
Grassland	Karoo dolerite, Beaufort sediments (mudstones, sandstones)	Sandy clay loams (e.g. Sepane, Oakleaf, Tukulu, Glenrosa, Hutton & Clovelly)	Gleyic Luvisols, Rhodic Cambisols, Chromic Luvisols, Gleyic Cambisols, Haplic Regosols, Rhodic Acrisols & Chromic Acrisols	Livestock, dairy, nature reserves, sum-mer pastures (kikuyu, <i>Eragrostis</i>), maize, winter pastures (ryegrass).
Bushveld	Nelspruit granite, basalt	Loamy sands (e.g. Hutton, Bainsvlei, Clovelly, Cartref & Avalon) and clays (e.g. Shortlands, Swartland, Mayo & Milkwood)	Rhodic Lixisols, Paraplinthic Cambisols, Dystric Regosols & Paraplinthic Lixisols; Rhodic Nitisols, Haplic Luvisols & Leptic Phaeozems	Long term burning trial. Unburnt and annually burnt plots sampled.

^aSoil Classification Working Group (1991), ^bFAO (1998)

(b) **Karoo** - dolerite- and shale-derived soils were sampled from beneath pentzia bushes (*Pentzia incana* [Thunb.] Kuntze) and *Stipagrostis* grass species as well as from adjacent bare ground. All sites were at least 500 m apart.

(c) **Thicket** - soils were sampled from one hectare plots in (i) intact thicket and (ii) goat-transformed savanna at eight fenceline contrasts. All sites were at least 1 km apart.

(d) **Grassland** - dolerite-derived soils were sampled from (i) grazed indigenous grassland; (ii) cultivated maize lands; (iii) kikuyu pastures (*Pennisetum clandestinum*, Hochst ex Chiov); (iv) ryegrass pastures (*Lolium* spp.); (v) pine plantations (*Pinus* spp.); and (vi) *Eragrostis* spp. pastures. Sandstone-derived soils were sampled from grazed indigenous grassland. All sites were at least 400 m apart.

(e) **Bushveld** - soils were sampled from the long-term burning experiment in the Kruger National Park (KNP), which started in 1955 and comprises treatments of differing frequency and season of burns in seven-hectare plots (Van Wyk, 1971). Soils in the southern burn plots (Numbi and Napi) are derived from Nelspruit granite and those in the central burn plots (Satara and Mopane) from basalt. Soils were sampled from unburnt plots and plots burnt annually in August at fifteen sites. At each site, the unburnt and annually burnt treatments were located within a string of 13 different treatments and were not further than 3 km apart. All sites were at least 4 km apart. Subsamples for each composite sample were taken at ~20 m intervals across the middle of each plot. Soil type varied across plots, but for the purposes of this study it was assumed that composite samples of topsoils would reflect sufficient differences between treatments to ascertain the effect of fire on soil C. Vegetation structure in unburnt plots ranged from dense to open woodlands while annually burnt plots were more open and grassy.

Soil samples were also taken either by auger or from excavated pits at 10 cm intervals to a depth of 50 cm. In bushveld, profiles were sampled at 1 cm intervals to 10 cm. Stocks of C and N in tonnes per hectare to different depths were calculated from bulk density estimates. Bulk density was calculated from the texture and C content of the 0-10 cm layer, using algorithms developed by Saxton *et al.* (1986). These algorithms generate an approximate bulk density that can be used to determine stocks of C and N and thereby place total soil C and N percentage values in a C sequestration context.

Soil analyses

Soils were air-dried and sieved to <2 mm. Total C and N were determined by complete combustion using a Eurovector Euro EA Elemental Analyzer. An analysis of the contribution of inorganic and organic C to total C was not undertaken as free carbonates were absent from the majority of soil samples collected (as determined by adding 10% hydrochloric acid and checking for effervescence). Where effervescence was observed (usually in calcareous B horizons) soil C concentration was often double the mean concentration of non-effervescent samples from other soils taken at the same depth (as is evident in Figure 2 for two samples taken at 40-50 cm). Clay content was determined by the hydrometer method, sand content by sieving and silt by difference. The clay fraction was dispersed using a Calgon dispersing solution of sodium hexametaphosphate and sodium carbonate. Organic matter

was removed by oxidation with hydrogen peroxide (Soil Classification Working Group, 1991).

Statistical analyses

Statistical analyses were performed using the software package Unistat 5.0 (Unistat Limited, 2000). A graphical investigation showed that the condition for an ANOVA of a normal distribution was not always met in the data from renosterveld on Dwyka sediments and grassland and consequently a non-parametric approach was taken. A Kruskal-Wallis test was applied to data from renosterveld on Dwyka sediments (4 groups: vegetation, open, *Medicago*, wheat) and grassland (7 groups: grassland-dolerite, grassland-sandstone, maize, ryegrass, *Eragrostis*, kikuyu, pine). Significant differences between groups ($P < 0.05$) were detected using a t-distribution multiple comparison (Conover, 1980). Data from renosterveld on dolerite were analysed using a student t-test. Data from paired contrasts of intact thicket and savanna (thicket site) and burnt versus unburnt plots in bushveld (two separate analyses: granite and basalt) were analysed using a paired t-test. Differences were deemed significant where $P < 0.05$.

Results

Stocks of soil C and N to a depth of 10 cm and 50 cm are presented in tonnes per hectare in Tables 3 and 4, respectively. The stocks of soil C varied between regions in the following order: thicket > grassland > renosterveld > bushveld > karoo. In the 0-50 cm layer of soil, stocks of C in virgin veld ranged from 21 t ha⁻¹ in karoo to 168 t ha⁻¹ in thicket and stocks of N ranged from 3.4 t ha⁻¹ in karoo to 12.8 t ha⁻¹ in grassland. Land under cultivation with wheat or maize, farmed intensively with goats or burnt frequently, tended to have lower soil C and N than virgin veld. Stocks of C and N were also greater in soils under a cover of woody vegetation than in open, exposed soils. The distribution of C and N, as well as the C:N ratio with depth in selected soil profiles, are presented in Figs. 2-5 for karoo, renosterveld, thicket, grassland and bushveld, respectively. Soil C and N, as well as the C:N ratio declined in most profiles. Soil samples taken at 1 cm intervals in bushveld showed that the concentrations of C and N at 0-1 cm are several times greater than at depths below 4 cm.

Table 4 Estimated stocks of total soil C and N to a depth of 50 cm in renosterveld, karoo, thicket and grassland. Three bulk density scenarios are depicted. A bulk density range was calculated for each profile from means and standard errors of clay, silt and sand content in each vegetation type and soil carbon content for each profile, using algorithms developed by Saxton *et al.* (1986).

Site	Land use/sampling site	Geology	Carbon 0-50 cm (t ha ⁻¹)											Nitrogen 0-50 cm (t ha ⁻¹)						
			BD 1 (minimum)	BD 2 (mean)	BD 3 (maximum)	Carbon (BD1)		Carbon (BD2)		Carbon (BD3)		n	P<0.05	Nitrogen (BD1)		Nitrogen (BD2)		Nitrogen (BD3)		P<0.05
						Carbon	se	Carbon	se	Carbon	se			Nitrogen	se	Nitrogen	se	Nitrogen	se	
Renosterveld	Elytropappus	Dwyka tillite	1.44	1.51	1.59	62	6	65	6	68	6	3	a	6.4	0.6	6.6	0.7	7.0	0.7	ab
	Open soil	Dwyka tillite	1.47	1.53	1.62	38	3	40	3	42	3	3	ab	4.7	0.4	4.9	0.4	5.2	0.4	b
	Medicago	Dwyka tillite	1.46	1.53	1.61	44	6	46	6	48	6	4	ab	6.5	0.6	6.8	0.6	7.2	0.7	a
	Active wheat	Dwyka tillite	1.47	1.54	1.63	36	0.3	37	0.4	39	0.4	3	b	5.2	0.3	5.4	0.3	5.7	0.3	b
	Virgin veld	Dolerite	1.18	1.23	1.30	33	5.3	34	5.5	36	5.8	4		3.9	0.5	4.0	0.5	4.3	0.5	
	Active wheat	Dolerite	1.19	1.24	1.31	33	4.9	34	5.1	36	5.4	3		4.3	0.4	4.5	0.4	4.7	0.5	
Karoo	Avondale 3	Shale	1.62	1.70	1.85	26		27		30		1		3.5		3.7		4.0		
	Kamferskraal 3	Shale	1.62	1.70	1.86	20		21		23		1		4.2		4.4		4.8		
	Elandsfontein 4	Dolerite	1.61	1.69	1.84	29		31		34		1		3.7		3.9		4.3		
	Bleakhouse 2	Dolerite	1.59	1.67	1.82	48		50		54		1		3.3		3.4		3.7		
Thicket	Intact	Shale/sandstone	1.21	1.27	1.35	161	25	168	26	178	27	8		12.1	1.3	12.7	1.3	13.5	1.4	a
	Transformed	Shale/sandstone	1.26	1.32	1.40	125	15	131	16	140	17	8		10.7	0.7	11.2	0.8	11.9	0.8	b
Grassland	Grassland	Shale/dolerite	1.09	1.15	1.24	155	21	164	22	177	23	8	ab	12.3	1.3	12.8	1.3	13.6	1.4	ab
	Grassland	Sandstone	1.16	1.23	1.33	91	27	97	29	105	31	3	a	7.0	1.4	7.4	1.5	8.0	1.6	a
	Maize	Shale/dolerite	1.12	1.18	1.27	144	7	153	8	164	8	3	ab	10.8	0.5	11.5	0.6	12.3	0.6	ab
	Kikuyu	Shale/dolerite	1.08	1.14	1.22	189	22	199	23	214	24	3	b	14.1	2.3	14.8	2.4	15.9	2.6	b
	Ryegrass	Shale/dolerite	1.10	1.17	1.26	160	23	169	24	182	26	3	ab	11.8	1.2	12.5	1.3	13.4	1.4	ab
	Pine plantations	Shale/dolerite	1.10	1.17	1.25	162	29	172	31	185	33	3	ab	11.3	1.9	12.0	2.0	12.9	2.2	ab
	Eragrostis	Shale/dolerite	1.09	1.15	1.24	174	39	184	40	198	43	3	b	13.5	2.5	14.2	2.6	15.3	2.7	b

BD = mean bulk density for each land use; se = standard error of the mean; n = number of samples; where letters are different, means were significantly different at P = 0.05.

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Site	Land use/sampling site	Geology	Carbon 0-50 cm (t ha ⁻¹)											Nitrogen 0-50 cm (t ha ⁻¹)						
			BD 1 (minimum)	BD 2 (mean)	BD 3 (maximum)	Carbon (BD1)			Carbon (BD2)			n	P<0.05	Nitrogen (BD1)			Nitrogen (BD2)			P<0.05
						Carbon	se	Carbon	se	Carbon	se			Nitrogen	se	Nitrogen	se	Nitrogen	se	
Renosterveld	Elytropappus	Dwyka tillite	1.44	1.51	1.59	62	6	65	6	68	6	3	a	6.4	0.6	6.6	0.7	7.0	0.7	ab
	Open soil	Dwyka tillite	1.47	1.53	1.62	38	3	40	3	42	3	3	ab	4.7	0.4	4.9	0.4	5.2	0.4	b
	Medicago	Dwyka tillite	1.46	1.53	1.61	44	6	46	6	48	6	4	ab	6.5	0.6	6.8	0.6	7.2	0.7	a
	Active wheat	Dwyka tillite	1.47	1.54	1.63	36	0.3	37	0.4	39	0.4	3	b	5.2	0.3	5.4	0.3	5.7	0.3	b
	Virgin veld	Dolerite	1.18	1.23	1.30	33	5.3	34	5.5	36	5.8	4		3.9	0.5	4.0	0.5	4.3	0.5	
	Active wheat	Dolerite	1.19	1.24	1.31	33	4.9	34	5.1	36	5.4	3		4.3	0.4	4.5	0.4	4.7	0.5	
Karoo	Avondale 3	Shale	1.62	1.70	1.85	26		27		30		1		3.5		3.7		4.0		
	Kamferskraal 3	Shale	1.62	1.70	1.86	20		21		23		1		4.2		4.4		4.8		
	Elandsfontein 4	Dolerite	1.61	1.69	1.84	29		31		34		1		3.7		3.9		4.3		
	Bleakhouse 2	Dolerite	1.59	1.67	1.82	48		50		54		1		3.3		3.4		3.7		
Thicket	Intact	Shale/sandstone	1.21	1.27	1.35	161	25	168	26	178	27	8		12.1	1.3	12.7	1.3	13.5	1.4	a
	Transformed	Shale/sandstone	1.26	1.32	1.40	125	15	131	16	140	17	8		10.7	0.7	11.2	0.8	11.9	0.8	b
Grassland	Grassland	Shale/dolerite	1.09	1.15	1.24	155	21	164	22	177	23	8	ab	12.3	1.3	12.8	1.3	13.6	1.4	ab
	Grassland	Sandstone	1.16	1.23	1.33	91	27	97	29	105	31	3	a	7.0	1.4	7.4	1.5	8.0	1.6	a
	Maize	Shale/dolerite	1.12	1.18	1.27	144	7	153	8	164	8	3	ab	10.8	0.5	11.5	0.6	12.3	0.6	ab
	Kikuyu	Shale/dolerite	1.08	1.14	1.22	189	22	199	23	214	24	3	b	14.1	2.3	14.8	2.4	15.9	2.6	b
	Ryegrass	Shale/dolerite	1.10	1.17	1.26	160	23	169	24	182	26	3	ab	11.8	1.2	12.5	1.3	13.4	1.4	ab
	Pine plantations	Shale/dolerite	1.10	1.17	1.25	162	29	172	31	185	33	3	ab	11.3	1.9	12.0	2.0	12.9	2.2	ab
	Eragrostis	Shale/dolerite	1.09	1.15	1.24	174	39	184	40	198	43	3	b	13.5	2.5	14.2	2.6	15.3	2.7	b

BD = mean bulk density for each land use; se = standard error of the mean; n = number of samples; where letters are different, means were significantly different at P = 0.05.

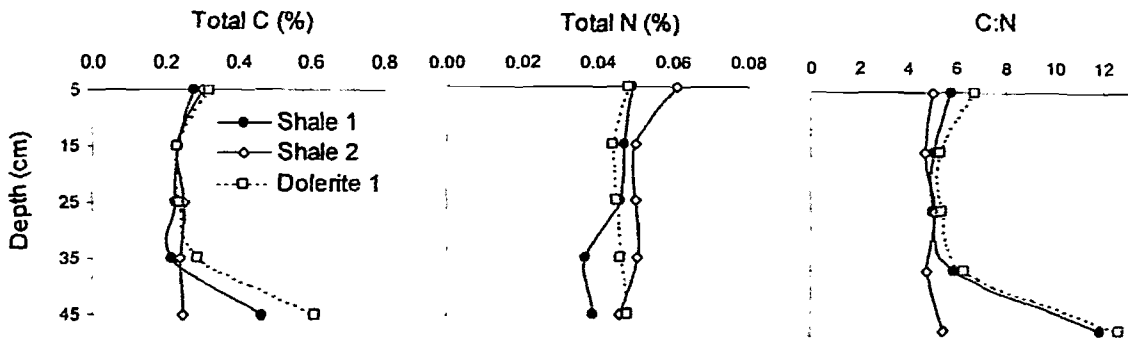


Figure 2 The change in total C, N and C:N ratios with depth in two shale-derived soils and one dolerite-derived soil in the karoo.

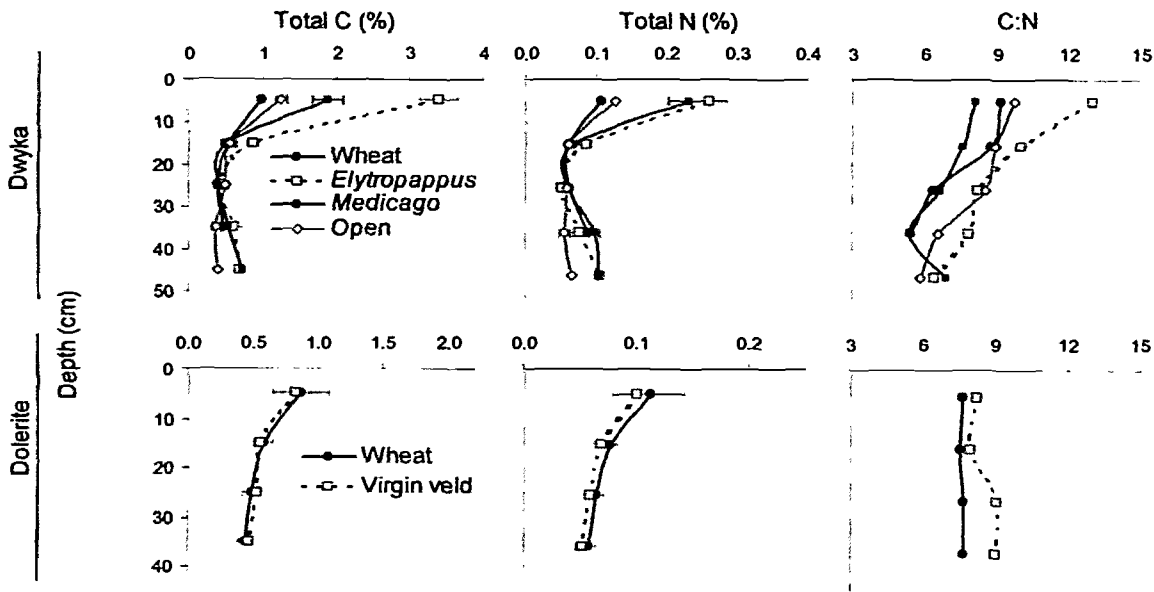


Figure 3 The change in total C, N and C:N ratios with depth in Dwyka sediment-derived (0-50 cm) and dolerite-derived (0-40 cm) soils in renosterveld. Where error bars are depicted, these are the standard errors of the mean.

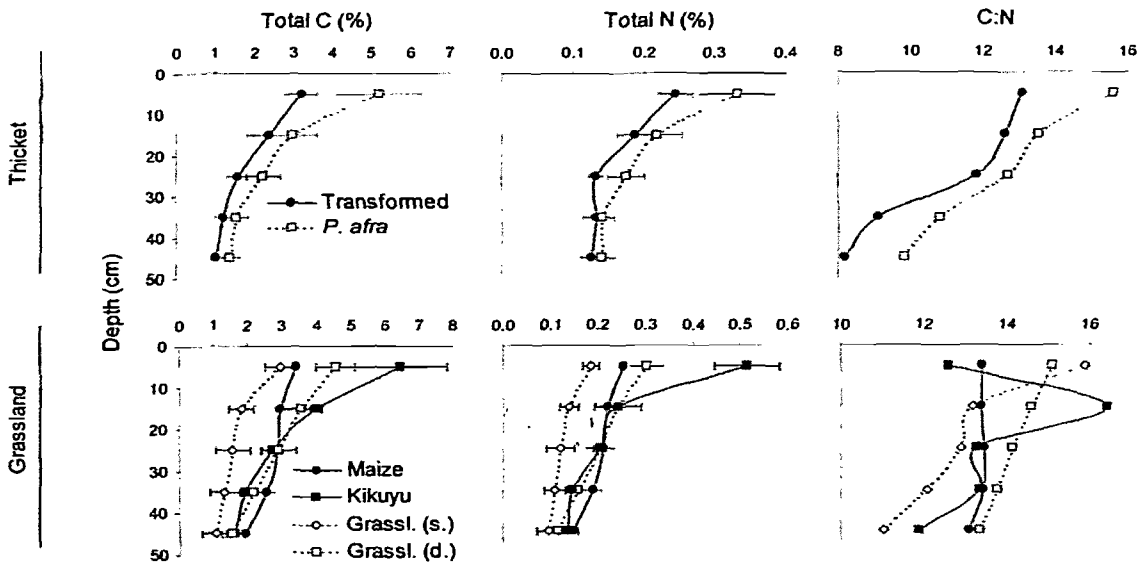


Figure 4 The change in total C, N and C:N ratios with depth in thicket and grassland in relation to land use and geology. s = sandstone-derived; d = dolerite-derived. Where error bars are depicted, these are the standard errors of the mean.

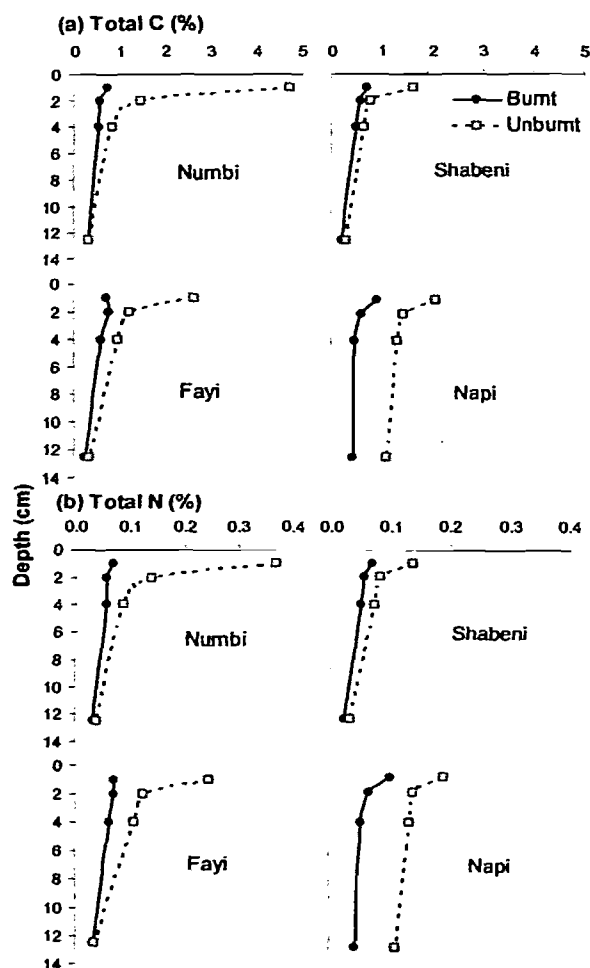


Figure 5 (a) Total carbon and (b) total nitrogen as a function of soil depth and burning treatment at Numbi, Shabeni, Faai and Napi burnt and unburnt plots in the southern Kruger National Park. Soils on these plots are derived from Nelspruit granite.

Discussion

In the 0-50 cm layer of soil, stocks of C in virgin veld ranged from 21 t ha⁻¹ in karoo to 168 t ha⁻¹ in thicket and stocks of N ranged from 3.4 t ha⁻¹ in karoo to 12.3 t ha⁻¹ in grassland. The soil C content of thicket is exceptionally high for a semi-arid region and is comparable with the organic-rich soils in tall-grass prairie, Wisconsin, USA (80-120 t C ha⁻¹) (Brye & Kucharik, 2003) and European forests (40-193 t C ha⁻¹) (Schulze, 2000). The mean soil C and N content of intact thicket in the 0-10 cm layer was 5.6% and 0.33%, respectively, which are values approximately five times greater than most other semi-arid regions (Whitaker *et al.*, 1968; Du Preez & Snyman, 1993; Allsopp, 1999; Bird *et al.*, 2000; Lobe *et al.*, 2001). An explanation may be that the dense and succulent bush matrix not only deposits about 4 t ha⁻¹ yr⁻¹ of biomass (dry matter) (Lechmere-Oertel, 2003) but also excludes fire, shades the soil surface and intercepts rainfall. Where general trends in soil C are referred to in the ensuing discussions, it should be inferred that these trends apply to soil organic matter as a whole and therefore also to soil N. A general covariance of C and N content was evident across sites and land uses, notwithstanding the fact that certain shifts (with soil depth, for example) were evident in the C:N ratio.

Such trends are discussed where appropriate.

Across all sites, land use practices that reduce the cover of vegetation in space or time, such as cultivation, livestock production and veld burning were associated with lower stocks of soil C and N than those of sites in untransformed indigenous veld, particularly in the upper 10 cm of soil. Declines in soil C due to cultivation were proportionately greater in renosterveld than in mesic grassland. In renosterveld, soil C under renosterbos was greater than in wheat fields (means of 65 vs 37 t ha⁻¹ in the top 50 cm of soil, whereas in the grassland biome, soil C under virgin grassland was not significantly different from that under maize cultivation (164 vs 153 t ha⁻¹). A consistently lower soil C content in maize fields did, however, suggest that soil C was being lost (the small sample size of n=3 was probably inadequate to detect a significant difference) probably due to a greater rate of mineralisation and reduced returns of organic matter to the soil (Edwards *et al.*, 1992; Du Toit *et al.*, 1994; Francis, Tabley & White, 2001).

The climate at the renosterveld site is warmer and drier than the grassland site and consequently the Birch effect (Birch, 1958) and raised soil temperature (Savage and Vermeulen, 1983) are likely to have a greater effect on microbial metabolism and hence the rate of mineralisation in renosterveld than in grassland. Du Toit *et al.* (1994) and Du Toit & Du Preez (1995) also found that decline in soil C under cultivation on the highveld was greatest in areas that were relatively warm and dry as opposed to cool and moist.

Livestock, if poorly managed, can degrade the condition of veld by reducing the cover of vegetation that in turn reduces soil C (Du Preez & Snyman, 1993). Soil C under spekboom (*Portulacaria afra* Jacq.) at intact sites was greater than in goat-transformed savanna sites (means of 71 and 40 t ha⁻¹, respectively, in the top 10 cm of soil). The annual rainfall at the renosterveld site is comparable to the thicket site (250-400 mm) and consequently stocks of soil C were expected to fall within a similar range. Stocks of soil C and N were greatest in renosterveld under renosterbos (65 t C ha⁻¹ and 7 t N ha⁻¹ in the top 50 cm of soil), yet were only approximately half of those found in thicket. The mean mass of C lost from the top 10 cm of soil in thicket after transformation to open savanna is more than the total mass of C in the soil profile in open areas of renosterveld.

A comparison of stocks of soil C under vegetation and in adjacent open soil can give an indication of the potential effect of livestock on soil C, although this effect was not investigated directly. In renosterveld, soil C under renosterbos was greater than in adjacent bare soil (means of 28 versus 15 t ha⁻¹, respectively to a depth of 10 cm. In the karoo, soil C under *Pentzia* bushes was greater than in adjacent open soil (7 vs 5 t ha⁻¹). Consequently, for every 1 ha of bushes removed by livestock, on average 13 tonnes of C maybe lost from the top 10 cm of soil in renosterveld and 2 tonnes in the karoo.

In addition to climate, land use and vegetation type, soil parent materials can affect stocks of soil C. In grassland, stocks of C in soils with reddish colours (indicating an influence of dolerite) were greater than in soils with greyish colours (derived predominantly from sandstone) (respective means of 164 and 97 t C ha⁻¹ in the top 50 cm of soil). The reason for this effect of parent material is not apparent in the

data collected. The texture, (NH₄)OAc-extractable cation concentrations, pH and EC of these soils were similar (Mills, 2003). The data, however, corroborate the findings of Sumner (1957), that in KwaZulu-Natal the soil C content of dolerite-derived soils was greater than that in Beaufort sediment-derived soils within the same biome perhaps because dolerite-derived soils tend to have a greater sesquioxide content than sedimentary-derived soils (Sumner, 1957; Olson, Thomson & Wilson, 2000). Percival, Parfitt & Scott (2000) also concluded that chemical stabilisation of organic matter by sesquioxides is the key process controlling accumulation of soil C in New Zealand.

An effect of parent material on soil C was also evident at the bushveld site in the KNP. Stocks of C in burnt plots on clayey, basalt-derived soils were greater than in sandy, granite-derived soils (means of 28 and 14 t ha⁻¹, respectively to a depth of 10 cm), despite a greater mean annual rainfall in the region with granite-derived soils. Bird *et al.* (2000) similarly found that the concentration of C in clay soils in a tropical savanna ecosystem at Matopos, Zimbabwe was twice that of C in sandy soils (10 vs 5 t ha⁻¹ to a depth of 5 cm). Stocks of C in the KNP were greater in unburnt plots than burnt plots on granite-derived soils (14 vs 11 t ha⁻¹ to a depth of 10 cm) and were consistently (but not significantly) greater in unburnt plots than burnt plots on basalt-derived soils (28 vs 25 t ha⁻¹). In comparison, Bird *et al.* (2000) found in the Matopos, Zimbabwe plots that soil C in the 0-5 cm interval in unburnt plots was 40-50% greater than burnt plots. This apparently larger effect may reflect the narrower sampling interval (0-5 cm as opposed to 0-10 cm in the KNP). Indeed, differences in soil C between burnt and unburnt plots in bushveld were greatest at 0-1 cm where the unburnt plots had 2 to 3 times more C than burnt plots (Fig. 5). This highlights how sampling to depths greater than a few centimetres may obscure differences related to land use. The reduction in soil C as a result of burning can be attributed to reduced returns of organic matter and to an increase in soil microbial activity due to the Birch effect and greater soil temperatures (Birch, 1958; Knapp, Conrad & Blair, 1998). Immediately after fire, the alkalinity of ash may raise pH in the first few centimetres of surface soil where the organic matter is most concentrated, stimulating microbial activity and organic matter oxidation (Greenwood, 1968). Interestingly, pH in the top centimetre of soil in the southern KNP was consistently lower in burnt plots than unburnt plots (Mills, 2003) and was ascribed to the generation of acidity during organic matter oxidation (Russell, 1988). Another possible factor affecting soil C loss from burnt plots is a reduction in plant roots and root exudates. Theron (1951; 1963) showed that N mineralisation was greatly reduced under grass swards and suggested that root exudates may be inhibiting mineralisation. This hypothesis warrants further investigation, particularly in relation to understanding how to manage soil C sequestration.

The pattern of decreasing C:N ratio with depth is common to most profiles (Figures 2-4) and is particularly pronounced in thicket. This suggests that the unusually high concentration of C in the surface soil is predominantly fine plant material that has only partly decomposed. Virgin veld in renosterveld, thicket, grassland and bushveld biomes had a consistently greater C:N ratio in surface soils in comparison to soils in

adjacent cultivated, goat-transformed or frequently burnt landscapes. This suggests that these land uses return less fresh organic matter with a high C:N ratio and/or increase the rate of mineralisation, thereby reducing the C:N ratio of organic matter in surface soils.

Occasionally land use practices can result in an increase in soil C. This effect is evident in kikuyu pastures established in grassland. Stocks of soil C in the top 10 cm under kikuyu pastures were consistently (but not significantly) greater than in virgin grassland (69 vs 54 t ha⁻¹). The lack of a significant difference between C stocks in kikuyu pastures and grassland is probably a function of small sample size (n=3). The beneficial effects of pastures in terms of increasing soil organic matter and maintaining soil structure are well documented (Haynes, Swift & Stephen, 1991; Francis *et al.*, 2001). The trend of greater soil C under kikuyu pastures is probably due to (i) increased shading of the soil surface that reduces the rate of mineralisation; (ii) greater productivity of the grass sward in comparison to virgin veld and hence greater returns of organic matter; (iii) fertilization of pastures with N, P and S (Campbell *et al.*, 1991; Paustian, Parton & Persson, 1992) which allows for a potential accumulation of soil C (given that soil C:N, C:P and C:S ratios tend towards their initial equilibrium ratios); and (iv) a possible repression of mineralisation due to release of antibacterial exudates from grass roots (Theron, 1951; 1963). In particular, fertilization with N is likely to increase sequestration of soil C, due to greater plant productivity and stabilisation of the soil C:N ratio. Burke, Lauenroth & Parton (1997) summarised this notion by stating that "N is required for the capture of C".

Where degraded ecosystems in semi-arid regions (that have lost soil C over time) have been rehabilitated in order to sequester C, stocks of soil C tend to increase slowly and are difficult to measure (Robles & Burke, 1998). Of the five biomes in this study, thicket has the greatest potential for rapid and considerable C sequestration. The removal of the dense thicket vegetation through goat farming reduced soil C by about two fifths in the top 10 cm of soil (from 71 to 40 t C ha⁻¹) and by about a quarter in the top 50 cm (from 168 to 131 t ha⁻¹). Restoration of degraded thicket areas by planting spekboom could potentially sequester at least an equivalent amount of C. The international trade in C may make such a restoration activity financially viable (Rosenzweig *et al.*, 2002). In addition, spekboom is a valuable fodder plant, and can thus supplement income through sustainable browsing of livestock. The high litter production of spekboom (~4 t dry matter ha⁻¹) (Lechmere-Oertel, 2003) suggests that return of C to pre-degradation levels (via root, stem and leaf growth) may occur more quickly than in other degraded semi-arid systems.

Conclusions

The potential of soils in South Africa to sequester C from the atmosphere is largely a function of climate, parent material and the cover of vegetation. Where vegetation has been removed due to cultivation, goat farming or frequent burning, stocks of soil C tend to decline. The C:N ratio also declined in the upper part of the soil under these land uses, which suggests that inputs of fresh organic matter were reduced and/or that the rate of mineralisation had increased. The effect of

vegetation removal on soil C content is most evident in semi-arid areas. Degradation of thicket by goats resulted in a mean loss of 31 t C ha⁻¹ to a depth of only 10 cm. Similarly, in bushveld in the KNP, annual burning resulted in a 200-300% reduction in soil C in the 0-1 cm layer in comparison to unburnt plots. These results illustrate how land use effects on stocks of soil C are often most evident in the top few centimetres of the soil profile. By focusing on the 0-1 cm layer, C sequestration accountants and soil quality researchers may reveal short-term effects that are likely to be obscured by sampling at greater depth intervals. Such short-term effects on soil C at the surface may provide important clues for longer term trends at greater depth. The restoration of thicket by planting spekboom could potentially sequester in excess of 40 t C ha⁻¹ in these soils. This is a large amount of soil C (even compared with mesic forest ecosystems) and could amount to considerable monetary benefits if it were to be traded on world markets.

Acknowledgements

The authors extend their grateful thanks to: H. C. Biggs and A. L. F. Potgieter of the South African National Parks for logistical support and the opportunity to work on the experimental burn plots in the Kruger National Park; M. Gordon for analytical work and J.S. Donaldson for facilitating the research through the GEF Conservation Farming Project at the National Botanical institute, South Africa. Financial support from the Global Environment Facility, the Mazda Wildlife Fund, the South African National Research Foundation (Grant number 2047381) and the Eskom Tertiary Education Support Programme is gratefully acknowledged.

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