Woody encroachment and related soil properties in different tenure-based management systems of semiarid rangelands

Alexandra Sandhage-Hofmann[1*], Jörg Löffler[2], Elmarie Kotzé[3], Stef Weijers[2], Vladimir Wingate[5], Dirk Wundram[2], Lutz Weihermüller[4,] Roland Pape[2], Chris C du Preez[3], Wulf Amelung[1]

[1] Institute of Crop Science and Resource Conservation, Soil Science and Soil Ecology, University of Bonn, Germany

[2] Department of Geography, University Bonn, Germany

[3] Department of Soil, Crop and Climate Sciences, University of the Free State, South Africa

[4] Agrosphere Institute IBG-3, Forschungszentrum Jülich, Germany

[5] Department of Geography, University of Zurich, Switzerland

Corresponding author: *Sandhage-Hofmann, Alexandra

Institute of Soil Science and Soil Ecology

University of Bonn,

Nussallee 13

D-53115 Bonn

Germany

sandhage@uni-bonn.de

Phone +49 228 73 2780

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Abstract

Woody encroachment is increasingly threatening savanna ecosystems, but it remains unclear how this is driven locally by tenure and management systems. In South Africa, communal land is mainly managed under continuous grazing, while commercial land is under rotational grazing. We hypothesize that woody encroachment has increased since the end of the Apartheid era in 1994, when rotational grazing systems changed to continuous grazing ones in communal land. To test this hypothesis, we sampled six subsites in each of three replicates of these tenure systems in the savannah biome, South Africa, and monitored the degree of woody encroachment and effects on soil using remotely-sensed normalized difference vegetation index (NDVI), dendro-ecology, and grid-based soil analyses. The results confirmed that there has been a positive greening trend over the past 25 years in communal areas due to the higher degree of woody cover, especially for tree height classes between 50 and 150 cm. These trees corresponded to *Senegalia* tree ages between 10 and 25 years. The higher woody cover in communal areas was accompanied by height-dependent elevated nutrient and organic matter concentrations that increased in the topsoils by up to a factor of 1.5 relative to the freehold systems. Isotopic analyses identified debris of C_3 bushes and trees as main carbon input into the soil of communal areas, where the $\delta^{13}C$ value of -20.1‰ was significantly lower than it was at private farms (-19.2‰). Isotopic values also indicated that this carbon input took place beyond the edges of the bush canopy. We conclude that the tenure-based management system in the communal areas has promoted woody encroachment, with the associated changes in soil properties homogenizing the savanna system.

1. Introduction

Savannas cover up to 20 percent of the Earth's terrestrial surface and are home to 20 percent of the Earth's population (Eldridge et al., 2011). Mostly used as rangelands, great parts of these areas have experienced a vegetation change towards a significant encroachment of trees and shrubs over the past 100-200 years. Encroachment means that (mostly) indigenous woody species replace palatable perennial grass species (van Auken, 2009; Angassa and Oba, 2010; Daryanto and Eldridge, 2010; Archer et al., 2017). Such an increase of woody species in density, cover, and biomass has been observed in numerous field (Moleele and Perkins, 1998; Sandhage-Hofmann et al., 2015; Dougill et al., 2016) and satellite-based studies around the world (D'Odorico et al., 2012; Saha et al., 2015; Huang et al., 2018). Current estimates indicate that approximately 10–20 percent of drylands are affected by encroachment (Stevens et al., 2017b). Absolute encroachment rates range between 0.0 and 3.3 percent woody cover year^{-1}, with differences among regions; for example, encroachment rates in Africa were 2.5 times higher than they were for Australia (Barger et al., 2011; Archer et al., 2017; Stevens et al., 2017a).

Woody encroachment appears to result from multiple global and local drivers and interactions between them (Wigley et al., 2010; Eldridge et al., 2011; O'Connor et al., 2014; Archer et al., 2017), although it is still difficult to generalize about causes at regional scales. As a worldwide phenomenon, there is a consensus that global drivers, such as elevated CO_2 concentrations in the atmosphere, can promote growth of woody species via the C_3 photosynthetic pathway (Archer and Stokes, 2000; Stevens et al., 2017a). Also, climate warming or changed precipitation patterns have been discussed as prominent drivers for woody encroachments (Knapp et al., 2008; D'Odorico et al., 2012). However, as the world's population grows, regional drivers such as cattle numbers, grazing practices, and changes in fire management are changing and are likely to contribute to woody encroachment (Valone et al., 2002; Archer et al., 2017). Among these, non-adapted rangeland management practices with overgrazing and associated spreading of bush seed by the animals has been assumed to particularly promote woody encroachments (Reid et al., 2008; Teague et al., 2011; Sandhage-Hofmann et al., 2015). Losses of grass cover provide new spaces and resources (nutrients, water) for the establishment of woody plants (February et al., 2013; Archer et al., 2017; Hempson et al., 2017). Furthermore, perennial grass composition is replaced by annual grass species, which are less competitive against shrubs (Oomen et al., 2016). To counteract such management-induced woody encroachment from continuous grazing, it may be helpful to use a rotational rangeland management practice at which soil and vegetation recover in camp-based systems (Teague et al., 2011; Roche et al., 2015; Sandhage-Hofmann et al., 2015).

In South Africa, extensive livestock ranching is mainly practiced on two different land-tenure systems, both closely related to two different rangeland management practices: (i) the privately owned freehold farms with moderate stocking rates under a rotational grazing system; and (ii) the communal areas, where, after the end of Apartheid, management changed from a rotational to a continuous grazing system. Stocking rates are mostly higher than on commercial farms (Naumann, 2014; Sandhage-Hofmann et al., 2015). The communal land tenure system and associated rangeland management are often criticized for having insufficient foresight and permanently high grazing pressure and stocking rates, which leads to a potential deterioration of herbaceous vegetation, even at low stocking rates. Despite criticism of the continuous grazing in communal areas, commercial farms in Botswana have also been found to be affected by the bush invasion (Dougill et al., 2016). Much of this criticism is based on observations near water points. These zones are heavily overused in both management systems, but clearly more difficult to manage under continuous grazing (Snyman and Du Preez, 2005; Kotzé et al., 2013; Sandhage-Hofmann et al., 2015). However, for a correct comparison of systems we must also consider the areas that are more far away from the water point, also belonging to the farm though less frequently visited by the animals. Woody encroachment is mostly seen as a degradation process, because it threatens the livelihood of the rural populations. However, the increase in woody cover does not necessarily imply that the ecological functions of an ecosystem are lost (Eldridge et al., 2011; Archer et al., 2017). For example, studies in rangelands of the Kalahari, but also worldwide, showed that woody encroachment led to an increase of soil fertility with higher carbon, nitrogen, and nutrient concentrations in encroached areas compared to conditions under perennial grasses (Mureva et al., 2018; Thomas et al., 2018). In particular, semi-arid soils with sandy textures may profit from these effects of encroachment (Li et al., 2016), albeit at the expense of rangeland quality usable for the farmer from a social-economic perspective.

It is not easy to measure changes in soil properties in these areas of the savanna because of a pronounced spatio-temporal variability (Scholes and Archer, 1997; Vetter, 2005), which may interact with the density and abundance of woody plants (Sankaran et al., 2005; Holdo and Mack, 2014; Sandhage-Hofmann et al., 2015). A higher degree of woody cover could potentially reduce the spatial variability of properties (Breshears, 2006). To unravel the direction of change in the savanna's heterogeneity, stable ^{13}C isotope tracing in soils may help, because grass and woody plants have different photosynthetic pathways that lead to higher $\delta^{13}C$ values in C_4-grasses (~13‰) and lower $\delta^{13}C$ values in C_3 trees (~26‰) and, thus, also in soils (Liao et al., 2006b). Therefore, a well-documented, plant-specific soil sampling followed by carbon isotope analyses at natural abundance level can provide information on the source of C-input, their spatial distribution in soils, as well as on past vegetation shifts (Liao et al., 2006a; Bai et al., 2012a).

This study was performed to test the hypotheses that (i) woody encroachment is more pronounced in communal areas with continuous grazing, (ii) that the higher degree of woody cover led to higher soil nutrient concentrations and higher organic matter status, and (iii) to reduced spatial heterogeneity in these soil properties. For this purpose, we sampled both tenure systems in three independent replicates, with each replicate containing six randomly selected plots within the Kuruman area of the savanna biome, South Africa. We mapped vegetation by aerial photography, with grid-based plant assessment and soil sampling (0–10 cm) on the ground. Historical changes in woody encroachment were traced using both past remote sensing records and stable carbon isotopic analyses.

2. Material and Methods

2.1 Study Sites

The study was conducted close to Kuruman, situated at the border of the Northern Cape and North-West Province of South Africa, at the fringe of the Kalahari (27°-28° S, 22°-24° E, 1047 m – 1161 m a.s.l.) (Fig. 1). The climate is semiarid. Precipitation occurs mainly during summer months, from October to March, with around 300–340 mm annually (see Table 1). The mean annual temperature is 17.5°C (Sandhage-Hofmann et al., 2015; Kotzé et al., 2017). The vegetation has been described as the Eastern Kalahari Thornveld (Mucina and Rutherford, 2006), which is characterized by a fairly well developed tree stratum with *Vachellia erioloba, Senegalia mellifera, Acacia haematoxylon*. The shrub layer is dominated by *Senegalia mellifera, Acacia hebeclada, Grewia flava* and *Vachellia haematoxylon*. The herbaceous layer contains perennial C_4 bunchgrasses, such as *Schmidtia pappophoroides* and *Schmidtia uniplumis, Aristida stipitata*, and *Eragrostis lehmanniana* (Oomen et al., 2016). Geologically, northern South Africa is comprised of Kalahari sands. Here, deep and nutrient-poor Arenosols (WRB, 2007) of aeolian origin developed with an average total sand content of 94 percent (Table 1) (Sandhage-Hofmann et al., 2015) .

In the study region, the grazing land was predominantly dominated by grass at the beginning of the 19th century, but later became a more bushy region (Jacobs, 2000, 2003; Joubert et al., 2013). Two tenure systems – commercial, freehold farms with rotational grazing and communal areas practicing continuous grazing – can be found in close proximity (Fig. 1). We sampled both systems at regional scale (that is, consciously decoupled from grazing gradients) in order to evaluate woody encroachment and its effect on soil properties as related to tenure and associated management system.

2.2. Current rangeland management

Communal and commercial tenure systems are common in the Kuruman area, but they differ in their management practices. Freehold commercial farms utilize a rotational grazing system with long-term moderate stocking rates, located in the Northern Cape. Camps are fenced and cattle herds moved between camps to allow vegetation and soil to restore between grazing periods. The communal areas current practice a continuous grazing system. These areas belong to the former homeland of Bophuthatswana, North-West Province, where most of them were previously owned by commercial farmers (Jacobs, 2003). Historical studies show highly fluctuating data for livestock numbers, including cattle, sheep, goats, and donkeys. The first large increases in livestock numbers occurred between 1920 and 1960, together with growing human population. A second rise followed after the implementation of self-government in Bophuthatswana in 1972, where cattle numbers doubled within 10 years (Jacobs, 2000). During the Apartheid regime, there was a three-camp, three-year system of seasonal rotation for soil conservation and controls were imposed on livestock numbers to prevent overgrazing (Jacobs, 2000). After end of Apartheid, this system was continued only in the commercial farms; in the communal areas, the practice of rotational grazing was replaced by a continuous grazing system (Naumann, 2014). There, communal production systems are based on pastoralism and grazing areas are shared by the community members. Communal stocking rates likely fluctuated from 1990–2010 depending on drought events, which reduced livestock drastically (Oomen et al., 2016). Fire is consciously excluded in the Kuruman area. Woody density was partly controlled by herbicides (van de Booysen and Tainton, 1984) on freehold farms, but not intensely. In communal areas, however, targeted bush control was absent; here woody plants were used as firewood and browsed by goats (Williams and Shackleton, 2002).

In the study area, the estimated grazing capacity of the rangelands is 13 ha per livestock unit (LSU^{-1}) (Department of Agriculture, Forestry & Fisheries, 2018). The main encroacher species is *Senegalia mellifera*, which exists as a multi-trunked bush or as a single-trunked tree.

2.3 Collection of soil samples

We selected three villages from communal areas, and three freehold farms as independent replicates of land use (n= 6) (Figure 1). Within each of these farms and villages, soil samples were taken in March 2014 on six randomly selected plots of 100 x 100 m (1 ha) on each independent replicate; we sampled a total of 36 plots. Random plot selection was performed using ArcGis 10.3, where we first established buffer zones of 100 m around streets, fences, and buildings to avoid confounding effects. We explicitly excluded water points with grazing gradients, as these had been studied in previous research (Sandhage-Hofmann et al., 2015). Before soil sampling, we laid a regular grid of 25 sampling points across the plots of 1 ha, each point being linked to GPS coordinates (see Fig. 1). At each sampling point, soil samples were taken with a soil auger from 0–10 cm soil depth. We also performed a ground truthing, where we recorded the respective plant species – grass, bushes– or, if present, bare soil. If the GPS point was under a shrub or tree, we recorded the height of the bushes/trees as well as the diameter of the crowns. If not, we measured the distance between the sampling point, canopy and stem to the next woody species, where the height and diameter were also recorded. Additionally, for each tenure system, we sampled a representative soil profile up to 1 m soil depth under grass.

2.4. Aerial imagery and remote sensing

2.4.1. Land cover categorization using octocopter images

Aerial photographs were taken to analyze the effective encroached area of the sampled plots in both tenure systems using an octocopter (Highsystems, www.mikrokopter.de), equipped with a camera (Sigma DP1 Merrill, 14 megapixel, 19 mm focal length). Images were categorized in three different land cover categories or units: “bushes/shrubs”, “grass”, and “bare soil”. The unit “bushes” included any woody plant (for details, see SI).

2.4.2. Annual Landsat time-series

An annual time-series of composite Landsat imagery was processed using Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus 7 (ETM+), and Landsat 8 Operational Land Imager (OLI), Top of the Atmosphere (TOA) reflectance scenes, available via Google’s Earth Engine. We used these images to record the time trajectory of woody encroachment between 1984 and 2015 with minimum dry season Normalized Difference Vegetation Index (NDVI) as a measure of vegetation productivity and an indicator presence of woody vegetation, which remains partially photosynthetic during the dry season (Symeonakis et al., 2016; Wingate et al., 2018). Accordingly, trends were calculated for communal areas and freehold farms, using the trend estimation based on annual aggregated time series method proposed by (Forkel et al., 2013). Trend slope (%) and P-value were calculated, with the NDVI data series being the dependent variable and time being the independent variable.

2.5. Soil analyses

Particle-size analyses was performed by the sieve-pipette method (The Non-Affiliated Soil, Analysis Work Committee, 1990), where five out of the 25 samples of each plot (n=180) were taken. These five samples were also taken for nutrient analyses. For carbon and nitrogen, as well as for isotope analyses, all soil samples were processed (n=962). Samples were air-dried, sieved (<2 mm), and homogenized prior to analysis. 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, based on Na). The abovementioned elements were determined by atomic absorption spectroscopy. Total C and N were determined by dry combustion using a CHNS analyzer (Elementar-Analysensysteme GmbH, Germany). There was no detectable inorganic C, which meant that the total C was equal to organic C, further called SOC). $\delta^{13}C$ and $\delta^{15}N$ were analyzed using an isotope ratio mass spectrometer (Delta V Advantage IRMS, Thermo Electron Corporation, Germany) according to Equation (1)

$$\delta = [(R(sample)-R(standard)) / R(standard)] * 1000 \qquad (1)$$

where R(sample) is the $^{13}C/^{12}C$ and $^{15}N/^{14}N$ isotope ratio of the sample and R(standard*)* is the $^{13}C/^{12}C$ and $^{15}N/^{14}N$ isotope ratio of the standard with respect to the V-PDB standard for carbon isotopes and the atmospheric dinitrogen standard for nitrogen isotopes (Coplen et al., 2006).

2.6. Tree-ring analyses

Tree-ring analyses were performed for dendrochronical studies to ascertain the ages of the woody vegetation. Stem discs were taken as near to the soil surface as possible. Additional discs were cut to test whether discs at the defined root-shoot boundary indeed displayed the highest ring counts. In total, 285 discs were analysed. The discs were polished on a belt sander to see the wood's anatomical structure using a stereo microscope at 10–80 x magnification. Tree-rings were counted along two to four radii. For further details see Zacharias et al. (2017).

2.7. Statistical analyses

All statistical analyses were performed using Statistica 9.1 package for Windows (StatSoft Inc, 9.0 2010). Data were first checked for normality using the Shapiro-Wilk test. Data were found to be normally distributed and required no transformation. To test the hypothesis that mean values of the dependent factors (woody cover, soil organic carbon, TN, main nutrients) were significantly different at different tenure systems with different management system, we used main-effects analysis of variance (ANOVA), also testing the interactions between tenure * soil cover types. Levene's F statistic was used to test the homogeneity of variance. Fisher's post-hoc test was used.

3. Results

3.1 Woody encroachment

Aerial photographs showed that the communal areas with continuous grazing had significantly more woody cover than the freehold farms ($p<0.001$); the same was true for the percentage of bare soil ($p<0.001$) (Fig. 2). In contrast, the freehold farms with rotational grazing showed significantly more grass cover. The analyses of ground records confirmed the greater abundance of woody species in in communal study sites; there, 32 percent of all soil samples were located under woody vegetation, values on freehold farms were only 20 percent. In contrast, only 20 percent of the samples in communal areas were beneath grass (vs. 40 percent for FRG). Ten percent were classified as unpalatable herbs, which were almost non-existent at private farms. The time series trends of the NDVI confirmed the results and showed that communal areas exhibited a significant greening trend over the past 25 years (Fig. 3). The freehold farms showed only a weak positive trend, but no significant temporal trend in NDVI. Hence, woody encroachment was more advanced in communal systems than in freehold systems, and these differences largely manifested in the last 25 years; that is, since the end of Apartheid.

3.2. Height and age of woody vegetation

The height distribution of *Senegalia mellifera* revealed that, in the communal areas, 67 percent of all recorded bushes were between 25 and 150 cm high, with an enhanced occurrence in the range of 50–100 cm. On freehold farms, all height classes were more equally distributed (Fig. 4a). Dendro-ecological studies, combined with measurements of height and crown diameter, showed that the height of *Senegalia mellifera* was linearly correlated with age (r^2=0.8 and r^2=0.84; $p<0.0001$, for freehold and communal, respectively) (Fig. 4b). Heights of 25–150 cm in continuous grazing system were equal to ages of the bushes up to 28 years. This means that 67 percent of the bushes recorded in communal areas developed within the last 25 years.

3.3. Physical soil properties

The soils in the Kuruman area showed the Arenosol-typical predominance of sand (94 percent) with low contents of silt and clay (Table 1). The overall textural composition was identical at the different sites. Detailed analyses of the silt and sand composition pointed to some significant variations within the sand fraction, with more fine sand in communal areas and higher contents of coarse sand at freehold farms, respectively (Table 1). To test whether these fine differences might have affected water status, we modeled the actual evapotranspiration using hydraulic parameters. They did not point to any significant differences between both tenure types. (Data and results, see Table S1–S2; SI). Additionally, no significant relations between sand composition and bush encroachment were detected. Hence, basic soil properties like texture did not control the differences in woody encroachment between communal and freehold systems.

3.3. Soil chemical properties

3.3.1 Nutrients and pH

The Arenosols typically showed a low nutrient status with an averaged cation exchange capacity (CEC) of 571 (±107) mg kg^{-1} soil at 0–10 cm soil depth in freehold farms, and of 600 (±130) mg kg^{-1}soil in the samples from communal areas (Table 2). These differences were significant ($p<0.001$). The higher nutrient status in the latter was also evident for Ca and Mg, as well as for the pH value. In contrast, concentrations of P, Fe and Mn were higher in freehold farms ($p<0.001$).

3.3.2 Soil organic matter

Concentrations of soil organic carbon (SOC) and nitrogen (TN) were significantly larger in the communal systems with continuous grazing than in the freehold ones with rotational grazing (3.7 vs. 2.5 g SOC kg^{-1} soil, respectively) (Table 2). There were also significant differences in SOC concentrations between the three main land cover units, following the order *Senegalia mellifera* > grass > bare soil (Fig. 5), with consistently larger values in the communal areas.

With increasing height of the trees, which simultaneously means increasing age of *Senegalia mellifera,* we found higher carbon and nitrogen concentrations at 0–10 cm soil depth (Figure 6 a-d). This relationship was significant in both tenure systems (communal: $r=0.41$ and $r=0.48$, for C and N, respectively; freehold: $r=0.47$, and $r= 0.44$ for C and N; $p < 0.05$ for all correlations). Again, the communal systems displayed consistently larger SOC concentrations at a given tree height than the freehold ones did.

3.3.3. Origin of carbon

The stable carbon (C) isotopic composition ($\delta^{13}C$) of plant litter reflected the differences in the photosynthetic pathways between the C_4 grasses ($\delta^{13}C$ = -13.3‰) and the C_3 plant *Senegalia mellifera (*$\delta^{13}C$= -27.7‰). For instance, the soil $\delta^{13}C$ values under grasses ranged from -18.9 and -17.4‰, while beneath *Senegalia spec* they ranged from -22.0 to -21.7‰ in both systems, respectively. Overall, the topsoils of communal areas showed a significantly smaller averaged $\delta^{13}C$ value of -20.1‰ (± 2.2) than did the freehold ones with a $\delta^{13}C$ value of -19.2‰ (± 2.5) (F=3.98, p=<0.001). The $\delta^{13}C$ values were larger in deeper soil and approached values of -14.2‰ and -15.3‰ below 30–40 in communal areas and freehold farms, respectively. Hence, grasses had been the main vegetation type at both study sites (Table 3).

The size of the *Senegalia* bushes correlated inversely with the isotopic composition of soil carbon: samples near larger bushes exhibited smaller soil $\delta^{13}C$ values (Fig. 6 e-f). The influence of the C_3 vegetation on SOC concentrations and $\delta^{13}C$ values diminished with increasing distance from the canopies and the stems of the woody vegetation (Fig. 7). This effect was weaker in communal areas (r=0.36 for distance to stem; r=0.40 for distance to canopy; p<0.001) than in freehold farms (r=0.55 for stem; r=0.60 for canopy; <=0.001).

The soil $\delta^{15}N$ were significantly larger in freehold farms (8.3‰) than at communal areas (6.1‰) (Table 2). There was a significant positive correlation between bush/tree height and soil $\delta^{15}N$ values (Fig. 6 g, h).

4. Discussion

4.1 Woody encroachment in different management systems

Around 50 years ago, the Northern Cape and North West province of South Africa were open grassland savannas, as documented by historical aerial photographs as well as oral and written records (Jacobs et al., 2000; Belayneh, 2017). Nowadays, they are one of the regions in South Africa most affected by woody encroachment, with between 3.5 and 14 percent threatened by *Senegalia mellifera* as the main encroaching species (Department of Agriculture, Forestry and Fishery, 2017). In our study, 25 percent of the investigated areas were encroached, which clearly exceeds the above-mentioned values. Confirming our hypothesis, but in contrast to the results of former studies, the degree of woody cover was larger at communal (32 percent) than at freehold farms (20 percent) (Kgosikoma et al., 2012; Dougill et al., 2016); this is largely due to greening from 1984–2017, as indicated by our trend analysis using Landsat NDVI.

Our soil isotopic analyses confirmed the presence of C4 grass vegetation residues ($\delta^{13}C \leq 15‰$) in deeper soil, suggesting that the establishment of woody plants has occurred mainly in recent decades, as other researchers have reported (Table 3) (Liao et al., 2006b). Isotopic values in the topsoil of the communal systems were much larger, exceeding 3‰ as potentially attributed to 13C discrimination processes upon SOM degradation (Biggs et al., 2002; Dumig et al., 2008), and thus representing plant debris from the trees and bushes, mainly via litter into the surface soil. The isotopic shift was missing in freehold farms, supporting the argument that there was little recent wood encroachment.

The causes for woody encroachment can be manifold, but the global drivers such as rising atmospheric CO_2 levels affected both land-use systems in a similar way and cannot explain the observed differences. However, higher rainfall could promote growth of woody species (Sankaran et al., 2005; Devine et al., 2017), and differences of up to 40 mm can be deduced for the different coordinates of the systems. Nevertheless, a 40 mm difference in rainfall would only lead to a maximum increase of 5 percent in bush/tree cover (Sankaran et al., 2005). This worst-case scenario is much lower than the 12 percent difference in tree cover observed at our plots. Also, as there was no significant difference in the effects of sand composition on evapotranspiration rates, our study clearly points to local drivers such as rangeland management as the main reason for the differences in woody cover.

Over the last half-century, the communal areas have been stocked more heavily than the freehold ones, which is likely to have had a predisposing effect on subsequent woody encroachment (see 2.1). Increasing grazing pressure is considered as one of the main causes of land degradation in the Kuruman area (Department of Agriculture, Forestry and Fishery, 2017) and is generally correlated with elevated woody cover (Oba et al., 2000). Apart from an excessive number of animals, overgrazing may also be caused by animals staying longer at a particular stop (Tefera et al., 2007). In this regard, the continuous grazing system experienced permanent grazing pressure over time, thus promoting the degradation of rangeland in a similar way as long-term high average stocking rates (Ward et al., 2014; Sandhage-Hofmann, 2016). Since the end of Apartheid, such a permanent and intense grazing pressure was maintained on vegetation and soil in the communal grazing systems of Kuruman area, largely because the breakdown of infrastructure like broken water pumps and lacking fences did not provide alternatives for herd movement (Naumann, 2014).

4.2 Impact on soils

Increasing woody cover is known to alter soil properties, leading to elevated SOC, TN, and nutrient concentrations (Mureva et al., 2018). In our study, the Arenosols formed by Kalahari sand are typically poor in nutrients (Dougill et al., 2010). Given a larger degree of woody cover and according to our hypothesis, the soil nutrient concentrations were larger in the communal systems than in the freehold ones (most pronounced for K and Mg, but also valid for SOC and TN), which corresponds with previous reports on the impact of woody cover on these soil properties (Dougill et al., 1999; Sandhage-Hofmann et al., 2015; Li et al., 2016; Mureva et al., 2018). Various aspects contribute to this nutrient and organic matter enrichment, such as higher above- and below-ground productivity, litter fall, dung of resting livestock, lower decomposition rates under shaded trees, as well as elevated biochemical recalcitrance of woody litter (Liao et al., 2006a; Knapp et al., 2008; Throop et al., 2013).

According to Ward et al. (2018), nutrient and SOM accrual correlate with shrub size. This was also true for our study; however, as we dated the trees, we could relate these data directly to tree age. The data suggest that it takes about 15–17 years for the tree to grow 1 m, which is accompanied by an increase in SOC concentration of about 3.5 g kg^{-1} soil at both management systems during this period (Fig 6).

In general, the distribution of nutrients and soil organic matter is patchy and potentially related to the expansion of woody species ("islands of fertility") in dryland ecosystems (Hagos and Smit, 2005; Bai et al., 2012a; Bai et al., 2012b). In both tenure systems of our study, SOC-enrichment factors under woody species relative to areas below grass and bare patches reached factors between 1.7 and 2.0, respectively (Table 2; Fig. 5). This was lower than found in Botswana, where differences in SOC concentrations between woody species (*Vachellia erioloba*) and grass reached a factor of up to 4 (Thomas et al., 2018). *Vachellia erioloba* was also part of the savanna system in Kuruman area, although here this species did not occur as an encroacher but as trees reaching heights of more than 10 m. The SOC enrichment factors under such large trees were similar to those reported by Thomas et al. (2018).

It is noteworthy that elevated SOC concentrations in communal systems were also observed in areas under grass and bare soil (Table 2). Obviously, woody vegetation influenced the input of organic carbon far beyond the canopy. The stable ^{13}C isotope analyses supported this assumption and showed that SOC derived from grass was partially replaced by SOC from the invading C_3 woody vegetation (Liao et al., 2006a; Bai et al., 2012a; Mureva et al., 2018). The analyzed mean values of $\delta^{13}C$ in soils of the Kuruman area were finally similar to those reported for wooded landscape elements worldwide (-20‰– -15‰) (Boutton et al., 1998), suggesting that our findings are well representative also for other areas of the world.

Bai et al. (2012) analyzed the influence of mesquite plants (in this case encroached ones) in soils of the surrounding grassland. Their results showed that the woody vegetation affected the soils even to a distance of 10 m away from the tree. The authors attributed their findings to the extensive rooting system of trees and shrubs in semi-arid and arid regions, which may often expand by several meters. Our soil $\delta^{13}C$ values confirmed that the influence of the tree on soil properties was largest near the stem (Belsky, 1994). With increasing distance to the stem, soil $\delta^{13}C$ values increased due to elevated portions of grasses. However, the respective gradients were smaller at communal than at freehold farms (Fig. 7); that is, at the scale of the landscape soil properties homogenized. Studies in Australia showed that SOC accrual was largest when the cover was between one-third and a half of the area (Soliveres et al., 2014a; Soliveres et al., 2014b), due to optimum connectivity between canopy and inter-canopy patches (Breshears, 2006). Above 50 percent woody cover, competition between woody vegetation for nutrients and water outweighs the benefits of SOC accumulation. However, this threshold was not reached at our sites and homogenization of soil properties is most likely.

The encroachment of woody plants not only influenced the $\delta^{13}C$ values, but also resulted in lower soil $\delta^{15}N$ values. As *Senegalia mellifera* is a nitrogen-fixing species (Bai et al., 2013), it lowers the soil $\delta^{15}N$ value when incorporating atmospheric N_2 into the biomass (for more details, see Houlton et al., 2007). In our study, the soil $\delta^{15}N$ values were more than 2‰ lower in the communal systems than in the freehold ones ($p<0.001$). Thus, nitrogen isotope analyses also reflect that the elevated woody encroachment altered soil properties, not only via nutrients and SOC, but also by altering the origin of soil N (Liao et al., 2006a; Boutton and Liao, 2010; Zhou et al., 2018).

5. Conclusion

Woody encroachments threaten great parts of savanna systems worldwide. We have investigated the role of local drivers by different tenure systems on woody plant establishment and related soil properties. Woody encroachment occurred in both tenure systems, but was significantly more pronounced in communal systems. NDVI analyses suggested that this greening trend occurred after rotational grazing had to be switched to continuous grazing management since 1994, though the patterns were heterogeneous. Approximately 60 percent of bushes and trees have been established in the last 25–28 years. In accordance with our hypotheses, the advanced woody encroachment promoted the accrual of nutrients, as well as of soil organic carbon and total nitrogen, both largely derived from the upcoming *Senegalia mellifera* trees. We conclude that rangeland management was a major driver for woody encroachment in Kuruman area; however, our data also show that there is a chance to minimize woody plant encroachment by changing the management to more foresighted practices in the future, although this will require the support of communities in terms of establishing fences around diverse watering points.

Authors' contributions

Alexandra Sandhage-Hofmann, Jörg Löffler, Elmarie Kotzé, Chris C. du Preez, and Wulf Amelung worked together in preparation of the study design, and/or analysis and interpretation of the data. Dirk Wundram and Roland Pape were responsible for the aerial photographs, Vladimir Vingate for the evaluation of the remote sensing data. Stef Weijers conducted the dendro-ecological evaluation and Lutz Weihermüller was responsible for the hydrological modeling. The submitted paper was revised and approved critically by all authors.

Competing interest statement

There is no conflict of interest.

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Table 1: Study sites in the Kuruman area. Particle sizes in g $100g^{-1}$ soil followed by standard deviation (*±S.D*). Different letters indicated significant differences between freehold farms and communal areas using Tukey HSD t-test ($p<0.001$). Stocking rate calculated in ha Livestock Unit $(LSU)^{-1}$, data for the past 5 years.

Tenure	Grazing system	Manage-ment structure	Stocking rate	Mean annual Precipi-tation	Major referen-ce soil group [74]	Clay	Fine silt	Coarse silt	Very fine sand	Fine sand	Medium sand	Coarse sand
			ha LSU^{-1}	mm		<0.002 mm	0.002-0.02 mm	0.02-0.05 mm	0.05-0.1 mm	0.1-0.25 mm	0.25-0.5 mm	0.5-2.0 mm
Free-hold	Rota-tional grazing	Single, commer-cial manager	14.2 *±4*	292+-72a	Haplic Areno-sol	3.3 *±0.7* a	2.26 *±1.2* a	0.65 *±0.4* a	10.0 *±1.6* a	55.3 *±8.3*a	19.6 *±4.0*	9.7 *±5.8*a
Com-munal	Conti-nuous grazing	Multiple managers in villages	13.1 *±3.8*	336 +-82b	Haplic Areno-sol	3.2 *±0.6* a	2.6 *±1.3* a	0.7 *±0.8* a	10.6 *±1.6* a	67.4 *±3.5*b	14.8 *±3.7*	1.4 *±1.1*b

Table 2: pH, soil nutrient concentrations followed by standard deviation (± S.D.) of commercial farms with rotational grazing and communal areas with continuous rangeland management systems. Different letters indicate significant differences between the tenure systems using Fishers post-hoc tests ($p<0.001$). (*results of ground-truthing.)

	total	*Senegalia spec.*	grass	bare soil
Freehold farms		n=93	n=177	n=142
N (g kg^{-1})	0.3^{a} ±0.1	0.4^{a} ±0.2	0.3^{a} ±0.1	0.2^{a} ±0.1
C (g kg^{-1})	2.5^{a} ±1.4	3.6^{a} ±1.8	2.1^{a} ±0 9	1.8^{a} ±0.9
Ca (mg kg^{-1})	247^{a} ±92.7	246^{a} ±86.4	249^{a} ±97.6	253^{a} ±88.1
Mg (mg kg^{-1})	43^{a} ±12.9	42.1^{a} ±12.1	43.5^{a} ±13.9	42.5^{a} ±12.1
K (mg kg^{-1})	54^{a} ±19.4	52.8^{a} ±15.7	54.8^{a} ±20.5	55.9^{a} ±18.3
Na (mg kg^{-1})	6.7^{a} ±3.7	6.7^{a} ±3.8	6.4^{a} ±3.7	7.2^{a} ±3.7
CEC (mg kg^{-1})	571^{a} ±130	585^{a} ±132	568^{a} ±126	579^{a} ±132
pH (H_2O)	5.9^{a} ±0.3	5.9^{a} ±0.3	5.9^{a} ±0.3	5.9^{a} ±0.3
Cu (mg kg^{-1})	0.2^{a} ±0.04	0.2^{a} ±0.0	0.2^{a} ±0.0	0.2^{a} ±0.0
Zn (mg kg^{-1})	0.2^{a}	0.2^{a} ±0.1	0.2^{a} ±0.1	0.2^{a} ±0.1
Fe (mg kg^{-1})	6.5^{a} ±0.1	6.7^{a} ±2.1	6.2^{a} ±1.6	6.7^{a} ±2.0
Mn (mg kg^{-1})	5.8^{a} ±1.9	6.0^{a} ±2.1	5.6^{a} ±1.8	6.0^{a} ±2.0
P (g kg^{-1})	3.8^{a} ±0.8	3.8^{a} ±0.7	3.8^{a} ±0.8	3.8^{a} ±0.7
$\delta^{13}C$ (‰)	-19.24^{a} ±2.6	-21.7^{a} ±2.1	-17.4^{a} ±1.4	-18.6^{a} ±1.7
$\delta^{15}N$ (‰)	8.3^{a} ±1.3	8.6^{a} ±1.3	7.9^{a} ±1.3	8.7^{a} ±1.1
Fc (%)	59.0^{a} ±17	41.5^{a} ±15	71.8^{a} ±10	63.1^{a} ±12
Vegetation (% ha^{-1})*		20	40	30
Communal areas		n=128	n=96	n=139
N (g kg^{-1})	0.4^{b} ±0.0	0.5^{b} ±0.3	0.4^{b} ±0.1	0.3^{b} ±0.1
C (g kg^{-1})	3.7^{b} ±2 0	5.1^{b} ±3.7	3.2^{b} ±1.1	2.6^{b} ±0.1
Ca (mg kg^{-1})	337^{b} ±92.6	339^{b} ±97.8	332^{b} ±97.5	337^{b} ±94.7
Mg (mg kg^{-1})	49^{b} ±17.0	52.1^{b} ±17.9	48.2^{b} ±18.1	45.8^{b} ±15.5
K (mg kg^{-1})	55^{a} ±26.1	59.6^{b} ±24.6	51.4^{a} ±23.2	49.3^{b} ±26.9
Na (mg kg^{-1})	4.9^{b} ±2.1	4.9^{b} ±2.0	5.1^{b} ±2.2	4.8^{b} ±2.2
CEC (mg kg^{-1})	600^{b} ±107	605^{b} ±112	591^{a} ±112	592^{a} ±108
pH (H_2O)	6.3^{b} ±0.4	6.3^{b} ±0.4	6.2^{b} ±0.4	6.4^{b} ±0.4
Cu (mg kg^{-1})	0.2^{b} ±0.3	0.2^{a} ±0.2	0.2^{a} ±0.3	0.3^{b} ±0.4
Zn (mg kg^{-1})	0.2^{a} ±0.1	0.2^{a} ±0.1	0.2^{a} ±0.1	0.2^{b} ±0.1
Fe (mg kg^{-1})	5.1^{b} ±0.9	5.1^{b} ±0.8	5.4^{b} ±0.9	5.1^{b} ±1.0
Mn (mg kg^{-1})	5.6^{a} ±1.3	5.6^{a} ±1.3	5.9^{a} ±1.7	5.4^{b} ±1.1
P (g kg^{-1})	3.6^{b} ±2.6	3.6^{a} ±2.7	3.5^{b} ±1.9	3.3^{b} ±2.4
$\delta^{13}C$ (‰)	-20.05^{b} ±2.3	-22.0^{b} ±1.9	-18.9^{b} ±1.6	-19.2^{b} ±1.5
$\delta^{15}N$ (‰)	6.1^{b} ±1.6	6.1^{b} ±1.	6.0^{b} ±1.8	6.3^{b} ±1.5
Fc (%)	53.5^{b} ±15	40.0^{b} ±13	62.2^{b} ±11	59.2^{b} ±11
Vegetation (% ha^{-1})		32	20	31

Table 3: $\delta^{13}C$ (‰) and $\delta^{15}N$ (‰) in bulk soil of soil profiles in freehold farms with rotational and communal areas with continuous grazing system (n=1) in different soil depth (cm).

	Soil depth (cm)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
Freehold farms	00–20	-16.3	8.6
	30–40	-15.3	9.1
	40–60	-15.1	9.1
	60–80	-15.0	9.0
	80>100	-15.4	9.2
Communal areas	0–10	-20.6	7.9
	10–20	-17.9	7.7
	30–40	-14.2	8.5
	40>60	-14.4	8.0

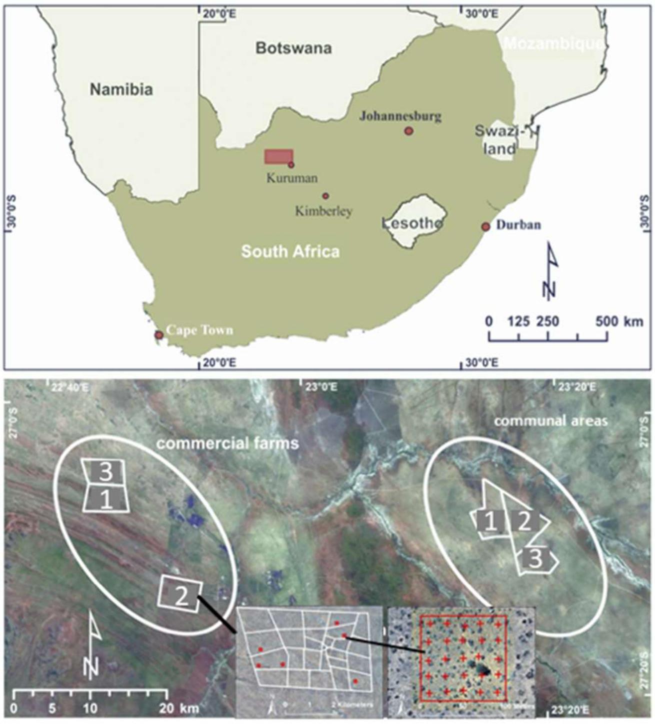

Figure 1: Location of studied sites in Kuruman. Communal areas with continuous grazing (1-3) were located in the East and freehold farms with rotational grazing (1-3) in the West. The small picture on the left shows an example of the random plots within one farm area; the small picture on the right shows the regular grid within each studied plot.

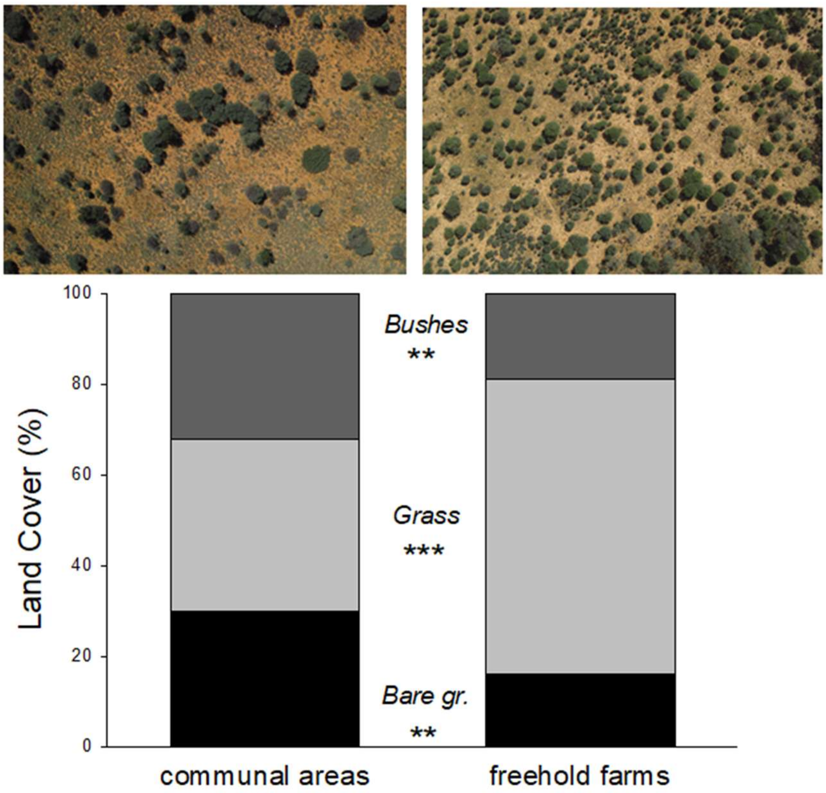

Figure 2: Selected aerial pictures, illustrated here for two random plots in the different tenure system, and resulting overall calculation of the percentages of the land cover units bushes (dark grey color) , grass (light grey color) and bare ground (black color) in freehold farms with rotational grazing, and communal areas with continuous grazing. Statistical difference is reported as **for the $p < 0.01$, and ***for the $p < 0.001$ level of significance, respectively.

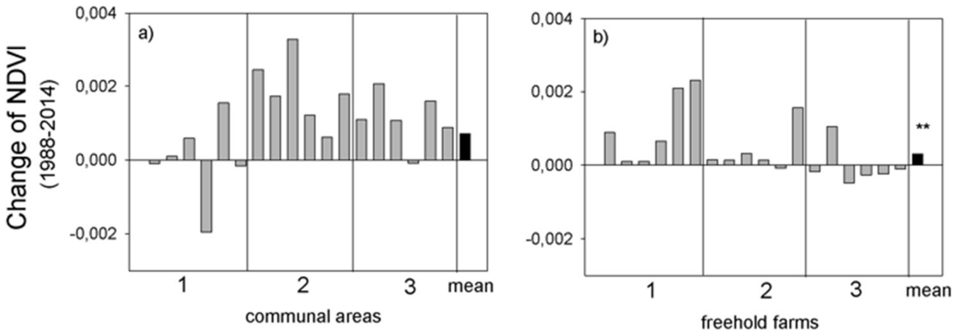
Change of NDVI
(1988-2014)
0,004
0,002
0,000
-0,002
a)
1
2
3
mean
communal areas
b)
**
1
2
3
mean
freehold farms

Figure 3: Slope of greening, calculated by the Normalized Difference Vegetation Index (NDVI) data series (1984-2014), plotted for each studied plot and as mean for all plots (black column) in a) communal areas with continuous grazing and b) freehold farms with rotational grazing; (see Fig. 1). Values above 0.00 represent an increasing greening trend, values below, a decreasing one. Black columns are the means of the 3 communal areas and freehold farms, respectively. The level of significance are reported as ***$p < 0.001$.

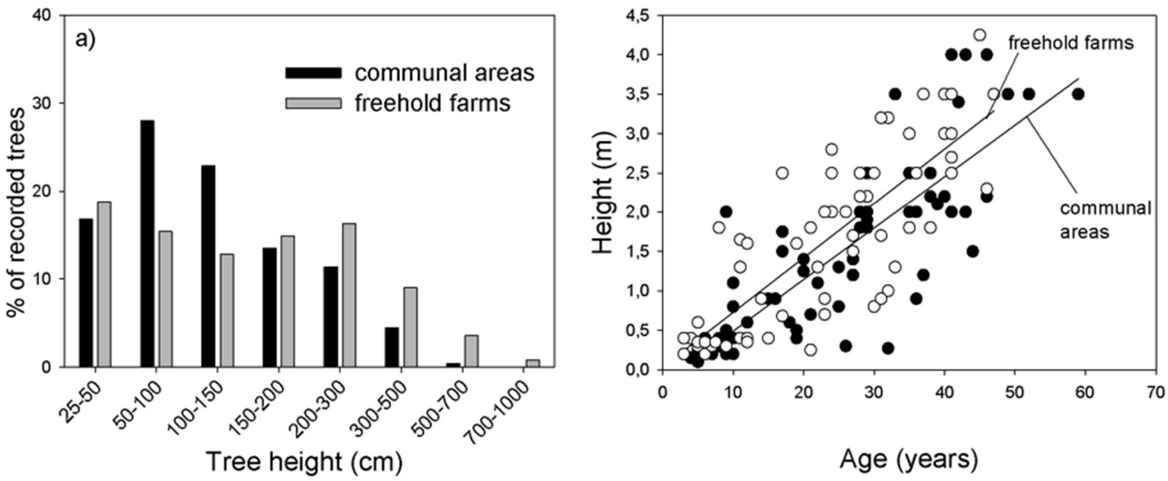

Figure 4: a) Height distribution (%) of *Senegalia mellifera* in communal areas with continuous grazing and commercial farms with rotational grazing and b) relationship between height and age of *Senegalia* mellifera. Values were plotted based on real tree-ring counts in both tenure systems, which means n=142 for communal areas and n=130 for freehold farms.

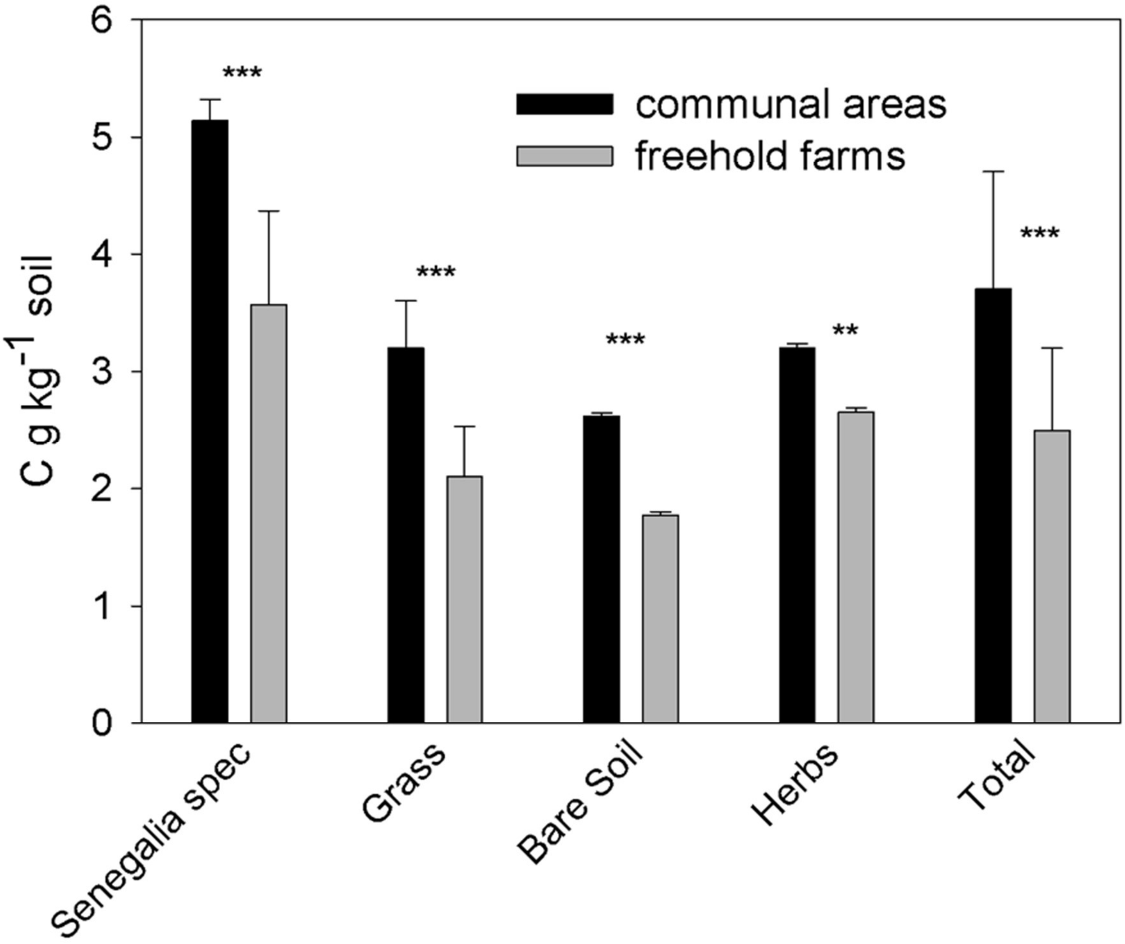

Figure 5: Soil organic carbon (SOC) in communal areas with continuous grazing and in commercial farms with rotational grazing, separated by different vegetation cover and mean. The level of significance are reported as **$p < 0.01$, ***$p < 0.001$.

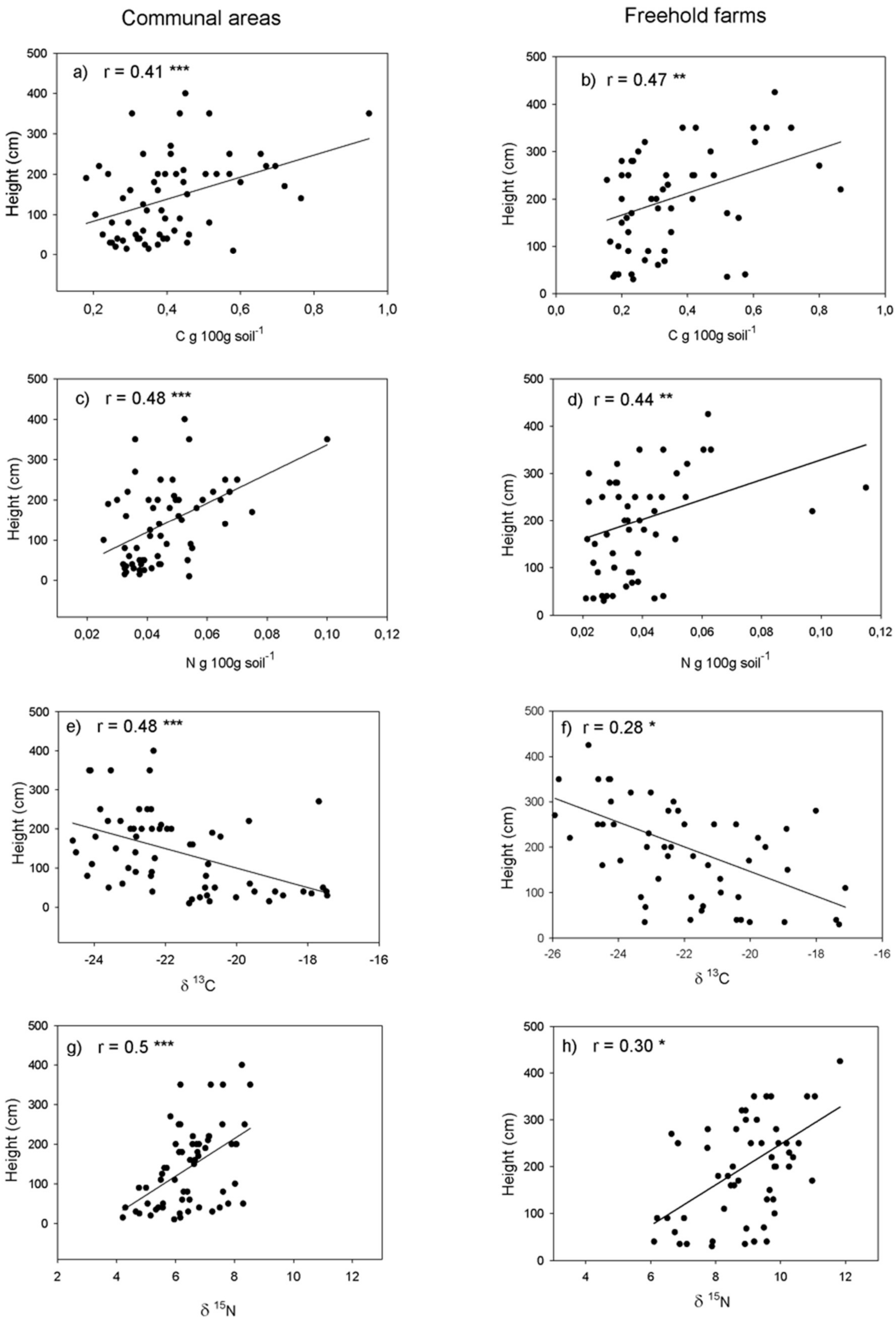
Communal areas
Freehold farms
a) r = 0.41 ***
b) r = 0.47 **
c) r = 0.48 ***
d) r = 0.44 **
e) r = 0.48 ***
f) r = 0.28 *
g) r = 0.5 ***
h) r = 0.30 *
Height (cm)
C g 100g soil-1
N g 100g soil-1
δ 13C
δ 15N

Figure 6: Relationship between heights of *Senegalia mellifera* and soil organic carbon (SOC), $\delta^{13}C_{soil}$ (‰), TN and $\delta^{15}N_{soil}$ (‰)in 6a, 6c, 6e) for communal areas with continuous grazing and 6b, 6d, 6f) for freehold farms with rotational grazing.

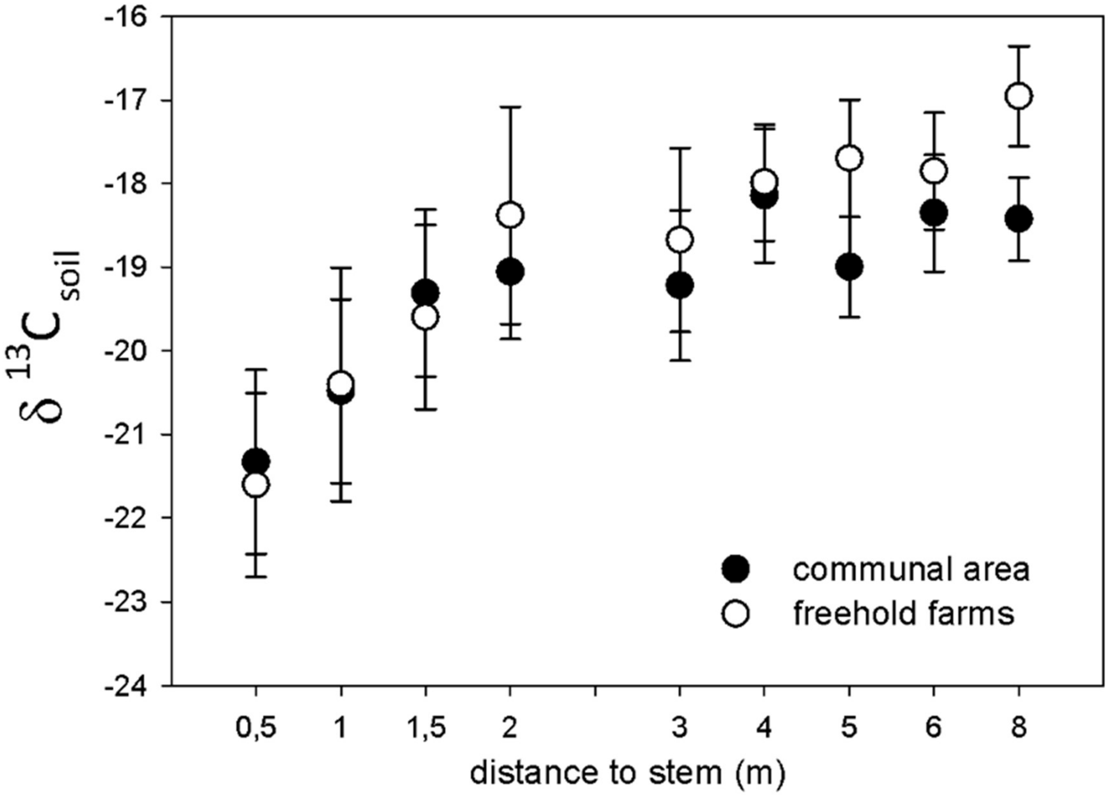

Figure 7: Values of $\delta^{13}C_{soil}$ (‰) (left) and carbon (right) including standard deviation depending on distance to stem of bushes in communal areas with continuous grazing – closed circles - and commercial farms with rotational grazing – open circles. Sample sizes ranged from 6 to 120, depending on distance and system.