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Rangeland management effects on soil properties in the savanna biome, South Africa: A case study along grazing gradients in communal and commercial farms

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A B S T R A C T

Although the savanna biome of South Africa is a major resource for rangeland management, little is known about how differences in rangeland management systems affect soil properties in such biomes. Near to Kuruman, commercial farms have practiced rotational grazing for decades. In communal areas of former homeland Bophuthatswana, similar strategies were used prior to 1994. Nowadays, a continuous grazing system is common. We hypothesized that these changes in management affected soil properties. To test this, we sampled soils at communal and commercial land along a gradient with increasing distance to water points. The results revealed that communal systems with continuous grazing showed enlarged spatial gradients. The soils were depleted in most nutrients close to the water relative to those of commercial systems. In contrast, as the distance to the water increased, the nutrient stocks of these communal systems were higher. Changes in soil nutrient stocks were related to a zone of increased bush encroachment (up to 25%). Specific analyses (phosphorus fractions, particulate organic carbon, $\delta^{13}C$) confirmed that the soils of the communal grazing systems benefited from the shift of grass-dominated to bush-dominated system with woody *Acacia* vegetation, while the rangeland degraded in the sense that it lost palatable grass species.

1. Introduction

Rangelands play an important role in the delivery of ecosystem services and goods for livelihoods worldwide, with the provisioning of livestock being one of the most important services in arid and semiarid savannas. In South Africa, these ecosystems comprise the northern and eastern parts of the country, with the arid savanna extending into the southern Kalahari. In such locations, the harsh and unpredictable environmental conditions require a flexible and adaptive management strategy regarding natural resources. Extensive livestock management is commonly practiced, either on privately owned commercial ranching or on communal rangeland management, where the land is used collectively by the members of small villages. The different ownership forms now coincide with differences in rangeland management practice. Commercial farmers have proceeded with rotational grazing systems, which include resting of camps to allow soil to restore after high grazing pressure, therewith promoting vegetation regrowth. In contrast, communal farms frequently lack fences, due to the fact that continuous grazing systems developed after the termination of the country's Apartheid regime in 1994. However, little is known about the effect that such differences have on soil properties in rangeland management.

Today, savannas are subject to various transformations, to the point of rangeland degradation, as they are exposed to climate change, but also to social, land-use or institutional change (Reynolds et al., 2007). The term land degradation as a sole ecological "problem" has been replaced by a social-ecological view

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on land changes, which is seen as a reduction in the capacity of land to perform ecosystem functions and services that support society and development (FAO, 2010). This reduction of ecosystem services may depend on a farmer's perception and options to support them. Rangeland degradation could be a major threat to the livelihood of the people living on the rangeland. In particular, the continuous grazing management system has faced criticism for its observed rangeland degradation (Smet and Ward, 2006). According to Hardin (1968) and his “tragedy of the commons,” communal systems were often regarded as endangered because of their inability to collectively manage common resources on a sustainable basis (Palmer and Bennett, 2013). However, communal sites have to be related to the amount of time they have been under “free” communal management (Wessels et al., 2007), and a historical view on environmental development may be necessary. Most of the communal land in South Africa belongs to former homelands that were established during the 1970s as geographically separated areas in the country, occupying 13% of the country's total land surface and having a maximum concentration of humans and animals. One of these homelands was located on the edge of the Kalahari, close to Kuruman. From 1910 to 1977, the Kuruman area had a long history in the segregation of black and white communities (Jacobs, 2003). At the end of this period, “black spots” – small reserves in areas designated for whites only – were cleared and blacks were moved to “Bophuthatswana,” northeast of Kuruman. This, combined with the Betterment Scheme (a development program for reserves), involved relocating people in compact villages, demarcation and fencing off of areas for cultivation and grazing, and calculation of carrying capacities of grazing land (Jacobs, 2003). Consequently, a system of rotational grazing with development of artificial water sources arose in the former homeland, northeast of Kuruman. After 1994, however, a breakdown of institutions and infrastructure transformed the use of the communal grazing land.

Nowadays, fences are broken or even lacking, and livestock is allowed to continuously and selectively graze without any control around water sources, such as artificial water points. A detailed survey of 453 agricultural resource experts compiled in the *National Review of Land Degradation* found that communal areas are widely believed to be degraded (Hoffman and Todd, 2000). Despite this, the former homeland near Kuruman provides us with the opportunity to investigate the effects that the rangeland management system has had on soil properties in communal areas, where management has changed within the last 20 years from a rotational to a continuous grazing system. On commercial farms, the rotational grazing systems in contrast has prevailed and may therefore serve as a kind of benchmark for the effects that rangeland management has on soil properties.

Changes of rangelands in savannas are often accompanied by bush encroachment, which has become a widespread phenomenon in arid and semi-arid environments. Worldwide, 10–20% of these drylands have already undergone encroachment of woody plants (Eldridge et al., 2011). This includes large areas of rangelands in South Africa, especially in the arid sandy savanna biome of the Northern Cape and North-West Provinces (Jacobs, 2003; Wigley et al., 2010). Several factors have promoted the spread of bushes and trees in arid savannas. External drivers (Sankaran and Anderson, 2009) or so-called bottom-up controls (Bond, 2008) such as climate change (for example, rising temperatures, frequency of droughts, rising atmospheric CO_2 levels) and soil nutrient supply interact with internal drivers or top-down controls such as fire and herbivores on bush abundance (Vetter, 2009). With regard to the latter, land use practices regarding animal species, stocking numbers and management systems may exert a strong influence on bush encroachment (Bond and Midgley, 2012). In this context, the continuous grazing system has faced particular criticism, as the removal of palatable grasses by the animals may go along with the encroachment of woody species and changes in plant composition (Todd, 2006).

Nevertheless, the role that grazing and rangeland management have played in the extent of degradation, such as bush encroachment, remains under debate. In the 1980s and 1990s, a paradigm shift in ecological thinking replaced equilibrium theory. Equilibrium theory assumes that vegetation tends towards a climax state in equilibrium with long-term rainfall, soil, and topographic factors (Behnke and Scoones, 1993). Hence, an optimum carrying capacity can be calculated based on the survival of near-climax-state vegetation. In contrast, non-equilibrium theories have described savannas as ecosystems in which temporal and spatial variability are normal characteristics of vegetation. Main factors for the variability are animals and climate (Thomas and Twyman, 2004). Cause analysis for rangeland degradation must include both natural heterogeneity and livestock management. In communal areas of Kuruman, the livestock system changed from 1994 onwards, from a rotational system to a continuous grazing system.

Early indicators of a change in management practices may first become visible in areas with maximum load. As the distribution of livestock is restricted by water availability, water points are areas of the highest animal activities. Grazing pressure changes considerably over short distances – which was equated early on with the “piosphere” pattern (Lange, 1969) – and environmental changes as consequence of management could be interpreted as first signs of shifts (Dougill et al., 1999). Piospheres are “hotspots” of land degradation with a sacrifice zone close to the water points (and with radial zones around. However, this piosphere model increasingly faced criticism in heterogeneous environments because of the fact that animal movement is affected not just by water, but also by the spatial heterogeneity of vegetation (Farmer, 2010). Heterogeneity within the surroundings of water points could have ecological relevance and could be important to management (Chamaillé-Jammes et al., 2009). In particular, when implementing the piosphere model as a management tool for water supplementation, this approach has clearly failed in heterogeneous environments (Farmer, 2010) because the development of radial, concentric rings around water requires homogeneous environments. Putting all the criticism to one side, an approach that investigates changes in “distance to water” is still very valuable for finding early warning indicators about how different rangeland management systems may affect soil properties. Such an approach makes it possible to allocate rangeland management impacts on areas with maximum load (e.g., Kotzé et al., 2013) and study areas away from the water points provides a sensitive study area to changes in rangeland management, which happened in this location 20 years ago.

The study of grazing effects on vegetation and soil properties along transects with decreasing grazing intensity remains a widely used approach today (e.g. Tefera et al., 2007; Moreno Garcia et al., 2014). Moreover, combining this “distance to water point approach” with a “rangeland condition-driven approach” (Snyman and Du Preez, 2005; Van der Westhuizen et al., 2005) makes it possible to compare several ecological properties of different management systems under the same visual rangeland conditions. The term rangeland condition is used here to describe vegetation in relation to its long-term potential for livestock production (Van der Westhuizen et al., 2005). Therefore, the assessment is related to grass and palatable species and excludes woody species. Differences in rangeland quality are linked to the dominance of several main palatable grass species (e.g., *Stipagrostis uniplums, Centropodia glauca*), which may be lacking or replaced by annual species (poor rangeland conditions), have poor-to-intermediate abundance (moderate), or be frequent as observed under sufficient rainfall and low grazing pressure conditions (good). The results of various studies have shown changes in soil properties; examples include increases in carbon (C), nitrogen (N), and phosphorus (P) contents in the vicinity of water points due to the deposition of animal excreta and/or feed supplements (Fernandez-Gimenez and Allen-Diaz, 2001; Smet and Ward, 2006). In finer textured sites of the grassland biome, such changes in soil properties by grazing were related to a deterioration of soil structure by trampling (Kotzé et al., 2013). However, changes could be different in the different management systems of the savanna biome close to Kuruman, where sandy soils and bush encroachment may evoke different processes in the soils under rotational and continuous grazing.

Bushes promote nutrient inputs via wildlife by providing shelter to birds and animals and by protecting soil from organic matter degradation and erosion. Monitoring organic matter and major nutrients provides an initial clue for detecting any soil changes. Among the latter, P may be of particular interest because it is usually a limiting nutrient in tropical soils due to fixation processes (Zhao et al., 2009) and added as a feed supplement in commercial farms. Hence, tracing P in different chemical forms using, for example, Hedley's fractionation scheme (Tiessen and Moir, 1993) helps to elucidate the processes. However, these analyses hardly explain the origin of organic matter in soils and the portion formed from bush in Northern Cape and North-West Provinces of South Africa, mainly *Acacia mellifera*. The grasslands are dominated by C4 grasses undergoing a succession to woody C3 trees and shrubs. As both vegetation types differ in their degree of ^{13}C isotope discrimination during photosynthesis, tracing the natural abundance of $\delta^{13}C$ provides a clue with which to evaluate the impact of past vegetation changes on soil properties (e.g., Boutton et al., 1998). Combining techniques for the physical fractionation of soil organic matter with isotopic analyses ($\delta^{13}C$) could additionally help to determine which sources of soil organic carbon (SOC) are stored as particulate organic matter (POM) in litter residues, and which portions are already bound to minerals by, for example, metabolization and humification processes and the sorption of dissolved organic compounds (Kögel-Knaber and Amelung, 2014). Therefore, stable C isotopic composition ($\delta^{13}C$) of SOC within soil fractions is a tool with which to make direct assessments of vegetation shifts of C4 grasses ($\delta^{13}C$ −13‰) to C3 woody plants ($\delta^{13}C$ −27‰) on the fate of SOC (Liao et al., 2006b), promising insights into patterns and processes of recent and past woodland development (Boutton et al., 1998; Bai et al., 2012). We are not aware of any studies that have combined these analytical tools with the rangeland condition-driven "distance to water" approach under different rangeland management systems in South Africa.

The present study was designed to evaluate the impact of rotational and continuous grazing on soil properties in the savanna biome. We focused specifically on the hypothesis that rangeland degradation by bush encroachment biome alters soil properties, although not necessarily negatively. In fact, nutrient reallocation and soil protection under the shrubs could improve soil fertility, thereby offering chances for future soil management at unadjusted rangeland use. To test this hypothesis, we evaluated the status of soil chemical and physical characteristics in relation to land-use systems along a gradient from water points in an arid sandy savanna ecosystem of South Africa. The analyses included physical (texture, bulk density) and chemical (organic matter, nutrients, pH) soil parameters, with a special focus on isotope composition in particulate organic matter and P fractions.

2. Materials and methods

2.1. Study area

The study sites are located near Kuruman, at the border of the Northern Cape and North-West Province of South Africa (RSA), on the fringe of the Kalahari (Latitude 27–28°S, Longitude 22–24°E; at an altitude of 1047–1161 m above sea level) (Fig. 1). The mean annual rainfall of Kuruman varies between 266 mm and 478 mm, and the mean temperature ranges from 17.5 °C to 17.7 °C. The soils are deep Arenosols with aeolian origin, underlain by calcrete (WRB, 2007).

The vegetation in the area has been classified as the savanna biome, dominated by the Kalahari thornveld and shrub bushveld vegetation. The vegetation has been described as the Kalahari Mixed Thornveld A16 (Mucina and Rutherford, 2006), and is characterized by a fairly well developed tree stratum, with *Acacia erioloba*, *A. mellifera, Acacia haematoxylon* (≤2 m height) and some *Boscia albitrunca* as the dominant trees. The shrub layer was dominated by individuals of *A. mellifera, Acacia hebeclada, Lycium hirsutum, Grewia flava* and *A. haematoxylon*. The grass cover contained species such as *Stripagrotis uniplumis, Eragrostis lehmanniana and Schmidtia kalihariensis.*

2.2. Rangeland management

Communal and commercial livestock ranching are the most common rangeland management systems in the Kuruman area (Smet and Ward, 2006). The commercial farms, which are well developed and mainly market-orientated, are situated west of the former Bophuthatswana in the Northern Cape Province. Commercial farms (which represent approximately 70% of all land used in the RSA) are typically managed using a rotational grazing system at moderate stocking densities (14 ha LSU^{-1}). The communal farms belong to the former homeland of Bophuthatswana, North-West Province (Fig. 1), where most of them were developed as an integral part of the Betterment Villages. Some of this land had been previously owned by commercial farmers (Jacobs, 2003). Nowadays, the communal production systems are based on pastoralism and grazing areas are shared by members of a community. The rangeland is a common pool resource with a continuous grazing system and no restrictions on stocking rates. Boundaries are often unclear, with open access rights to grazing areas.

2.3. Fieldwork

Fieldwork was conducted during March and April of 2011. Communal (continuous grazing) (CO) and commercial (rotational grazing) (CF) rangeland management systems were selected for this study. We sampled three replicates per tenure system, hence three communal and three commercial farms. For each farm, a representative grazing gradient was selected, starting close to an artificial water point at which first vegetation appeared. In commercial farms, the gradient belonged to one single camp. The gradients included six single plots, each of which was 10 m × 10 m in size. These plots were defined exclusively through grass quality conditions, according to Van der Westhuizen et al. (2005), independent of bush encroachment. Related grass species included *Centropodia glauca* and *Stipagrostis uniplums* for good rangeland condition, *Eragrostis lehmanniana* for moderate conditions, and *Schmidtia kalihariensis* for poor conditions. The latter is an annual species. Rangeland condition ranged from poor to moderate (poor and moderate = grazing gradient) to good (good = pasture plot outside the grazing gradient) defined on-site by plant experts. The length of the grazing gradients varied between and within the different management systems (Table 1), but distances between the six plots were kept constant within each sampling site. Along a centerline, a soil sample was taken every 2 m with an auger and combined into a composite sample for three depth intervals

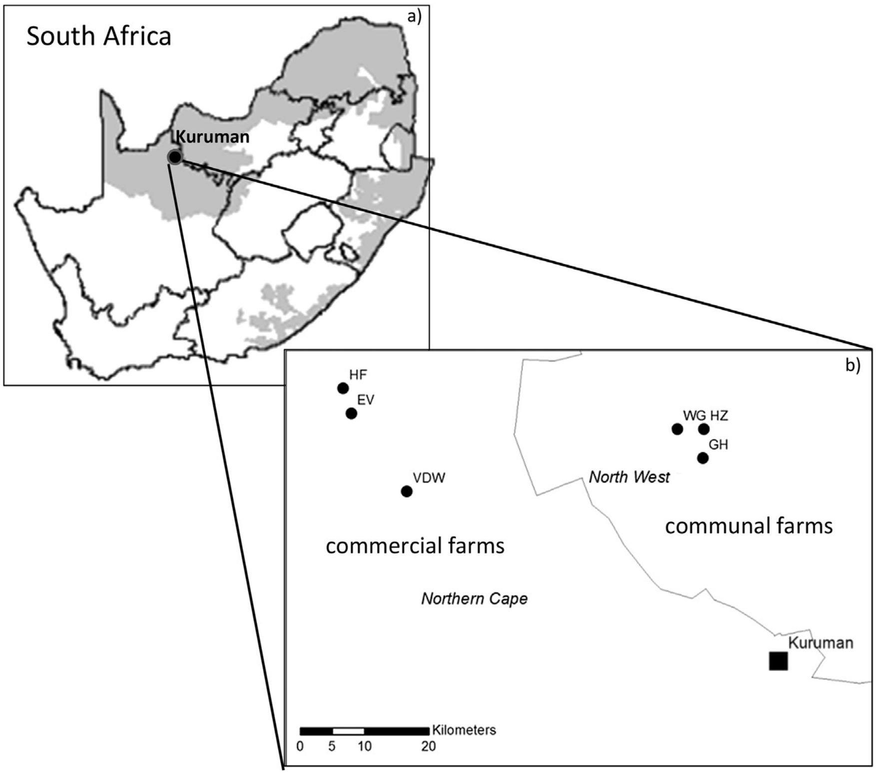

Fig. 1. a) Map of the savanna biome in South Africa (gray) and b) map of the study areas, indicating the position of commercial and communal farms. (GH = Good Hope; HZ = Hertzog; WG = Wingate; EV = Elisabethville; HF = Harefield; VDW = Olivepan).

(0–5 cm, 5–10 cm, and 10–20 cm). Additionally, composite samples were taken in direct proximity to the water points, where no vegetation grew (the "sacrifice zone"). Samples for bulk density were taken under all rangeland conditions of both management types, assuming that the bulk density of the sacrifice zone is similar to that under poor rangeland conditions. Additional soil samples (0–10 cm) were taken outside the gradients under *A. mellifera* and grass in order to obtain an understanding of the influence that specific overlying vegetation had on soil parameters.

Plant experts estimated the percentage of bare ground, shrub, litter, moribund, and senescent in the plots of the grazing gradients of commercial farms (three replicates) and communal farms (two replicates).

2.4. Analyses

The composite soil samples were air-dried, sieved (<2 mm), and prepared for analyses. All chemical analyses were performed in duplicate according to the following standard methods (The Non-Affiliated Soil Analysis Work Committee, 1990): pH (1:2.5 soil to water suspension), exchangeable Ca, Mg, K and Na (1 mol dm^{-3} NH_4OAc at pH 7), extractable Cu, Fe, Mn and Zn (DTPA solution), and CEC (1 mol dm^{-3} NH_4OAc at pH 7). All of the above-mentioned elements were determined by atomic absorption. The total C and N were determined by dry combustion using a CHNS analyzer (Elementar-Analysensysteme GmbH, Hanau, Germany). There was no detectable inorganic C, which meant that the total C was equal to organic C, further called SOC.

Plant-available P was measured using the Olsen method (The Non-Affiliated Soil Analyses Work Committee, 1990) for all samples; for samples of 0–5 cm soil depth, sequential extraction of P fractions was conducted according to the scheme of Hedley et al. (1982) and Tiessen and Moir (1993), albeit slightly modified in that the soil volume for analyses was doubled. Preliminary tests

Table 1
Characteristics of commercial and communal farms (standard deviations in parenthesis).

Management system (n = 3)	Extension whole gradient [m]	Extension sacrifice zone [m]	Stocking rate [ha LSU $^{-1}$]	Rangeland condition	Bare soil (%)*	Grass cover (%)*	Shrubcover (%)*	Sand (%)	Silt (%)	Clay (%)
								0–5 cm soil depth		
Commercial farms	256 (±18)	24 (±3)	14.2 (±4)	Sacrifice zone	100	0	0	95.6 (±1.2)	1.8 (±0.5)	2.6 (±0.5)
				Poor	56 (±10)	42 (±8)	4.6 (±1.2)	97.1 (±0.1)	1.1 (±0.3)	2.6 (±0.3)
				Moderate	47 (±5)	46 (±9)	3.1 (±0.6)	96.6 (±0.4)	1.1 (±0.04)	2.95 (±0.4)
				Good	25 (±7)	71 (±11)	3.6 (±1.6)	94.7 (±1.3)	1.8 (±0.8)	3.9 (±0.3)
Communal farms	613 (±58)	45 (±5)	13.1 (±3.8)	Sacrifice zone	100	0	0	98.0 (±0.4)	0.5 (±0.1)	1.9 (±0.2)
				Poor	68 (±12)	27 (±5)	9.1 (±0.5)	98.2 (±1.5)	0.8 (±0.3)	3.15 (±0.3)
				Moderate	68 (±4)	27 (±8)	24.7 (±0.8)	96.7 (±0.05)	1.4 (±0.2)	2.0 (±0.5)
				Good	60 (±3)	38 (±11)	5.9 (±0.9)	96.6 (±0.3)	1.4 (±0.4)	2.7 (±0.4)

had shown that this did not affect the overall fraction yields (own unpublished data). The method is generally based on the extractability of P fractions. First, the easily-extractable (labile) P forms were extracted in a batch, where for resin P anion exchange strips were used and 0.5 M $NaHCO_3$ and the bioavailable P (Po and Pi) was then extracted. Three fractions – bicarbonate P, Al and Fe bound P, and Ca bound P – were extracted through the same procedure, but with different reagents (0.5 M NaHCO3 buffered at pH 8.5; 0.1 M NaOH; 1 M HCl). For the very stable phosphorus pool, we took concentrated HCl (cHCl) and at least the residual P pools were achieved with an aqua regia digestion.

Particle size analyses were conducted using the standard sieve-pipette method (The Non-Affiliated Soil Analysis Work Committee, 1990). Bulk density was determined by gravimetric analysis using 0.1 dm^3 steel cylinder samplers.

A two-step particle size fractionation was conducted using an ultrasonic dispersion method of Amelung and Zech (1999). Samples were gently sonicated (60 J ml^{-1}) so that microaggregates were preserved from disruption. The coarse fraction (cPOM: 2000–250 μm) was separated by wet sieving and the filtered remnant was sonicated a second time at 440 J ml^{-1}. Intermediate (mPOM: 250–53 μm) and fine (fPOM: 53–20 μm) fractions were also gained by wet sieving and all fractions were dried at 40 °C prior to elemental analysis. Sieving was supported by gentle agitation using small rubber spatulas. Mineral-associated matter (MOM) was calculated from data of POM.

Bulk soil (0–5 cm) and soil fractions were analyzed for $\delta^{13}C$ using an Isotope Ratio Mass Spectroscope (Delta V Advantage IRMS, Thermo Electron Corporation, Germany) with respect to the Peedee Belemnite standard according to equation (1):

$$\delta^{13}C = [(R(sample)/R(standard)) - 1] \times 1000 \quad (1)$$

where R(sample) is the $^{13}C/^{12}C$ isotope ratio of the sample and R(standard) is the $^{13}C/^{12}C$ isotope ratio of the international Peedee Belemite standard.

The relative proportions of SOC derived from the original C4 grassland vegetation (F_C) vs. the more recent C3 woody vegetation were estimated by mass balance (Liao et al., 2006b) according to equation (2):

$$Fc = (\delta P - \delta A)/(\delta G - \delta A) \quad (2)$$

where δP is the $\delta^{13}C$ value of the SOC in a POM fraction, δG is the average $\delta^{13}C$ value of SOC in that same fraction from remnant grasslands, and δA is the average $\delta^{13}C$ value of woody plant material from *Acacia* vegetation (Table 3). $\delta^{13}C$ of remnant grassland in Kuruman was defined as −17.1‰, according to our analyses of $\delta^{13}C$ under grass vegetation under good conditions (Table 3). The $\delta^{13}C$ woodland SOC at equilibrium is not known because there is no stable forest in this area; that is, the $\delta^{13}C$ of soil in wooded areas is still changing. Hence, we assumed that woodland soils would ultimately achieve a $\delta^{13}C$ value similar to that of *Acacia* plant inputs (−26.96‰). This ignores the fact that during SOM formation there may be an isotopic enrichment of 1–3 delta units; yet, we only analyzed very surface soils here that probably have very slow organic matter degradation due to dryness.

2.5. Statistical analyses

Statistical analyses were performed using ANOVA with repeated measures design in order to test the influence of different rangeland management systems and rangeland conditions on all measured soil properties. To compare means we used the least significant difference (LSD) method with a $p < 0.05$ level of significance. All analyses were conducted using the Statistica 9.1 package for Windows (StatSoft Inc, 2010).

3. Results

The visual grazing gradients were significantly longer in the communal farms (610 m) than in the commercial farms (256 m) (Table 1). Additionally, the sacrifice zone around the water points (bare soil) was significantly larger on communal farms (45 m) than on the commercial farms (24 m). These findings were underlined by visual estimations of bare ground surface in the gradients. Bare ground was highest in the sacrifice zone (100%) nearby the water points and reached 68% in poor and moderate rangeland conditions of communal farms. Under good rangeland condition, 60% of the land surface still remained bare ground. The commercial farms also exhibited 100% of the land surface as bare ground in the sacrifice zone, but values declined to 56% for poor rangeland conditions, 47% for moderate conditions, and 26% for good conditions (Table 1). Additionally, the area influenced by shrubs (including beneath the canopy) varied within the gradients. In communal farms the space influenced by shrubs amounted to 9% under poor rangeland conditions, 25% under moderate conditions, and 10% under good conditions. In the commercial farms, by contrast, shrub cover was much lower and reached only 3.8% of the area of the surface soil on average (Table 1 and Fig. 2). Thus, the rotational grazing at the commercial farms and measures taken against bush encroachment did not prevent only bare soil from remaining nearby the water points. However, the overall area of rangeland degradation was reduced significantly, as indicated by the lengths of the grazing gradients, the areal extension of bare ground, and the presence of bushes.

3.1. Physical soil properties

Increased animal trampling did not alter bulk densities (Table 2) within the grazing gradients of both management systems and we were unable to detect any clear management effect on bulk densities with increasing soil depth. Hence, in order to understand changes in soil chemical properties (see below), it was sufficient to consider changes in element concentrations, because at constant bulk densities they paralleled changes in element stocks.

The lack of soil compaction corresponded to the soils' sandy texture and coincided with an absence of aggregate formation. Specifically, the Arenosols of the studied sites contained between 95 and 98% sand, where communal farms had the highest sand content in the sacrifice zones (97.9%) and under poor rangeland conditions (98%) in the 0–5 cm soil layer. The differences were small, but the topsoils (0–5 cm) of the commercial farms had more silt ($p < 0.05$) in the sacrifice zones (1.8%) and under poor rangeland conditions (1.1%) than the communal farms (0.5% and 0.8%, respectively). Under moderate rangeland conditions, the silt content of communal farms in the 0–5 cm soil layer increased to 1.4% and in the 0–10 cm soil layer even to 2.1%, and exceeded values of commercial sites with 1% silt in the same soil depth (data not shown). Although these differences were small in an absolute sense, they may already affect the result of POM fractionation.

Fractionation of particulate organic matter clearly separated the soil properties of the different farm types: POM fractions, expressed as percent of bulk soil, reflected the slight texture differences in rangeland management. The relationship between coarse sand and cPOM was linear ($r = 0.94$; $p < 0.001$), as was that of fine sand and mPOM ($r = 0.96$, $p < 0.001$). As a result, communal farms with higher contents of fine sand showed significantly higher values for mPOM (81%) and lower levels for cPOM (12%) than the commercial farms (63% mPOM and 29% for cPOM), respectively.

Table 2
Bulk density, pH, plant nutrient concentrations and standard deviation of the rangeland management systems (commercial farms – CF, communal farms – CO, in different rangeland conditions (sa – sacrifice zone; p – poor; m-moderate; g- good) and soil depth.

Tenure system	Rangeland condition	Depth (cm)	Bulk density [g cm^{-3}]	pH [H_2O]	C [g kg^{-1}]	N [g kg^{-1}]	P [mg kg^{-1}]	Ca [mg kg^{-1}]	Mg ([mg kg^{-1}]	K [mg kg^{-1}]	Na ([mg kg^{-1}]	Cu [mg kg^{-1}]	Fe [mg kg^{-1}]	Mn [mg kg^{-1}]	Zn [mg kg^{-1}]
CF	**sa**	0–5		8.0 ± 1.0	13.7 ± 0.5	1. ± 0.04	96.6 ± 44	1164 ± 465	140 ± 31	404 ± 264	26 ± 36	0.4 ± 0.09	12.4 ± 6	6.1 ± 2.8	3.1 ± 0.5
		5–10		8.1 ±1.2	11.3 ± 0.3	1.0 ± 0.03	99 ± 57	1381 ± 441	169 ± 84	521 ± 367	34 ± 51	0.4 ± 0.2	19.7 ± 11	7.6 ± 5.3	3.5 ± 0.9
		10–20		8.1 ± 0.9	4.2 ± 0.1	0.4 ± 0.0	82 ± 70	652 ± 223	87 ± 35	281 ± 209	10 ± 12	0.4 ± 0.2	24.5 ± 25	5.4 ± 1.6	2.9 ± 1.2
	p	0–5	1.54 ± 0.03	6.9 ± 0.5	4.8 ± 0.16	0.38 ± 0.01	8.7 ± 1.5	331 ± 45	53 ± 13	80 ± 14	3.7 ± 1.1	0.2 ± 0.02	6.6 ± 1.6	5.2 ± 2.4	1.2 ± 0.4
		5–10	1.58 ± 0.0	6.6 ± 0.6	2.9 ± 0.1	0.25 ± 0.01	6.4 ± 3.6	326 ± 84	42 ± 11	77 ± 17	3.7 ± 1.2	0.25 ± 0.0	9.0 ± 1.4	4.8 ± 1.7	0.9 ± 0.4
		10–20	1.58 ± 0.04	6.6 ± 0.5	1.4 ± 0.0	0.07 ± 0.0	12.1 ± 8.6	255 ± 21	37 ± 4.7	91 ± 8.1	4.1 ± 0.8	0.2 ± 0.0	7.6 ± 1.5	4.1 ± 1.4	0.3 ± 0.1
	m	0–5	1.56 ± 0.02	6.2 ± 0.4	1.9 ± 0.05	0.1 ± 0.0	2.2 ± 0.2	209 ± 45	35 ± 15	51 ± 13	3.4 ± 0.6	0.2 ± 0.0	7.2 ± 1.6	4.9 ± 0.5	0.2 ± 0.0
		5–10	1.55 ± 0.09	6.3 ± 0.4	1.5 ± 1.2	0.1 ± 0.0	3.4 ± 3.8	219 ± 31	36 ± 14	58 ± 13	3.3 ± 0.2	0.2 ± 0.0	7.5 ± 3.0	4.9 ± 0.6	0.1 ± 0.0
		10–20	1.54 ± 0.09	6.3 ± 0.3	1.3 ± 0.0	0.05 ± 0	1.6 ± 0.8	242 ± 54	42 ± 16	59 ± 17	3.5 ± 0.3	0.2 ± 0.0	6.2 ± 2.2	3.8 ± 1.1	0.1 ± 0.1
	g	0–5	1.53 ± 0.08	6.2 ± 0.4	2.7 ± 0.07	0.2 ± 0.04	2.1 ± 1.1	299 ± 108	50 ± 25	64 ± 17	3.3 ± 0.5	0.2 ± 0.0	8.5 ± 4.1	5.6 ± 1.4	0.2 ± 0.0
		5–10	1.5 ± 0.0	6.4 ± 0.5	1.9 ± 0.1	0.1 ± 0.07	1.2 ± 0.7	268 ± 94	45 ± 18	62 ± 17	3.6 ± 0.7	0.2 ± 0.0	7.3 ± 3.8	4.1 ± 0.8	0.1 ± 0.1
		10–20	1.54 ± 0.08	6.5 ± 0.4	1.6 ± 0.0	0.1 ± 0.0	1.1 ± 0.4	321 ± 140	59 ± 34	75 ± 32	3.2 ± 0.2	0.2 ± 0.0	6.1 ± 2.7	3.4 ± 0.5	0.1 ± 0.0
CO	**sa**	0–5		8.5 ± 0.1	2.4 ± 0.03	0.2 ± 0.0	5.5 ± 1.2	411 ± 13	41 ± 1.4	191 ± 10	3.4 ± 0.6	0.1 ± 0.0	3.0 ± 0.0	4.5 ± 0.9	1.1 ± 0.0
		5–10		8.1 ± 0.1	1.3 ± 0.1	0.2 ± 0.01	7.6 ± 2.0	370 ± 14	35 ± 7	139 ± 9.9	3.3 ± 0.4	0.2 ± 0.0	2.6 ± 0.7	2.8 ± 0.8	0.7 ± 0.1
		10–20		8.1 ± 0.1	1.0 ± 0.1	0.01 ± 0.0	8.8 ± 2.7	331 ± 4.2	35 ± 7	135 ± 24	3.4 ± 0.5	0.19 ± 0.0	2.9 ± 0.5	3.1 ± 0.7	0.5 ± 0.0
	p	0–5	1.6 ± 0.02	6.9 ± 0.8	2.2 ± 0.1	0.2 ± 0.0	2.7 ± 0.4	309 ± 84	31 ± 12	72 ± 35	2.7 ± 0.2	0.15 ± 0.01	4.5 ± 0.8	5.6 ± 1.9	0.3 ± 018
		5–10	1.6 ± 0.03	6.7 ± 0.8	1.5 ± 0.03	0.1 ± 0.03	1.9 ± 0.6	277 ± 61	27 ± 8	67 ± 35	2.9 ± 0.2	0.16 ± 0.0	4.3 ± 1.4	4.8 ± 1.7	0.2 ± 0.1
		10–20	1.56 ± 0.02	7.1 ± 0.1	1.4 ± 0.1	0.1 ± 0.03	1.5 ± 0.02	358 ± 90	29 ± 8	79 ± 32	2.9 ± 0.2	0.18 ± 0.0	4.1 ± 1.4	4.7 ± 2.7	0.15 ± 0.1
	m	0–5	1.5 ± 0.05	7.0 ± 0.8	3.4 ± 0.5	0.2 ± 0.0	1.6 ± 0.3	392 ± 218	29 ± 3	51 ± 8	4.5 ± 0.9	0.2 ± 0.0.	7.6 ± 2.3	8.7 ± 6.2	0.2 ± 0.04
		5–10	1.6 ± 0.03	7.0 ± 0.8	2.2 ± 0.1	0.2 ± 0.04	1.1 ± 0.2	371 ± 201	31 ± 8	54 ± 11	3.7 ± 1.1	0.2 ± 0.02	4.9 ± 1.2	5.6 ± 2.9	0.2 ± 0.1
		10–20	1.5 ± 0.05	6.4 ± 0.8	1.7 ± 0.1	0.2 ± 0.05	1.1 ± 0.3	347 ± 184	32 ± 7	52 ± 10	1.4 ± 0.2	0.1 ± 0.01	4.6 ± 0.8	6.5 ± 3.8	0.1 ± 0.01
	g	0–5	1.55 ± 0.03	6.8 ± 0.6	3.0 ± 1.2	0.2 ± 0.01	1.4 ± 0.5	285 ± 41	32 ± 3.5	48 ± 5.3	2.7 ± 0.2	0.15 ± 0.01	5.3 ± 1.2	6.0 ± 2.2	0.2 ± 0.05
		5–10	1.58 ± 0.04	6.9 ± 0.5	1.9 ± 0.2	0.15 ± 0.02	1.1 ± .3	281 ± 28	31 ± 3.1	54 ± 5.3	3.0 ± 0	0.15 ± 0.03	4.3 ± 0.4	4.1 ± 1.8	0.1 ± 0.01
		10–20	1.52 ± 0.05	6.9 ± 0.5	2.0 ± 0.2	0.18 ± 0.0	1.2 ± 0.32	308 ± 60	34 ± 4	55 ± 7	1.5 ± 0.3	0.1 ± 0.01	3.9 ± 0.39	5.1 ± 2.3	0.09 ± 0.06

3.2. *Chemical soil properties*

3.2.1. *Nutrients*

The Arenosols typically showed poor nutrient status with an average CEC (based on adsorbed Na) of 500 mg kg^{-1} soil. There were significant differences between management systems, particularly for the soils of the sacrifice zone nearby the artificial water points (Table 2), where the CEC of the commercial farms reached extraordinarily high values of 1068 mg kg^{-1} in the topsoil (data not shown). This amount was almost three times higher than the values of the communal farms (377 mg kg^{-1} soil). The pH values, as well as the contents of Ca, Mg, K, and Zn, were also elevated near the water points of both management systems, with significant higher contents for Cu and Zn under poor rangeland condition in the commercial farms with rotational grazing (Table 2). The concentration of most nutrients decreased slightly as the soil depth increased. Notably, the two management systems showed different patterns for nutrients within the grazing gradients. In the communal farms, the topsoils (0–10 cm) under the moderate and good rangeland conditions were more enriched with nutrients than those under poor rangeland conditions and of the sacrifice zones. In contrast, the commercial farms were depleted of most nutrients in the topsoils under moderate and good rangeland conditions relative to the poor rangeland conditions and sacrifice zones (Table 2).

The total P content of all farms was low and ranged between 71 mg kg^{-1} P for commercial farms and 52 mg kg^{-1} P for communal farms in the surface soil layer (data not shown). The highest values were again found under poor rangeland condition, with significantly higher P contents in soils of the commercial farms. Along the grazing gradient, the P contents decreased with increasing distance from the water points, but P was elevated in the commercial farms at all sites relative to the respective rangeland conditions of the communal farms. The proportions of Pi and Po did not vary greatly among rangeland conditions. Plant-available P (Table 2) followed the same trend as total P in commercial farms, whereas the differences across all rangeland conditions remained low in communal farms.

In contrast to the assessment of P contents, sequential fractionation of P into different fractions detected variation between the two management systems and, in parts (Fig. 3; for extraction agents see Section 2.3), also along the gradients (data not shown). In the commercial farms, although the labile P pool (resin and bicarbonate extractable P fractions) was not significant, it was higher in the commercial farms than in the communal farms, with a tendency to decrease along gradients away from the water points of the commercial farms (46.9% under poor, 42.0% under moderate, and 42.5% under good rangeland condition). This trend was reversed for the communal farms (33.7% under poor, 35.6% under moderate, and 36.0% under good rangeland condition). In both management systems, the labile pool was dominated by bicarbonate extractable P_o, although its contents were consistently lower along the gradient of the communal farms than along that of the commercial farms. In contrast, portions of the recalcitrant P were higher under poor rangeland conditions of the communal farms with continuous grazing system, whereas this fraction accounted only for 17% of the recalcitrant pool in commercial farms. Fractionation of the P pools under certain overlying vegetation showed differences between grass and *Acacia* vegetation. Specifically, changes in the proportions of these vegetation types were also likely to affect P pool composition (Fig. 3).

3.2.2. *Soil organic matter*

Although the stocks of SOC and total N followed the patterns of nutrients, the relative differences among sites were greater. Under

Table 3
Carbon [g kg^{-1}] and δ^{13}C [‰] in bulk soil and fractions of particulate organic matter in grazing gradients (0–5 cm), of commercial and communal farms, under *Acacia* and grass (0–10 cm), and in plant material, Kuruman. (Standard deviation in parentheses).

	Bulk soil δ^{13}C ‰	C g kg^{-1}	δ^{13}C ‰	C g kg^{-1}	δ^{13}C ‰	C g kg^{-1}	δ^{13}C ‰
		cPOM (250–2000 μm)		mPOM (53–250 μm)		fPOM (20–53 μm)	
Commercial farm							
Poor	−18.6 (±1.2)	15.8 (±1.2)	−19.3 (±1.6)	8.7 (±0.7)	−20.8 (±1.1)	4.5 (±0.3)	−20.1 (±1.6)
Moderate	−18.1 (±0.6)	1.4 (±0.1)	−18.9 (±1.0)	3.5 (±0.4)	−21.8 (±1.3)	1.4 (±0.05)	−20.9 (±0.6)
Good	−19.4 (±2.2)	6.2 (±0.1)	−20.5 (±1.3)	4.1 (±0.4)	−21.5 (±0.9)	2.0 (±0.08)	−21.8 (±1.0)
Communal farm							
Poor	−18.4 (±2.5)	5.1 (±0.3)	−22.4 (±2.7)	2.0 (±0.2)	−21.1 (±1.6)	1.4 (±0.06)	−22.5 (±2.2)
Moderate	−19.9 (±0.7)	8.7 (±0.1)	−23.9 (±2.4)	2.6 (±0.4)	−22.4 (±0.6)	2.3 (±0.1)	−21.7 (±0.8)
Good	−19.6 (±1.6)	7.3 (±0.5)	−23.0 (±2.5)	4.2 (±0.2)	−22.0 (±1.3)	2.0 (±0.08)	−21.5 (±1.0)
			δ^{13}C ‰ plants				
Under *Acacia*	−21.4		−26.96				
Under *grass*	−17.1		−13.6				

poor rangeland conditions, the SOC and N stocks of the commercial farms exceeded those of the communal farms by a factor of 2.1 for the top 5 cm soil layer and by a factor of 2 for the top 10 cm soil layer. In contrast, communal farms with continuous grazing showed high SOC and N stocks in the 0–10 cm soil layer under moderate and good rangeland conditions; these stocks now exceeded the stocks of commercial farms with rotational grazing by almost 2 t SOC ha^{-1} under moderate rangeland conditions and 1.3 t SOC ha^{-1} under good conditions. Notably, the effects were restricted to the 0–10 cm soil layer, whereas SOC and N stocks in the 10–20 cm soil layer were similar along the entire grazing gradient and between both land-use systems (Table 2; Fig. 4).

The C/N ratios ranged between 11 and 23, although the ratios of commercial and communal farms were similar in the topsoil of the sacrifice zone (11.5–11.9). In the 5–10 cm and 10–20 cm soil layers, the C/N ratios in communal farms increased to 15 and 20, respectively, whereas the ratios in commercial farms remained more or less constant. Hence, there was a significant change in soil quality in the deeper soil layers.

The different patterns of soil fertility at both management systems were underlined by Pearson correlations, which revealed close positive relationships between the C (0.81,***) and N (0.78,***) contents and grazing intensity at the commercial farms. At the communal farms with continuous grazing, the strongest rank correlations were detected between C stocks (0.71***) and CEC (0.78***) with shrub cover.

The stocks of the three different POM fractions and the mineral associated fraction (MOM) reflected differences in total SOC. Most SOC (approximately 46% of the total) was found in the MOM fraction, and the least SOC were found in fPOM. Under poor rangeland condition, however, commercial farms again showed higher SOC and N stocks in all isolated POM fractions, including MOM relative to the communal farms. Differences for cPOM and fPOM were significant. With increasing distance to the water point and under moderate rangeland conditions, SOC stocks in the POM fractions of communal farms exceeded those of the commercial farms, particularly for cPOM (Fig. 5). Only under good rangeland conditions did both farming systems exhibit similar POM-C contents. The N stocks in the POM fractions followed the same trend as SOC, but differences were most pronounced for MOM in moderate and good rangeland conditions, with higher N stocks in communal farms (data not shown).

The stable C isotopic composition (δ^{13}C) of the plants in Kuruman reflected the differences in photosynthetic pathways between

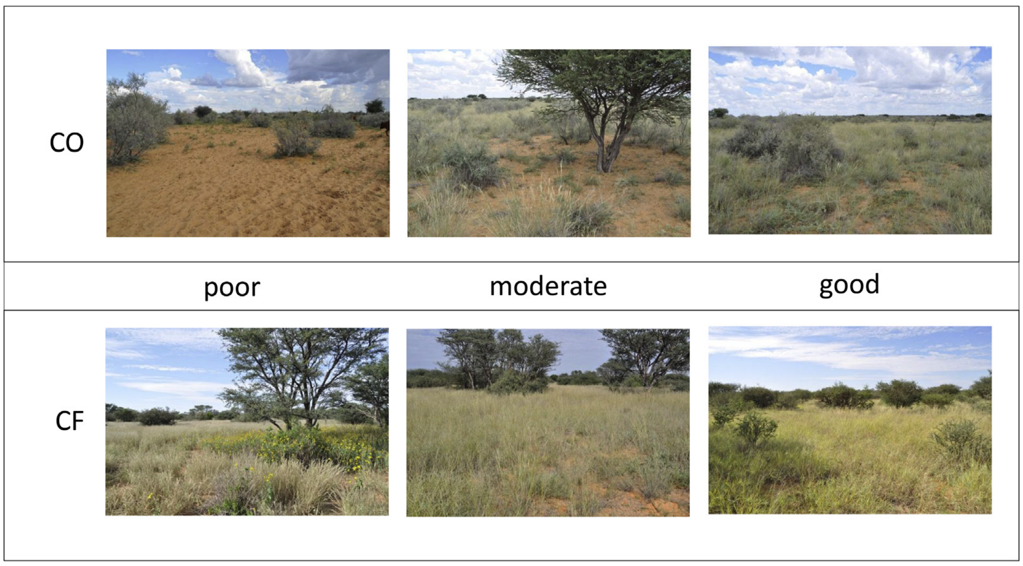

Fig. 2. Illustration of examples for poor, moderate and good rangeland condition of a communal farm (CO; Good Hope) and a commercial farm (CF; Elisabethville) in the Kuruman area.

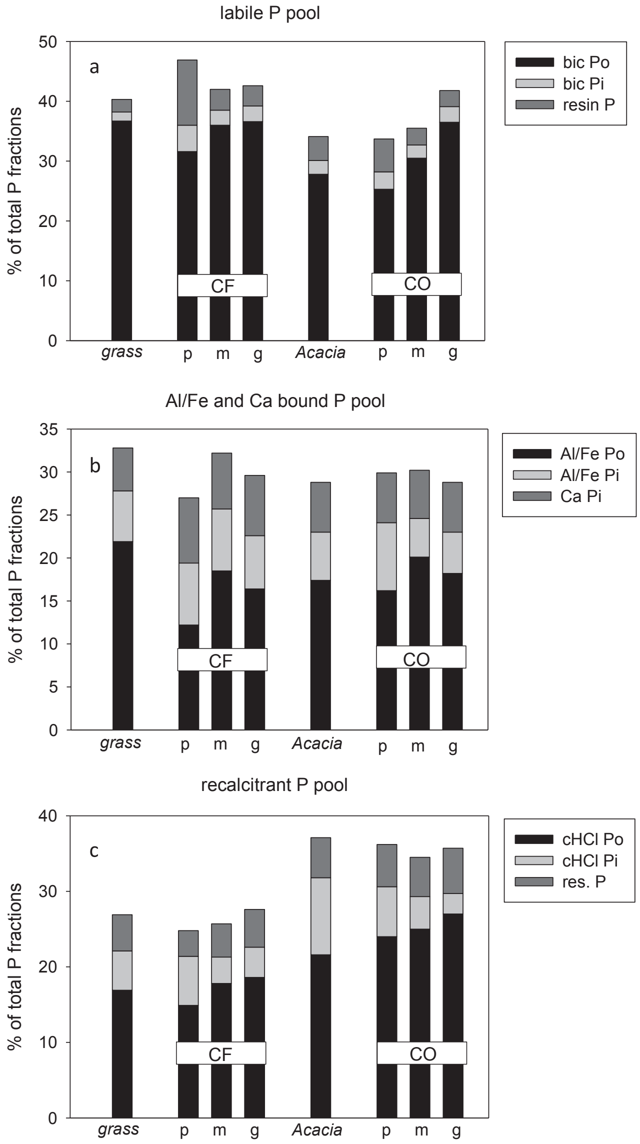

Fig. 3. Proportion of P fractions (mg of total P) in commercial (CF) and communal farms (CO) (0–5 cm) under different rangeland conditions (p = poor; m = moderate; g = good) and under grass and *Acacia* (0–10 cm); (a) labile P-pool (resin P: anion exchange; bioavailable: 0. 5M $NaHCO_3$); (b) Al/Fe (0.1 M NaOH) and Ca bound (1 M HCl) P-pool (c) recalcitrant P-pool (concentrated HCl; residual P: aqua regia digestion). (Po for organic P; Pi for inorganic P).

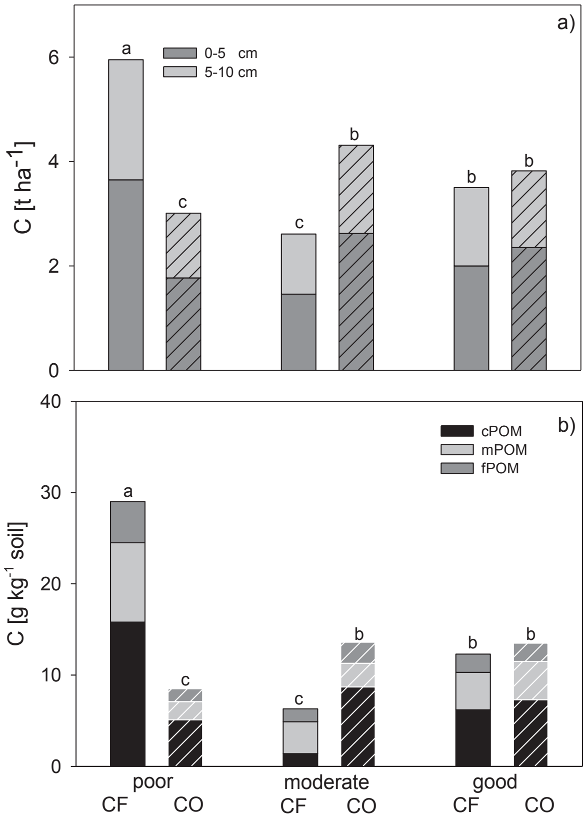

Fig. 4. a) Carbon stocks (t ha^{-1}) along the grazing gradients of commercial (CF) and communal (CO) farms. Different letters indicate significant differences ($p < 0.01$), b): Carbon in different fractions of particulate organic matter along the grazing gradients (0–5 cm soil depth). CF for commercial farms; CO for communal farms. cPOM (250–2000 μm), mPOM (53–250 μm), fPOM (20–53 μm). Significant differences caused mainly by differences in cPOM (see text).

the C4 grasses and the C3 *Acacia* bushes and trees (Table 3). In the bulk soil (0–5 cm), the $\delta^{13}C$ values decreased with increasing distance to the water points in both management systems along the grazing gradient with higher levels in commercial farms (Table 3). Despite the small and non-significant differences in bulk soil between the two management systems, the $\delta^{13}C$ values differed significantly in the cPOM fraction. In general, cPOM had a $\delta^{13}C$ of −18.9 to −20.5‰ in commercial farms and −22.4 to −23.9‰ in the communal farms. This difference in isotopic composition was most pronounced under moderate rangeland conditions (Table 3) and reflects different portions of, for example, C4-derived C in the POM fraction (Fig. 5). The calculation outlined in Eq. (2) revealed that, under poor and good rangeland conditions of the communal farms, more than half of the SOC was derived from C4 grasses. This proportion declined under moderate conditions to 33.6% of the total SOC. In the commercial farms, by contrast, 75% of SOC was derived from the C4 grasses, and this proportion rose to 90% under moderate rangeland conditions.

4. Discussion

The Kuruman area in South Africa provides an ideal opportunity to compare different management systems under highly similar abiotic conditions. Before and during Apartheid, communal lands practiced a rotational grazing system similar to that of commercial farms, using fenced camps and calculating the carrying capacity (stock numbers) of the grazing land. Over the past 20 years, the system at the communal farms then changed to continuous grazing. However, the fact that the soil types on these farms were similar to those on the commercial farms enabled us to trace this influence of changed rangeland management on soil properties during this period. We focused our study on water points and the degraded zone around them because changes in ecological parameters will be first visible in zones with maximum livestock load (Snyman and Du Preez, 2005). The results showed that 20 years of changed rangeland management had already left a mark on soil properties.

Since water is the main limiting factor of plant production and animal welfare in this savanna biome, the activities of animals in the rangelands are concentrated around the water points. Consequently, gradients developed near the water points. These gradients showed a sacrifice zone in close vicinity to the drinking points,

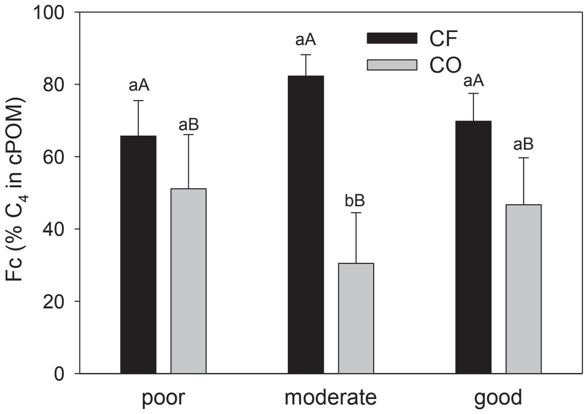

Fig. 5. Proportion of $\delta^{13}C$ of C4 grassy vegetation vs C3 woody plants (Fc) in coarse particulate organic matter (250–2000 μm) along the grazing gradients of commercial and communal farms (0–5 cm). Different letters indicate significant differences ($\alpha < 0.05$) (capital letters (A, B) for differences within a farm, small letters for differences between farms).

and the impacts of animals attenuate with increasing distance to the water points. Most of the studies that have dealt with this "distance to water approach" have measured soil properties or vegetation patterns in defined distances to the water points up to 500 m (e.g., Fernandez-Gimenez and Allen-Diaz, 2001; Snyman and Du Preez, 2005; Smet and Ward, 2006) or more (Thomas and Twyman, 2004) and tested whether soil or vegetation properties changed with distance. Instead, we chose a visual defined grass quality gradient to estimate the total length of the gradient until the averaged pasture conditions (=good) were reached. We did this in order to compare the effects of different management systems on soil properties, as had also been done by local rangeland extension services (Van der Westhuizen et al., 2005). This means that the expressions "poor, moderate or good condition", according to the local rangeland classification, were linked to palatable grass composition and grazing intensity, but not to the occurrence of bushes. The results showed distinct differences between the grazing systems, with significantly enlarged sacrifice zones and enlarged lengths of the grazing gradients in the continuous grazing system of the communal farms compared with those in the rotational grazing system of the commercial farms.

The estimated carrying capacity of the rangelands under study is 13 ha LSU^{-1} (Department of Agriculture and Rural Development, (2003)) and the averaged stocking number of commercial farms fitted well with this carrying capacity (averaged stocking rates of about 14 ha LSU^{-1}). Interestingly, our personal conversations with commercial farmers revealed that some of them knowingly exceeded this carrying capacity. They avoided negative impacts on their rangeland by forecasting management, which included frequent estimations of grass growth and quality in the grazed camps. In contrast, and against general expectations, rough estimates of stocking rates in communal farms fitted to the carrying capacity suggested an average stocking rate of 13 ha LSU^{-1}. Also, prior to 1994, overstocking was sometimes avoided and realized by the government through Betterment Schemes involving the culling of animals (such as donkeys) to prevent degradation (Jacobs, 2003). Therefore, reasons other than differences in stocking rates and animal numbers clearly led to the enlarged grazing gradients under the continuous grazing system.

A fundamental driver for animal's movement is the number of intact water points and the establishment of fences. During the Betterment Schemes, the number of wells in new villages increased and supported an increasing grazing range (Jacobs, 2003). However, after Bophuthatswana was incorporated under the South African Government in 1994, financial support from the government for fences and water points ran dry and the communal farms were not able to repair them. Both management tools increasingly lost their function. Hence, animals were forced to enlarge tracks to reach water, which probably resulted in an overall extension of the grazing gradient. These arguments are supported in a recent study by Graz et al. (2012), who modeled grazing patterns after the closure of water points and the removal of fences simultaneously. Consequently, the grazing area extended, concentrated on the single remaining water points. Unlike communal farms, commercial farms are divided into camps with artificial water points in every camp. This makes it possible to manage the movement of the animals and the grazing in a given camp, which allows soil restoration. The grazing time within a camp may be a matter of weeks and may also depend on permanent evaluation of grassy vegetation.

Interestingly, the effects of the two management systems on soil properties and rangeland conditions studied in the savanna biome in the Northern Cape and North-West Provinces were more pronounced than in a grassland biome in the Free State Province (between 28.95″S, 26.46″E and 29.41″S, 27.00″E). In the latter case, no significant differences between extension of grazing gradients of continuous and rotational grazed rangelands were observed, but the soils clearly degraded as evidenced from increasing SOM loss and deterioration of aggregates (Kotzé et al., 2013). Both processes were absent here.

The different management systems had minimal effects on bulk density in this sandy savanna biome. In contrast, many studies have detected soil compaction as a consequence of increased grazing pressure (e.g. Kotzé et al., 2013); however, most of these studies were not conducted on such sandy soils, lacking the formation and thus also the destruction of aggregates. The sand content in the Kuruman area exceeded 93% on both farming systems, and Van Haveren, 1983 observed strong correlations between texture and bulk density under different grazing pressure, with heavy grazing having no effects on coarse textured soils. Hiernaux et al., 1999 were also unable to find any higher bulk density under increasing grazing of sandy soils. Hence, soil compaction does not seem to be an issue for rangeland degradation in this savanna biome.

Nevertheless, due to continuous grazing and frequent trampling by sheep and cattle, the ground surface become bare and exposed to wind erosion. Yong-Zhong et al. (2005) observed in China that decreased vegetation cover and litter accumulation resulted in soil coarsening and higher sand content. We also found soil coarsening and a loss of fine soil fractions in communal farms, but our findings were restricted to the sacrifice zone and the poor rangeland condition. Here, sand content increased by 1.7%. A lower increase of 1.1% was observed in the commercial farms. Simultaneously, there was a loss of fine fractions near the water point and under poor rangeland condition of communal farms. In particular, fine silt was lost, which resulted in less than half of the quantities we analyzed in moderate and good rangeland conditions. The vegetation cover at the water point and under poor rangeland conditions reached 0% and 27%, respectively, which indicates that the soils were indeed prone to erosion. Evidence for wind erosion was also visible in the field, where roots of *Acacia eriloba*, for example, were blown free off soil under poor management conditions at the communal farms. The rangelands under moderate and good conditions showed less bare soil and more vegetation cover, although this especially comprised shrubs in the communal farms. Hence, erosion risk diminished as the distance to the water points increased, and higher silt content prevailed. In this regard, the increasing bush encroachment increasingly protected the soils, while overall rangeland quality declined.

4.1. Soil fertility changes

At the commercial farms, our study confirmed earlier findings that most changes in soil properties and nutrients occurred in the direct vicinity of the water points (Fernandez-Gimenez and Allen-Diaz, 2001). The high levels of nutrients can mostly be attributed to the excreta of the animals around the water points (e.g., Smet and Ward, 2006). At the commercial farms in particular, we found an enrichment of P from feed additives, which improved the overall low P status of the soils compared with other sandy soils in these or other regions (O'Halloran et al., 2010).

In contrast to the commercial farms, communal farms showed lower nutrient levels under poor rangeland conditions and higher nutrient levels under moderate and good rangeland conditions. The distribution of nutrients along the grazing gradient also differed markedly from commercial farms: nutrients were enriched under moderate and good rangeland conditions relative to the nutrient status at the sacrifice zone and under poor rangeland conditions. For grasslands, it has been generally acknowledged that high grazing pressure reduces the growth rate and reproductive potential of individual grass plants, which has led to the nutrient status of the soils being depleted, as seen under the poor rangeland conditions of the communal farms (Abule et al., 2005; Kotzé et al., 2013). In the communal savanna area under study, however, the degradation of the grass layer by grazing resulted in the formation of bare soil surfaces under poor rangeland, but resulted in bush encroachment under moderate rangeland conditions. This ecological change is frequently observed in semiarid and arid environments. For example, Dougill et al. (1999) found similar patterns in the Kalahari of Botswana. They attributed the change of vegetation community to grazing patterns.

Overall, the continuous grazing as practiced had a stronger impact on vegetation types along the grazing gradient than the rotational grazing. Bushes encroached and the soils' nutrient status improved. Soil enrichment with nutrients under tree canopies was well documented. Various processes contribute to these so-called “islands of fertility” (Archer et al., 2001). These include litter from leaf fall, stem flow, and through fall; droppings from birds and mammals (Belsky et al., 1989); accumulation of nutrients from areas beyond the crowns by means of lateral tree roots; or increasing termite activity. A greater organic matter input (Daryanto et al., 2013), combined with slower decay rates of the woody debris (Liao et al., 2006a) support the accumulation of POM with lower $\delta^{13}C$ values (Table 3) at the communal farms. Hence, and in line with our hypothesis, increased rangeland degradation at the moderate veld coincided with soil restoration.

Phosphorus content did not follow the general trend of nutrient enrichment under moderate rangeland conditions of the communal farms. This is in line with Dougill et al. (1999), who did not detect any changes in bush encroached areas. However, the vegetation influenced the P fractions in our soils. For example, studies under the canopy and around the stem of *A. mellifera* revealed higher P contents than in the open areas (Hagos and Smit, 2005). Turrión et al., 2007 found particular differences in inorganic P fractions under different trees and shrubs. Conversely, soils under grass and pasture may promote the build-up of a large labile, probably microbially derived P_o pool due to the arbuscular mycorrhiza activity. As a result, the proportion of P_o under grass and pasture exceeded that of forests (Negassa and Leinweber, 2009). Our results also pointed to lower P_o levels of 55.4% under *Acacia* vegetation relative to elevated proportions of 63.8% under grass. Additionally, the P fraction yields under grass fitted well to the P fractions of the commercial farms. In contrast, the P fractions of the communal farms represented those found under *Acacia* vegetation. Therefore, we surmise that the feed supplements mainly influenced the amounts of total P, especially under poor rangeland conditions, but also that plant stands and grazing controlled the P status and bonding forms of the soils under moderate and good rangeland conditions.

4.2. Origin of soil organic matter

Vegetation controls on soil properties should particularly affect the properties of soil organic matter. The tree-shrub-grass composition of study sites in the Kuruman area has changed in recent decades (Jacobs, 2003). Communal farms with continuous grazing and an insufficient number of water points seemed to be affected more than commercial farms with a rotational grazing system in camps. The subtropical vegetation mainly comprises grasses with a C4 photosynthetic cycle, as well as trees and shrubs with a C3 photosynthetic cycle. As both photosynthetic pathways exhibit different ^{13}C discrimination, isotope analyses provided insight into the origin of SOC. The overall $\delta^{13}C$ values were similar to those reported for other C4 grasslands in the world (Boutton et al., 1998). Increasing woody encroachment usually changed the isotopic signature in the direction of the C3 plants (Bai et al., 2012; Throop et al., 2013). Our analyses from distinct overlying vegetation showed an average $\delta^{13}C$ value of −21.4‰ for soils under *Acacia* vegetation and a $\delta^{13}C$ value of −17.1‰ for soils under grass, which reflects the increased input of C4 debris in the latter. The $\delta^{13}C$ values of the bulk soil within the gradients were intermediate. This suggests that their SOC comprised a mixture of C4 grasses and C3 plants like shrubs, herbs, and trees, with the latter inputs being more pronounced in the communal than in commercial farms.

As the $\delta^{13}C$ signal of bulk soils may integrate across time scales that exceed the age of the water points, we also analyzed the POM fractions for isotopes in order to better identify residues of the C3 and C4 plants. The analyses revealed that $\delta^{13}C$ values of cPOM in communal farms did approach that of the savanna trees and shrubs. This finding supports the idea that cPOM consists of plant fragments that have little if any degree of microbial degradation (Amelung et al., 1998). In contrast, cPOM in commercial farms had higher $\delta^{13}C$ values across the whole gradient, which were comparable to the cPOM values we analyzed under grass. The low $\delta^{13}C$ values of the cPOM fraction are in line with results from the Rio Grande Plains in Texas. In a chronosequence approach, Liao et al. (2006b) studied the $\delta^{13}C$ signature in soil fractions of various ages of woody stands (10–130 years) and remnant grassland. They also observed that, beside the macro- and micro-free POM, the coarse cPOM (>250 μm) adapted most rapidly to the $\delta^{13}C$ value of the woody stands; that is, they confirmed the rapid turnover and recent origin of this fraction. In this regard, cPOM at the communal farms reflected the shift of an erstwhile grass-dominated system to an increasingly bush-dominated system (Fig. 5), whereas at commercial farms it reflected the dominance of grass. Hence, monitoring the $\delta^{13}C$ signature of cPOM may be a valuable proxy for monitoring the effects of grazing on soil properties in this ecosystem.

In summary, our results showed that the drier and sandier rangelands of the savanna biome – also allowing for the encroachment of bushes – are clearly more vulnerable to management systems with continuous grazing than the systems of the grassland biome, where climate restricts the occurrence of bush and where the loamy soils better preserved organic matter.

5. Conclusions

The grazing system in the communal areas of the savanna biome near Kuruman has changed since 1994. The deterioration of infrastructure, including fences and water points, has forced communal farms to adopt a continuous grazing system. However, contrary to general expectations, the stocking rates of communal farms were similar to those of commercial farms. In contrast, commercial farms practiced a rotational grazing system with a more foresighted management system in fenced camps that had the aim of selling animals. For several months of the year, vegetation and soil have the possibility to restore. Our results showed that this restoration worked. The grazing gradients were shorter, and supplement feeding and a high deposition of animal excreta meant that the topsoils close to the water points were elevated in most nutrients relative to those under moderate and good rangeland conditions and relative to those of the communal farms. Hence, less adapted management resulted in a degradation of soil quality close to the water points, and the degraded area was also larger than at commercial farms.

The communal farms exhibited similar stocking rates. However, due to broken water points and more frequent animal return, more animals reached a water point each year (in absolute numbers) than under rotational grazing. These higher animal numbers favored bush encroachment under moderate and good veld conditions. This process was reflected by an increased accumulation of particulate organic C. Its isotopic composition ascertained its elevated woody origin in the communal farms. Hence, the soils under continuous grazing showed an effect of bush dominance, which was accompanied by a co-accumulation of nutrients, at least in the studied areas. As a result, the soils improved under moderate veld condition, which may be beneficial for future land use. However, this happened at the expense of palatable grass proportions in the studied area of communal farms. Nonetheless, such grazing gradients only reflect small sections of a whole farm unit, although changes therein may be interpreted as an initial sign of environmental changes as induced by rangeland management in the savanna biome. One potential challenge for future land management options could be how to best utilize these improved soil conditions, particularly in view of the limited water in these arid regions.

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