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Impact of communal land use and conservation on woody vegetation structure in the Lowveld savannas of South Africa

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ABSTRACT

Millions of people rely on savannas for ecosystem services, such as the provision of grazing and fuel wood, so it is important to determine the extent to which utilization affects woody vegetation resources. Using airborne LiDAR from the Carnegie Airborne Observatory (CAO), we quantified and compared tree canopy cover and height distributions between areas of contrasting management in the Lowveld savanna region of South Africa – a region connecting communal landscapes with heavy utilization (especially fuel wood harvesting) to fully protected public (Kruger National Park – KNP) and private reserves (SabiSand Game Reserve – SSGR) that conserve biodiversity. Differences in total woody vegetation cover and cover within functional height classes (1–2 m, 2–3 m, 3–5 m, 5–7 m and >7 m) were investigated between 7 sites located within (i) conservation areas (in KNP, SSGR), (ii) communal rangelands or (iii) cultivated fields in communal areas. The impact of human utilization on wood resources in the communal areas varied widely between sites. Heavy utilization on gabbro substrate greatly reduced total woody cover of the rangelands, while two other communal rangelands that were presumably less intensively utilised had double the total woody cover of conservation areas. Rangelands and fields in most of the communal sites had more vegetation cover in the 5–7 m and >7 m classes than most of the conservation sites, presumably due to the absence of elephants in communal rangelands and the active preservation of large fruiting trees. On granite substrates, which account for the majority of the study area, there was a 50% reduction in woody cover below 5 m in communal rangelands. Although large trees were clearly being conserved in communal rangelands and fields, there was a relatively low cover of vegetation below 5 m, which raise doubts about recruitment and long-term sustainability of the tree resources. These results in conjunction with other studies based on the CAO LiDAR data for experimental burn plots and large mammal exclosures in KNP, suggest that communal land use on granite substrates have a higher impact on the woody cover below 5 m than both elephants and fire.

1. Introduction

Savannas are ecosystems with a continuous herbaceous layer and a discontinuous woody stratum (Sankaran et al., 2005). At a regional scale the extent of woody vegetation cover in savannas is largely determined by precipitation (Sankaran et al., 2005), while the landscape-scale woody cover and structure is largely determined by geologic substrate, topography, fire and large herbivores, notably elephants (Witkowski and Oconnor, 1996; Venter et al., 2003; Bond and Keeley, 2005; Sankaran et al., 2008; Asner et al., 2009; Levick et al., 2009). Human land use has also been demonstrated to be a significant determinant of savanna vegetation structure (Higgins et al., 1999; Luoga et al., 2004), but has often been considered to be secondary to the aforementioned primary drivers. As millions of people rely on savannas for ecosystem services, such as the provision of grazing, fuel wood, construction timber, edible fruits and traditional medicinal plants (Twine et al.,

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Abbreviations: KNP, Kruger National Park; SSGR, SabiSand private game reserve; LiDAR, light detection and ranging; DEM, digital elevation models; CAO, Carnegie Airborne Observatory.

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2003; Shackleton and Shackleton, 2004), it is important to determine to what extent human utilization affects woody vegetation resources relative to other drivers and whether this utilization is sustainable.

The impacts of fire and large herbivores on woody vegetation were recently demonstrated in Kruger National Park (KNP) with the aid of experimental burn plots and large mammal enclosures which have been maintained for 60 and 35 years respectively (Higgins et al., 2007; Asner et al., 2009; Levick et al., 2009; Smit et al., 2010). The juxtaposition of the KNP next to private game reserves and communal rangelands in the Lowveld of South Africa provides the opportunity to investigate the impact of land use on woody vegetation structure along this east–west, land use gradient. More than 2 million people reside within 50 km of the western boundary of Kruger National Park, mostly within the apartheid-era self-governing territories or "homelands" (Pollard et al., 2003). These are generally characterized by high livestock numbers, overgrazing, soil erosion, excessive wood harvesting and potentially lower productivity (Hoffman and Todd, 2000; Wessels et al., 2004, 2007). While the woody vegetation of the conservation areas (private game reserves and national parks) are indirectly impacted by people through their management of fires, elephant populations, and artificial provision of surface water (Eckhardt et al., 2000; Levick et al., 2009; Smit and Grant, 2009), humans in the communal areas directly impact the wood resource through intensive livestock grazing and harvesting for timber and fire wood (Higgins et al., 1999; Twine, 2005).

Wood is still the primary source of fuel for cooking and heating in South Africa's rural areas and particularly in the Lowveld region where the average household use is in excess of 3 t of fuel wood per annum (Shackleton and Shackleton, 2000; Twine et al., 2003; Madubansi and Shackleton, 2007). Almost a decade after the introduction of electricity, over 90% of households still used fuelwood for cooking and the mean household consumption rates has not reduced (Madubansi and Shackleton, 2007). As much as 93% of current demand is not met by available dead wood, but is harvested as live wood. This intensive utilization of woody vegetation near settlements has significant impacts on the biomass, composition and structure of woody vegetation (Shackleton et al., 1994; Higgins et al., 1999). Some tree species are sensitive to intensive harvesting and have declined in abundance, while other species respond through coppice regrowth, which significantly changes tree morphology (Shackleton et al., 1994). The changes in size-class distribution and the scarcity of reproductive growth stages of trees have significant implications for the sustainability of the resource utilization (Twine, 2005). In addition, the natural woodlands are also rapidly being transformed for subsistence cultivation around growing human settlements (Giannecchini et al., 2007). Therefore, there is great concern that these areas may be over-utilised to the point where the ecosystem may soon not be able to sustain the services on which the local people's subsistence livelihoods depend (Banks et al., 1996; Higgins et al., 1999; Shackleton and Shackleton, 2004; Dovie et al., 2002).

Most of the above-mentioned studies have been based on labour-intensive surveys which often lack regional-scale generality as they cover small areas, e.g., belt transects covering only 1 ha (Higgins et al., 1999), and were therefore not fully representative of the spatial heterogeneity and processes of the larger landscape (Higgins et al., 1999; Neke et al., 2006; Asner et al., 2009). A relatively novel sensing approach, namely light detection and ranging (LiDAR), provides the opportunity to measure and map vegetation structure over large areas. LiDAR data have been extensively used to assess vegetation structure in forested environments (Means et al., 1999; Lefsky et al., 2002; van Aardt et al., 2006), while savanna vegetation has received limited attention (Asner et al., 2009). The present study used high point density, small-footprint, multiple, discrete return LiDAR data to assess structural differences along a land use gradient, covering 25,000 ha of African savannas. The objective of this study was specifically to quantify the differences in tree canopy cover and height distribution between Kruger National Park (KNP), SabiSand private game reserve (SSGR), and neighbouring communal areas. The outcomes of this study contribute to an understanding of the influence of human utilization on savanna structure.

2. Methods

2.1. Study area

The study area is located in the Lowveld of the savanna biome in the north-eastern part of South Africa (Fig. 1). The Lowveld is a low-lying landscape extending between the foot slopes of the Drakensberg Great Escarpment to the west and the Mozambique coastal plain to the east (Venter et al., 2003). The topography is gently undulating with a slowly decreasing terrain height toward the east, average height ca. 450 m. Rains occur mainly in summer from October to May (wet season) and are generally in the form of convective thunderstorms. The mean annual precipitation (MAP) is approximately 630 mm. Interannual coefficient of variation in the MAP is 25% and the MAP increases over the study area from the western boundary of KNP to the foot slopes of the escarpment from 580 to 800 mm/yr, respectively. Mean annual temperature is 22 °C and frost is uncommon. Dominant geology includes granite and gneiss with local intrusions of gabbro (Venter et al., 2003).

Total woody canopy cover ranges from widely dispersed individuals totalling 5% cover to near-closed canopy woodlands with a cover of 60% (Venter et al., 2003). Woody plants are mostly in the 2–5 m height categories. Vegetation communities are classified as "granite lowveld" or "gabbro grassy bushveld" (Muncina and Rutherford, 2006). Granite landscapes are characterized by nutrient-poor soils (moderately deep to shallow coarse sand and loam on upland and duplex sodic soil on bottomland) and slightly undulating terrain. Woody communities are dominated by deciduous trees, with broad leaves and no thorns, mostly Combretaceae, e.g., *Terminalia sericea*, *Combretum zeyheri*, *C. apiculatum*, while grasses are wiry, unpalatable, and sparse. In contrast, Timbivati gabbros produced wider catchments and flatter terrain (near flat plain) as well as nutrient-rich soils (dark vertic clayed soils). Grassy bushveld vegetation consists of a dense cover of nutritious, high-bulk grasses and a few scattered trees and shrubs, mostly Mimosaceae (especially *Acacia* spp.), but with fine compound leaves and many thorns (Muncina and Rutherford, 2006).

The three dominant land tenure systems are (i) state-owned conservation (Kruger National Park, KNP), (ii) privately-owned conservation (SabiSand Game Reserve, SSGR), and (iii) state-owned communal areas (Fig. 1). The Kruger National Park was officially proclaimed in 1926 and today is the largest conservation area in South Africa with 20,000 km^2. SabiSand Game Reserve (SSGR) is a 63,000 ha privately protected area with a common boundary with KNP on its southern and eastern limits. The reserve was officially established in 1965 prior to which the land was generally used as commercial cattle farms. Today SSGR is an association of freehold owners with a strong tourism-based approach to conservation, including commercial safari ventures. The fence erected between KNP and SSGR in 1961 was removed in 1993. This was followed by a 16-fold increase of elephant density (entering the reserve from KNP during the winter months), generating significant tree damage (Hiscocks, 1999). The communal lands of Bushbuckridge are former self-governing territories or "homelands" inherited from the resettlement policies during the apartheid era. The area supports high human population densities of between 150 and 300

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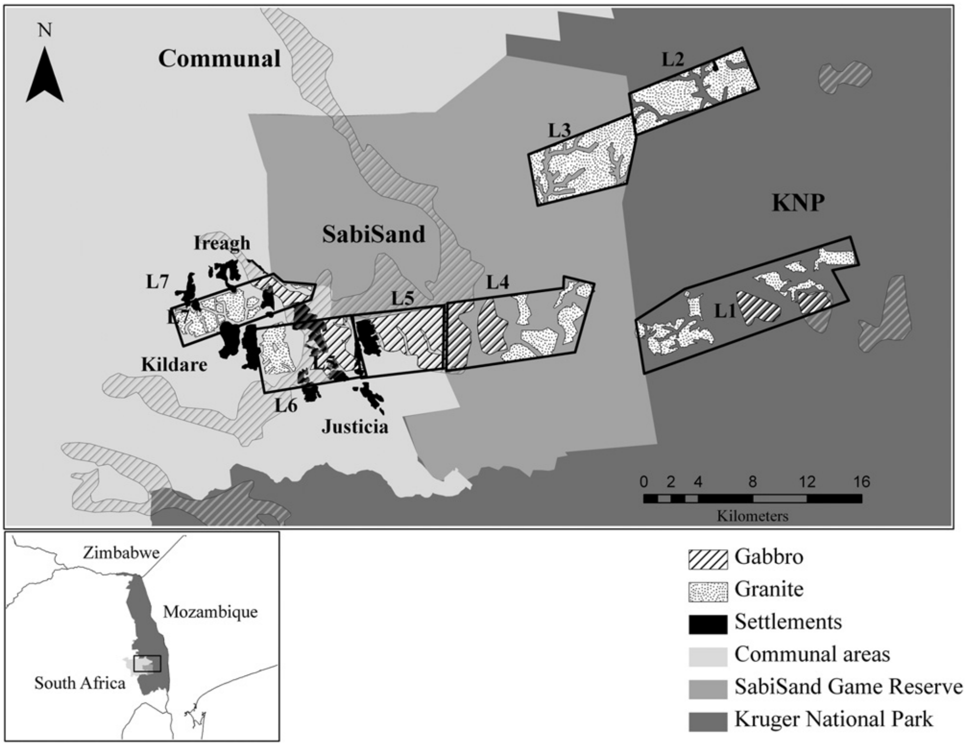

Fig. 1. Study area in the Lowveld of South Africa, including (from east to west) Kruger National Park, SabiSand Game Reserve and communal areas. Sites are delineated as L1–7. Gabbro intrusions are indicated within the predominantly granitic landscape. Human settlements are also mapped.

people/km^2. Levels of unemployment are high. Cash transfers from urban centres consist of salaries from migrant labour and social government grants and constitute a large part of the rural economy. People therefore largely rely on land-based livelihood strategies that include a combination of farming, livestock farming, consumption and/or trade on informal markets of various natural resources (Shackleton et al., 2001; Dovie et al., 2002). Subsistence rain-fed crops, e.g., maize, peanut, watermelon, Bambara nut, are grown at the homestead or in arable fields located in the proximity of the settlements.

The 25,000 ha covered by the LiDAR data cover 7 sites, from Land use site 1 (L1) in the east to Land use site 7 (L7) in the west (Fig. 1). L1 and L2 are located in KNP, L3 and L4 in SSGR and L5, L6 and L7 in the communal areas. The spatial delineation of the granite and gabbro sites was made using 1:250000 geology maps and refined using recent SPOT5 imagery. The delineation was conservative and excluded transition areas between granite and gabbro. Within the communal areas, a distinction was made between rangelands and cultivated fields. Areas under consideration are denoted as L(1–7)-geology(gabbro/granite)-land use (KNP/SabiSand/rangeland/fields), for example L6-gabbro-fields.

2.2. Airborne LiDAR data

Discrete lidar data were acquired in April–May 2008 with the Carnegie Airborne Observatory (CAO) system (Asner et al., 2007), across the study sites covering 25,000 ha. The CAO system combines three instrument sub-systems into a single airborne package: (i) High-fidelity Imaging Spectrometer (HiFIS); (ii) Waveform Light Detection and Ranging (LiDAR) scanner; and (iii) Global Positioning System-Inertial Measurement Unit (GPS-IMU) (Asner et al., 2007). The CAO HiFIS uses a pushbroom imaging array with 1500 cross-track pixels, and sampling across the 367–1058 nm range at up to 2.4 nm spectral resolution. The spectrometer is fully integrated with the waveform LiDAR having an adjustable laser pulse repetition rate of up to 100 kHz. The GPS-IMU sub-system provides three-dimensional positioning and altitude data for the sensor package onboard the aircraft, allowing for highly precise and accurate projection of HiFIS and LiDAR observations on the ground (Asner et al., 2007). In April–May 2008, the CAO collected data over the study region from an altitude of 2000 m above ground level, providing combined HiFIS and LiDAR measurements at 1.1 m spatial resolution. The LiDAR was operated at a laser pulse repetition frequency of 50 kHz. Parallel flight lines were acquired with 50% overlap.

The GPS-IMU data were combined with the laser ranging data to determine the 3-D location of the laser returns. From the laser point cloud data, a physical model was used to estimate top-of-canopy and ground surfaces (i.e. digital elevation models; DEMs) using the REALM (Optech Inc., Vaughn, Canada) and Terrascan/Terramatch (Terrasolid Ltd., Jyväskylä, Finland) software packages. Ground returns for the DEMs were classified from the LiDAR point cloud using a user-defined search radius in which the lowest point is identified as a potential ground return; adjacent points are added to this ground class if they fall below a user-defined threshold angle subtended at the original point. This algorithm regards sudden, distinct angular differences between points as an indication that a LiDAR return is from a higher-level or above-ground object. Vegetation height is then estimated by differencing the top-of-canopy and ground surface DEMs.

2.3. Field validation

Field surveys were conducted during the CAO flight campaign in order to determine the accuracy of the woody vegetation heights derived from the LiDAR data. Surveys involved measuring the highest leaves of 883 trees or shrubs using either a graduated range pole, a laser rangefinder (TruPulse^{TM} 360° B), or a Vertex hyp-

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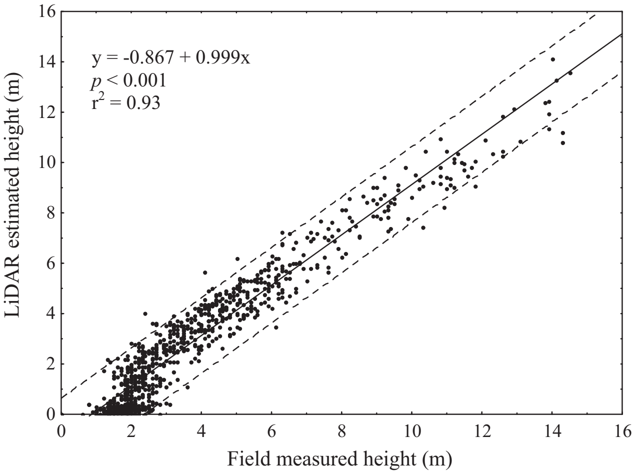

Fig. 2. Field validation of LiDAR estimated tree heights calculated from 883 trees or shrubs measured during the April 2008 Carnegie Airborne Observatory aerial flight campaign (dashed lines – 95% predicted confidence interval).

Table 2
Total percentage woody vegetation cover above 1 m, per site (L1–7), geologic substrate (granite or gabbro – shaded) and land use. Land use includes the conservation areas namely, Kruger National Park (KNP), SabiSand Game Reserve (SSGR) or communal areas (rangeland or fields).

Site no.	Geologic substrate	Land use	Woody cover
L1	Granite	KNP (conservation)	27.9%
L1	Gabbro	KNP (conservation)	6.3%
L2	Granite	KNP (conservation)	21.6%
L3	Granite	SSGR (conservation)	22.9%
L4	Gabbro	SSGR (conservation)	5.9%
L4	Granite	SSGR (conservation)	27.7%
L5	Gabbro	Rangeland (communal)	11.8%
L6	Gabbro	Rangeland (communal)	2.0%
L7	Gabbro	Rangeland (communal)	11.8%
L7	Granite	Rangeland (communal)	9.8%
L5	Gabbro	Fields (communal)	5.6%
L6	Gabbro	Fields (communal)	3.8%
L6	Granite	Fields (communal)	7.2%
L7	Gabbro	Fields (communal)	6.4%
L7	Granite	Fields (communal)	8.7%

someter within 36 field sites, distributed systematically throughout the areas covered by CAO data (April 2008). The geographic location of each vegetation height measurement was recorded using a differential GPS and the data were post-processed to sub-meter accuracy using one-second data from the Nelspruit reference station. The highest vegetation canopy was visually extracted from the LiDAR vegetation height surfaces around each GPS location. The corresponding LiDAR-derived vegetation heights showed a strong positive relationship with field measurements ($r^2 = 0.93$, $p < 0.001$, standard error = 0.73 m) (Fig. 2). The relationship was weak for woody vegetation below 2 m, which was often estimated at below 0.5 m, or not distinguished from the ground DEM. This limitation resulted from a combination of factors including the limited target cross section within 1.1 m pixels of small woody plants below 2 m, the user-defined thresholds for identifying ground returns and the LiDAR reset time which equates to approximately 0.71 m. Woody vegetation cover below 2 m is therefore likely to be underestimated.

2.4. *Comparison of woody vegetation cover and height distributions*

All riverine areas, dirt roads and human settlements were digitized using the simultaneously collected hyperspectral data and excluded from analyses. Cultivated fields were also digitized and treated as a separate class. Settlements and cultivated fields accounted for significant portions of CAO data collected in the communal areas, as these areas were underestimated by other Landsat-based data sets, e.g., National Land Cover 2000 (Thompson, 2001).

The goal was to compare the woody vegetation cover of sites per height class. The analysis concentrated on the vegetation canopy height surfaces as an indicator of the woody cover at various heights and not volumetric woody occupation of this space (van Aardt et al., 2006). The authors will be evaluating the complex within-canopy structural and biomass differences between land uses in subsequent studies.

The woody vegetation was binned into five functional height classes to facilitate ecological interpretation of the LiDAR data (Table 1). These classes relate to the influence of fire and herbivory, their function in the landscape, as well as human utilization (Belsky et al., 1993; Scholes and Walker, 1993; Bond and Midgley, 2000; Shackleton and Shackleton, 2004; Neke et al., 2006; Treydte et al., 2009).

LiDAR data analysis can be summarised as follows:

(i) Only height values greater than 1 m were considered to ensure that ground and herbaceous vegetation were excluded from subsequent analyses.
(ii) The spatial autocorrelation in vegetation height was investigated using omnidirectional semi-variograms applied to the 1.1 m vegetation height surface (Beale et al., 2010). Exponential models fitted to the semi-variograms indicated that there was negligible spatial autocorrelation beyond a lag distance of approximately 50 m (range), demonstrating the high spatial heterogeneity of savanna vegetation. Therefore, samples taken

Table 1
Functional height classes of woody vegetation according to which the LiDAR estimates of canopy heights were classified.

	Description	Functional significance
1–2 m	Woody vegetation in fire/browse trap (saplings, small shrubs)	Within "fire trap" and heavily browsed. Coppiced and encroached woody vegetation. Used as live fuel wood production.
2–3 m	High shrubs, small trees	Within "fire trap" and browsed by small browsers. Coppiced and encroached woody vegetation. Used as live fuel wood production.
3–5 m	Emerging tall trees	Less influenced by fire, targeted by megaherbivores.
5–7 m	Tall trees	Less influenced by fire and herbivory and of great use to people for non-timber products.
>7 m	Very tall trees	Fire and herbivory have little influence. High cultural, biodiversity and functional value.

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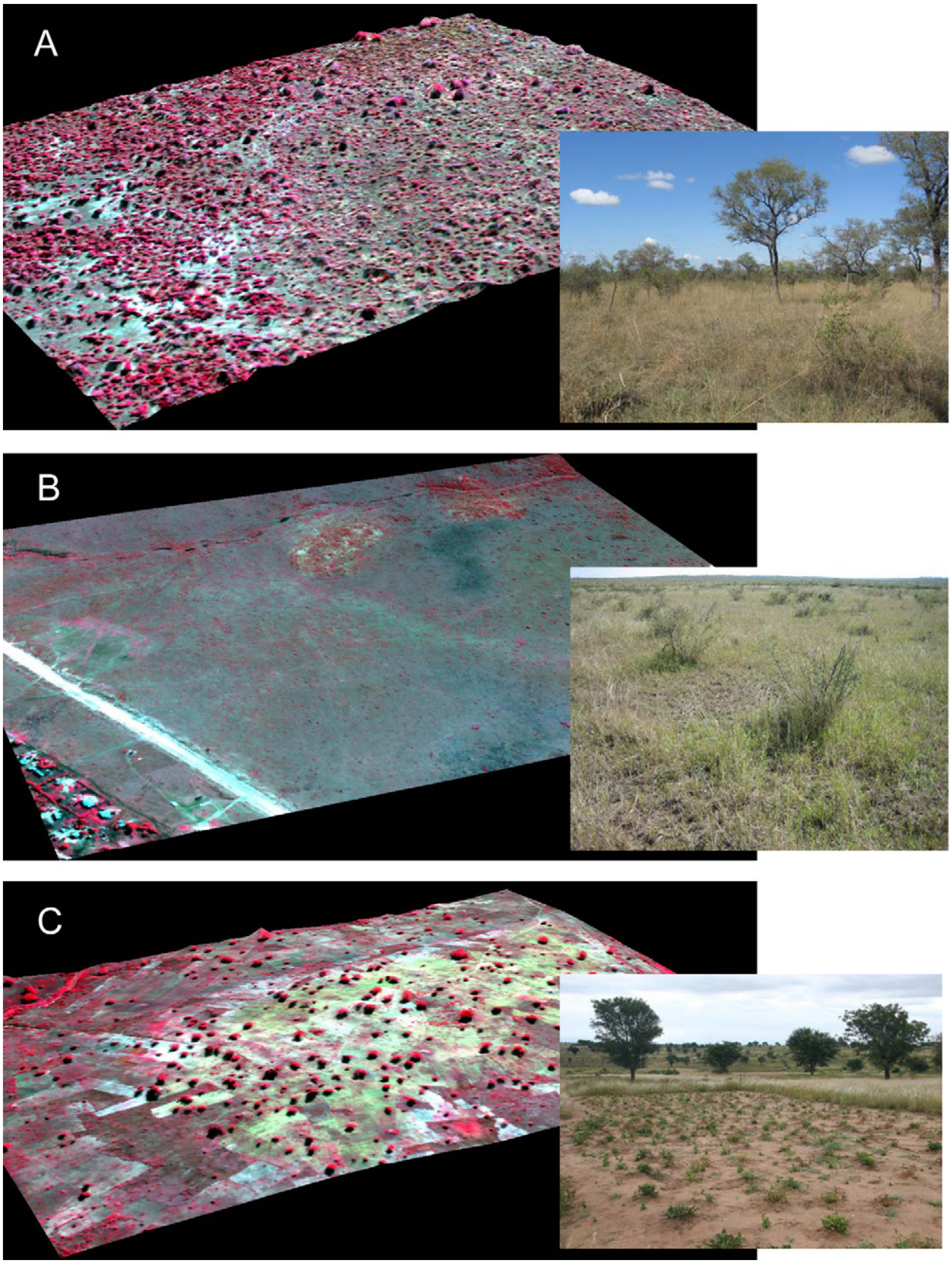

Fig. 3. False colour images draped over the surface height model derived from Lidar data for selected sites. Data recorded by Carnegie Airborne Observatory. (A) dense woodland in private reserve, L3-granite-SabiSand, (B) highly impacted rangeland in communal rangeland with very low woody vegetation cover, L6-gabbro-rangeland and (C) cultivated and fallow fields in communal areas with large trees, L6-granite-fields.

50 m apart, or further, could be treated as independent (Beale et al., 2010).

(iii) Each site (L1–7) was sampled using 200 m × 200 m blocks, spaced 50 m apart. The 200 m block size was chosen as it optimally represents samples of the landscape which includes multiple terrain units, e.g., crest, midslope, valley bottom, in order to stabilise the inter-block variability whilst characterising the site. The percentage area of each block covered by each height class was calculated. Blocks for which more than 50% block-area fell outside of the site polygons, were excluded as they effectively sampled smaller areas, which increased the inter-block variability. However, since cultivated fields were small relative to these blocks, data were included if more than 30% of the block fell inside polygons for cultivated fields.

(iv) The average and standard deviation of percentage area woody cover per height class were calculated for each site (L1–7), geology (gabbro or granite), and land use (conservation, cultivated fields or rangeland) combination using all of the 200 m blocks that were included in the relevant polygons.

(v) A non-parametric, unequal variance version of the Mann–Whitney test was used to test if sites differed significantly in term of their percentage woody vegetation cover within each height class. The null hypothesis of the Mann–Whitney test is that the two samples are drawn from a single population, and therefore that their probability distributions are equal (Mann and Whitney, 1947). The alternative hypothesis is that one sample mean is stochastically greater.

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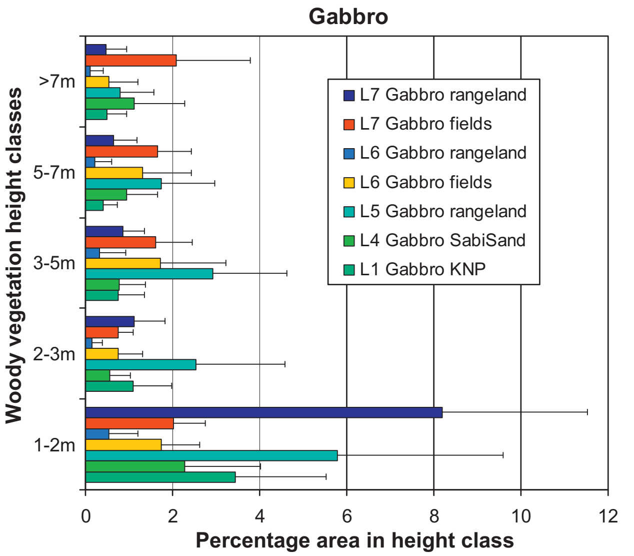

Fig. 4. Percentage area of each site covered by vegetation in height class on gabbro geological substrate. The values are calculated as the average of all 200 m blocks included in the site, while the error bars indicate the standard deviation.

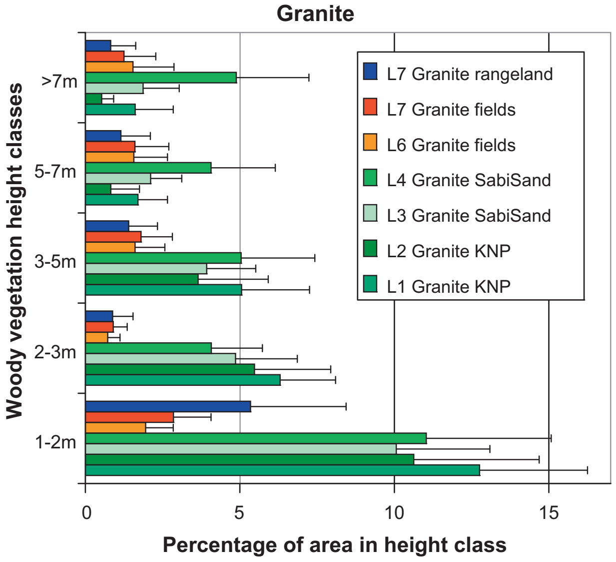

Fig. 5. Percentage area of each site covered by vegetation in height class on granite geological substrate. The values are calculated as the average of all 200 m blocks included in the site, while the error bars indicate the standard deviation.

3. Results

3.1. Woody vegetation cover

The total percentage woody vegetation cover above 1 m was calculated for each site (Table 2). On the gabbro substrate the state-owned and privately-owned conservation sites (L1-gabbro-KNP, L4-gabbro-SabiSand) had a similar tree cover (6%). Of all the sites located on gabbro geology, L6-gabbro-rangeland had the lowest percentage woody vegetation cover of 2%. This site is situated on a patch of heavily utilised rangelands between two settlements (Figs. 1 and 3B). In contrast, L5-gabbro-rangeland and L7-gabbro-rangeland in the communal areas had approximately double the woody vegetation cover of L1-gabbro-KNP and L4-gabbro-SabiSand in conservation areas (11% vs. 6%). Interestingly, the woody cover of communal fields, L5-gabbro-fields and L7-gabbro-fields, was similar to that of conversation areas (approximately 6%), while L6-gabbro-field had a lower cover (3.8%) (Table 2).

As expected, woody vegetation cover in granite areas is much higher than on gabbro patches in conservation areas (24% vs. 6%) (Venter et al., 2003) (Table 2). State-owned and privately-owned conservation sites on granite (L1, 2, 3, 4) again had similar woody vegetation cover (22–27%), while L7-granite-rangeland had less than half that of the conservation sites (9.8%).

3.2. Woody vegetation height distribution in rangelands and conservation areas

The average percentage area covered by woody vegetation in each height class for all 200 m blocks in a site was plotted in histograms to visualise the structural vegetation differences (Figs. 4 and 5). The intra-site, inter-block variability was expressed as the standard deviation per height class. The results of the Mann–Whitney tests are given in Appendix A. Most pair-wise comparisons between site, per height class, yielded a statistically significant difference, with the exception of the communal fields, which regularly showed no significant difference with the other sites (see Section 3.3).

There was an expected and consistent decline in the percentage vegetation with increasing height for conservation areas on gabbro and granite, with granites showing a more marked pattern (Figs. 4 and 5). The impact of communal land use on the woody vegetation structure was very diverse on the gabbro geology. Only 0.5% of the area of L6-gabbro-rangeland was covered by woody vegetation below 2 m compared to the other sites, while more than 8% of L7-gabbro-rangeland was covered by woody vegetation at this height. The conservation sites, L1-gabbro-KNP and L4-gabbro-SabiSand fell between the two afore-mentioned extremes (Fig. 4). L6-gabbro-rangeland had less than half the woody vegetation cover in all height classes, indicating a high utilization impact (Fig. 3B). L5-gabbro-rangeland was covered by significantly more woody vegetation in the 2–3 m, 3–5 m and 5–7 m classes compared to all the other gabbro sites (Fig. 4), indicating a high abundance of small to large trees and thus low impact within this communal area or potentially attributable to bush encroachment.

On granite, the conservation sites L1–L4, had very similar percentage woody vegetation in all classes below 5 m (Fig. 5). The woody cover of L7-granite-rangeland was less than half that of conservation sites (L1–L4) between 1 and 5 m, demonstrating a very significant impact of rural utilization on the woody vegetation (Fig. 5). The biggest difference was in the 2–3 m height class, where the cover of L7-granite-rangeland was approximately four times less than that of the conservation sites (L1–L4). L7-granite-rangeland had a very similar vegetation height distribution to L6-granite-fields and L7-granite-fields, resulting in very few significant differences (Appendix A). L4-granite-SabiSand had more than double the woody cover in the 5–7 m and >7 m classes when compared to any of the other granite sites. This site is a low-lying area next to the Sand River covered by tall woodlands.

3.3. Woody vegetation height distribution in communal fields

The woody cover of L6-gabbro-fields and L7-gabbro-fields was significantly higher than the conservation sites (L1-gabbro-KNP and L4-gabbro-SSGR) in the 3–5 m and 5–7 m classes, while L7-gabbro-fields even had double woody cover in the >7 m height class (Fig. 4) (Appendix A). L5-gabbro-fields had a significantly higher cover in the 5–7 m and 3–5 m class than L1-gabbro-KNP, and in the 3–5 m and 2–3 m classes than L4-gabbro-SSGR. Fields on gabbro substrates were most often not significantly different from one another (Appendix A).

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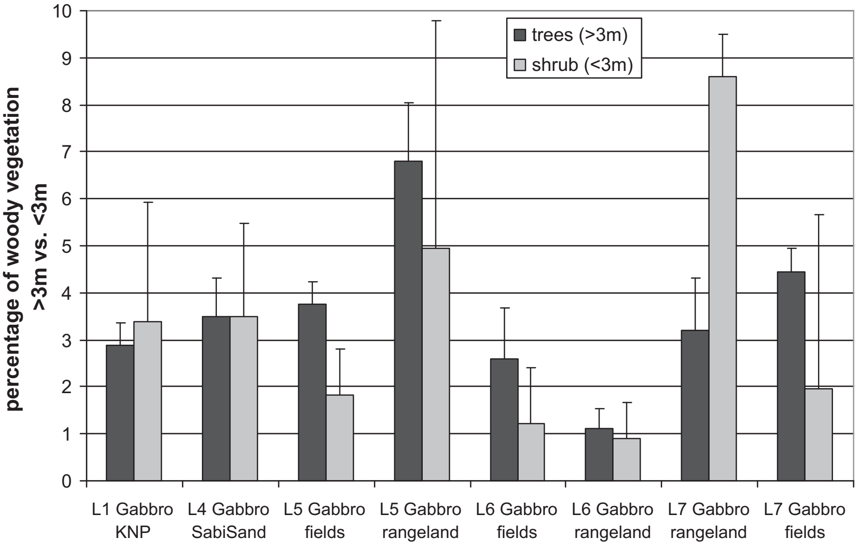

Fig. 6. Percentage of woody cover of gabbro sites below 3 m and above 3 m, indicating the relative cover of shrubs and trees respectively. The values are calculated as the average of all 200 m blocks included in the site, while the error bars indicate the standard deviation.

The overall woody vegetation cover of fields on granite substrates was only approximately 25% of the cover in conservation areas (Table 2). L6-granite-fields and L7-granite-fields have 4–6 times less woody vegetation cover in the 1–2 m, 2–3 m and 3–5 m classes than the other granite sites, but mostly similar cover in the 5–7 and >7 m classes (Fig. 5). More specifically, L6-granite-fields and L7-granite-fields had no significant difference with L1-granite-KNP in the 5–7 m and >7 m classes, while these two communal field sites had significantly more cover than L2-granite-KNP in the 5–7 m and >7 m classes (Appendix A). A distinguishing feature of the fields on granite (L7-granite-fields, L6-granite-fields) was that there was more woody vegetation in each of the height classes above 3 m than in the class 2–3 m (Fig. 5).

3.4. Tree vs. shrub cover

The woody vegetation was classified into two height classes in order to approximate ratio of tree cover (>3 m) vs. shrub cover (<3 m) (Levick et al., 2009). On the gabbro substrate in the conservation area (L1-gabbro-KNP and L4-gabbro-SabiSand) the tree cover and shrub cover were almost equal, while in the communal rangelands the tree/shrub cover ratio varied widely, from 1.37 for L5-gabbro-rangeland (dominated by tree cover) to 0.37 for L7-gabbro-rangeland, which was completely dominated by shrub cover (Fig. 6). Tree cover (>3 m) was clearly dominant in the cultivated fields of L5-gabbro-fields, L6-gabbro-fields, and L7-gabbro-fields (Fig. 6).

On the granite substrate, the conservation areas L1–3 had very similar tree and shrub cover, with trees being slightly dominant in L1 and L3 (Fig. 7). L4 in SabiSand was dominated by very large trees (ratio = 1.69). In contrast, in the communal rangelands (L7-granite-rangeland), shrub cover was dominant and tree cover much lower than in the conservation areas (L1–4) (Fig. 7). Tree cover was dominant in both L6-granite-fields and L7-granite-fields, where shrub cover was low (2%).

4. Discussion

As previously demonstrated in the communal miombo woodlands (Luoga et al., 2002), the impact of human utilization on wood resources in the present study differed in type, intensity and frequency from one place to another. Heavy utilization on the gabbro substrate radically reduced total woody cover of the rangelands (e.g., L6-gabbro-rangeland) (Fig. 3B), while the two other communal rangelands that were presumably less intensively utilised (L5-gabbro-rangeland, L7-gabbro-rangeland) had double the woody cover of conservation areas (L1-gabbro-KNP, L4-gabbro-SabiSand) (Table 2). These two communal rangelands furthermore had highly contrasting woody vegetation structures, with L5-gabbro-rangeland being dominated by larger trees and L7-gabbro-rangeland dominated by shrubs (Figs. 4 and 6). The high percentage of woody cover below 3 m in L7-gabbro-rangeland is caused by Silver Cluster-leaf (*Terminalia sericea*) and Sicklebush (*Dichrostachys cinerea*), which are known to coppice vigorously when harvested by humans (Neke et al., 2006) and encroach as the result of overgrazing (Papanstasis, 2009) (Figs. 4 and 6). However, this was not the case in L6-gabbro-rangeland which had a very low cover of woody vegetation below 3 m (Fig. 3B). It has been demonstrated elsewhere that intensive browsing by livestock can severely reduce coppice regrowth (Stromgaard, 1985) and this may be the case in L6-gabbro-rangeland, which is heavily grazed and utilised due to its location between two villages (Fig. 1).

When the woody vegetation of L5-gabbro-rangeland was compared to L4-gabbro-SabiSand just to the east in the SabiSand game reserve (Fig. 1), it was clear that L5-gabbro-rangeland had more than double the woody cover at all heights, except the >7 m class (Fig. 4). This could be attributed to the relatively low utilization impact of the single village (Justicia) with access to this site which is nestled into a corner of SSGR (Fig. 1), as well as the reduction in woody cover due to the 16-fold increase in elephant numbers in SSGR since 1993 when fences between SSGR and KNP were removed (Hiscocks, 1999).

On the granite substrates the results were different. The overall woody vegetation cover of L7-granite-rangeland was less than half that of the conservation areas (L1–L4) (Table 2). L7-granite-rangeland had less than 50%, 25% and 50% of the woody vegetation cover of conservation areas in the 1–2 m, 2–3 m, and 3–5 m classes, respectively (Fig. 5). This supports the findings of Higgins et al. (1999) that woody biomass on granite substrates was lower in communal rangelands compared to conservation areas in the same study area. Interestingly, while woody vegetation cover in the communal rangelands was lower than that of the conservation areas on the granite substrate of L7 (9.8% vs. 25%), the woody cover was higher compared to conservation sites on gabbro substrate of L7

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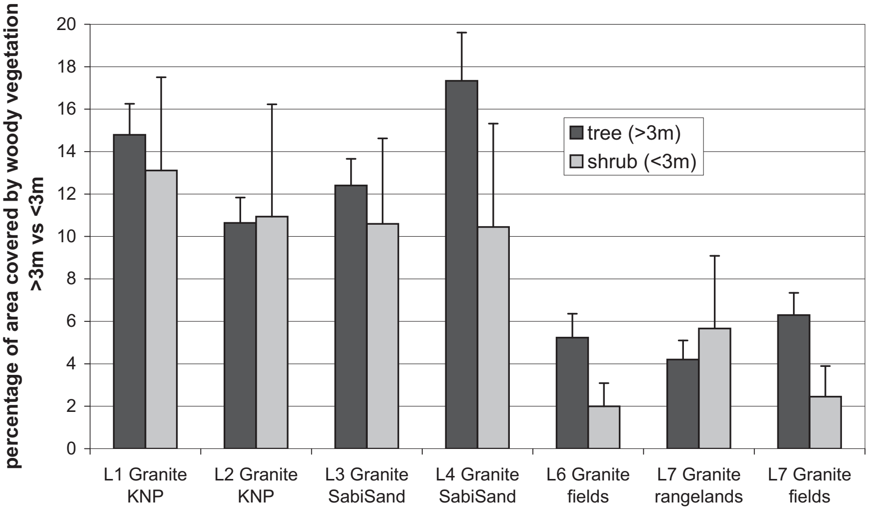

Fig. 7. Percentage of woody cover of granite sites below 3 m and above 3 m, indicating the relative cover of shrubs and trees respectively. The values are calculated as the average of all 200 m blocks included in the site, while the error bars indicate the standard deviation.

(11.8% vs. approx. 6%) (Table 2). While woody cover on L7-gabbro-rangelands was double that of conservation sites (L1 and L4 gabbro) in the 1–2 m class, it was less than half that of conservation sites in L7-granite-rangeland. As with the impact of fire and large herbivores, the impact of communal land use on woody vegetation thus appears to be largely influenced by the geological substrate (Eckhardt et al., 2000; Venter et al., 2003; Asner et al., 2009; Levick et al., 2009).

Cultivated fields either had more woody vegetation above 5 m on gabbro or similar cover above 5 m on granite. This is a clear indication that trees are being conserved within these communal fields as they provide fruit, shade and other goods, e.g., Marula (*Sclerocarya birrea*), Jackalberry (*Diospyros mespiliformis*) (Shackleton et al., 2002, 2003; Shackleton and Shackleton, 2004). Therefore, although woodlands are transformed by the expansion of cultivated fields (Giannecchini et al., 2007), the large trees are retained within the fields (Fig. 3C). However, the recruitment of new small trees is a major concern as there was relatively little woody vegetation in the 2–3 m height class in the fields compared to the classes above 3 m (Fig. 5) (e.g., L6-granite-fields).

Shackleton et al. (1994) found that woody stem density, basal area, biomass, height, seedling density, and species richness all exhibited a significant decrease with increasing disturbance intensity closer to villages in this study area. It is difficult to compare the results of these field-based measures to the landscape-scale LiDAR results which were only used to estimated woody cover and height distributions. The well-documented harvesting pressure on live trees (Banks et al., 1996; Dovie et al., 2002; Twine et al., 2003; Twine, 2005; Kirkland et al., 2007) appears to have a large impact on woody cover below 5 m on granite substrates, which was more than 50% reduced when compared to conservation sites (Fig. 5). This impact was not evident on the rangeland of the highly diverse gabbro sites (L5-, L6- and L7 -gabbro-rangeland). However, what is very clear from the LiDAR results is that there has not been a decrease in large trees (>5 m) in communal rangelands or fields compared to the conservation areas. Notably, the cover of trees above 5 m was the lowest of all sites inside KNP, for both granite and gabbro substrates (Figs. 4 and 5). This can largely be attributed to the active preservation of selected large trees species, especially the Marula trees (*Sclerocarya birrea*), in communal areas (Trollope et al., 1998; Shackleton et al., 2002) and the continued loss of these trees in conservation areas due mainly to elephant-induced mortality (Trollope et al., 1998; Eckhardt et al., 2000; Shannon et al., 2008; Helm et al., 2009). Since elephants are effectively excluded from communal areas by the game fences of the reserves, trees are protected from elephant impacts in the communal landscape. Moreover, there is evidence from other studies that people plant trees around homesteads, and actively maintain trees (mainly Marula trees) in cultivated fields (Shackleton, 2002; Shackleton et al., 2003).

The persistence of large single standing trees in the communal areas is highly beneficial to biodiversity and savanna function (Belsky et al., 1993; Manning et al., 2006; Treydte et al., 2009). The local abundance of rare tree species is a concern in communal areas (Shackleton et al., 1994). Recent studies indicate that a number of tree species in the study area can be reliably identified using the CAO's integrated imaging spectrometer data, thus providing the opportunity for investigating species-level patterns over large areas (Cho et al., in press). Repeated acquisitions of LiDAR and hyperspectral data over longer time periods would be needed for monitoring purposes, while the monitoring of seedling recruitment will however, remain a field-based activity.

Controlled experiments in the form of large mammal enclosures and experimental burn plots within KNP have made it easier to demonstrate the impact of large herbivores (Asner et al., 2009; Levick et al., 2009) and fire (Smit et al., 2010) on vegetation structure using the CAO LiDAR data. However, in the absence of such controlled experiments, it is more difficult to demonstrate that communal land use is the cause of the diverse differences in tree cover and structure in the present study, especially since the land use sites were so much larger (25,000 ha) and spatially diverse compared to the exclosures and plots (7–1640 ha), while their management history was not controlled and is often unknown. It is nevertheless useful to start comparing the impacts of communal land use to the CAO results for the experimental sites in KNP, in order to gauge the relative impacts of humans, elephants and fire. At the Makhohlola experimental site (7 ha), LiDAR data were used to explored structural patterns that have arisen from 34 years of reduced herbivory by large mammal exclusion, and 7 years of fire suppression. The total percentage woody cover was 36 times greater inside the exclosures, compared to the control area and contained five times more tall tree canopy (>9 m) and up to 66 times more small tree canopy (3–6 m) (Levick et al., 2009). Based on four other experimental large herbivore exclosures in KNP (1640 ha), Asner et al. (2009) found a 7–11-fold greater woody canopy cover

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inside herbivore exclosures, with a 2–3 fold increase below 5 m and a 5–8 fold increase in tall trees above 10 m. Considering the fact that the communal areas in the present paper are effectively elephant exclosures, while these areas only have half the woody vegetation cover below 5 m (Fig. 5) compared to conservation sites which already include the afore-mentioned elephant impacts, it could be inferred that the impact of communal land use is potentially double that of elephants on granite substrates.

The studies based on the experimental burn plots in KNP suggest that long-term fire exposure reduces woody vegetation cover below 4.5 m significantly (Smit et al., 2010). On average, a 30–40% reduction in woody cover was observed when comparing fire treatments with fire exclusion treatments in this landscape. However, the magnitude of the impact of fire on woody structure was highly dependent on the fire frequency and the fire season, with frequent fires and dry season fires (late winter, early spring) causing larger reductions in woody cover at a range of heights. No statistically significant impact of fire was observed for woody vegetation structure above 5 m, although the data did suggest fewer trees attained these heights on the fire treatment plots compared to the fire exclusion plots. Regular fires appear to create a so-called “fire-trap” from which smaller trees only rarely escape to become large trees, which in turn are largely immune to fire damage (Bond and Midgley, 2000; Higgins et al., 2007). In a similar manner, humans in communal areas appear to harvest woody vegetation below 5 m, but preserve larger trees (>5 m), although limbs are sometimes removed from large trees for fuel wood. Although little is known about the fire history in communal areas (Trollope et al., 1998), observations suggest that some rangelands are burned regularly, although these fires cover small areas and are of low intensity due to low grass biomass caused by intensive grazing (Shackleton and Twine, personal communication). Therefore, since elephants are absent and fires are not a major factor in communal areas, while the conservation sites, on the other hand, include both these impacts, it can be concluded that communal land use have a higher impact on the woody cover below 5 m than both elephants and fire, on granite substrates. As the vast majority of the communal areas and KNP are situated on granite substrates and the bulk of the woody vegetation occur below 5 m, this indicates a substantial impact on the wood resources in communal areas.

In conclusion, geologic substrate had an overriding influence on the impact of communal land use on woody vegetation. On the gabbro intrusions, this impact was diverse, ranging from a radical reduction in all woody cover in intensively used rangelands (e.g., L6) to a significant increase (e.g., L5, L7), depending on the current and historic management of the sites, which varied greatly. On the granite substrates, which account for the overwhelming majority of the study area, there was a 50% reduction in woody cover below 5 m due to communal land use, which appear to be more severe than the impact of elephants and fire in the KNP experiments (Asner et al., 2009; Levick et al., 2009; Smit et al., 2010). Although large trees are clearly being conserved in communal rangelands and fields, while they are threatened by elephants in conservation areas, their long-term recruitment needs to be ascertained in the field.

Given the reliance of people in communal areas on the woodland resources and questions surrounding the sustainability of this ecosystem service under intensive utilization, these initial findings warrant further investigation. The value of the LiDAR data for characterising savanna woody vegetation structure over large areas is undisputable. Therefore, additional CAO flight campaigns were undertaken over many of the same areas in the Lowveld of South Africa during 2010, with the long-term objective of developing an affordable and reliable LiDAR-based monitoring program.

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Appendix A.

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.foreco.2010.09.012.

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Results of Mann–Whitney test for significant differences in term of their percentage woody vegetation cover within each height class.

Granite	Height class	L2 KNP	L3SSGR	L4SSGR	L6Fields	L7Rangeland	L7Fields *N* = 73
L1	>7 m	**>L2	**<L3	**<L4	ns	**>L7	ns
KNP	5–7 m	**>L2	**<L3	**<L4	ns	**>L7	ns
N = 213	3–5 m	**>L2	**>L3	ns	**>L6	**>L7	**>L7
	2–3 m	**>L2	**>L3	**>L4	**>L6	**>L7	**>L7
	1–2 m	**>L2	**>L3	**>L4	**>L6	**>L7	**>L7
L2	>7 m		**<L3	**<L4	**<L6	**<L7	**<L7
KNP	5–7 m		**>L3	**<L4	**<L6	**<L7	**<L7
N = 534	3–5 m		**<L3	**>L4	**>L6	**>L7	**>L7
	2–3 m		**>L3	**>L4	**>L6	**>L7	**>L7
	1–2 m		**>L3	**>L4	**>L6	**>L7	**>L7
L3	>7 m			**<L4	**>L6	**>L7	**>L7
SSGR	5–7 m			**<L4	**>L6	**>L7	**>L7
N = 525	3–5 m			**<L4	**>L6	**>L7	**>L7
	2–3 m			**>L4	**>L6	**>L7	**>L7
	1–2 m			**>L4	**>L6	**>L7	**>L7
L4	>7 m				**>L6	**>L7	**>L7
SSGR	5–7 m				**>L6	**>L7	**>L7
N = 430	3–5 m				**>L6	**>L7	**>L7
	2–3 m				**>L6	**>L7	**>L7
	1–2 m				**>L6	ns	**>L7
L6	>7 m					ns	**<L7
Fields	5–7 m					ns	ns
N = 182	3–5 m					ns	ns
	2–3 m					ns	**<L7
	1–2 m					**<L7	ns
L7	>7 m						**<L7
Rangeland	5–7 m						**<L7
N = 125	3–5 m						**<L7
	2–3 m						**<L7
	1–2 m						**>L7

Gabbro	Height class	L4SSGR	L5Rangeland	L5Fields	L6Rangeland	L6Fields	L7Rangeland	L7Fields *N* = 17
L1	>7 m	**<L4	**<L5	**>L5	**>L6	**>L6	ns	**<L7
KNP	5–7 m	**<L4	**<L5	**<L5	**>L6	ns	**<L7	**<L7
N = 119	3–5 m	ns	**<L5	**<L5	**>L6	**<L6	ns	**<L7
	2–3 m	**>L4	**<L5	**>L5	**>L6	**>L6	ns	ns
	1–2 m	**>L4	**<L5	**>L5	**>L6	**>L6	**<L7	**>L7
L4	>7 m		**>L5	**>L5	**>L6	**>L6	**>L7	ns
SSGR	5–7 m		**<L5	**>L5	**>L6	**>L6	ns	ns
N = 287	3–5 m		**<L5	**<L5	**>L6	**<L6	ns	**<L7
	2–3 m		**<L5	**<L5	**>L6	ns	**<L7	**<L7
	1–2 m		**<L5	**>L5	**>L6	**>L6	**<L7	ns
L5	>7 m			**>L5	**>L6	**>L6	ns	**<L7
Rangeland	5–7 m			**<L5	**>L6	**>L6	**>L7	ns
N = 243	3–5 m			**>L5	**>L6	**>L6	**>L7	**>L7
	2–3 m			**>L5	**>L6	**>L6	**>L7	**>L7
	1–2 m			**>L5	**>L6	**>L6	**<L7	**>L7
L5	>7 m				**>L6	ns	ns	**<L7
Fields	5–7 m				**>L6	ns	ns	**<L7
N = 74	3–5 m				**>L6	ns	**>L7	ns
	2–3 m				**>L6	ns	**<L7	ns
	1–2 m				**>L6	ns	**<L7	ns
L6	>7 m					**<L6	**<L7	**<L7
Rangeland	5–7 m					**<L6	**<L7	**<L7
N = 133	3–5 m					**<L6	**<L7	**<L7
	2–3 m					**<L6	**<L7	**<L7
	1–2 m					**>L6	**<L7	**<L7
L6	>7 m						**<L7	**<L7
Fields	5–7 m						**<L7	**<L7
N = 41	3–5 m						ns	ns
	2–3 m						**<L7	ns
	1–2 m						**<L7	ns
L7	>7 m							**<L7
Rangeland	5–7 m							ns
N = 29	3–5 m							ns
	2–3 m							ns
	1–2 m							**>L7

Note: KNP, Kruger National Park; SSGR, SabiSand Game Reserve. *N*, number of 200 m block used as samples in analysis; ns, no significant difference; **, significant difference.

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