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Human-modified landscapes: patterns of fine-scale woody vegetation structure in communal savannah rangelands

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SUMMARY

Despite electrification, over 90% of rural households in certain areas of South Africa continue to depend on fuelwood, and this affects woody vegetation structure, with associated cascading effects on biodiversity within adjacent lands. To promote sustainable use, the interactions between anthropogenic and environmental factors affecting vegetation structure in savannahs need to be understood. Airborne light detection and ranging (LiDAR) data collected over 4758 ha were used to examine woody vegetation structure in five communal rangelands around 12 settlements in Bushbuckridge, a municipality in the Kruger to Canyons Biosphere Reserve (South Africa). The importance of underlying abiotic factors was evaluated by measuring size class distributions across catenas and using canonical correspondence analysis. Landscape position was significant in determining structure, indicating the importance of underlying biophysical factors. Differences in structure were settlement-specific, related to mean annual precipitation at one site, and human population density and intensity of use at the other four sites. Size class distributions of woody vegetation revealed human disturbance gradients around settlements. Intensity of use affected the amplitude, not the shape, of the size class distribution, suggesting the same height classes were being harvested across settlements, but amount harvested varied between settlements. Highly used rangelands result in a disappearance of disturbance gradients, leading to homogeneous patches of low woody cover around settlements with limited rehabilitation options. Reductions in disturbance gradients can serve as early warning indicators of woodland degradation, a useful tool in planning for conservation and sustainable development.

Keywords: Carnegie Airborne Observatory, communal rangelands, LiDAR, resource gradients, size structure, South Africa, sustainable resource use

INTRODUCTION

South African savannahs are home to over nine million rural residents, with over 90% of households dependent on fuelwood as a primary energy source, even where electricity is available (Twine *et al.* 2003). This dependence changes savannah vegetation structure (Freitag-Ronaldson & Foxcroft 2003); however, the interactions between socioeconomic and environmental factors that determine the level and type of use are complex, often resulting in non-linear trajectories of change that are difficult to quantify (Giannecchini *et al.* 2007).

Since the first South African democratic elections in 1994, the traditional authorities' control over natural resource use within the tribal trust lands has weakened (Kaschula *et al.* 2005; Twine 2005), people often being disinclined to limit personal consumption when others have unrestricted access due to diminished control (Scholes 2009). Population growth, coupled with non-residents using vehicles to collect large amounts of fuelwood for commercial purposes, has contributed to increased demand and subsequent decline in natural resources (Twine 2005). Distances walked to collect fuelwood increased from 100 m in the 1980s to approximately 1000 m in the 1990s, indicating the development of gradients of wood resource availability around settlements (Giannecchini *et al.* 2007). Since natural resources provide a buffer against adversity (Dovie *et al.* 2002; Shackleton *et al.* 2007), demand is unlikely to diminish.

These rural landscapes require continued management to ensure sustained availability of natural resources (Hobbs *et al.* 2006). Given that rural areas in South Africa are often situated around protected areas, resource use not only affects ecosystem services and function in the immediate area, but also the sustainability of neighbouring protected areas (Joppa *et al.* 2009). Biosphere reserves are intended to reconcile the real and perceived differences between conservation and sustainable use of natural resources (UNESCO [United

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Nations Educational, Scientific and Cultural Organization] 1996). However, since the inception of the Kruger to Canyons (K2C) Biosphere Reserve in South Africa in 2001, where this study is based, degradation of woodlands has continued. Between 1993 and 2006, intact natural vegetation, a priority conservation class, decreased by 7.3% in K2C (Coetzer *et al.* 2010). Settlement areas increased by 39.7%, predominantly in Bushbuckridge, with a concurrent increase of 6.8% for human-impacted vegetation (Coetzer *et al.* 2010). Between 1972 and 1994, human population density in Bushbuckridge doubled, and is currently estimated at 300 people km^{-2}, resulting in increased land use intensity and economic impoverishment (Pollard *et al.* 2003).

An understanding of local interactions between the biophysical factors, socioeconomics and natural resources is required to manage the resources sustainably (Hobbs *et al.* 2006; Giannecchini *et al.* 2007). The 'top-down' effect of fire and herbivory on savannah dynamics is relatively well understood (Scholes & Archer 1997; Sankaran *et al.* 2005; Helm *et al.* 2011); however, the factors influencing human use are not. The way people use savannahs depends on governance, socioeconomics, and individual and group behaviour, among other aspects (Scholes 2009), making the effects on savannah dynamics difficult to quantify and predict. Previous studies in Bushbuckridge suggested that patterns of use were settlement specific (Shackleton *et al.* 1994; Giannecchini *et al.* 2007), indicating the importance of village-level characteristics on resource extraction.

It is important to understand if patterns of vegetation structure are indeed settlement-specific, or whether generalizations across areas and communities can be made. Additional variables affecting patterns in rangelands are underlying biophysical factors. Higgins *et al.* (1999) included landscape position in their study of woody vegetation structure for three settlements. High levels of harvesting pressure in uplands relative to lowlands resulted in new vegetation patterns that did not reflect the undisturbed topographical differences measured in surrounding protected areas. However, at lower levels of use they showed that an interaction between abiotic factors and human impacts determine vegetation structural patterns. Given the ever-evolving human dynamics, the expectation is that vegetation structure will change within 10–20 years.

Light detection and ranging (LiDAR) sensors measure the three-dimensional structure of vegetation and the underlying terrain. Small-footprint, discrete return LiDAR allows for objective fine-scale (1.12 m spot spacing) measurement of woody vegetation over land areas much larger than those measured by field techniques to assess effects of fire, herbivores (Asner *et al.* 2009; Levick *et al.* 2009; Smit *et al.* 2010), reserve management and land use (Wessels *et al.* 2011). The overarching aim here was to quantify anthropogenic impacts on the finer-scale nature of patterns in woody vegetation structure in communal rangelands, relative to elements of underlying biophysical factors (rivers, topography, slope and aspect). The following questions were addressed: (1) How does rangeland woody vegetation structure, measured using size class distributions (SCDs), change with distance from settlements? (2) What are the relative effects of topographic position and distance from settlement on woody vegetation structure? (3) How do environmental variables, such as distance from settlements, roads and rivers, elevation above closest major river channel, slope, aspect and geology, influence the spatial and vertical distribution of woody vegetation in communal rangelands? We examined woody vegetation structure in five communal rangelands surrounded by 12 settlements using airborne LiDAR data collected in 2008 over large parts of Bushbuckridge.

METHODS

Study area

Bushbuckridge Municipality is located in the northernmost portion of Mpumalanga Province (South Africa) (centred on 24.731°S, 31.181°E; Appendix 1, Fig. S1, see supplementary material at Journals.cambridge.org/enc), a savannah region with three vegetation types: granite lowveld (dominant), gabbro grassy bushveld and legogote sour bushveld (Rutherford *et al.* 2006). In the granite lowveld, typical species include *Terminalia sericea*, *Combretum zeyheri* and *C. apiculatum* on the deep sandy uplands, while *Acacia nigrescens*, *Dichrostachys cinerea* and *Grewia bicolor* grow in the more clay-rich lowland soils. In the two other vegetation types, additional common species include *Sclerocarya birrea*, *Lannea schweinfurthii*, *Ziziphus mucronata*, *Dalbergia melanoxylon*, *Peltophorum africanum* and *Pterocarpus rotundifolius*. Mean annual precipitation, predominantly summer rainfall, ranges from > 900 mm in the west to 500 mm in the east, with a mean annual temperature of 22°C. The geology is dominated by granite, with Timbavati gabbro intrusions (Venter *et al.* 2003).

The study encompassed five areas of communal rangelands (A–E) associated with 12 settlements (Appendix 1, Fig. S1, see supplementary material at Journals.cambridge.org/enc). The human population in these settlements varies in the total number of people, density, age and gender (Appendix 1, Table S1, see supplementary material at Journals.cambridge.org/enc), thereby exerting different resource extraction pressures on each associated rangeland. Although rangelands are predominantly used by the closest settlements, they are not exclusive use areas, especially with regard to the immigration of foreigners (both South Africans from surrounding areas and immigrants from neighbouring countries) who do not adhere to the local traditional authority's regulations (Twine 2005). Sites A and C are exceptions since their rangelands cannot be accessed from more than one settlement.

Light detection and ranging (LiDAR) data

LiDAR data were collected over 4578 ha by the Carnegie Airborne Observatory (CAO) in April 2008, using an airborne laser scanner. A pulse was actively emitted in the direction of the ground and the return time from emission to detection was measured to estimate the distance from the sensor to the object (ground or any land cover, i.e. tree or roof) (Wehr & Lohr 1999). The CAO was operated in Alpha mode, intended for high-resolution mapping of up to 20 000 ha day^{-1} at a 0.5–1.5 m spatial resolution of the raster of interpolated points. The CAO LiDAR sub-system provides three-dimensional (3-D) vegetation structural information, as well as high resolution digital elevation models. For this study, the discrete-return LiDAR data were collected 2000 m above ground level with a laser pulse repetition frequency of 50 kHz, laser spot spacing of 1.12 m, and four returns per pulse. The first LiDAR return typically indicated the top of canopy, or the sole return in the case of a ground hit, while the last return was often associated with the ground, unless dense vegetation hindered signal penetration. Algorithms based on between-return angles are used in pre-processing steps to classify ground versus non-ground returns. This resulted in a 3-D point cloud (x,y,z), providing a detailed representation of woody vegetation height structure.

A canopy height model (CHM) was derived by subtracting a digital elevation model (DEM) from a digital surface model (DSM) of first canopy returns (van Aardt *et al.* 2006). The DSM and DEM are triangulated models generated through linear interpolation of all first (DSM) and ground (DEM) returns per 1.12 m grid cell. The CHM was resampled into one metre height increments to be used for vegetation structural analysis. For 3-D vegetation analysis (woody structure-environment relationships), the xyz point cloud was divided into volumetric pixels (voxels) of 5 × 5 × 1 m (length × width × height). The value of each voxel was represented by the number of LiDAR returns m^{-3} relative to the total number of returns in the entire 5 × 5 m column. Each column in the dataset was normalized to equal a total of 1000 returns (Asner *et al.* 2008). Ground validation of vegetation heights was conducted concurrent to the aerial data collection in 2008 (Wessels *et al.* 2011).

Vegetation structure with increasing distance from settlements and between landscape positions

Settlements, roads, rivers, crop fields and rangelands (used for natural resource extraction and grazing) were manually digitized across the study area using a combination of SPOT 5 imagery (panchromatic-multispectral merge (480–890 nm), 2.5 m spatial resolution, www.spotimage.com) and hyperspectral imagery collected by the CAO (1.12 m spatial resolution, 400–1050 nm; Asner *et al.* 2007). Distance classes of 200 m, radiating away from the settlements as sequential buffers, excluding riparian areas, roads and fields (Appendix 1, Fig. S1, see supplementary material at Journals.cambridge.org/enc), were created using ArcMap 9.3 (Esri 2009). If the rangeland was surrounded by settlements (sites B and D), the resulting distance classes were 'circular' with the furthest zone as a midpoint between adjacent settlements (Appendix 1, Fig. S2, see supplementary material at Journals.cambridge.org/enc). Seven distance classes were created for each site, except site B which, due to the circular nature of the distance classes and small area, could only accommodate six classes. For sites A, C and E, the maximum number and direction of distance classes were determined by a combination of the extent of the LiDAR data and either the distance to the Sabi Sand Wildtuin Private Game Reserve (SSW) boundary (Appendix 1, Fig. S1, see supplementary material at Journals.cambridge.org/enc, sites A and C) or the distance to a natural landscape boundary (for example hills, site E). Upland and lowland areas were delineated manually using a winter SPOT 5 image (2.5 m spatial resolution) and the CAO DEM (1.12 m spatial resolution) within the study sites situated on granite (sites C, D and E). We were unable to reliably differentiate between topographic positions for sites occurring on gabbro, which has a much more subdued relief relative to granite, and hence topographic position was not included for these sites (sites A and B).

Within each distance class, 10% of the pixels in the top-of-canopy image were randomly sampled in ENVI v4.7 (ITT Vis [ITT Visual Information Systems] 2009), with five repeats of each. This 10% allowed for a representative number of pixels to be sampled per site ($n_A = 391\ 747$; $n_B = 576\ 572$; $n_C = 168\ 603$; $n_D = 533\ 684$; $n_E = 1\ 103\ 537$; $n_{total} = 2\ 765\ 143$ pixels), while ensuring pixels were not spatially autocorrelated (Asner *et al.* 2009). We recorded the mean value of the five repeats per distance and height class. Woody vegetation was defined as vegetation above 1 m. Per cent woody cover of each height (1–12 m) and distance class was calculated from the top-of-canopy data to derive a SCD of woody vegetation with increasing distance from each settlement. SCDs are useful indicators of vegetation change and population structure (Lykke 1998; Wilson & Witkowski 2003; Botha *et al.* 2004). Care must be taken when assessing SCDs at a landscape scale, as many species with various height structures are present. A SCD with an inverse-J shape is generally characteristic of vegetation with good rejuvenation and continuous replacement, whereas a flatter distribution indicates a lack of recruitment (Mwavu & Witkowski 2009). In disturbed savannah landscapes, people influence SCDs through harvesting of live wood and trees respond by coppicing (Neke *et al.* 2006), resulting in increased density of vegetation below three metres. Alternatively, the selective conservation of taller more mature trees for fruit and/or shade may be practised (Luoga *et al.* 2005; Twine 2005; Wessels *et al.* 2011).

ANOVA was used to test for differences in the mean per cent cover, as measured from the top of canopy images, between sites (five categories) in relation to distance (six categories) and height classes (14 categories) (Fig. 1). For each site separately, ANOVAs were used to explore differences in SCDs between distance (seven categories for sites A, C, D and

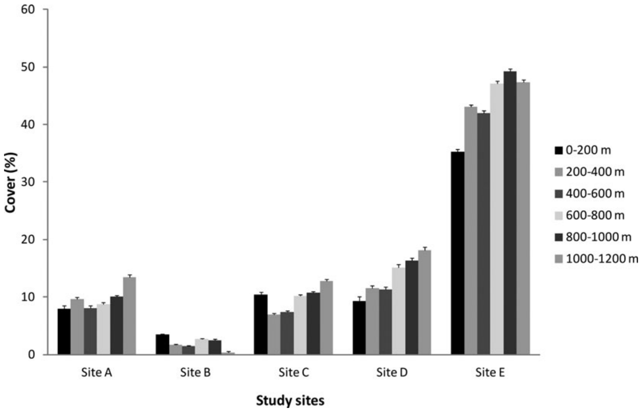

Figure 1 Per cent woody cover in rangelands at increasing distances from settlements for five sites in Bushbuckridge municipality, Mpumalanga Province, South Africa. Error bars denote standard deviation.

E, and six for site B) and height classes (14 categories). For sites C, D and E, an additional ANOVA including topography was conducted (treatment = topography [two categories], factors = height and distance class). Significant differences between treatment combinations were evaluated using a Tukey post-hoc test ($\alpha = 0.05$) (Zar 1999).

Woody structure-environment relationships

The relationship between three-dimensional woody vegetation structure and environmental variables was investigated using canonical correspondence analysis (CCA), a constrained ordination technique (ter Braak & Smilauer 2002). CCA represents synthetic environmental gradients from ecological datasets, in this case how woody vegetation density in different height classes extracted from the voxel dataset was affected by the environmental variables (Leps & Smilauer 2003). Environmental variables were chosen according to available data and their hypothesized influence on woody vegetation structure. All variables were classified into one of two categories: 'anthropogenic' (distance to closest settlement, distance to closest road), or 'natural' (horizontal distance to closest river channel, geology, slope, aspect and elevation relative to the nearest river channel [REM = relative elevation model]). The 'anthropogenic' variables were selected according to their perceived effect on resource use: fuelwood is more accessible closer to settlements and closer to roads and therefore use should be higher closer to these features. 'Natural' variables were chosen due to their known effect on savannah vegetation structure (Scholes & Walker 1993). Fire was not included in the set of 'natural' variables as there is no reliable fine-scale fire scar data for the area, but due to high human use and thus low fuel loads, fire is generally a less important variable than in conservation areas (Archibald *et al.* 2009).

Raster maps of distances to settlement, rivers and roads were created using the spatial analyst function in ArcMap 9.3, with a spatial resolution of 5 m, corresponding to the voxel data. Slope and aspect were calculated at 5 m spatial resolution in ENVI 4.7 using the topographical modelling feature and the CAO DEM. Only north (exposed slopes) and south (sheltered slopes) aspects were included in the analysis. The REM was constructed using the 'terrain: relative heights and slope position' module in SAGA (weighting = 5, search window = 100 m; see www.saga-gis.org). The 'normalized height' product was used, which is a normalized version of the slope heights output (values recalculated to range from 0–1; calculated as AACL/(AACL + ABRL), where AACL = altitude above closest channel and ABRL = altitude below ridge line [Bock *et al.* 2007]).

A minimum distance between each sampling point (voxel) was enforced to ensure points were not spatially autocorrelated, since vertical data from each voxel were used for the CCA and not mean of top-of canopy values. The minimum distance over which sampling points should be spread was determined using semivariograms, calculated in ENVI 4.7, as the range at which the sill occurs on the semivariogram (150 m). Points were randomly sampled across the study area, using Hawth's analysis tools for ArcGIS, with a minimum distance of 150 m enforced between points to negate the effects of spatial autocorrelation, resulting in a total of 1651 points across the study area. Environmental variables for each point were extracted in ArcGIS and the frequency of LiDAR returns per voxel in the column was extracted in ENVI 4.7. By using the voxel data, which is a measure of vegetation density in 1 m height increments, we were able to characterize the actual structure of the vegetation. CANOCO v5 (ter Braak & Smilauer 2002) was used to perform the CCA.

Partial canonical correspondence analysis (PCCA) was conducted for all sites to establish the contribution of each group of explanatory variables ('natural' versus 'anthropogenic') to the total variance explained by a combination of the factors. A difference in the contribution of each group of variables was analysed using a t-test. PCCA is conducted by using the variable of interest as the explanatory variable (for example distance to settlement) and the other factors as covariates (all other natural and environmental explanatory variables) (Pysek & Leps 1991; Leps & Smilauer 2003). Once the variation explained by 'natural' and 'anthropogenic' variables was calculated, ordinations were performed for all sites combined, and then site-specific ordinations to establish which natural and anthropogenic factors influenced vertical vegetation structure. Geology was not included in the site specific ordinations, as each site only fell within a single geological type. All variables were tested for normality before performing the CCA, while rare height classes (such as > 10 m) were down-weighted. Forward selection by Monte Carlo tests (9999 permutations) were used to select significant environmental variables ($p < 0.05$) in the ordination, however, all variables were depicted. The total variance in each dataset accounted for by the explanatory variables was calculated as a percentage of the canonical eigenvalue contribution to the sum of all eigenvalues.

RESULTS

Vegetation structure with increasing distance from settlements and between landscape positions

Mean per cent woody vegetation cover was significantly different between sites (Fig. 1; $F_{4,258} = 923.35$, $p < 0.0001$), except between sites A and D ($p > 0.05$). There was a significant interaction between site and distance from settlement (Fig. 1; $F_{20,258} = 3.57$, $p < 0.0001$), with only site B experiencing a decrease in per cent canopy cover with increased distance from settlements (8.6 × less cover in the furthest distance class; Fig. 1). Increases in per cent canopy cover with increased distance from a settlement were as follows: site A = 1.7, site C = 1.2, site D = 2.0 and site E = 1.3 ×. Site E had significantly higher woody cover than all others for all distance classes ($p < 0.0001$), while site B had significantly lower woody cover across all height classes (Fig. 1). The overall trend was an increase in canopy cover with increased distance from settlement, although the opposite was true for site B (Fig. 1; site A: $F_{6,76} = 6.2$, $p < 0.0001$; site B: $F_{5,65} = 16.35$, $p < 0.0001$; site C: $F_{6,78} = 47$, $p = 0.0006$; site D: $F_{6,78} = 3.29$, $p = 0.0061$; site E: $F_{6,78} = 45$, $p = 0.0006$).

SCDs at increased distances from settlements followed an approximate inverse J-shape for sites A, C and D (Fig. 1*a*, *c* and *d*). There was a significant interaction between height class and distance from settlement ($F_{65,258} = 1.82$, $p = 0.0005$). The trend for sites A, C and D was a decreasing disturbance gradient with increased distance from settlement; however, the woody cover in each height class was site specific (Fig. 2*a*, *c* and *d*). Site B was severely impacted, with reduced vegetation cover in all size classes relative to the other sites (Fig. 2*b*).

Size class distributions of per cent cover on uplands and lowlands with increased distances from settlements

In the analysis that included topography as a factor (sites C, D and E only), there were significant interactions for sites D and E between height and distance class (Fig. 3; site D, distance class: $F_{65,65} = 1.77$, $p = 0.011$; topography: $F_{13,65} = 8.3$, $p < 0.0001$; site E, distance class: $F_{78,78} = 1.51$, $p = 0.0356$; topography: $F_{13,78} = 63$, $p < 0.0001$). However, for site C, only topography was significant (Fig. 3; distance class: $F_{36,36} = 0.88$, $p = 0.65$; topography: $F_{12,36} = 5.91$, $p < 0.0001$). The difference in SCDs between landscape positions is therefore greater than differences at increased distances from settlement, reflecting the greater importance of the physical template.

Woody structure-environment relationships

Total variance accounted for in the spatial (horizontal and vertical) distribution of woody vegetation, measured by the explanatory variables from the voxel data, was relatively low (site A = 7.4%, B = 24.8%, C = 29.5%, D = 17.7%, site E = 3.6%). Even so, results of the PCCA showed 'natural' variables contributed more to total variance than 'anthropogenic' variables for each site, as well as for all sites combined (Fig. 4; $t_4 = 3.75$, $p = 0.0199$). However, this was expected as there are five 'natural' and only two 'anthropogenic' variables. For 'all sites', the proportion of the total variance explained by 'natural' and 'anthropogenic' variables included in the PCCA was 52%, implying that 48% of the total variance may be attributed to interactions between these variables and others not measured. For 'all sites' (A–E), 'natural' variables contribute more to the total variance explained than the 'anthropogenic' variables (Fig. 4).

The exploration of the spatial effects of individual 'natural' and 'anthropogenic' factors on vegetation density at 1 m height increments, measured from the voxel data using CCA, was first performed on a dataset including all sites (1650 samples). A combination of 'anthropogenic' and 'natural' variables was significant, with only aspect and geology not significant at this large scale (Fig. 5*a*). Distance to settlement was the most significant factor explaining the spatial distribution of vegetation density, followed by REM (both positively correlated with tall vegetation). These were followed by distance to roads, distance to rivers and finally slope, which was positively correlated with the tallest vegetation (10–12 m) (Fig. 5*a*). At this broad scale of analysis, a combination of 'anthropogenic' (increasing distances from settlement) and 'natural' (REM) factors was most important in affecting vertical structural heterogeneity. However, this pattern changed at finer site-specific scales (Fig. 5*b*–*f*).

Vegetation in the 1–2 m height class was always separate from all other vegetation and not strongly correlated with any explanatory variable (Fig. 4*a*–*f*). Distance to settlement was significant in explaining the spatial distribution of vegetation for sites A, C and E (Fig. 5*b*, *d* and *f*), the three sites where the rangelands were only used by one settlement. Distance to roads, the other 'anthropogenic' factor, was only significant for site E. Only 'natural' explanatory variables were significant for sites B and D (Fig. 5*c* and *e*), the two sites where the rangelands were used by more than one settlement. We therefore identified trends across the sites related to the intensity of use (inferred from number of settlements accessing the rangeland), with vegetation structure on intensively used sites being more related to 'natural' variables (Fig. 5*c* and *e*) and those less intensively used related to 'anthropogenic' variables (Fig. 5*b*, *d* and *f*).

Vegetation within sites A, B and C tended to be more homogeneous, with many height classes occurring in close proximity in the ordination and thus indicative of greater spatial cohesion. When examining the SCDs of vegetation around settlements (Fig. 2), we saw that for all sites except site B, the cover of vegetation within size classes < 3 m was far greater compared to classes > 4 m. The same pattern emerged in the ordinations, where, for all sites, although to a lesser degree in site B, the lower height classes were more dispersed from the taller height classes, whereas taller vegetation was more grouped. Taller vegetation (> 5 m) was usually positively correlated with either slope or REM,

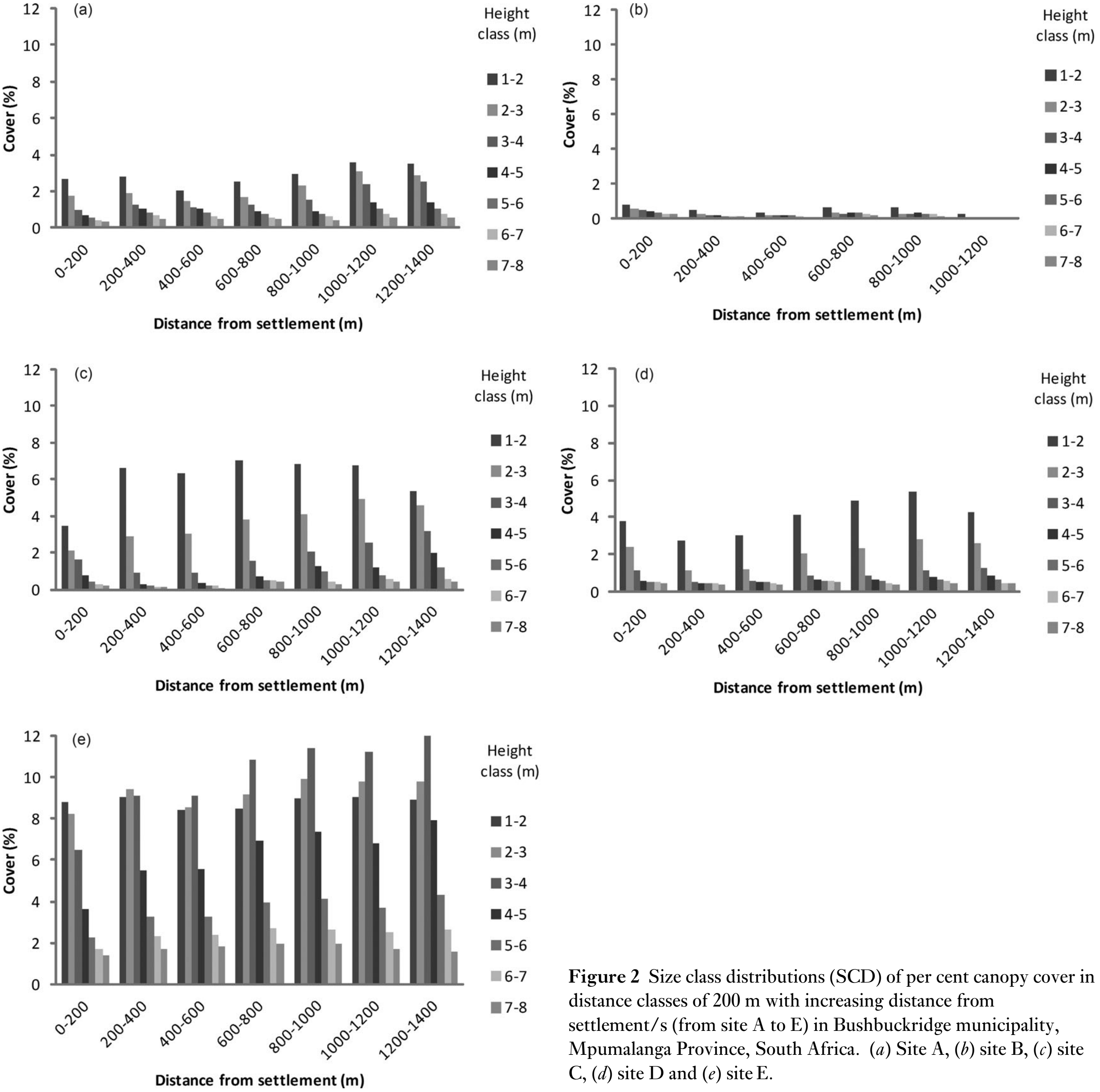

Figure 2 Size class distributions (SCD) of per cent canopy cover in distance classes of 200 m with increasing distance from settlement/s (from site A to E) in Bushbuckridge municipality, Mpumalanga Province, South Africa. (*a*) Site A, (*b*) site B, (*c*) site C, (*d*) site D and (*e*) site E.

high values of each indicating a drainage line or crest in the landscape, respectively. We would therefore expect short vegetation to be spatially widespread across the landscape, while tall vegetation would be clumped and tending to occur on crests and near rivers.

DISCUSSION

In rural landscapes, understanding the interactions between underlying biophysical factors and human activities is critical for predicting future changes and planning for sustainable development. Our study covered 4578 ha, larger by orders of magnitude than the sampling areas examined by Shackleton *et al.* (1994) (0.81 ha) and Higgins *et al.* (1999) (1.08 ha). The findings of Shackleton *et al.* (1994) have held true over this greater sampling area, with disturbance gradients present around settlements that are only moderately used, as opposed to those with either high or low use intensity, where a gradient is not apparent. However, while Higgins *et al.* (1999) found vegetation structure within the rangelands to 'fall outside the topographic continuum' due to use, we found that significant differences in structure still existed across slope position (Figs 3 and 5). Woody vegetation structural patterns were a result

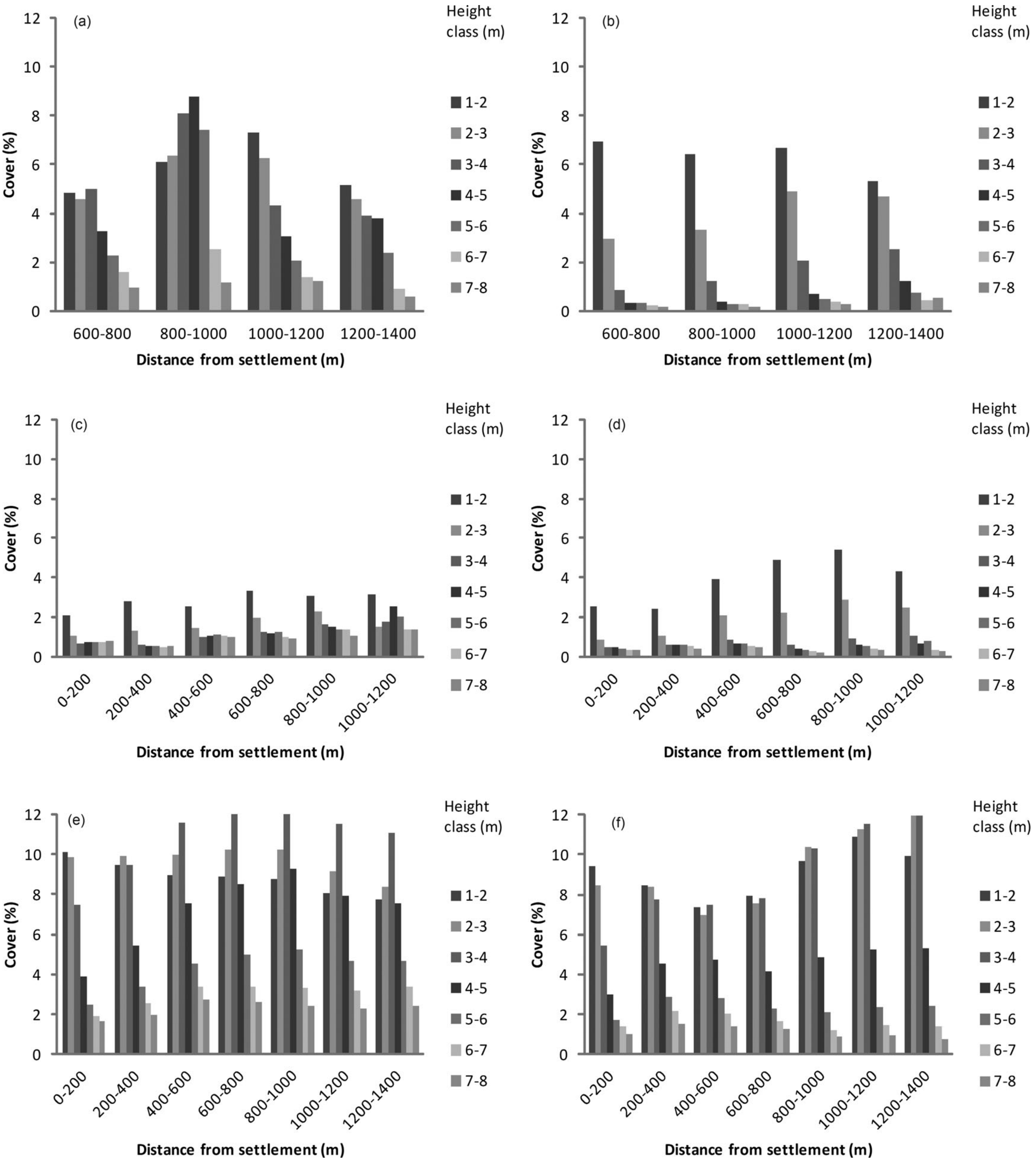

Figure 3 Size class distributions (SCD) of per cent canopy cover in distance classes of 200 m with increasing distance away from settlement/s on uplands and lowlands in Bushbuckridge municipality, Mpumalanga Province, South Africa. (*a*) Site C uplands, (*b*) site C lowlands, (*c*) site D uplands, (*d*) site D lowlands, (*e*) site E uplands and (*f*) site E lowlands.

of a combination of anthropogenic and natural factors (Figs 2–5), although the total variation explained in the CCA was relatively low (< 30%, Fig. 5). Much of the unexplained variation is likely to be due to species-specific variation in height structure along disturbance and topoedaphic gradients (Witkowski & O'Connor 1996).

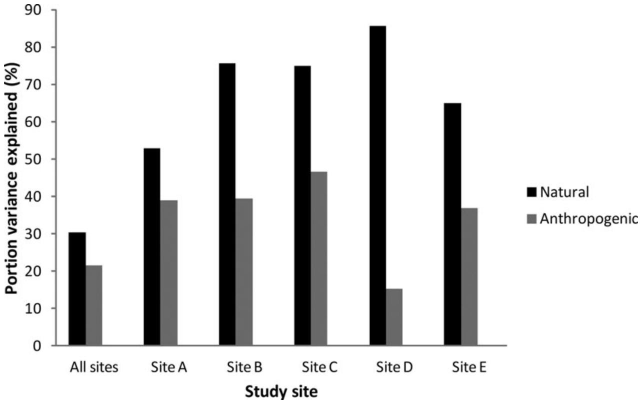

Figure 4 Contribution of 'natural' and 'anthropogenic' factors to total variance explained in the spatial distribution of vegetation within rangelands in Bushbuckridge Municipality, Mpumalanga Province, South Africa

Wessels *et al.* (2011) compared the overall tree canopy cover and height distributions between communal rangelands (the same rangelands of sites A, B, C and D, this study) and conservation areas at the landscape scale. They found geology to be an overriding factor affecting vegetation structure across this land-use gradient. At the finer scale of our investigation, geology was not significant (Fig. 5*a*), but landscape position was (Figs 3 and 5), highlighting that the hierarchical abiotic determinants of vegetation structure (Gillson 2004) remain true even in human-modified landscapes. The significant difference in the shape of SCDs between uplands and lowlands in the rangelands (Fig. 3) indicated that underlying fine scale abiotic factors have a stronger influence than resource extraction at moderate levels of land use.

The presence or absence of disturbance gradients around settlements and the shape of SCDs appear to be settlement specific. Giannecchini *et al.* (2007) highlighted the importance of settlement specific studies that incorporate local information, as broad-scale studies often neglect fine-scale variation. At site B, the low cover and lack of disturbance gradient was attributed to high use intensity, with the rangeland being surrounded by five settlements (Appendix 1, Fig. S1, see supplementary material at Journals.cambridge.org/enc). One settlement using site B, Lillydale B, had a human population increase of 67.1% over the period 1993–2008, greater than for any other settlement in the area (Appendix 1, Table S1, see supplementary material at Journals.cambridge.org/enc). As this increase cannot be attributed to births (1.1% increase), it seems most likely to be a result of immigration. This has negative impacts on sustainable resource use, as outsiders are less likely to respect traditional authorities (Kaschula *et al.* 2005). Similarly, settlements around site D (Ireagh A, Ireagh B and Kildare A; Appendix 1, Table S1, see supplementary material at Journals.cambridge.org/enc) showed signs of immigration, as there was a decline in the birth rate and population decreases in the 5–19 year old age group, yet the overall population increased.

We found that 'natural' factors were more significant in determining the spatial pattern of woody vegetation for sites B and D, both used by more than one settlement (Fig. 5*c* and *e*). This result was confirmed by the SCDs and absence of disturbance gradients (Fig. 2*b* and *d*). High and increasing demand on these rangelands, caused by surrounding settlement density and thus higher population density (Appendix 1, Table S1, see supplementary material at Journals.cambridge.org/enc), therefore appear to create a homogeneous landscape as a result of high use across the entire site. Homogeneous landscapes are negative for biodiversity, as habitat diversity is decreased especially for small-bodied fauna (Manning *et al.* 2006) and landscape function related to ecosystem services such as fruit, shade and fuelwood also declines.

Alternatively, for the rangelands used by only one settlement (sites A, C and E), distance to settlement was a significant explanatory variable of the spatial distribution of vegetation (Fig. 5*b*, *d* and *e*). Settlements using these areas (Justicia A and Xanthia) showed relatively high population increases of 27.5% and 23.6%, respectively (Appendix 1, Table S1, see supplementary material at Journals.cambridge.org/enc). However, use intensity remained low because use of the rangelands was geographically restricted to one settlement. Each of these three sites showed human-driven disturbance gradients (Fig. 2*a*, *c* and *e*), although differences in SCDs are greater between sites than between distance classes. Although the amount of cover is settlement specific, the presence of disturbance gradients is common in this landscape, as shown here and by Shackleton *et al.* (1994).

With increased demand on natural resources and more people collecting fuelwood using vehicles (Twine 2005), we expect disturbance gradients to diminish and few to develop as more areas become accessible, especially in these areas with dense settlements and reduced control over resource use. Disturbance gradients are expected in a human-modified landscape (Shackleton *et al.* 1994). Is the decline of these gradients into homogenous highly-used patches coupled with low woody cover a cause for concern? Coppice regrowth of harvested trees could change the tree's structure to a shrub form, which at a broad-scale might be viewed as bush encroachment (Luoga *et al.* 2005). In addition, adult coppicing trees are prevented from reaching sexual maturity, resulting in a lack of juvenile recruitment and therefore limited regeneration ability. A potential result of unsustainable harvesting of coppice regrowth following this trajectory is woodland degradation (Banks *et al.* 1996) unless community action is taken (R. Matsika, unpublished data 2011).

In conclusion, although results are inherently settlement specific and potentially dependent on an array of socioeconomic factors, some generalizations can be made. The shapes of the SCDs are similar for each settlement, but the cover of woody vegetation present within each size

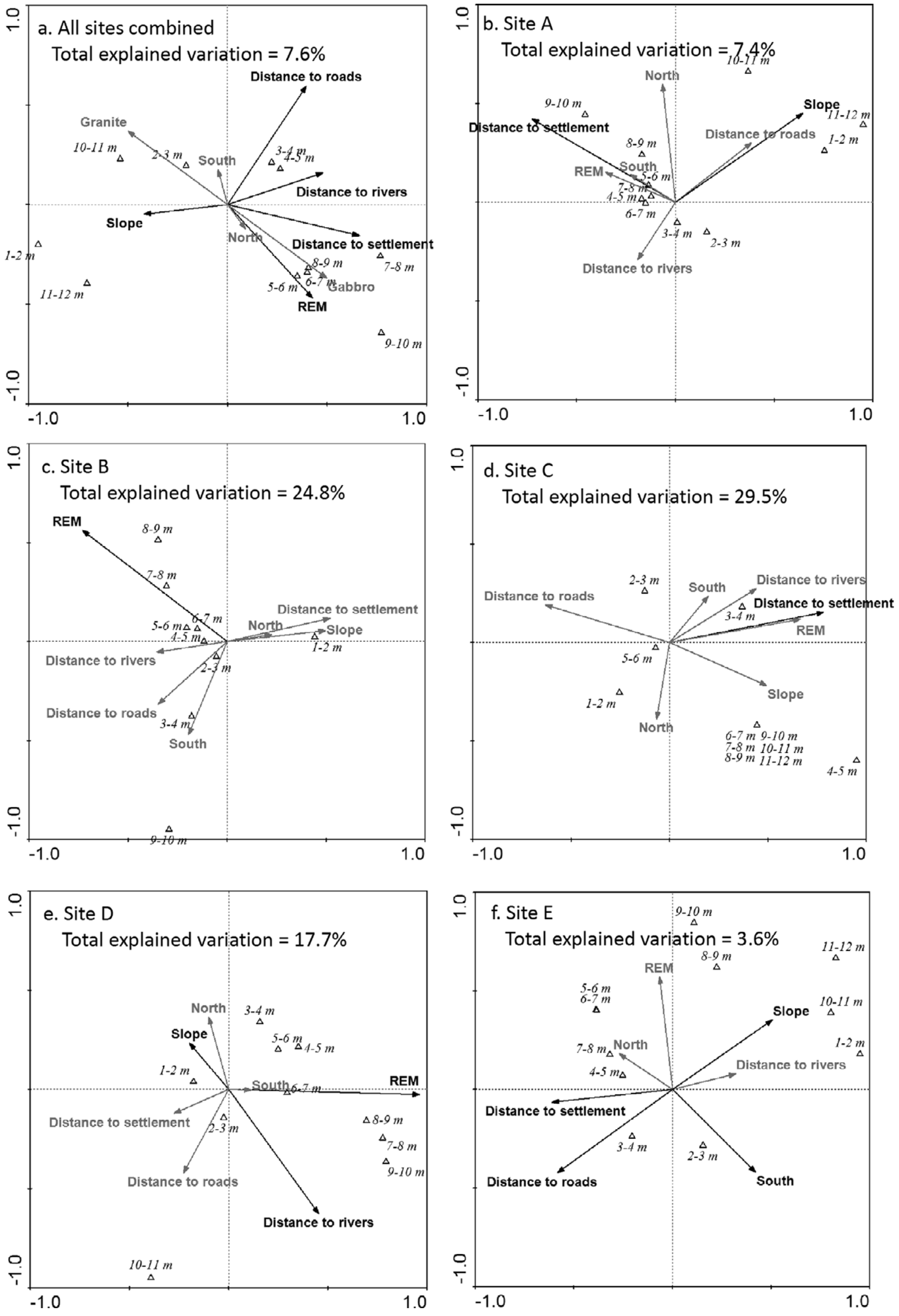

Figure 5 'Anthropogenic' (distance to settlements and distance to roads) and 'natural' (distance to rivers, elevation above river channel (REM), slope and aspect = north and south) factors in relation to patterns of three-dimensional woody vegetation structure. (*a*) All study sites combined, (*b*) site A, (*c*) site B, (*d*) site C, (*e*) site D and (*f*) site E. Total explained variation was calculated as sum of all canonical eigenvalues as a per cent of all eigenvalues. Significant explanatory variables are shown in bold, non-significant indicated in grey. The length of an arrow of an explanatory variable is proportional to its influence on the responding variable. Angle between arrows indicates correlation between the explanatory variables (<90° = positive correlation, 90° = no correlation, >90° = negative correlation). Proximity of triangles on the diagram indicates either spatial proximity or that the variables respond in a similar fashion (ter Braak & Smilauer 2002).

class is dependent on the use intensity. High use intensity in rangelands results in a disappearance of disturbance gradients, creating homogeneous patches of low woody cover. This will ultimately decrease structural diversity and thus biodiversity and woodlands will be unable to provide the necessary ecosystem services of fuelwood, shade and fruit. Therefore, land and conservation planners within the Kruger to Canyons Biosphere Reserve can use the early warning sign of initial development and later reduction of disturbance gradients, or indicators of them, to focus their conservation and sustainable development efforts. The continued high reliance on natural resources, especially fuelwood (Twine *et al.* 2003), highlights the need for continuous monitoring of this resource base to assess sustainability and provide solutions if use is unsustainable. Using LiDAR, it is possible to quickly and reliably measure and map woody vegetation structure across entire rangelands without observer bias. Repeated data collection will permit monitoring of the changes in woodland structure and biomass, change in patterns of rangeland use as natural resources decrease, and the effectiveness of management interventions (such as rotational harvesting). LiDAR will thus facilitate adaptive management of natural resources by providing an objective monitoring tool.

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