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Rotational grazing management has little effect on remotely-sensed vegetation characteristics across farm fence-line contrasts

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ABSTRACT

The consensus from world-wide experimental studies is that rotational grazing management has little effect on enhancing vegetation cover and animal productivity relative to conventional management. Critics of these studies claim that experimental trials fail to capture the complexity of adaptive management decisions that bring about long-term vegetation changes at the landscape scale. Thus, we surveyed 48 working farms nation-wide in South Africa to test the hypothesis that rotational grazing sustains higher animal numbers while increasing grass cover and reducing bare ground and woody plant cover. A subset included 23 fence-line comparisons between farm neighbors or paddocks with a similar fire regime but with grazing management varying from continuous to ultra-high density grazing, and we coupled this with remotely-sensed vegetation indices.

Results from 48 farms under consistent management for 15 ± 0.8 years (mean ± standard error), revealed that farm stocking rates were relatively higher than those recommended by agricultural extension services at 59 ± 12% ($\frac{Farms - Recommended}{Farms} * 100$ ± standard error) and that adherence to high density rotational grazing management did not affect this. For fence-line contrasts, the change (Δ) in each management or explanatory variable (stocking rate, stock density and proportion of grazers versus all livestock) across the fence was expressed using Hedge's g effect size as $\Delta = \frac{(a-b)}{a} \times 100$ where (a) is the farm with the highest grazing density and (b) is its neighbour. As intended, the comparisons yielded a 85 ± 5% relative difference in grazing densities but revealed non-significant differences in normalised difference vegetation indices (NDVI), fractional bare ground, grass and woody plant cover at 82% of fence-lines. The absolute magnitude of fence-line differences in stocking rate (30 ± 7%) and grazer percentage (55 ± 16%) also had no consistent effect on vegetation cover. This regional analysis of working farms corroborates findings from multiple experimental studies on rotational grazing and adds weight to it by including a diversity of rotational grazing intensities. Evidence in this study was not compatible with commonly observed negative effects of high stocking rates on vegetation cover, implying that the relatively high stocking rates were within the carrying capacity of farms studied. Further, the previously untested hypothesis that rotational grazing alters woody plant cover was not supported in our study. Based on these and the findings of others, continued advocacy for extreme forms of rotational grazing management is unfounded.

1. Introduction

Meat and dairy consumption is set to increase world-wide with projected global economic growth, which will place increasing pressure on rangeland managers to preserve ecosystem services flowing from rangelands (Tilman and Clark, 2014). Understanding the interaction between various management practices and vegetation and animal responses that form the basis of ecosystem function and services is thus important. However, rangelands are ecologically complex and dynamic systems in which vegetation responses to some management interventions (e.g. herbivore stocking and fire) are strongly influenced by subtle nuances of the management interventions and by differences in climate and other ecosystem properties (Vetter, 2005; Gillson and Hoffman, 2007).

Despite this, stocking rate, referring to the number of large stock units (LSUs) per hectare of available rangeland, has long been considered the most important management variable in maintaining palatable vegetation production within rangelands (Skovlin, 1987; Ralphs et al., 1990; Willms et al., 1990; Gillen et al., 1998; Briske et al., 2008; Derner et al., 2008). Maintaining stocking at rates higher than the

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capacity for vegetation to recover leads to mortality of palatable plant species and consequent degradation of rangeland carrying capacity (Wessels et al., 2007; Briske et al., 2011). Grazing management approaches define the spatio-temporal pattern or rotation of livestock movements, typically using fencing (or shepherds) to achieve desired livestock grazing densities (Briske et al., 2008). Grazing density, sometimes referred to as 'stock density', is the number of LSUs per subunit of area at any point in time on that rangeland so that two farms may have the same stocking rate but different densities depending on the number of defined camps in which stock are held per unit time. It has been argued that stocking rate has a stronger effect on vegetation and animal productivity than the grazing management (Briske et al., 2011; Hawkins, 2017).

Replacement of native herbivores from Africa and the New World with exotic herbivores (largely Eurasian cattle, sheep and goats) has facilitated invasions by exotic and indigenous plant species, that thrive with these exotic herbivores in contrast to some native plants (Parker et al., 2006). Simplified guilds of herbivores (livestock) may repeatedly select palatable vegetation patches and species (Fuls, 1992; Kellner and Bosch, 1992; Illius and O'Connor, 1999b; WallisDeVries et al., 1999; Teague et al., 2004) leading to plant mortality and competitive release of less palatable species that may consequently encroach or become invasive (Anderson and Briske, 1995). Human population growth and associated livestock farming in Africa has further simplified the functional composition of browsing, grazing and mixed-feeding herbivores to one dominated by grazers (Hempson et al., 2017). Indeed, overgrazing has been implicated as a driver of woody plant encroachment into grassy areas of Africa (O'Connor et al., 2014; Stevens et al., 2016; Venter et al., 2018). Woody plant encroachment can alter hydrological cycles and reduce the carrying capacity of the rangelands (Archer et al., 2017). Grazers reduce herbaceous biomass and allow for the competitive release of woody plants, primarily through the reduction of fuel loads for fires, thereby releasing woody plants from the fire trap (Roques et al., 2001; O'Connor et al., 2014). Incorporating browsers combined with high density grazing and the supposed reduced ability for herbivores to selectively overgraze palatable vegetation might suppress woody plant encroachment (Venter et al., 2018).

Overgrazing under excessive stocking rates and selective overgrazing under continuous year-long (non-rotational) grazing management increases soil exposure and reduces overall vegetation basal cover (Thurow, 1991; Fuls, 1992; Ash and Smith, 1996; Teague et al., 2011). Piospheres around farm watering points offer an extreme example of where localised stocking rates cause loss of vegetation cover, increased soil exposure, compaction and erosion (Andrew, 1988; Jeltsch et al., 1997). Despite the evident detrimental effects of extreme stocking rates, proponents of Holistic Management maintain that adopting forms of high-density grazing can enhance rangeland productivity, while doubling stocking rates (Savory, 1983; Butterfield et al., 2006). Evidence from experimental trials investigating rotational grazing systems including holistic planned grazing, however, show no consistent effect on vegetation production, basal cover, or animal gain (Briske et al., 2008, 2011; Hawkins, 2017; Venter et al., 2019).

Experimental trials are often implemented over small spatial and temporal scales, failing to capture the landscape-scale and long-term consequences of complex management decisions that constitute a grazing management system (Teague et al., 2013; Venter et al., 2019). To overcome this, some have attempted to use multiple cross-site comparisons of working farms (Teague et al., 2011), while others have employed the use of satellite remote sensing to monitor landscape-scale long-term changes in vegetation cover, quality and even composition (Booth and Tueller, 2003; Palmer and Fortescue, 2004; Svoray et al., 2013; Ali et al., 2016). Satellite remote sensing has been used previously to distinguish degraded from non-degraded rangeland in South Africa, typically using the normalised difference vegetation index (NDVI) as a proxy for vegetation productivity and vigour (Botha and Fouche, 2000; Archer, 2004; Wessels et al., 2004; Munyati and Makgale, 2009). However, these studies have limited their analysis to the influence of stocking rates and have largely ignored possible interactions with the adoption of rotational grazing management. Further, few studies have investigated the effects of rotational grazing management across a range of rotational intensities (Hawkins, 2017).

Using a grazing management questionnaire survey, along with a comparison of neighbouring farms or paddocks using satellite remote sensing, we investigated the effects of grazing management on fractions of vegetation cover in South Africa. We tested the hypothesis that increasing grazing densities through forms of rotational grazing management facilitates higher stocking rates while preventing woody plant encroachment or the loss of grass cover. We also predicted that farms with relatively high stocking rates and herds dominated by grazers will exhibit higher fractions of woody plant and bare ground cover with variable effects on NDVI.

2. Methods

2.1. Survey questionnaire

Questionnaire surveys have previously been used in rangeland science to assess vegetation responses to various grazing management practices (Stinner et al., 1997; Archer, 2004; de Villiers et al., 2014; Roche et al., 2015; Becker et al., 2017). We distributed an online questionnaire survey (see Appendix S6 in supporting information) via the SurveyMonkey website (www.surveymonkey.com) to a range of extensive commercial livestock farmers within South Africa between 2016 and 2017 (Fig. 1). The University of Cape Town provided ethical clearance (certificate no. FSREC 16–2017). We employed the use of national farmer associations to disseminate the survey and encouraged respondents for forward the survey link to other farmers in their respective districts. Each participant signed an online form consenting to the interview. We did not aim to interview a spread of ages nor to approach a particular gender ratio due to the gender bias in livestock farming. Online interviews comprised semi-structured questions including Likert items (Brooke, 1996), closed- and open-ended questions with scales and indices and follow-up interviews with selected farmers were conducted face-to-face. Participants were excluded if their farms

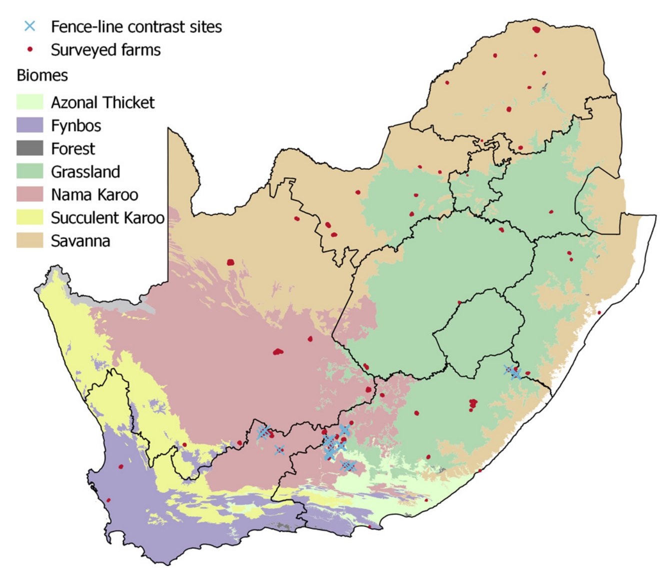

Fig. 1. Distribution of the 48 farms that participated in the online questionnaire survey (farm boundaries in red) and the subset of those (14) that were visited for the fence-line contrast study (blue crosses). Fence-line contrasts were clustered around the Grassland – Nama Karoo biome transition. Provinces are outlined in black (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

Table 1
Description of grazing management systems with which farmers were asked to align themselves in the questionnaire survey.

System	Acronym	Description	Suggested rotationality	Reference
Continuous grazing	CG	Access to all grazing areas for at least a full season. Particularly common in communal rangelands and wildlife areas.	Very low	(De V. Booysen, 1967; Tainton, 1999)
Low-density grazing	LDG	Can be considered very similar to continuous grazing. Might incorporate season-long grazing where half of the farm is rested for an entire growing season.	Low	(De V. Booysen, 1967; Fynn, 2012)
Four-camp rotation	FCG	Farm divided into four camps. One is rested while others are grazed at varying levels of intensity. Rested camp is burnt before the next growing season. Camps are then rotated.	Medium	(Venter and Drewes, 1969)
Time-controlled grazing	TCG	Names used interchangeably to refer to the practice of rotational grazing management. Grazing area divided into multiple paddocks to create reoccurring periods of grazing and rest. Generally managed according to a fixed rotation plan, however does not exclude adaptive approaches.	High	(Merrill, 1954; Tainton, 1999; Briske et al., 2008)
Short-duration grazing	SDG		High	
High-density grazing	HDG		High	
Holistic planned grazing	HPG	A proactive and adaptive management framework which operates within a defined holistic management context. Often associated with the use of rotational grazing and high animal densities.	Very high	(Savory, 1983)
Ultra-high density grazing	UHDG	A variant of rotational grazing with higher stocking densities (more camp divisions and shorter grazing durations) of hundreds or thousands of animals per hectare. Often associated with HPG.	Very high	(McCosker, 2000)

were not managed under a particular grazing management for more than 5 years or if they did not farm with livestock including cattle, sheep and/or goats where > 75% of their diets constituted natural vegetation.

To capture the complexity of management decisions that constitute a grazing system, we asked farmers to score their alignment with a range of established grazing management systems (Table 1) using a Likert-scale (Brooke, 1996). We assessed these scores using a principle components analysis (PCA) to distil a composite index of grazing management. To calibrate and interpret the PCA result, we asked specific questions regarding camp number, camp size, rotation frequency, and grazing densities. A further set of questions (Table A1) focussed on holistic planned grazing (HPG) were used to quantify the extent to which a farm was aligned with the core principles of HPG. These questions were derived from a combination of the Holistic Management Adoption Index devised by de Villiers et al. (2014) and principles highlighted in the book by Savory and Butterfield (2016) on Holistic Management.

To calculate farm stocking rates (LSU ha^{-1} yr^{-1}) we used the respondent's reported farm size (ha) and total livestock units (LSU). Relative stocking rates were calculated as the percentage difference between the actual (a) and recommended (b) stocking rates as $\frac{a-b}{a} * 100$ where (b) was derived from the South African Department of Agriculture, Forestry and Fisheries (Avenant, 2016). Grazing densities (LSU ha^{-1} d^{-1}) were quantified as the average herd size (LSU) per average camp size (ha) per average occupancy (d). To quantify the functional type of herbivory, a "grazer index" was defined as the percentage of total farm LSUs constituted by grazer LSUs relative to all livestock. Cattle were considered as grazers and goats, sheep as mixed-feeders and goats as browsers. A few farms stocked a diversity of wild herbivores (game) in very low numbers (on average 2% of total farm LSUs), the exact composition of which was often unknown. Due to the low numbers and diversity of species game counts were excluded from the grazer index calculation.

2.2. Remote sensing of fence-line contrasts

Vegetation cover in managed rangelands can be influenced by a range of environmental variables besides management practice, such as soil, vegetation type, and climate (Wessels et al., 2012). Thus, testing hypotheses about the effect of rangeland management on vegetation change at regional scales requires disentangling the relative influence of management and environmental variables. Comparisons of management practices across farm fence-lines overcomes this problem by controlling for major environmental variables (Kilpatrick et al., 2015). Using the responses from the online questionnaire survey, farms were selected for visitation to identify fence-lines with strong grazing management contrasts. Farms were selected that reported grazing management most strongly aligned to HPG or with very high grazing densities (highly rotational). The rationale behind this was that these farms were likely to have more extreme management differences to their neighbours and if grazing management has any effect on vegetation, it would be most evident at these fence-lines.

During May 2018 the selected farms were visited and the location of fence-lines (Fig. 1) between neighbours willing to participate in the study identified. For each fence-line, we sampled remotely sensed vegetation variables (see below) at eight paired points 60 m apart and 60 m from the fence (Fig. A1) according to the cross-fence comparison methodology of Kilpatrick et al. (2015). These distances were chosen to control for landscape-scale variations in topography, soil, landcover and vegetation type. Sites were selected based on a visual interpretation of landscape features so that the slope, aspect, and terrain heterogeneity were relatively homogenous across 120 m distance between cross-fence paired points and would thus be unlikely to confound grazing effects on vegetation cover.

The change in each management or explanatory variable (stocking rate, grazing density, proportion of grazing livestock) across a fence-line was expressed as a relative percentage difference (Graff, 2014), $\Delta = \frac{(a-b)}{a} \times 100$ where a was the farm with highest grazing density and b was the farm with lowest grazing density. To quantify the effect of the management difference on the vegetation response variables we calculated the Hedge's g (Brockwell and Gordon, 2001) effect size and 95% confidence interval for each fence-line contrast as well as the combination of all fence-line contrasts using the 'effsize' package in R (Torchiano, 2017).

To measure vegetation response variables, we performed a satellite remote sensing analysis using the Google Earth Engine (GEE) cloud computing platform (Gorelick et al., 2017). All vegetation response variables were derived from composites of all imagery between Jan 2016 and Jan 2018. Sampling over a time period reduced the risk, often encountered when using single-date scene acquisitions, of biasing sampling by detecting anomalous events (e.g. livestock grazed a camp prior to satellite image capture). The satellite datasets used included the Landsat 8 Operational Land Imager (OLI), Sentinel-2 MutiSpectral Instrument, Sentinel-1 Synthetic Aperture Radar (SAR) C-band Level-1 Ground Range Detected, and Phased Array type L-band SAR (PALSAR) collections. Landsat 8 scenes were masked for clouds using the 'pixel_qa' band and Sentinel-2 scenes were filtered for those with 'CLOUDY_PIXEL_PERCENTAGE' scores of less than 15. Radar data, insensitive to cloud cover, included the Sentinel-1 image collection and PALSAR annual composites, pre-processed by Google Earth Engine, for 2016 and 2017.

Spectral unmixing techniques (Bateson et al., 2000) were used to derive fractional bare ground cover (Fig. A1) over South Africa using imagery from Sentinel-2 and -1. Spectral mixing models are based on the understanding that each pixel contains a mixture of information from several spectrally distinct surface components or 'endmembers'. Using a 0.5 × 0.5° sampling grid over South Africa, we defined polygons in each grid cell characterising pure bare ground and pure vegetation through visual interpretation of very-high resolution satellite imagery in Google Earth. In order to produce a balanced sample, polygon size was restricted to between 0.01 km^2 and 1 km^2. Sentinel-2 data included all spectral bands, along with the normalised difference vegetation index (NDVI). Sentinel-1 single co-polarization, vertical transmit/vertical receive (VV) and dual-band cross-polarization, vertical transmit/horizontal receive (VH) bands were also used. We obtained the mean reflectance value for all bands and indices over all digitized polygons. Given that vegetation displays phenological cycles, we also included the standard deviation in NDVI and VV over time to help distinguish vegetation from bare ground. These values were used as endmembers in a mixing model to discriminate pixel fractions of bare ground and vegetation at fence-lines contrast sites.

We employed a Random Forest (RF) regression model to quantify fractional woody plant cover (Fig. A1). RF is a machine-learning supervised classification method often used in remote sensing analyses because it avoids overfitting and can incorporate non-parametric data (Belgiu and Drăguţ, 2016). We used the techniques outlined in Venter et al. (2018) with the addition of Sentinel-1, -2, and PALSAR data as explanatory variables in the RF model. Briefly, training data were derived from visual interpretation of fractional woody vegetation cover at 4000 randomly scattered 30 x 30 m sampling quadrats, aligning with the Landsat pixel grid. Reflectance metrics for all satellite data time stacks (2016 to 2018) were then extracted. From Sentinel-2 and Landsat 8 collections we extracted temporal reflectance data for visible, near infrared, and shortwave infrared bands, as well as three vegetation indices, namely normalised difference vegetation index (NDVI), soil-adjusted vegetation index (SAVI), and enhanced vegetation index (EVI). The ratio of VV to VH was calculated for Sentinel-1 imagery. We then calculated the minimum, maximum and selected percentile values (10, 25, 50, 75 and 90% percentiles) and the mean reflectance values for observations between selected percentiles (10–25%, 25–50%, 50–75%, 75–90%, and 25–75%). Similar time-series metrics have been successfully used in forest cover mapping using Landsat data (Broich et al., 2011; Potapov et al., 2012; Hansen et al., 2013). To further assist in differentiating between woody and herbaceous cover, which have different phenological metrics (Helman et al., 2015), we derived the variance and range in vegetation indices.

Fractional grass/herbaceous plant cover was simply taken to be the remaining fraction of each pixel once woody and bare ground cover were accounted for. In addition to this we derived the median normalised difference vegetation index (NDVI) for each fence-line sampling point (Fig. A1). NDVI has been widely used as an indicator of vegetation productivity (Svoray et al., 2013; Ali et al., 2016). Fire activity has an important, often contrasting, influence on vegetation relative to herbivory (Archibald and Hempson, 2016; Venter et al., 2017). Although we included only fence-lines with camps that farmers reported had not been burned in the previous 10 years, we also verified this using the MODIS (MCD45A1.051) burned area monthly product at 500 m resolution (Roy et al., 2008).

2.3. Statistical tests of significance

The effect of management differences across fence-lines on the Hedge's g effect sizes in vegetation response variables were assessed using multiple linear regression R (RCoreTeam, 2017). Vegetation response variables were regressed on fence-line differences in stocking rate, grazing density, and grazer index using the 'car' package (Fox and Weisberg, 2018). Linear models were thus constructed as *vegetation response ~ stocking rate difference + grazing density difference + grazer index difference*. Analysis of variance was run on the linear regression models to assess overall significance of explanatory variables when accounting for the effect of other variables. Proportional, and non-normal variables were logit- and log-transformed, respectively, if the assumptions of linear regression were violated. Wilcoxon signed-rank tests were used to test if paired vegetation responses were significantly different across fence-lines.

3. Results

We received over 100 survey responses, some of which were disqualified, being from farms younger than 5 years old or farming animals other than cattle, sheep or goats on natural vegetation. After excluding ineligible farms, we retained a final sample of 48 farms covering a total surface area of 1322 km^2 (Fig. 1). Farms had been managed consistently for 15 ± 0.8 years (mean ± standard error), covered 61 ± 23 km^2 and were spread across five vegetation biomes (Mucina and Rutherford, 2006) and covered a large mean annual precipitation gradient (150 to 850 mm). Most farms (60%) stocked a mix of cattle, sheep and goats, while 40% stocked cattle only.

The PCA of farmer's Likert-scale scores for alignment with various grazing management practices revealed a strong horizontal separation between highly rotational (HPG, SDG, HDG) and less rotational (CG, FCG, LDG) approaches (Fig. 2A). The PC 1 axis explained 37% of the variance and was correlated with log grazing density ($p < 0.0001$, $R^2 = 0.47$, Fig. 2b) and HPG alignment score ($p < 0.0001$, $R^2 = 0.4$, Fig. 2C). On-farm stocking rates were on average 59 ± 12% (mean ± standard error) higher than those recommended by extension services (Fig. 2D). There was no linear relationship between farm management practice (PC 1) and stocking rates ($F_{(146)} = 0.276$, $p = 0.677$) and management practices with high grazing density (far right Fig. 2D) did not have double the stocking rate of those with low grazing densities (far left Fig. 2D). Farms with moderate rotational management had up to double the recommended stocking rates although 95th percentiles reveal that this is highly variable between farms (Fig. 2D).

We visited 14 farms selected for having high grazing densities (high PC 1 scores, Fig. 2a) and identified 23 fence-lines bordering neighbours

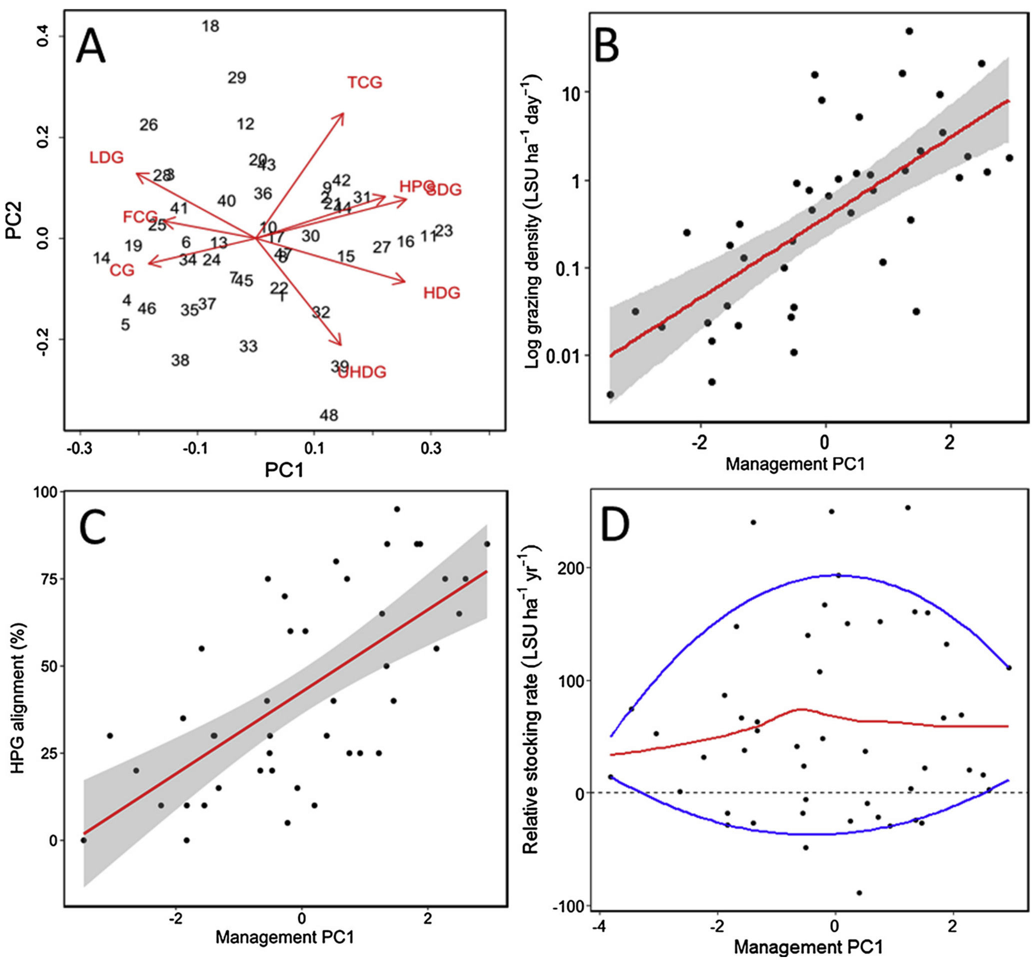

Fig. 2. Principle components analysis biplot (A) representing the multivariate interactions between farmer alignment scores for various management practices (see Table 1 for acronym definitions). The relative proximity of management practices on the plot space are an indication of similarity. The direction and length of the arrows are an indication of the extent to which management practices align with the composite variable (PC1 or PC2). Here, management practices display a strong horizontal separation, along the first principle component. According to management definitions (Table 1), we propose that the composite variable PC1 quantifies the intensity of grazing rotation. Indeed, this index correlates significantly with the log-transformed grazing densities (number of LSUs per subunit of fenced area at any point in time on a farm, B), and the percentage alignment (Table A1) with holistic planned grazing (C). Linear regression lines with 95% confidence intervals are fitted in B and C. The relative percentage difference between farm and extension service recommended stocking rate is related to PC1 with 5th, 95th (blue) and 50th (red) quantile regression lines (D) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

Table 2
Summary statistics for farm management variables and remotely-sensed vegetation response variables measured on all farms in the fence-line contrast study. Raw variable units are reported to assist in the interpretation of results reported as effect sizes and relativized fence-line comparisons in Fig. 3. Data means ± standard error (SE), minimum and maximum values are reported.

Attribute measured	Mean ± SE	Min	Max
Management explanatory variables:			
Grazing density (LSU ha^{-1} day^{-1})	1.45 ± 4.46	0.0003	30
Stocking rate (LSU ha^{-1} yr^{-1})	0.14 ± 0.16	0.001	0.59
Grazer index	41.3 ± 33.6	0	100
Vegetation response variables:			
Bare ground cover (%)	40.7 ± 15.9	0	96.2
Woody plant cover (%)	8.5 ± 13	0	74.5
Grass cover (%)	50.8 ± 15.8	3.8	89.3
NDVI	0.15 ± 0.06	0.07	0.34

NDVI is the normalized difference vegetation index.

with contrasting management (Fig. 1). Participating farms implemented a wide range of stocking rates and grazing densities, with cattle constituting on average 41.3 ± 3.6% of farm herds (Table 2). Farms were dominated by grass and bare ground cover, with woody plants constituting 8.5 ± 13% of fractional ground cover (Table 2). There were large percentage differences (x-axis values in Fig. 3) in grazing density (85 ± 5%) and moderate differences in stocking rate (30 ± 7%) and livestock grazer index (55 ± 16%) across fence lines (means ± standard errors are of absolute difference values – i.e. magnitude and not direction of difference), where grazer index was expressed as the percentage of total herd constituted by grazers. The effect of fence-line management (Hedge's g) on fractional bare ground, woody plant cover, grass cover, and NDVI were non-significant at 74, 91, 83, 78% of the fence-lines, respectively (Fig. 3). Significant effect sizes (Fig. 3) were a balance of both positive and negative effects (variation along the y-axis) and were related to a range of grazing density differences (delta), and both positive and negative delta stocking rate and grazer index (variation along the x-axis). For example, two fence-line contrasts with low (34%) and high (99.8%) relative differences in grazing density (see point i and ii in Fig. 3) both increased bare ground cover and decreased grass cover. The farm with the higher grazing density at fence-line 'i' also had lower stocking rates and a herd composed of much fewer grazers compared to its neighbour, while the farm with the higher grazing density at fence-line 'ii' had a much higher stocking rate and very low grazer component compared to its neighbour (Fig. 3). This variation in response was observed for all management variables and vegetation responses. Thus, the overall vegetation Hedge's g effect sizes (difference in vegetation characteristics across fence-lines) were unrelated to fence-line differences in stocking rate, grazing density or grazer index (Table 3) as indicated by the non-significant overall Hedge's g effect sizes (see grey bands in Fig. 3). Where positive or negative effects on vegetation responses was observed, this was a complex interaction between stocking rate, stock density and the proportion of grazers to browsers (Fig. 3).

4. Discussion

The fence-line contrast study presented here overcomes the limitations inherent in farm-scale experimental trials including restricted temporal and spatial extents and the inability to accurately mimic the complexity of adaptive rotational grazing approaches such as holistic planned grazing. This regional-scale analysis, however, supports

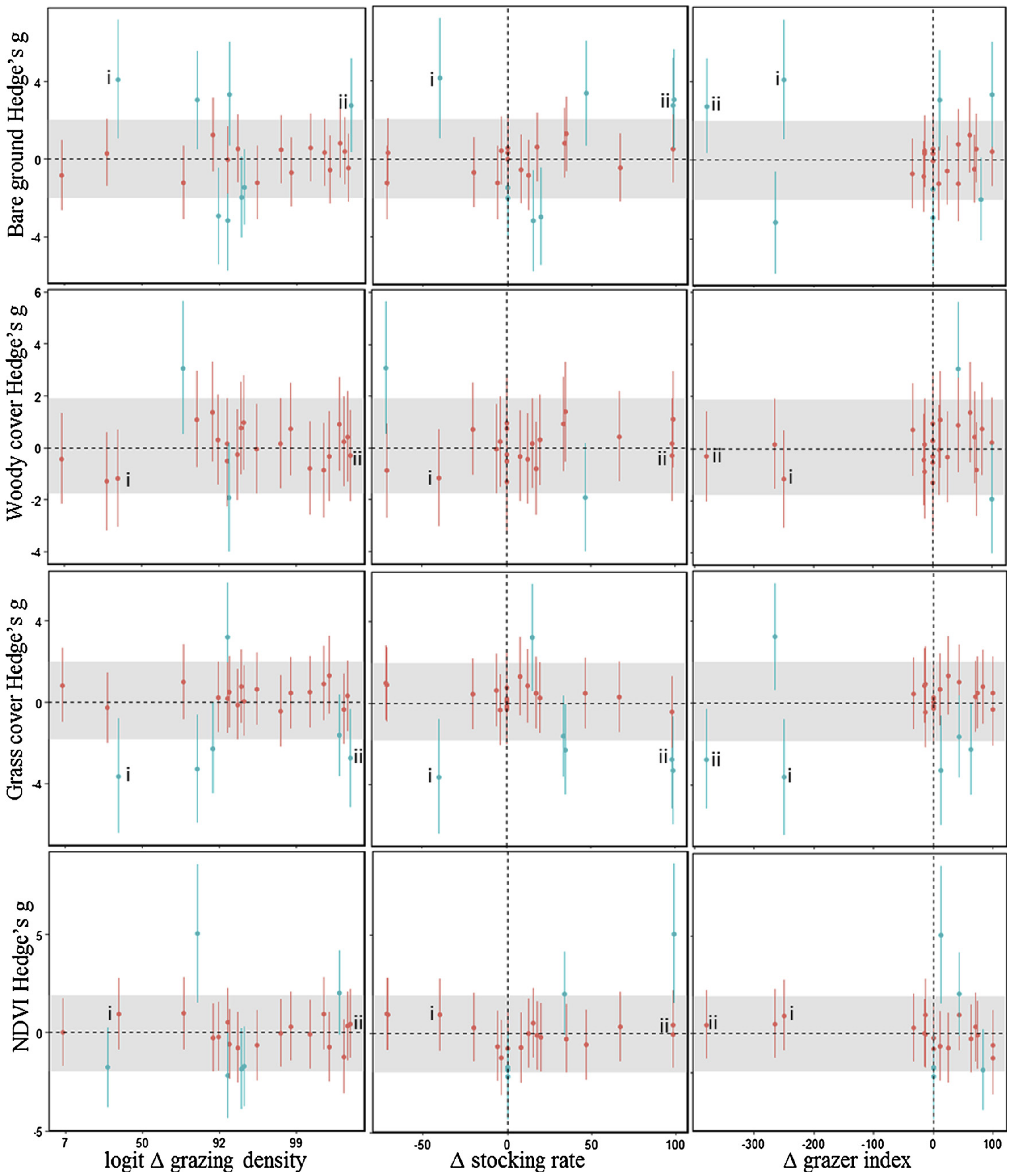

Fig. 3. The effect of grazing density, stocking rate, and grazer index differences (panel columns) across fence-line contrasts on remotely sensed vegetation response variables (panel rows). Cross-fence comparisons of response variables were expressed using the Hedge's g effect size (points ± 95% confidence intervals) which quantifies, for each fence-line contrast, the magnitude of difference between the farm with highest grazing density (a) and its neighbour (b). The change in each management (explanatory) variable across a fence-line was expressed as a relative percentage difference, $\Delta = \frac{(a-b)}{a} \times 100$. The Δ grazing density was plotted on a logit scale to better view the data spread. Positive x-axis values reflect that the farm with the higher grazing density in the fence-line contrast pair had higher stocking rates and grazer index scores relative to their neighbour. The overall effect size confidence interval across all fence-line contrasts is depicted by the grey band. A farm's grazer index is calculated as the percentage grazer LSUs contribute to the sum of browser and grazer LSUs. Wilcoxen signed-rank tests were used to identify significant ($p < 0.05$) and non-significant fence-line effects, coloured blue and red, respectively. None of the overall effect sizes were significantly different to zero. Letters 'i' and 'ii' indicate specific fence-line contrasts used for discussion purposes (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

multiple farm-scale experimental studies most of which reported no evidence that rotational grazing has an enhanced effect on vegetation characteristics relative to less rotational practices (Briske et al., 2008; Hawkins, 2017). Specifically, we found that across a range of fence-line management contrasts, most farms with a high level of rotational grazing and thus high grazing densities had vegetation NDVI, fractional bare ground, woody plant and grass cover similar to that of their neighbours. The lack of vegetation differences is especially meaningful in an agricultural context given that grazing densities were substantially different (on average 85% different, ranging between 0.0003 and 30 LSU ha^{-1} d^{-1}) across fence-lines. Further, using stocking rates recommended by extension service as reference, we found that the implementation of high or low grazing density extremes did not alter the extent to which farmers elevated stocking rates above

Table 3
The effect of grazing density, stocking rate, and grazer index differences across fence-line contrasts on remotely sensed vegetation response variables. Statistical results of linear regression models are reported. Cross-fence comparisons of response variables were expressed using the Hedge's g effect size which quantifies, for each fence-line contrast, the magnitude of difference between the farm with highest grazing density (*a*) and its neighbour (*b*). The change in each management (explanatory) variable across a fence-line was expressed as $\Delta = \frac{(a-b)}{a} \times 100$. A farm's grazer index is calculated as the percentage grazer LSUs contribute to the sum of browser and grazer LSUs.

	F	*df*	*P*
Bare ground cover ˜			
Δ Grazing density	1.13	1	0.301
Δ Stocking rate	2.045	1	0.169
Δ Grazer index	0.196	1	0.663
Woody cover ˜			
Δ Grazing density	1.674	1	0.211
Δ Stocking rate	0.064	1	0.803
Δ Grazer index	0.319	1	0.582
Grass cover ˜			
Δ Grazing density	1.507	1	0.235
Δ Stocking rate	3.315	1	0.084
Δ Grazer index	0.487	1	0.494
NDVI ˜			
Δ Grazing density	0.057	1	0.815
Δ Stocking rate	1.61	1	0.22
Δ Grazer index	0.452	1	0.51

Significant *p* values at $p < 0.05$ indicated with *.
NDVI is the normalized difference vegetation index.

recommended limits, while practitioners using a moderate grazing density tended to be able to support higher stocking rates. Thus, either the livestock behavioural mechanisms claimed to induce vegetation responses under high density rotational grazing are not present or there is some critical level of grazing density that farms are not reaching to achieve necessary animal impact on vegetation change.

Experimental trials that have shown no effect of rotational grazing on vegetation or animal responses (see references in Hawkins, 2017) have been criticized for implementing grazing densities that are of insufficient magnitude to bring about enhanced productivity (see comments in Venter, 2017). It is unlikely that there is some critical threshold of grazing density not reached by farms in this study given that the respondents were strongly aligned with some of the most intensive forms of rotational grazing practices, including HDG, HPG and UHDG (Table 1). A global meta-analysis found that no studies on variants of high density grazing implemented grazing densities exceeding 12 LSU ha^{-1} (Hawkins, 2017). While upper limits of high density grazing are uncertain due to a lack of definition by practitioners (Hawkins, 2017), the upper grazing densities of 30 LSU ha^{-1} d^{-1} (Table 2) reported by farmers likely constitute high density grazing especially considering that most fence-line contrast farms were located in the transition zone between the Nama Karoo and Grassland biomes (Fig. 1), and are thus relatively less productive than mesic grasslands. Further, increasing grazing densities in these arid rangelands with low stocking rates is unreasonable because it requires large monetary investment in fencing and watering infrastructure with little to no gain in productivity to offset these costs.

Although few studies test what behavioural mechanisms might explain the claimed effects of rotational grazing, those that do have presented mixed results. For example, studies in the USA found that rotational grazing may increase (Walker et al., 1989), reduce (Hepworth et al., 1991) or have little effect (Hart et al., 1993; Venter et al., 2019) on cattle walking or trampling behaviour. Rotational grazing is often cited as a means to reduce selective grazing behaviour, however, experimental work suggests rotational management has no significant influence on spatial grazing patterns and that other factors such as the location of water points, topography or stocking rates are more important (Launchbaugh and Howery, 2005; Soder et al., 2009; Bailey and Brown, 2011). A recent experimental trial in a mesic grassland of South Africa showed that HPG, apart from reducing the ability of cattle to select for patches of forage with high NDVI at the landscape scale, did not alter the majority of cattle behaviours of walking, grazing, dung trampling or resting (Venter et al., 2019).

At the fence-line with the strongest grazing density contrast (fence-line 'ii' in Fig. 3), the farm with higher grazing densities had double the stocking rate of its neighbour but had significantly greater bare ground cover and less grass cover. Thus, claims by HPG practitioners that doubling of farm stocking rates is enabled by enhanced primary production (Savory, 1983; Butterfield et al., 2006) are not supported here. The hump-shaped relationship between relative stocking rate and rotational grazing index (Fig. 2d) indicates that farms with moderate and not extremely low (e.g. CG or LDG, Table 1) or high (i.e. HDG or HPG, Table 1) grazing densities are associated with higher stocking rates. Nevertheless, higher relative stocking rates are not necessarily sustainable and one would have to consider the vegetation responses before concluding that moderate densities more beneficial than low or high densities.

A potential benefit of rotational grazing practices, assuming it prevents the competitive release of woody plants through overgrazing of palatable grasses, might include the suppression of woody plant encroachment. Woody plant encroachment is widespread across Africa (Venter et al., 2018) and can have negative consequences for rangeland grazing capacities (Archer et al., 2017). The balance of the fence-line contrasts in grazing density showed no significant effect on woody plant cover (Fig. 3), including where woody cover was as high as 74%. (considering a mean of 8 ± 1.5%). This suggests that rotational grazing management might not be able to mitigate woody plant encroachment. Increasing stocking rate and shifting livestock functional composition to include more browsers also appeared to have no effect across the studied farms on woody plant cover. This is surprising given that increasing browser densities combined with increasing fire frequencies have been suggested as a tool to mitigate woody plant encroachment (O'Connor et al., 2014; Venter et al., 2018). The lack of response in woody plant cover to grazing density might be because fence-line contrasts were largely limited to the arid and less productive rangelands of South Africa (Fig. 1) where background changes in woody plant cover are slow relative to mesic savannas (Skowno et al., 2016). Further, we selected fence-lines where fire was not applied for the previous 10 years. One might expect differences in woody plant cover to emerge under varying burning regimes. It is also possible that animals classed as grazers in this study are adapted to obtaining some of their diet from small woody shrubs. Aspects of grazing management, including heterogenous prescribed burning techniques (Fuhlendorf et al., 2009), combined with browser herbivory and their effects on woody plant encroachment warrants further research.

Stocking rate, as noted by many studies on rotational grazing effects, is more important than grazing system (i.e. manipulating grazing densities) in inducing vegetation change (Hawkins, 2017). A long-held principle in rangeland management is to maintain farm livestock populations below the ecological carrying capacity, often defined by the forage availability during the non-growing season (Illius and O'connor, 1999a). We found that fence-line contrasts in stocking rate were unrelated to vegetation response variables (Table 3) even though most farm stocking rates were higher (59%) than those recommended by extension services (Fig. 2d). Perhaps the lack of vegetation response is because the magnitude of fence-line differences in stocking rate were low (30% different), or that the magnitude of recommended stocking rates are conservative and that the carrying capacity of farms is higher than previously estimated.by extension services It is also possible that abnormally high rainfall and associated vegetation productivity during our sampling period masked the effects of stocking rate, however we attempted to account for this by sampling vegetation characteristics over two full years (2016–2018).

Finally, a common critique of experimental studies aiming to investigate HPG by testing rotational grazing management is that the experimental trials are not actually testing HPG because rotational grazing is claimed to be distinct from HPG practices (Savory and Butterfield, 2016) while rangeland scientists consider rotational grazing to be a core tenant of HPG (Briske et al., 2011; Hawkins, 2017). Thus, results from experimental trials testing rotational grazing management are dismissed by HPG advocates (Savory and Butterfield, 2016). We found that farmers who aligned themselves strongly with HPG were also strongly aligned with other forms of high density rotational grazing (Fig. 2), suggesting that rotational grazing is indeed a core practice within HPG.

5. Conclusion

These results confirm global reviews of experimental trials showing rotational grazing management has little effect on vegetation responses. Although some fence-line management differences did produce significant contrasts in vegetation cover, the direction of this change was not regionally consistent. Thus, although anecdotal evidence exists and is often used in the advocacy for high density grazing management, it is seldom replicated on other farms and fails to emerge under experimental manipulation where confounding variables are controlled for. Contrary to our hypothesis, farms implementing moderate rather than extremely high or low grazing densities appear to sustain slightly higher stocking rates without apparent declines in vegetation cover. We suggest that continued advocacy for high density rotational grazing management is unfounded, particularly given that there was no added benefit for reducing woody plant encroachment in the absence of fire.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agee.2019.05.019.

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