SOUTH AFRICAN GEOGRAPHICAL JOURNAL
2026, VOL. 108, NO. 1, 2432874
https://doi.org/10.1080/03736245.2024.2432874

Routledge
Taylor & Francis Group

OPEN ACCESS Check for updates

From species to pixels: monitoring rangeland quality & productivity by leveraging the NDVI-RCI relationship

Basanda Xhantilomzi Nondlazi[a], Moses Azong Cho[b,c], Brian Khanyisa Mantlana[a] and Abel Ramoelo[d]

[a]Council for Scientific and Industrial Research (CSIR), Smart Places Cluster, Holistic Climate Change, Tshwane, South Africa; [b]Council for Scientific and Industrial Research (CSIR), Advanced Agriculture and Food, Precision Agriculture Platform, Tshwane, South Africa; [c]Faculty of Natural and Agricultural Sciences (NAS), Department of Plant and Soil Science, Forest Science Postgraduate Programme, University of Pretoria (UP), Tshwane, South Africa; [d]SANSA Earth Observation, Pretoria, South Africa

ABSTRACT

Grasslands are highly vulnerable to climate and changes in grazing management, yet little is known about the national rangeland response to long-term (>18 years) grazing management that may confound climate effects. This study assessed the correlation between Normalized Difference Vegetation Index (NDVI), *i.e.*, productivity and Rangeland Condition Index (RCI) *i.e.*, quality and predicted historical grazing management (26 years) using Ecological Index Method (EIM) analysis of 72 relevés in the Highland Sourveld (HSV). Relationships between 150 NDVI and 72 RCI samples showed a rate of 0.125 change in NDVI for every 12.5% change in RCI. In 1983, the HSV's rangeland carrying capacity (RCC) ranged from 2.0 - 2.2 ha/AU/yr (land required to support one mature bovine for 1 year), with an NDVI of 0.43, like the benchmark. site. By 2009, the RCC decreased to 3.2 ha/AU/yr, with NDVI <0.30. Selective overgrazing, reduced RCC by increasing Increaser II species and reducing Decreaser species presence. Findings suggest combining NDVI and RCI is more effective than using either alone. Integrating remote sensing with traditional ecological data (Ecological Remote Sensing - eRS) improves our understanding of rangeland vulnerability, thus, ideal for permanent monitoring of public rangelands in South Africa.

ARTICLE HISTORY
Received 6 January 2024
Accepted 19 November 2024

KEYWORDS
Rangeland monitoring; South Africa; veld condition; NDVI–RCI relationship; grazing capacity; species diversity

Introduction

Public rangeland monitoring is essential for South Africa's economy, livelihoods and biodiversity (Milton et al., 2003; Vetter, 2013). South Africa's iconic biodiversity fuels its tourism economy and traditional medicinal market (Blench & Sommer, 1999; Boon et al., 2016; Cowling et al., 2003), valued at ZAR 270 million annually (Mander, 1998). Rangelands provide biodiversity a refuge but face threats from degradation and climate

CONTACT Basanda Xhantilomzi Nondlazi BNondlazi@csir.co.za Council for Scientific and Industrial Research (CSIR), Spatial Systems for Smart Places, Smart Places Cluster, PO Box 395, Pretoria 0001, South Africa

change, which exacerbate issues related to poverty, water access and livelihoods (Cousins, 1999; Semenya & Machete, 2019; Stanway, 2016a).

The Intergovernmental Panel on Climate Change (IPCC) predicts a temperature increase of up to 5.4°C by 2100 and 2.1°C by 2065 in Southern Africa (Hulme et al., 2001). Mean annual rainfall may decline by 5% by 2035, leading to reduced water availability (du Pisani et al., 1998). Climate change intensifies droughts and fosters bush encroachment (Mndela et al., 2022; O'Connor et al., 2014; Scogings & Mopipi, 2008; Tjelele et al., 2012; W. S. W. Trollope, 1980; Ward, 2005). The impact on primary production, ecological status and rangeland condition remains uncertain. Timely monitoring is crucial to safeguard farming systems (Ramoelo, Cho, et al., 2015). Meanwhile, long-term monitoring programmes are based on ground ecology and lack long-range monitoring (>18 years) with remote sensing (RS) (Hlatshwayo et al., 2007; Mentis, 1984; Milton et al., 2007; A. Short & Morris, 2016). This is likely due to the absence of integrative approaches that combine both remote sensing (RS) and rangeland ecological techniques. Long-term (>18 years) monitoring of rangelands through floristic composition and remote sensing at large spatial scales is scarce. Previous studies either use remote sensing which relies on signal–object interactions, where a sensor or the sun emits a wavelength signal interacting with diverse materials, influencing the signal's interaction based on an object's material, physical, structural and chemical properties (Mikhail et al., 2001; Schellberg et al., 2008). Objects exhibit different behaviours along this spectrum: some strongly interact with the wave, delaying and absorbing the wave's energy, resulting in less captured or returned energy to the sensor; while others minimally interact, reflecting most of the sunlight energy back to the atmosphere, thus resulting in more energy being captured by the sensor (Jensen, 2000). These differences define rangeland characteristics (Schellberg et al., 2008). In this study, we hypothesize that remote sensing can detect rangeland health variations due to differences in plant composition (*e.g.* nitrogen-rich, broad-leafed) and soil substrate interactions. Healthy rangelands with minimal interference exhibit distinct spectral signatures compared to degraded ones with high erosion and background noise. While indicators like the Normalized Difference Vegetation Index (NDVI) have been used to demonstrate rangeland changes (Ndungu et al., 2019), it is often limited to smaller spatial scales or shorter timescales (Mbatha & Xulu, 2018; Mermer et al., 2015). Ground data in the HSV, traditional ecological assessments and grazing pattern changes have not been linked to NDVI (Muavhi, 2021). Section 6.1 and 2(h) of the South African Conservation of Agricultural Resources Act (CARA 43 of 1983) states that:

> (Vetter, 2013) To achieve the objectives of this Act, the Minister may prescribe control measures that land users must comply with.
>
> (Milton et al., 2003) Such control measures may pertain to: . . . (h) the grazing capacity of veld, expressed as an area of veld per large stock unit; the maximum number and types of animals that may be kept on the veld.

These provisions establish a foundation for a permanent national rangeland monitoring programme for public rangelands in South Africa (Government of the Republic of South Africa, 1983).

Traditional techniques used in previous long-term rangeland monitoring in South Africa, are precise and straightforward, practical and robust enough to discern the direction, rate and magnitude of changes in rangeland quality, productivity and management practices (Tidmarsh & Havenga, 1955). Traditional vegetation survey techniques, such as the Multiple Indicator Monitoring (MIM) framework (*see methods section*), furnish data essential for crafting management recommendations aimed at remedying and determining rangeland carrying capacity, however, lacks historical, spatial and 'bird's-eye' view required to effectively contextualize and implement these management recommendations (Evans & Love, 1957; Owensby, 1973). Using historical remote sensing data with data from botanical surveys offers a fresh array of advantages for conservation agriculture and environmental management, ushering in a new era of public rangeland management (Ndungu et al., 2019). While the application of ecological remote sensing is rare, opportunities are untapped, to understand the long-term relationship between rangeland quality (RCI) and productivity (NDVI), which is unknown. Even though these two indices have enjoyed nearly half a century of continuous use to determine rangeland health (Foran et al., 1978; Rouse et al., 1973). A similar question can be asked about the Ecological Index Method (EIM) detailed by Vorster (Vorster, 1982) and updated to the Grazing Index Method (du Toit, 1995). While the robustness of these methods is unparalleled, on the other hand, the spectral, spatial and temporal characteristics of recently available remote sensing data are unprecedented. For example, data from the Landsat collection 8 and 9 at Level-1, as well as the Sentinel 2A and 2B constellations, are now freely accessible, some within 12–24 h (Ramoelo et al., 2011).

Against this background, the objectives of this study are as follows: *(a)* To determine the long-term pattern, in the direction and magnitude of change in the grazing capacity of rangelands in the HSV based on the NDVI–RCI relationship. *(b)* To determine and describe changes in the grass species diversity that may have influenced the grazing capacity of rangelands in the HSV. *(d)* To forecast the historical grazing patterns that may have influenced the grazing capacity of rangelands in the HSV and *(e)* To propose grazing management recommendations for attaining ideal grazing capacity of rangelands in the HSV. Using historical remote sensing data with data from botanical surveys offers a fresh array of advantages for conservation agriculture and environmental management, ushering in a new era of public rangeland management (Ndungu et al., 2019). Synergizing ecology and remote sensing (Ecological Remote sensing approach) by leveraging the relationship between the Normalized Difference Vegetation Index (NDVI) and Rangeland Condition Index (RCI) is a practical approach for National Rangeland Monitoring (Figure 1).

Materials and methods

General methodology

The Ecological Remote sensing approach combines ecological principles with remote sensing data and could be used to assess and monitor the health and condition of rangeland ecosystems nationally. The monitoring programme must provide grazing capacity as an index for managing rangelands. Veld or rangeland condition score; the rating of grazing camps using an index value, *i.e*. Rangeland Condition Index that

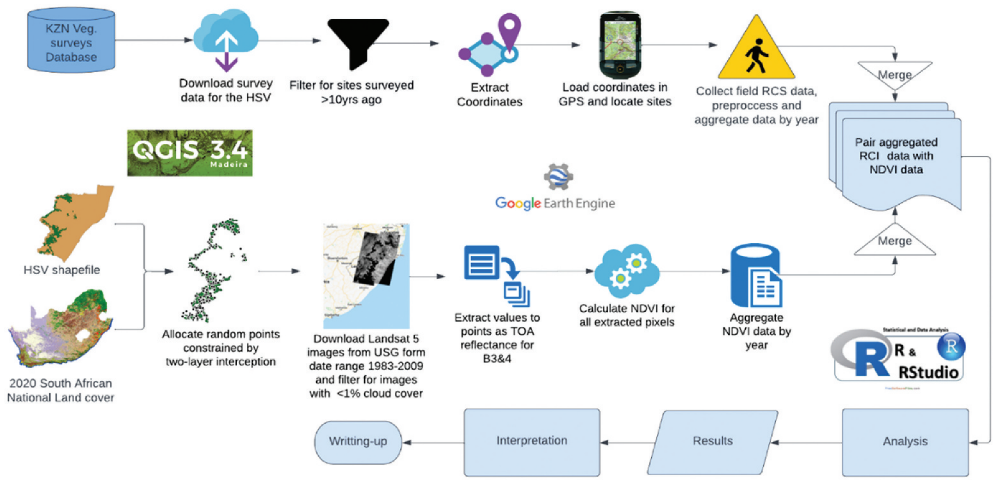

Figure 1. Overview of the general methodology used in the study. The data analysis was conducted using R version 4.2.0.

describes the abundance ratio of nutritious, palatable grasses (high grazing value) to less nutritious and unpalatable ones (low grazing value) relative to a benchmark, has been widely used to describe the status of grazing camps on South African farms and derive grazing capacity (Hardy & Hurt, 1989; Mentis, 1981; Tainton, 1988, 1999). The benchmark is the possible ideal site with the best balance of high to low grazing value for a particular rangeland type. The Rangeland Condition Index can provide grazing capacity (W. S. W. Trollope et al., 1990). However, grazing capacity does not explain what causes the change in the ratio of palatable to unpalatable grasses. The Ecological Index Method (EIM) was developed through long-term grazing trials to close this gap.

Long-term studies on developing the EIM revealed that cattle defoliated grass species at different rates (Barnes et al., 1984). The species' responses and the varying grazing pressures were recorded. Grasses were grouped into three categories based on their ability to withstand grazing pressure and palatability (Barnes et al., 1984). Decreaser species decline in abundance when overgrazed or underutilized. The species that increased relative abundance when the veld was not utilized or underutilized were called Increaser I species. The species that increased relative abundance when the rangeland was overgrazed were Increaser II species. The species that increased relative abundance when the rangeland was selectively grazed were called Increaser III species (Foran et al., 1978). These two methods, the Rangeland Condition Index and Ecological Index, enabled the scoring of rangeland conditions relative to the benchmark and prediction of historical grazing management on an initial rangeland survey. As a result, it would be possible to recommend changes in the grazing management to improve the condition of the rangeland to approximate that of the benchmark on the initial survey (Whitford et al., 1998). However, these methods are yet to be tested at aggregated scales larger than the Camp or farm scale. Even more novel would be their use to assess rangeland conditions over large spatial scales and a longer timescale (>20 years) in regression with remote sensing indices measuring leaf biophysics, *i.e.* NDVI (Wang et al., 2022). Setting Monitoring rangeland conditions over a larger temporal scale is essential, because long-term environmental cycles in Southern Africa occur at about 18-year cycles (Hlatshwayo et al., 2007; O'connor & Roux, 1995; A. Short & Morris, 2016). Therefore, for effective long-term planning of rangeland and drought management under climate change, a long-term understanding of changes in rangeland conditions is crucial. Furthermore, in conjunction with ground ecological techniques, remote sensing is ideal for achieving long-term knowledge of rangeland conditions and biophysical changes.

The Nearest-Plant Technique (NPT), utilizing 100 step-points for vegetation assessment, is widely used in South Africa (A. Short & Morris, 2016). The NPT meets all the requirements outlined for assessing carrying capacity and stocking rates as mandated by national legislation CARA (Government of the Republic of South Africa, 1983; Hlatshwayo et al., 2007). Therefore, NPT is robust and effective for collecting floristic composition data, which is essential for determining the Rangeland Condition Index and the Ecological Index Ratio (A. Short & Morris, 2016). Trollope *et al.* (W. S. W. Trollope et al., 1990) proposed determinants of rangeland health as ecological status, soil erosion and primary production. Among the many determinants of rangeland health proposed, vegetation is most influenced by humans, and it is easily managed with fast responses on the temporal scale. However, most rangeland health monitoring focuses on the herbaceous layer, predominantly basal or aerial cover, primary productivity and composition of dominant species or growth forms, *e.g.* (O'connor & Roux, 1995; A. D. Short et al., 2003; Tainton et al., 1980; W. Trollope et al., 2014; Whitford et al., 1998). However, this study aimed to assess the capability of remote sensing in detecting grassland rangeland condition changes in the floristic composition at aggregated spatial scales, which are more extensive than plot and farm scales. Furthermore, to determine and describe changes in the rangeland condition of the Highland Sourveld over two decades and associated management recommendations. Observer bias and Type I error (false positive rangeland conditions), and Type II error (false unfavourable rangeland conditions) that may occur in long-term rangeland monitoring are other vital considerations (A. Short & Morris, 2016).

Study area

The HSV is a vegetation ecosystem in South Africa, KwaZulu-Natal (Acocks & Killick, 1953; Downing, 1968; Hardy & Hurt, 1989). Vegetation is classified as GS12-East Griqualand Grassland in Mucina and Rutherford (Mucina & Rutherford, 2006). It can be divided into two moist and dry regions (Camp, 1999). Both are located along the western border of KwaZulu-Natal. However, the Dry HSV is concentrated south of the Drakensberg escarpment of KwaZulu-Natal. Meanwhile, the Moist HSV stretches north to south (Figure 2). The altitude of the HSV ranges from 1400 to 1800 m above sea level. The mean annual rainfall ranges between 620 and 1265 mm, although the MHSV has a higher minimum (800 mm) and the DHSV has a lower maximum, 816 mm (Downing, 1968). Although the HSV has a reasonably warm summer, the mean annual temperature is low (14.1–14.3°C) due to icy winters with severe frost in winter and some light frost in summer. The term HSV was coined due to the grassland in the area, which loses nutrition in winter but is highly nutritious in summer (A. D. Short et al., 2003). Furthermore, the vegetation type is abundant at high altitudes.

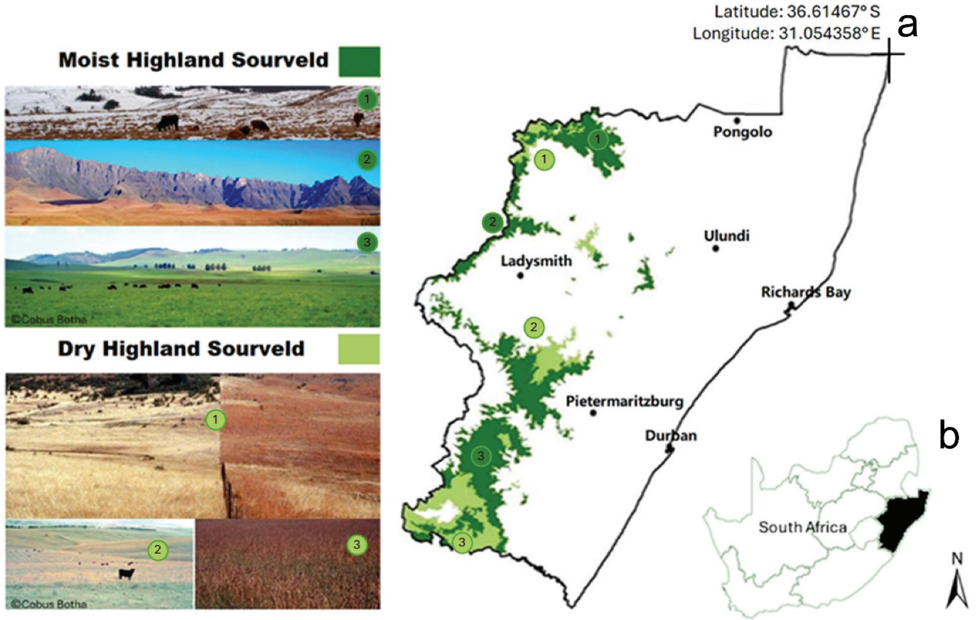

Figure 2. Map of KwaZulu-Natal (a) showing the distribution of moist (dark green) and dry (light green) Highland Sourveld vegetation types. Inset (b) locates KwaZulu-Natal within South Africa (shaded in black). Points 1, 2 and 3 (in insert A) for each vegetation type indicate specific locations, with corresponding photographs illustrating characteristic landscapes and typical vegetation conditions. The moist Highland Sourveld predominantly occurs in higher rainfall regions, while the dry Highland Sourveld is found in drier areas. Coordinates for the northernmost boundary are provided in (a).

Data acquisition

Geographical positioning and site location

The historic sampling plots were tracked and located at each site using the Trimble sub-metre Global Positioning System (GPS) device. We used a Trimble Geo 7X Handheld (NMEA) running WEHH 6.5 with TerraSync Professional (Trimble Inc., Sunnyvale, California, U.S.A.). The sites were predominantly located on commercial farms, except for the two nature reserves, the one commonage and land reform property. When the GPS coordinates could not be obtained, descriptions from text notes were used to locate the old survey plots within a defined camp. Thus, the relocation accuracy can be guaranteed only to be within 100–300 m of the old site in cases with no permanent markers or coordinates. Some plots could only be paired with their previous data with caution that, there were no permanent markers. A few tens of metres can make a big difference in mountainous countries' vegetation data.

Historic Rangeland Condition Index(RCI) values

A dataset on a floristic composition comprising only sites in the HSV was extracted from the database of vegetation surveys held by the Department of

Agriculture and Rural Development in KwaZulu-Natal. After that, the data were filtered for only sites surveyed >10 years before the project year (2009) as far as possible.

Historic Normalized Difference Vegetation Index (NDVI) values

The region of interest (ROI) was loaded as the Google Earth Engine (GEE) assert of the shapefiles containing 150-point location coordinates that were randomly distributed across the rangelands of the HSV and these points aggregated to calculate NDVI (Figure 2). The GEE platform is a geospatial cloud computing platform developed by Google that provides researchers and scientists with access to a vast archive of remotely sensed satellite imagery and geospatial data. GEE enables users to analyse and process this data using powerful computational resources, making it an invaluable tool for a wide range of environmental, ecological and geospatial research applications. This platform allows for the efficient extraction of valuable insights and information from large-scale geospatial datasets, making it a valuable resource for scientific investigations involving land cover analysis, environmental monitoring and geospatial modelling. Using the 2020 South African rangeland Land-Cover map and the HSV boundary shapefile, the randomization of points was constrained to the rangeland cover type in the HSV (Figure 2). The Landsat 5 TM Collection 1 Tier 1 calibrated top-of-atmosphere (TOA) reflectance (*viz.* 'LANDSAT/LT05/C01/T1_TOA') was then downloaded from USG through the Google Earth Engine catalogue using the 'GEE' assert of the shapefiles of the KwaZulu-Natal provincial boundary as the ROI (Figure 3). Calibration coefficients were extracted from the image metadata. See Chander *et al.* (Chander et al., 2009) for details on the TOA computation. The collection was filtered for images acquired between 1 January 1983 and 31 December 2009 with less than 1% cloud cover (though the data starts from March 1983). Since Landsat, especially in the studied region, is obscured by cloud cover, in the case of missing values, the authors used the moving average to filled data to complete the time series.

Selecting sampling sites

Before conducting vegetation surveys in the growing season of 2008–2009, a detailed examination of site distribution was implemented using Geographic Information System (GIS) software to select sample sites (Figure 3). The site distribution review assessed the coverage of land use and environmental features. A total of 72 sites were selected and surveyed. The vegetation surveys were conducted, as far as possible, using the same techniques used previously at each location. The only sites not surveyed more than 10 years ago consisted of survey plots or relevé surveyed <7 years ago. The sites were in Mount Currie Nature Reserve, one recently (2009) proclaimed Matatiele Nature Reserve, one Matatiele town commonage and one land reform farm. The 72 sites reflected a rainfall gradient (Figure 3), using the Bioresource Groups of the KwaZulu-Natal map as a reference for vegetation types. The vegetation types include Moist HSV and Dry HSV. The sites were scattered across the HSV in 20 properties, with between 1 and 11 relevé in each property (usually two or three). The KwaZulu-Natal Department of Agriculture and Rural Development supplied the historical dataset under a data agreement compelling

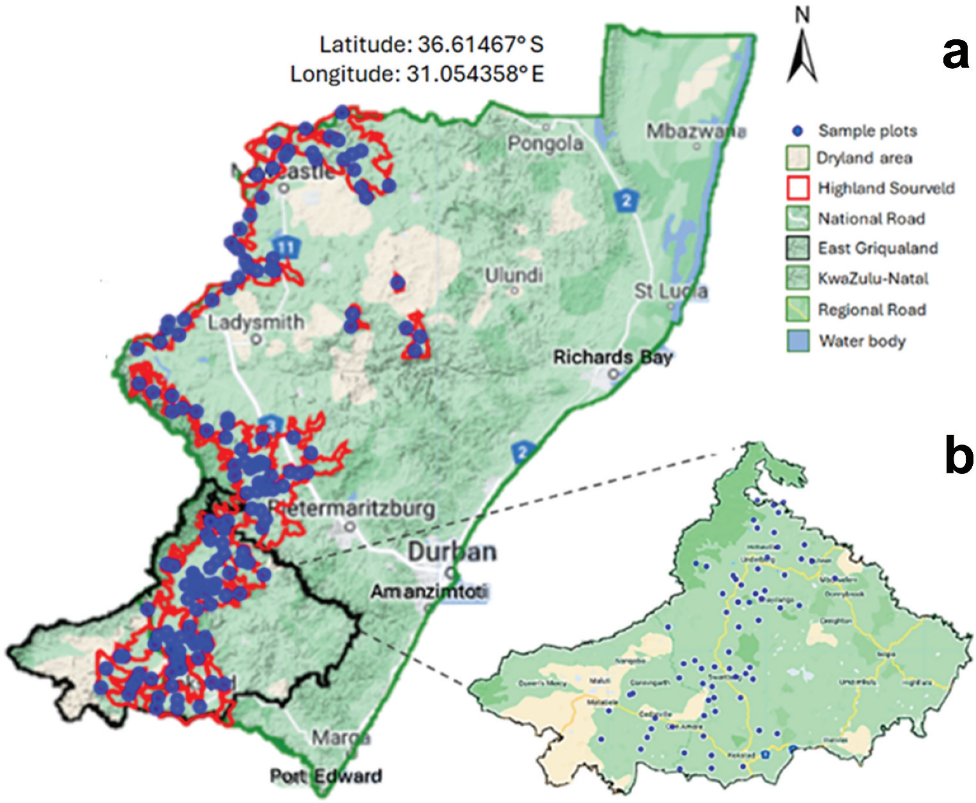

Figure 3. Geographic distribution of sample plots within the Highland Sourveld region in KwaZulu-Natal, South Africa. Sample plots (blue circles) are overlaid on a map distinguishing key environmental features, including dryland areas, water bodies and major roads. The Highland Sourveld is demarcated with red boundaries and is further divided into Moist Highland Sourveld (light green) and dry Highland Sourveld (dark green) regions. The map also highlights East Griqualand, major towns and road networks within KwaZulu-Natal. Inset map shows an enlarged view of the sampling area with more detailed plot locations. Coordinates for the region are indicated as latitude: 36.61467° S and longitude: 31.054358° E.

non-disclosure of the properties' locations on publications to protect the identity of the farming communities.

Sampling floristic data for calculating Rangeland Condition Index (RCI)

A standard Nearest-Plant Technique (NPT) using 200 points was used at each site to determine the botanical composition. Once the plot location was decided, a 200-m-long transect was plotted downslope in the perceived direction of dominant resource flow by rolling out a 100 m tape measure. A spike was thrust into the ground every metre to record species composition. Where the spike had struck the ground, the name of the plant species nearest to the spike was recorded. The sampled species were sampled systematically along a transect whose positioning was downslope in the direction of the resource flow and thus determined the position of each metre

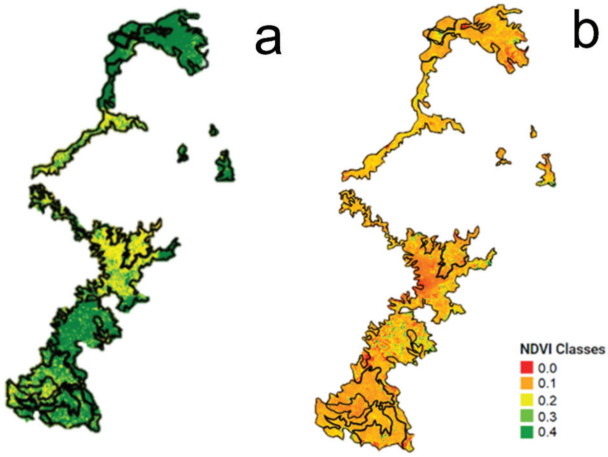

Figure 4. Over 26 years, the Highland Sourveld rangeland condition has declined, with 'year' representing 12-month periods. Rangeland condition percentages are based on the benchmark by camp (1999). (A) A time series graph (1983–2009) shows the mean annual Rangeland Condition Index (RCI) and Normalized Difference Vegetation Index (NDVI). Moving averages are represented by dashed lines, and the benchmark is marked with a bold horizontal line. (B) A regression graph illustrates the quadratic relationship between RCI (x-axis) and NDVI (y-axis), with lines showing the linear regression and 1:1 relationship.

reading. The observer walked along the tape with a second observer to confirm species and collect voucher specimens and a scribe. The scribe recorded the date, farm name, owner, recorder, observer, transect number and the dominant rangeland type. Nomenclature followed Camp (Camp, 2006) and van Oudtshoorn (van Oudtshoorn, 2012).

Data pre-processing

Calculating Rangeland Condition Index (RCI)

The RCI for 2008/9 was calculated and added to the dataset of the long-term RCI from 1983/4 growing season to 2006/7 growing season that was extracted and supplied by the KwaZulu-Natal Department of Agriculture and Rural Development from their data database of rangeland condition surveys. According to Barnes *et al.* (Ramoelo, Cho, et al., 2015), the rangeland condition score was calculated by allocating grazing values to each identified species (Barnes et al., 1984). The grazing values for species ranged from 0 to 10, with 10 assigned to mostly palatable Decreaser species and 0 for all Increaser III species and some unpalatable Increaser II species. The number of encounters of each species along the 200 m transect was summed and recorded as the abundance for each species. The abundance was then multiplied by the grazing value to obtain the score of each species. The species scores were then summed to get the site scores. The site scores were then aggregated for HSV to obtain the time series for the rangeland condition. Each rangeland condition score for each year was divided by the rangeland condition score of the HSV benchmark site for BRG8 and 9 to obtain the RCI in percentage (Camp & Smith, 1997; Foran et al., 1978).

Calculating Normalized Difference Vegetation Index (NDVI)

For each pixel the NDVI was calculated using Bands 4 – Near Infrared (0.76–0.90 μm) and 3 – Red (0.63–0.69 μm), with 30 m spatial resolution. The NDVI was computed in the GEE platform as $(NIR - R)/(NIR + R)$, *i.e.* $NDVI = (Band\ 4 - Band\ 3)/(Band\ 4 + Band\ 3)$. The values of NDVI were then extracted for each of the 150 pixels across 26 years, resulting in a matrix of 36,024 NDVI values. The NDVI values were aggregated by year resulting in 24 mean annual NDVI values. This was done by year to mask seasonal effects because the interest was not seasonal differences. Hence, both winter and summer values influence the mean. Also, because the same season of different years is not the same. Hence, we used the mean, because the interest of the study is the aggregate the variable at the level of the vegetation type, *i.e.* the HSV. The mean allows all the values from each sampled image to

BOX 1 Method for calculating the Rangeland Condition Index (RCI): Species abundance is multiplied by grazing values to obtain species scores, which are summed for site scores. Annual site scores form a time series, with the RCI for each year benchmarked as a percentage for trend analysis. The resulting RCI values offer a percentage comparison of rangeland condition relative to the benchmark site, enabling evaluation of rangeland condition changes over time.

Abundance

For each species s along a 200m transect T, the number of individual encounters was counted and summed, yielding the abundance A_s of species s.

Species Score

Each species' abundance A_s was then multiplied by its corresponding grazing value G_s, producing the species score S_s:

$$S_s = A_s \cdot G_s$$

Site Index

The scores S_s for all species at a given site were summed to yield the site score S:

$$S = \sum_{s=1}^{m} S_s$$

Time Series of Rangeland Condition Index

The site scores S from multiple sites were aggregated to create a time series of Rangeland Condition Index values, RCI_t, for each growing season t.

Relative Condition Index (RCI)

Each Rangeland Condition Index RCI_t for each year was normalized by dividing it by the RCI from the benchmark site (HSV benchmark site for BRG8 and 9), noted as $RCI_{\mathrm{benchmark}}$, yielding the **Relative Condition Index (RCI)** as a percentage:

$$\mathrm{RCI}_t = \left(\frac{RCI_t}{RCI_{\mathrm{benchmark}}}\right) \times 100$$

BOX 2 How does this research contribute to the sustainable use of rangelands and to achieving the United Nations' Sustainable Development Goals?

The sustainable utilization of rangelands has a direct or potential positive impact on all of the United Nations' Sustainable Development Goals (SDGs). Conversely, unsustainable practices in rangelands can hinder the achievement of global targets. Overgrazing and degradation, for instance, lead to increased runoff at the expense of infiltration, resulting in reduced stream flow, water availability, water quality and soil erosion (SDG8). The integration of ecology and remote sensing through the relationship between the Normalized Difference Vegetation Index (NDVI) and Rangeland Condition Index (RCI) is an effective approach for national rangeland monitoring, a great innovation and monitoring infrastructure that supports biodiversity conservation and sustainable use of plant species (SDG4, SDG14, SDG15, SDG9). The dependence on rangeland resources extends beyond rural regions, with an increasing demand for grass-fed beef in urban areas (SDG11). This research promotes sustainable species utilization through interdisciplinary approaches and multilateral cooperation in national rangeland monitoring (SDG17). It also aligns with responsible consumption and production (SDG12), reduces illegal wildlife trade and associated criminal networks (SDG16), synergizes with climate action efforts (SDG13) and supports biodiversity conservation (SDG14, SDG15). Water scarcity jeopardizes local food security (SDG2), while polluted rangelands contaminate water supplies, posing risks to plants, animals and human health, including the spread of zoonotic diseases and food poisoning (SDG3). However, sustainable rangeland management can enhance livestock sales, increase water availability and reduce poverty through agricultural food production (SDG1, SDG2, SDG3). The sustainable availability of medicinal plants in rangelands is linked to well-managed rangelands, benefiting traditional healers and contributing to income generation (SDG1, SDG3, SDG8, SDG9, SDG10). Income derived from trading medicinal plants can support education, and traditional medicine provides valuable learning experiences (SDG4). Various uses of rangelands, such as gathering firewood, rural farming and accessing medicinal remedies, particularly benefit women (SDG5, SDG10), while wood biomass is an important energy source (SDG7). Recent evidence highlights the critical role of natural ecosystems like rangelands in supporting vulnerable populations and livelihood needs in the face of climate challenges (SDG10).

influence the aggregate value, thus avoiding bias in using the median since there were missing values. Furthermore, the mean would allow the masking of seasonality, to obtain values that accommodate the effect of season. Missing values were due to unavailability of images or negative values. The NDVI values for 1988 and 2002 were excluded from the analysis because they were greater than the maximum NDVI values. These data points exhibited saturation behaviour due to dense vegetation and would therefore result in an overestimation of NDVI if included (Asner et al., 2003). The NDVI values were paired with rangeland condition values by year and uploaded in R for analysis.

Data analysis

RCI and NDVI time series analysis and polynomial regression

Time series analysis and polynomial regression were used to estimate changes in grazing capacity from rangeland conditions and NDVI data (Mbatha & Xulu, 2018; Mermer et al., 2015). Time series analysis is ideal for analysing data points across a time sequence; however, the variance may be hard to read and misleading when read independently. Fitting a polynomial regression is suitable for smoothing data to obtain the average pattern of a time series (Davis et al., 2016; Egbebiyi et al., 2019; Onyutha, 2018).

Polynomial regression models were fitted for NDVI and RCI to assess the nature, direction and magnitude of change in the rangeland condition of the HSV in terms of grazing capacity (Davis et al., 2016).

Prediction of historical grazing patterns (Ecological Index Methods)

Count data of the total abundance of species within each Ecological Index Method (EIM) category for 2009 were subtracted from the abundance in 1984 (Table 1) to analyse changes in each EIM category (Vorster, 1982; Xu et al., 2019). The chi-squared test assessed significant differences across all the EIM categories between the total expected 1984 abundances and the total observed 2009 abundances. The formula chi-squared test is $\chi^2 = \Sigma\ (O_i - E_i)2/E_i$, where O_i = observed value (actual value) and E_i = expected value (Schumacker et al., 2013). The chi-squared test helped us to evaluate if there is a relationship or association between two categorical variables by comparing the observed data with what would be expected if there were no relationship. It is a valuable tool for examining the independence or dependence of categorical variables. The Poisson regression test assessed the EIM categories responsible for significant effects on the rangeland condition changes. A subset of sites (20 sites) that could be relocated with absolute certainty, mainly in the former East Griqualand area of the HSV, was used to assess and interpret changes in the ecology of the HSV. Some assumptions included that the HSV was relatively similar as the same vegetation type. Also, that a site was least degraded if it exhibited the least signs of grazing, thus a good rangeland.

Species composition and diversity

Species abundance data were fitted with a paired line graph to contrast 1984 and 2009 abundances. A two-sample chi-squared (χ^2) test for equality of proportions with continuity correction was computed for each pair of abundance values for each species to assess significant differences between abundance values in 1984 against 2003–2004 abundances. Several diversity indices were used. Shannon (Beisel & Moreteau, 1997) was used to indicate differences in diversity between the start of the considered period and the end. It is different from other indices in that it is influenced by and considers the abundance of each species, thus considering functional diversity. It is best suited for comparing repeat measurements. Simpson Diversity Index is similar to the Shannon but instead of considering abundance as absolute values it considers abundance in relative terms; hence it is best for comparing two different habitats. Both indices are crucial to consider because our data fulfils both criteria. It is representative of repeated measurements of the same vegetation type. However, the unequal samples between NDVI and RCI result in the data points not being perfectly coincident in spatial terms.

Results and discussion

The NDVI–RCI relationship predicts changes in grazing capacity

There was a significant (F=$_{1,25}$5.832, $p < 0.02$) negative ($r^2 = 0.30$) polynomial relationship ($y = -0.0074x^3 + 44.744x^2 - 89673x + 6^{e+07}$) between the increase in the number of

Table 1. Species composition contrasting the 1983–1984 growing season versus the 2008–2009 growing season. The numbers on the left are useful for connecting Table 1 to Figure 6 x-axis.

		1983–1984		2008–2009	
Catagory	Species	*n*	%	*n*	%
1	*Acroceras macrum*	–	–	3	0.3
2	*Andropogon schirensis*	–	–	4	0.3
3	*Melinis nerviglumis*	–	–	2	0.2
4	*Panicum ecklonii*	–	–	4	0.3
5	*Panicum maximum*	–	–	6	0.5
6	*Panicum natalense*	–	–	3	0.3
7	*Panicum repens*	–	–	1	0.1
38	*Additional species*	1	0.1	2	0.2
52	*Setaria incressata*	3	0.2	–	–
59	*Diheteropogon amplectans*	5	0.3	9	0.8
66	*Monocymbium ceresiiforme*	8	0.5	12	1.0
70	*Digitaria eriantha*	12	0.8	–	–
74	*Setaria flabellata*	17	1.1	–	–
77	*Andropogon appendiculatus*	29	1.9	9	0.8
85	*Brachiaria serrata*	53	3.5	20	1.7
91	*Themeda triandra*	86	5.7	70	6.0
Decreaser		**214**	**14.1**	**145**	**12.5**
8	*Festuca costata*	–	–	3	0.3
9	*Helictotrichon hirtulum*	–	–	4	0.3
10	*Paspalum urvillei*	–	–	2	0.2
11	*Schizachyrium sanguineum*	–	–	2	0.2
12	*Setaria megaphyla*	–	–	1	0.1
40	*Andropogon eucomus*	1	0.1	–	–
41	*Cymbopogon plurinodis*	1	0.1	3	0.3
42	*Cymbopogon validus*	1	0.1	–	–
43	*Hyparrhenia filipendula*	1	0.1	–	–
48	*Digitaria diagonalis*	2	0.1	1	0.1
49	*Miscanthus capensis*	2	0.1	–	–
53	*Digitaria setifolia*	8	0.5	8	0.7
54	*Helictotrichon turgidulum*	3	0.2	2	0.2
60	*Eulalia villosa*	5	0.3	18	1.6
61	*Koeleria capensis*	5	0.3	18	1.6
72	*Cymbopogon excavatus*	14	0.9	4	0.3
75	*Setaria nigrirostis*	24	1.6	27	2.3
78	*Alloteropsis semialata*	30	2.0	53	4.6
81	*Digitaria tricholaenodes*	41	2.7	15	1.3
82	*Trachypogon spicatus*	47	3.1	50	4.3
92	*Tristachya leucothrix*	87	5.7	63	5.4
Increaser I		**272**	**17.8**	**274**	**23.7**
13	*Agrostis sp.*	–	–	2	0.2
14	*Bothriochloa insculpta*	–	–	1	0.1
15	*Digitaria velutina*	–	–	2	0.2
16	*Eragrostis chloromelas*	–	–	25	2.2
17	*Eragrostis superba*	–	–	1	0.1
18	*Loudetia simplex*	–	–	2	0.2
19	*Melinis repens*	–	–	4	0.4
20	*Setaria sphacelata var. torta*	–	–	3	0.3
21	*Sporobolus fimbriatus*	–	–	1	0.1
22	*Senecio*	–	–	17	1.5
44	*Aristida barbicollis*	1	0.1	–	–
45	*Aristida diffusa*	1	0.1	2	0.2
46	*Brachiaria eruciformis*	1	0.1	–	–
50	*Paspalum notatum*	2	0.1	2	0.2
51	*Paspalum scrobiculatum*	2	0.1	4	0.3
55	*Trichneura grandiglumis*	3	0.2	2	0.2
57	*Digitaria monodactyla*	4	0.3	4	0.3
58	*Paspalum dilatatum*	5	0.4	1	0.1
62	*Setaria sphacelata var. sphacelata*	5	0.3	9	0.8
64	*Cynodon dactylon*	6	0.4	1	0.1
65	*Sporobolus centrifugus*	7	0.5	–	0.0
67	*Aristida congesta*	8	0.5	5	0.4
68	*Eragrostis gummiflua*	8	0.5	2	0.2
69	*Sporobolus pectinatus*	11	0.7	–	0.0
80	*Eragrostis plana*	35	2.3	42	3.6
83	*Sporobolus africanus*	47	3.1	31	2.7
84	*Hyparrhenia hirta*	50	3.3	24	2.1
86	*Eragrostis racemosa*	71	4.7	42	3.6
87	*Eragrostis capensis*	76	5.0	11	0.9
89	*Harpochloa falx*	79	5.2	30	2.6
90	*Sedges*	85	5.6	66	5.7
93	*Microchloa caffra*	88	5.8	50	4.3
94	*Forbs*	89	5.8	93	8.0
95	*Eragrostis curvula*	92	6.0	51	4.4

(*Continued*)

Table 1. (Continued).

			1983–1984		2008–2009	
	Catagory	Species	*n*	%	*n*	%
96		*Heteropogon contortus*	94	6.2	59	5.1
	Increaser IIs		**870**	**57.2**	**589**	**50.9**
71		*Aristida junciformis*	12	0.8	29	2.5
76		*Rendlia altera*	25	1.6	4	0.3
79		*Diheteropogon filifolius*	33	2.2	32	2.8
88		*Elionurus muticus*	76	5.0	41	3.5
	Increaser IIIs		**146**	**9.6**	**106**	**9.2**
23		*Andropogon spp*	–	–	1	0.1
24		*Ctenium coninnum*	–	–	2	0.2
25		*Cymbopogon spp.*	–	–	1	0.1
26		*Cynodon-like spp.*	–	–	1	0.1
27		*Eragrostis spp.*	–	–	3	0.3
28		*Hemarthria altissima*	–	–	1	0.1
29		*Hyparrhenia spp.*	–	–	4	0.3
30		*Longea poa*	–	–	1	0.1
32		*Panicum spp.*	–	–	7	0.6
34		*Sporobolus spp*	–	–	2	0.2
35		*Stipagrotis Zeyheri var. Zeyheri*	–	–	1	0.1
36		*Unidentifyable*	–	–	2	0.2
37		*Bare ground*	–	–	7	0.6
47		*Setaria spp.*	1	0.1	4	0.3
56		*Pennisetum clandestinium*	3	0.2	4	0.3
73		*Aristida spp.*	16	1.1	3	0.3
	Unclassified		**20**	**1.3**	**44**	**3.8**
	Grand Total		**1522**	**100**	**1158**	**100**

years (1983 to 2009) and the rangeland condition score. There was a significant ($F=_{1,25}10.45784$, $p = 0.00341966$) negative ($r^2 = 0.27$) polynomial relationship ($y = -7^{e\text{-}05}x^3 + 0.408x^2 - 815.76x + 543619$) between the increase in the number of years (1983 to 2009) and the NDVI (Figure 4). The sampled sites in the HSV had the same rangeland carrying capacity as the benchmark of the HSV in 1983, at 2.0 to 2.2 hectares per animal unit per year (ha/AU/yr), which had the NDVI equivalence of 0.43. However, in 2009 the rangeland carrying capacity had declined to about 3.2 ha per animal unit per year. The mean NDVI of the HSV had declined to <0.3 (Figure 5). The two polynomial regression models for NDV and rangeland condition score significantly approximated a 1:1 relationship ($F=_{1,25}$ $1.02^{\,e+29}$, *SE*: $1.135^{\,e\text{-}15}$ $p < 2.2^{\,e\text{-}16}$). The approximation was 0.125 change in NDVI for every 12.5% change in RCS, above which there were negative returns for NDVI.

In 1983 when the Rangeland Condition Index (RCI) was 100%, the grazing capacity was 2.2 to 2.0 ha/AU/yr, and NDVI was about 0.5 (Camp, 2006). The grazing capacity of 2.0 ha/AU/yr for the HSV corroborated by Camp (Camp, 2006) and others (Camp & Smith, 1997). The significant difference in grazing capacity between 1983 and 2009 showed that the rangeland condition score was about 45% of what it was in 1983, and the grazing capacity had declined to 3.3 ha/AU/yr. This result shows the approach of using floristic composition is reliable. NDVI values of approximately 0.2 to 0.5 are considered moderate and are usually produced by sparse vegetation. While NDVI values between 0.6 and 0.9 are produced by dense vegetation, *e.g.* in tropical forests or crops at peak growth. Therefore, NDVI from 1983 can be considered the benchmark NDVI for the HSV, corresponding to the average RCS of 100% during the same period. The variance between peak growing season as measured with ecological techniques and

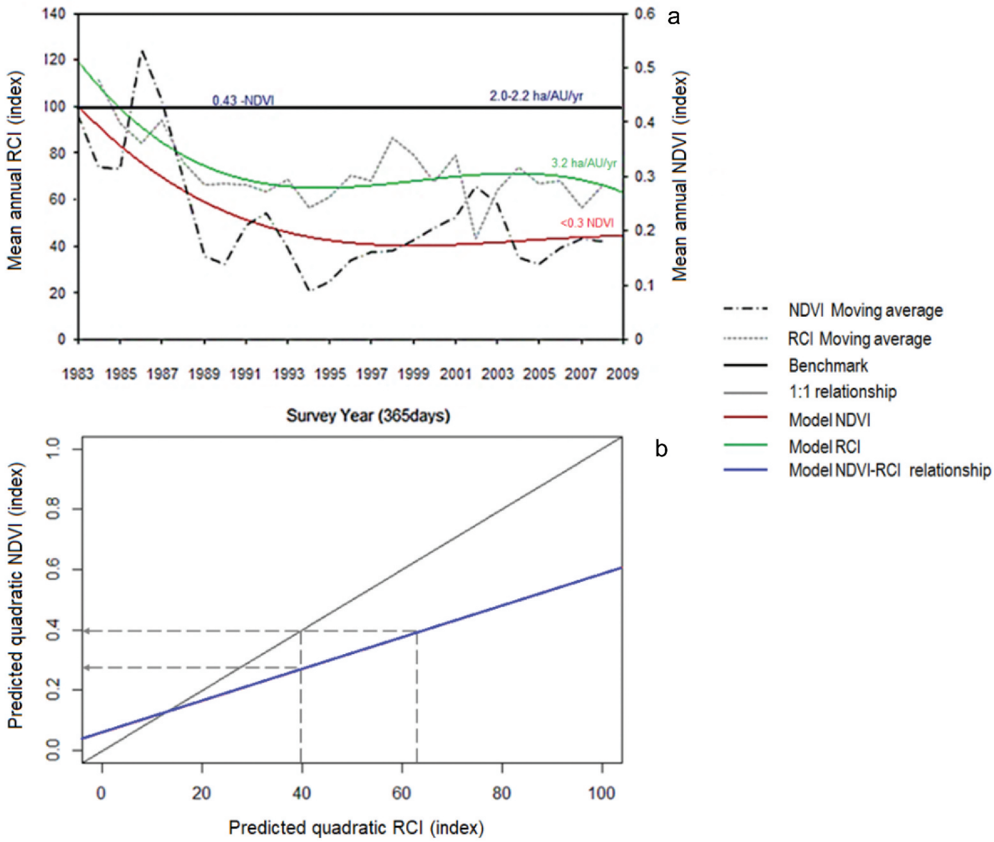

Figure 5. Decline in NDVI (Normalized Difference Vegetation Index) distribution in the Highland Sourveld over time. (A) Images show the distribution of NDVI for the period from 1 August 1984, to 20 February 1987, with high NDVI values ranging from 0.4 to 0.2. (B) Images show the distribution of NDVI for the period from 1 August 2007 to 20 February 2009, with lower NDVI values ranging from 0.1 to 0.2. Some areas around the Midlands still register NDVI values around 0.4, although these high NDVI regions are now smaller and more scattered.

NDVI can be explained by Mermer *et al.* (Mermer et al., 2015). They showed that NDVI is highest at the start of winter and, therefore, lowest in summer months to its legging. The negative returns in NDVI as the Rangeland Condition Indexincreases are probably related to the saturation effect in NDVI (Mutanga & Skidmore, 2004; Mutanga et al., 2012; Nyamugama & Kakembo, 2015).

Ecological Index Method (EIM) predicts historic grazing management

Changes in the absolute proportions of EIM groups show that the Highland Sourveld rangeland lost a high percentage of its palatable Decreaser species by 2009 (33%), having only 67% of the proportion of Decreaser species it had in 1983/84. There was no notable change in Increaser I species, with only an increase of 1% from 1984 to 2009. The HSV rangeland also lost a high percentage of its Increaser IIs species (33%), with only 67% of the proportion of Increaser II species in 1984. The Increaser III species declined by 27% only from 1984 (Figure 6).

There was a significant difference ($p < 0.00$) in the proportions ($\chi^2 = 16.764$, $DF = 3$) of the EIM categories (Pearson's chi-squared test). The chi-squared test considers the abundance of species within groups (Figure 6) between the expected 1983–1984 growing season and the observed 2008–2009 growing season as opposed to absolute total values (Table 2). All the EIM categories excluding Increaser I species significantly aggravated the decline in rangeland condition at Bonferroni adjusted p-value of <0.00 and a threshold residual of −2.955167 (chi-squared test of independence post hoc). However, Decreaser species and Increaser II species had a coefficient greater than zero and a probability of error less than the $p < 0.05$ (Poisson distribution analysis, Table 2). Therefore, the change in Decreaser and Increaser II species substantially influenced the predicted shift in rangeland conditions between 1984 and 2009 (Table 2).

The significant decline in palatable Decreaser species and the increase in unpalatable Increaser II species signifies the over-utilization of rangelands in the HSV over the past 26 years. The utilization might have been due to overgrazing, which has increased the visibility of the bare ground. This evidence of raised bare ground is supported by a

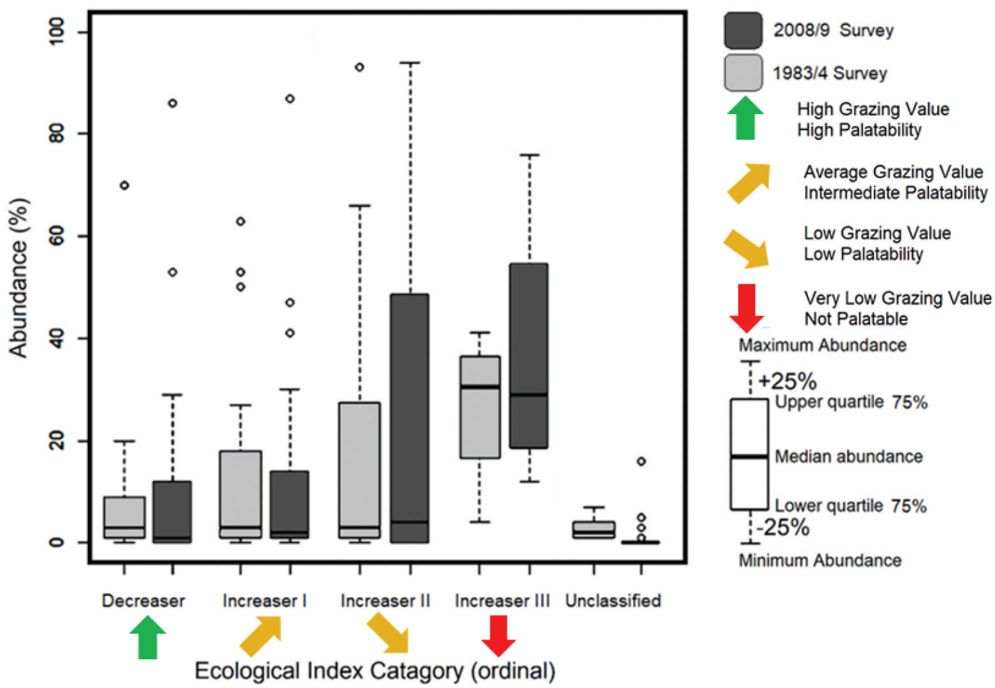

Figure 6. Comparison of plant abundance across different Ecological Index Method (EIM) categories over time. Box-and-whisker plots illustrate the abundance percentages of palatable versus unpalatable plant species across five EIM categories (decreaser, increaser I, increaser II, increaser III and unclassified) over two survey periods: 1983/4 (light grey) and 2008/9 (dark grey). Each box represents the interquartile range (IQR), with the median abundance indicated by the horizontal line within each box. Whiskers extend to 1.5 times the IQR, and outliers are represented by individual points (o). The EIM categories reflect species' grazing value and palatability, from high grazing value/high palatability (decreaser) to very low grazing value/non-palatable (increaser III). Colored arrows (↑↗↘↓) indicate the grazing value and palatability for each category, with green for high grazing value and palatability, yellow for moderate, orange for low, and red for very low grazing value. The analysis highlights shift in species abundance across categories over 26 years, comparing data from the 1983 and 2009 growing seasons.

Table 2. Absolute values of Ecological Index groups (# = Count data) and chi-squared test of independence post hoc results for effects of Ecological Index groups on changes in rangeland condition.

Catagory	#83–84	#08–09	μ #	μ #	# Diff	%Diff	%Change	SD83–84	SD08–09	N
Decreasers	215	145	13	9	70	67	−33	23.5	16.7	17
Increaser Is	267	269	13	13	2	101	1	22.2	19.4	21
Increaser IIs	869	585	25	17	284	67	−33	35.2	23.6	35
Increaser IIIs	146	106	37	27	40	73	−27	27.7	15.8	4

EI Category	Coefficient	χ^2Res 84	χ^2Res 09	Std. Error	z value	Pr(>|z|)
Decreasers	5.19296	0.9054369	−0.9054369	0.05	98.529	<2e-16
Increaser Is	0.39803	−4.057517	4.057517	0.06	5.841	5.19E−09
Increaser IIs	1.39597	2.593971	−2.593971	0.05	23.713	<2e-16
Increaser IIIs	−0.35667	0.1364726	−0.1364726	0.08	−4.343	1.41E−05

decline in the Normalized Difference Vegetation Index (NDVI) over 26 years (Meneses-Tovar NDVI as indicator of degradation, 2011). This result is supported by Phillips *et al.* (Phillips et al., 2008), who found the NDVI was highly correlated to both Gross and Net primary production. Phillips *et al.* (Phillips et al., 2008) also explained the lower values of NDVI as low productivity associated with bare ground pixels of backscatter. Indeed, previous studies have also reached the same conclusion (Filippa et al., 2022; Liu et al., 2011; Singh et al., 2015; Wang et al., 2022).

Changes in species diversity explain changes in grazing capacity

Generally, there was a significant difference (Table 3, two-sample chi-squared (χ^2) between the species composition in the 1983–1984 growing season and the 2008–2009 growing season (Table 1) test for equality of proportions with continuity correction). The significance was due to a few species (Figure 7), *i.e.* a significant increase in *Eragrostis chloromelas*, Senecio, *Alloteropsis semialata* and *Aristida junciformis*. Meanwhile, there was a substantial decline in Eragrostis capensis at $p < 0.00$. There was also a significant decline in *Setaria flabellata*, a considerable increase in *Koeleria capensis*, a substantial increase in *Eulalia villosa* ($p = 0.001$), a decline in *Harpochloa falx* ($p < 0.00$), a decline in *Rendlia altera* ($p < 0.00$), increase in Bare ground, increase in *Panicum* spp., the decline in *Digitaria eriantha* ($p < 0.00$) and decline in *Brachiaria serrata* ($p < 0.00$). There was no significant difference in other species (Table 4).

There was a higher diversity (3.63782) in 2008–2009 than (3.40434) in 1983–1984 (Shannon-Wiener Diversity Index). There were no differences in the ratio of the number of organisms per species and the total number of organisms in the community between 2008–2009 and 1983–1984 (Simpson Diversity Index). There was a small number of abundant species and a large proportion of 'rare' species in 2008–2009 than in 1983--1984, *i.e.* a log-series distribution (Figure 7).

Table 3. Comparison of diversity indices between 1983 and 2009.

Parameter	1983–84	2008–09	Difference
Total sampled individuals	1522	1158	−364
Shannon-Wiener Diversity Index	3.40434	3.63782	0.23348
Simpson	0.958425	0.96331	0.004885
'Fisher's log-series	12.2055	20.4814	8.2759
Rarefaction	56.3016	83	26.6984
Number of species	59	81	22

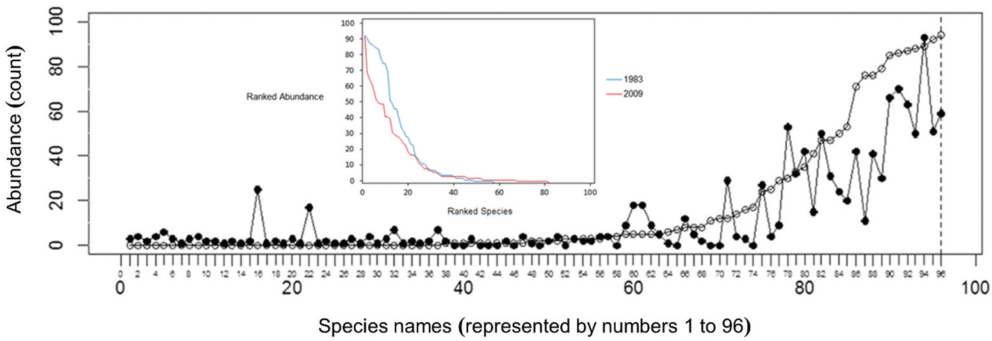

Figure 7. Differences in grass species composition between the 1983–84 (○) growing season (fire exclusion) and the 2008–09 (●) growing season (fire reversal). Each number on the *x*-axis represents a species concerning Table 1. The statistical test results of the paired comparisons between 1983 and 2009 for each species are in table. Species were ordered by ascending order of abundance of the 1983–84 (○) dataset (first survey of the two). While in the insert graph each survey has species ordered according to the descending order of abundance, allowing the examination of the distribution of abundance between the two surveys. We noted more of the top 20 species that had abundance values greater than 50% in 1983 than in 2009.

Table 4. Results for the two-sample chi-squared (χ^2) test for equality of proportions with continuity correction for data in Figure 6.

Species	χ2-value	P-value	CI 95%-84	CI 95%-09	Prop84	Prop09
Acroceras macrum	1.971	0.16040	−0.00628	0.00110	0.00000	0.003
Agrostis spp.	0.858	0.35430	−0.00487	0.00142	0.00000	0.002
Alloteropsis semialata	14.808	**0.00012**	−0.04107	−0.01188	0.01929	0.046
Andropogon appendiculatus	5.095	**0.02399**	0.00188	0.02036	0.01889	0.008
Andropogon eucomus	2.05E−29	*1.00000*	−0.00127	0.00257	0.00065	0.000
Andropogon schirensis	3.205	**0.07341**	−0.00759	0.00069	0.00000	0.003
Andropogon spp	0.026165	0.87150	−0.00330	0.00157	0.00000000	0.001
Aristida barbicollis	1.90E−29	*1.00000*	−0.00125	0.00252	0.000637349	0.000
Aristida congesta	2.04E−29	*1.00000*	−0.00515	0.00664	0.00506	0.004
Aristida diffusa	0.070101	0.79120	−0.00454	0.00236	0.000636943	0.002
Aristida junciformis	1.8326	**0.00034**	−0.02821	−0.00682	0.00753	0.025
Aristida spp.	4.2949	**0.03823**	0.00093	0.01372	0.00992	0.003
Bare ground	7.5077	**0.00614**	−0.01125	−0.00084	0.00000	0.006
Bothriochloa insculpta	0.022	0.88110	−0.00331	0.00158	0.00000	0.001
Brachiaria eruciformis	1.96E−29	*1.00000*	−0.00125	0.00252	0.00064	0.000
Brachiaria serrata	6.799	**0.00912**	0.00466	0.02981	0.03451	0.017
Ctenium coninnum	0.89461	0.34420	−0.00486	0.00141	0.0000000000	0.002
Cymbopogon excavatus	2.324	0.12740	−0.00098	0.01210	0.00901	0.003
Cymbopogon plurinodis	0.631	0.42690	−0.00589	0.00200	0.00065	0.003
Cymbopogon spp.	0.02637	0.87100	−0.00330	0.00157	0.00000	0.001
Cymbopogon validus	0.000	*1.00000*	−0.00127	0.00257	0.00065	0.000
Cynodon dactylon	1.2553	0.26250	−0.00129	0.00716	0.003802281	0.001
Cynodon spp.	0.026473	0.87080	−0.00330	0.00157	0.00000	0.001
Digitaria diagonalis	0.000	1.00000	−0.00246	0.00332	0.00129	0.001
Digitaria eriantha	7.427	**0.00642**	0.00266	0.01300	0.00783	0.000
Digitaria monodactyla	0.0062484	0.93700	−0.00586	0.00403	0.002539683	0.003
Digitaria setifolia	0.110	0.73970	−0.00846	0.00497	0.00516	0.007
Digitaria tricholaenodes	5.252	**0.02193**	0.00236	0.02443	0.02635	0.013
Digitaria velutina	0.860	0.35380	−0.00487	0.00142	0.00000	0.002
Diheteropogon amplectans	1.788	0.18120	−0.01107	0.00206	0.00327	0.008
Diheteropogon filifolius	1.8326	*1.12380*	−0.01944	0.00553	0.02068	0.028
Elionurus muticus	1.8326	0.14170	−0.00347	0.02784	0.04759	0.035
Eragrostis capensis	30.912	**0.00000**	0.02574	0.05104	0.04789	0.009
Eragrostis chloromelas	31.705	**0.00000**	−0.03071	−0.01247	0.00000	0.022
Eragrostis curvula	1.8326	0.12950	−0.00346	0.03096	0.05779	0.044
Eragrostis gummiflua	1.2278	0.26780	−0.00165	0.00832	0.00506	0.002

(*Continued*)

Table 4. (Continued).

Species	χ2-value	P-value	CI 95%-84	CI 95%-09	Prop84	Prop09
Eragrostis plana	4.4061	**0.03581**	−0.02788	−0.00043	0.02211	0.036
Eragrostis racemosa	1.0182	0.31290	−0.00707	0.02406	0.04477	0.036
Eragrostis spp.	2.1113	0.14620	−0.00626	0.00108	0.00000	0.003
Eragrostis superba	0.022664	0.88030	−0.00331	0.00158	0.00000	0.001
Eulalia villosa	10.536	**0.00117**	−0.02074	−0.00390	0.00322	0.016
Festuca costata	1.999	0.15740	−0.00628	0.00109	0.00000	0.003
Forbs	1.8326	**0.01390**	−0.04442	−0.00432	0.05594	0.080
Harpochloa falx	9.3702	**0.00221**	0.00902	0.03866	0.04975	0.026
Helictotrichon hirtulum	3.247	**0.07156**	−0.00759	0.00068	0.00000	0.003
Helictotrichon turgidulum	0.000	1.00000	−0.00324	0.00366	0.00194	0.002
Hemarthria altissima	0.026679	0.87030	−0.00330	0.00157	0.00000	0.001
Heteropogon contortus	1.8326	0.40870	−0.00984	0.02596	0.05901	0.051
Hyparrhenia filipendula	0.000	1.00000	−0.00127	0.00257	0.00065	0.000
Hyparrhenia hirta	2.5865	0.10780	−0.00182	0.02346	0.03155	0.021
Hyparrhenia spp.	3.4171	**0.06452**	−0.00758	0.00067	0.00000	0.003
Koeleria capensis	10.547	**0.00116**	−0.02074	−0.00391	0.00322	0.016
Longea poa	0.026886	0.86980	−0.00330	0.00157	0.00000	0.001
Loudetia simplex	0.863	0.86262	−0.00487	0.00142	0.00000	0.002
Melinis nerviglumis	0.826	0.36340	−0.00488	0.00142	0.00000	0.002
Melinis repens	3.315	**0.06865**	−0.00758	0.0006762694	0.00000	0.003
Microchloa caffra	1.8326	0.17580	−0.00481	0.02914	0.05535	0.043
Miscanthus capensis	0.259	0.61090	−0.00125	0.00384	0.00129	0.000
Monocymbium ceresiiforme	1.717	0.19010	−0.01276	0.00248	0.00522	0.010
Panicum ecklonii	3.210	**0.07317**	−0.00759	0.00068	0.00000	0.003
Panicum maximum	5.772	**0.01629**	−0.01008	−0.00029	0.00000	0.005
Panicum natalense	1.979	0.15950	−0.00628	0.00110	0.00000	0.003
Panicum repens	0.019	0.88940	−0.00331	0.00159	0.00000	0.001
Panicum spp.	7.4869	**0.00622**	−0.01125	−0.00084	0.00000	0.006
Paspalum dilatatum	0.74184	0.38910	−0.00169	0.00631	0.003172589	0.001
Paspalum notatum	0.070101	0.79120	−0.00454	0.00236	0.000636943	0.002
Paspalum scrobiculatum	0.62491	0.42920	−0.00674	0.00238	0.001271456	0.003
Paspalum urvillei	0.841	0.35920	−0.00488	0.00142	0.00000	0.002
Pennisetum clandestinium	0.19372	0.65980	−0.00632	0.00313	0.00186	0.003
Rendlia altera	1.8326	**0.00360**	0.00450	0.01993	0.01567	0.003
Schizachyrium sanguineum	0.842	0.35890	−0.00487	0.00142	0.00000	0.002
Sedges	0.097914	0.75430	−0.02159	0.01459	0.05349	0.057
Senecio	20.855	**0.00000**	−0.02236	−0.00700	0.00000	0.015
Setaria flabellata	11.209	**0.00081**	0.00509	0.01708	0.01108	0.000
Setaria incressata	0.855	0.35530	−0.00101	0.00494	0.00196	0.000
Setaria megaphyla	0.021	0.88570	−0.00331	0.00158	0.00000	0.001
Setaria nigrirostis	1.822	0.17700	−0.01926	0.00352	0.01544	0.023
Setaria sphacelata var. sphacelata	1.946	0.16300	−0.01112	0.00192	0.003170577	0.008
Setaria sphacelata var. torta	2.0479	0.15240	−0.00627	0.00109	0.00000	0.003
Setaria spp.	1.6348	0.20100	−0.00717	0.00150	0.00062	0.003
Sporobolus africanus	0.1123	0.73750	−0.01035	0.01615	0.02967	0.027
Sporobolus centrifugus	3.5557	**0.05934**	0.00041	0.00846	0.004433186	0.000
Sporobolus fimbriatus	0.023055	0.87930	−0.00331	0.00158	0.00000	0.001
Sporobolus pectinatus	6.4388	**0.01117**	0.00211	0.01180	0.00695	0.000
Sporobolus spp	0.90193	0.34230	−0.00486	0.00141	0.00000	0.002
Stipagrotis zeyheri var. zeyheri	0.027197	0.86900	−0.00330	0.00157	0.00000	0.001
Themeda triandra	0.169	0.68070	−0.02315	0.01416	0.05595	0.060
Trachypogon spicatus	2.887	**0.08928**	−0.02821	0.00223	0.03019	0.043
Trichneura grandiglumis	7.41E−31	1.00000	−0.00322	0.00358	0.00191	0.002
Tristachya leucothrix	0.006	0.93850	−0.01666	0.01953	0.05584	0.054
Small Unidentifyable	0.90376	0.34180	−0.00486	0.00141	0.00000	0.002

The change in diversity is characterized by a shift from a log-normal distribution or broken stick distribution to a more log-series distribution of species abundance (Darwin, 1960; Fisher et al., 1943). This shift means a decline in the abundance of the dominant species characterized by changes in species diversity. The rare species did not particularly benefit from this decline since only a few increase in abundance. This outcome is related to the findings of Ulrich *et al.* (Ulrich et al., 2022). Their discovery suggests that the distribution curves of species abundance within grassland plant communities (Wang et al., 2022) are significantly influenced by environmental conditions, including climate and soil quality. Particularly, the plant communities in poorer soils exhibited a strong alignment with log-series distributions independent of geographic plot position.

Conclusion

This study successfully achieved its objective by evaluating the potential of the NDVI–RCI relationship as a tool for a climate resilience-driven decision-support monitoring system. It effectively assessed long-term trends in the grazing capacity, rangeland condition (quality and productivity) of the Highland Sourveld (HSV) of KwaZulu-Natal, South Africa.

The significant decline in NDVI and Rangeland Condition Index (RCI) from 1983 to 2009 indicates a reduction in grazing capacity, with rangeland in the Highland Sourveld (HSV) requiring more land per animal unit. This supports the conclusion that over time, land degradation has diminished the productivity of the rangeland, with negative impacts on grazing potential. Key findings reveal a declining trend in grazing capacity, closely tied to reduced diversity of palatable grass species and an overall decline in rangeland quality. Specifically, the study identified a 10% decline in NDVI equivalence, reflecting reduced vegetation vigour and an increased land requirement of 1.0 ha per animal unit per year to sustain livestock. This trend, attributed to selective overgrazing, underscores the impact of unsustainable grazing on rangeland productivity.

The Ecological Index Method (EIM) revealed a substantial loss of palatable Decreaser species and an increase in unpalatable Increaser II species, which directly links to overgrazing and land degradation. This provides evidence of long-term damage to the rangeland, consistent with the conclusion that over-utilization has exacerbated rangeland degradation. In meeting the Conservation of Agricultural Resources Act (CARA) objectives, this research aligns with the Act's emphasis on sustainable resource use and combating land degradation. The NDVI–Rangeland Condition Index (RCI) model developed here provides a foundational tool for monitoring the health of public rangelands. By establishing a strong correlation between NDVI and RCI, the study validates this model as a practical, cost-effective method for tracking rangeland condition on a national scale. This model can serve as a basis for developing a national rangeland monitoring tool, supporting conservation agriculture and climate change mitigation in grasslands. It also offers a scientific basis for making informed grazing management decisions that enhance ecosystem resilience to climate impacts.

The shift in species composition, including decrease in functional diversity indicated by change to a log-series distribution of species abundance, indicates a decline in grazing capacity. The rare species did not benefit from historic management, pointing to a negative impact of management on overall ecosystem health and reinforcing the conclusion that the degradation of the diversity has led to a less productive and less resilient rangeland ecosystem. This study highlights the importance of incorporating climate change mitigation and adaptation into rangeland management. By regularly monitoring the NDVI–RCI data, we can track shifts in vegetation vigour and species composition, providing insights into both rangeland productivity and climate resilience. In line with South Africa's climate goals, this monitoring approach can contribute to a Just Transition by promoting sustainable land use practices that support biodiversity and enhance carbon sequestration in grasslands.

In conclusion, the insights gained from this research lay the groundwork for establishing a new comprehensive >18 South African National Rangeland Monitoring Program based on ecological remote sensing and climate action planning. Future research should continue to explore and refine the NDVI–RCI relationship, ultimately aiding in the development of a national dataset on rangeland health. Such a programme will enable effective public rangeland management, ensuring sustainable livestock production and ecosystem services that benefit communities and contribute to national climate goals.

Acknowledgments

The data used in this study were part of the lead author's bachelor's degree. At the same time, the corresponding author was the Provincial Coordinator in KwaZulu-Natal province, as a senior technician of the National Rangeland Monitoring and Improvement Programme (NRMIP) working for the Agricultural Research Council. Therefore, we would like to acknowledge fellow technicians of the NRMIP from the Agricultural Research Council involved in the project who assisted in the data collection. We would also like to recognize the Tshwane University of Technology academics (Dr Dibungi Luseba and Dr Linde du Toit) and the farmers in KwaZulu-Natal involved in the project for allowing access to their farms to conduct data collection. We also extend our appreciation to Dr. Luthando Dziba and Alan Short for their role in managing the National Rangeland Monitoring and Improvement Programme (NRMIP), and additionally, we acknowledge Tim O'Connor and the Department of Agriculture in the province of KwaZulu-Natal - Cedara Office, for access to historical datasets of rangeland surveys and we thank the role of the National Department of Agriculture (represented by Mr Victor Musetha and Ms Kedibone Chueu, funder) through funding the NRMIP.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Basanda Xhantilomzi Nondlazi http://orcid.org/0000-0001-6656-6048
Moses Azong Cho http://orcid.org/0000-0003-4435-5375
Brian Khanyisa Mantlana http://orcid.org/0000-0001-5869-0946
Abel Ramoelo http://orcid.org/0000-0002-9917-9754

References

Acocks, J. P., & Killick, D. J. B. (1953). Veld types of South Africa No. *Memoirs of the Botanical Survey of South Africa*, *40*(28), 1–192. https://ia802909.us.archive.org/26/items/veldtypesofsouth00acoc/veldtypesofsouth00acoc_bw.pdf

Asner, G. P., Scurlock, J. M. O., & Hicke, J. (2003, May). Global synthesis of leaf area index observations: Implications for ecological and remote sensing studies. *Global Ecology & Biogeography* [Internet], *12*(3), 191–205. https://doi.org/10.1046/j.1466-822x.2003.00026.x

Barnes, D. L., Rethman, N. F. G., Beukes, B. H., & Kotzé, G. D. (1984, January). Veld composition in relation to grazing capacity die verhouding tussen veld samestelling en weidingskapasiteit. *Journal of the Grassland Society of Southern Africa* [Internet], *1*(1), 16–19. https://doi.org/10.1080/02566702.1984.9647960

Beisel, J. N., & Moreteau, J. C. (1997, June 30). A simple formula for calculating the lower limit of Shannon's diversity index. *Ecological Modelling* [Internet], *99*(2–3), 289–292. https://www.sciencedirect.com/science/article/abs/pii/S0304380097019546

Blench, R., & Sommer, F. (1999). Understanding rangeland biodiversity. In *Portland house stag place* (Vol. 2, p. 121). Overseas Development Institute.

Boon, R., Cockburn, J., Douwes, E., Govender, N., Ground, L., Mclean, C., Roberts, D., Rouget, M., & Slotow, R. (2016, November 29). Managing a threatened savanna ecosystem (KwaZulu-natal sandstone sourveld) in an urban biodiversity hotspot: Durban, South Africa. *Bothalia-African Biodiversity & Conservation* [Internet], *46*(2), 1–12. https://doi.org/10.4102/abc.v46i2.2112

Camp, K. G. T. (1999). A bioresource classification for KwaZulu-Natal, South Africa [internet] [master of science in agriculture]. Klug, J, editor. *School of applied environmental sciences*. Retrieved July 5, 2023, from https://researchspace.ukzn.ac.za/xmlui/handle/10413/5406

Camp, K. G. T. (2006). *A bioresource classification for KwaZulu-Natal, South Africa. in: Smith, B, editor. The farming handbook [internet]*. University of KwaZulu-Natal Press. Retrieved June 22, 2022, from https://ukzn-dspace.ukzn.ac.za/handle/10413/5406

Camp, K. G. T., & Smith, J. M. B. (1997). Veld management planning in KwaZulu-Natal. *Cedara*. Report No.: N/A/97/5.

Chander, G., Markham, B. L., & Helder, D. L. (2009, May 15). Summary of current radiometric calibration coefficients for Landsat MSS, TM, ETM+, and EO-1 ALI sensors. *Remote Sensing of Environment* [Internet], *113*(5), 893–903. https://www.sciencedirect.com/science/article/pii/S0034425709000169

Cousins, B. (1999, June). Invisible capital: The contribution of communal rangelands to rural livelihoods in South Africa. *Development Southern Africa* [Internet], *16*(2), 299–318. https://doi.org/10.1080/03768359908440079

Cowling, R. M., Pressey, R. L., Rouget, M., & Lombard, A. T. (2003, July). A conservation plan for a global biodiversity hotspot—the Cape Floristic Region, South Africa. *Biological Conservation* [Internet], *112*(1–2), 191–216. https://doi.org/10.1016/s0006-3207(02)00425-1

Darwin, J. H. (1960). An ecological distribution akin to Fisher's logarithmic distribution. *Biometrics* [Internet], *16*(1), 51–60. http://www.jstor.org/stable/2527955

Davis, C. L., Hoffman, M. T., & Roberts, W. (2016). Recent trends in the climate of Namaqualand, a megadiverse arid region of South Africa. *South African Journal of Science* [Internet], *112*(3/4), 9–97. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84962143506&doi=10.17159%2fsajs.2016%2f20150217&partnerID=40&md5=40c55483a0e4657a51e630d5aba2ae5a

Downing, B. H. (1968, February). Notes on the ecology of natal highland sourveld vleis 1 [Internet], *Proceedings of the Annual Congresses of the Grassland Society of Southern Africa*, *3*(1), 131–134. https://doi.org/10.1080/00725560.1968.9648574

du Pisani, L. G., Fouché, H. J., & Venter, J. C. (1998, July 1). Assessing rangeland drought in South Africa. *Agricultural Systems* [Internet], *57*(3), 367–380. https://www.sciencedirect.com/science/article/pii/S0308521X98000249

du Toit, P. C. V. (1995, August). The grazing index method of range condition assessment. *African Journal of Range & Forage Science* [Internet], *12*(2), 61–67. https://doi.org/10.1080/10220119.1995.9647865

Egbebiyi, T. S., Lennard, C., Crespo, O., Mukwenha, P., Lawal, S., & Quagraine, K. (2019, September). Assessing future spatio-temporal changes in crop suitability and planting season over West Africa: Using the concept of crop-climate departure. *Climate* [Internet], *7*(9). https://www.scopus.com/inward/record.uri?eid=2-s2.0-85073239145&doi=10.3390%2fcli7090102&partnerID=40&md5=67c449a934fb559fadf5088b4443f9f4

Evans, R. A., & Love, R. M. (1957, September). The step-point method of sampling: A practical tool in range research. *Journal of Range Management* [Internet], *10*(5), 208. https://doi.org/10.2307/3894015

Filippa, G., Cremonese, E., Galvagno, M., Bayle, A., Choler, P., Bassignana, M., Piccot, A., Poggio, L., Oddi, L., Gascoin, S., Costafreda-Aumedes, S., Argenti, G., & Dibari, C. (2022, April). On the distribution and productivity of mountain grasslands in the Gran Paradiso National Park, NW Italy: A remote sensing approach. *International Journal of Applied Earth Observation and Geoinformation* [Internet], *1*(108), 102718. https://www.sciencedirect.com/science/article/pii/S0303243422000447

Fisher, R. A., Corbet, A. S., & Williams, C. B. (1943, May). The relation between the number of species and the number of individuals in a random sample of an animal population. *The Journal of Animal Ecology* [Internet], *12*(1), 42. https://doi.org/10.2307/1411

Foran, B. D., Tainton, N. M., & Booysen, P. D. E. (1978). The development of a method for assessing veld condition in three grassveld types in natal. *Proceedings of the Annual Congresses of the Grassland Society of Southern Africa* [Internet], *13*(1), 27–33. Retrieved April 16, 2022, from. https://www.ajol.info/index.php/ajrfs/article/view/790

Government of the Republic of South Africa. (1983. April 27). Conservation of agricultural resources act (CARA 43 of 1983) [internet]. *Sect*, *214*, 8673. https://www.gov.za/sites/default/files/gcis_document/201504/act-43-1983.pdf

Hardy, M. B., & Hurt, C. R. (1989, June 1). An evaluation of veld condition assessment techniques in Highland Sourveld. *Journal of the Grassland Society of Southern Africa* [Internet], *6*(2), 51–58. https://www.tandfonline.com/doi/abs/10.1080/02566702.1989.9648161

Hlatshwayo, M., Chueu, K., & Museth, V. (2007, June). Role of the national rangeland monitoring and improvement programme on the enhancement of animal production in South Africa. *Grassroots: Newsletter of the Grassland Society of Southern Africa*, *7*(2), 14–16.

Hulme, M., Doherty, R., Ngara, T., New, M., & Lister, D. (2001, August 15). African climate change: 1900-2100. *Climate Research* [Internet], *17*(2), 145–168. https://doi.org/10.3354/cr017145

Jensen, J. R. (2000). *Remote sensing of the environment: An earth resource perspective [internet]*. Pearson Education India. https://www.academia.edu/download/30929498/08_rs_vegetation.pdf

Liu, Y., Wang, X., Guo, M., Tani, H., Matsuoka, N., & Matsumura, S. (2011, July 1). Spatial and temporal relationships among NDVI, climate factors, and land cover changes in northeast Asia from 1982 to 2009. *GIScience & Remote Sensing* [Internet], *48*(3), 371–393. https://doi.org/10.2747/1548-1603.48.3.371

Mander, M. (1998). *Marketing of indigenous medicinal plants in South Africa: A case study in KwaZulu-Natal: Summary of findings*. Information Division, Food and Agriculture Organization of the United Nations. https://www.fao.org/4/w9195e/w9195e.pdf

Mbatha, N., & Xulu, S. (2018, November 30). Time series analysis of MODIS-Derived NDVI for the Hluhluwe-Imfolozi Park, South Africa: Impact of recent intense drought. *Climate* [Internet], *6*(4), 95. Retrieved April 29, 2022, fromhttps://www.mdpi.com/373616

Meneses-Tovar NDVI as indicator of degradation. (2011). *Unasylva* [Internet], https://www.fao.org/3/i2560e/i2560e07.pdf

Mentis, M. T. (1981, January 1). Evaluation of the wheel-point and step-point methods of veld condition assessment. *Proceedings of the Annual Congresses of the Grassland Society of Southern Africa [Internet]*, *16*(1), 89–94. https://doi.org/10.1080/00725560.1981.9648927

Mentis, M. T. (1984, September). Monitoring in South African grasslands. Committee for terrestrial ecosystems national programme for environmental sciences. *Report No.: 91*. South African National Scientific Programmes.

Mermer, A., Yıldız, H., Ünal, E., Aydoğdu, M., Özaydın, A., Dedeoğlu, F., Urla, O., Aydoğmuş, O., Torunlar, H., Tuğaç, M., Avağ, A., Ünal, S., & Mutlu, Z. (2015). Monitoring rangeland vegetation through time series satellite images (NDVI) in Central Anatolia Region. *2015 Fourth International Conference on Agro-Geoinformatics (Agro-geoinformatics) [Internet]*, Istanbul, Turkey, July 20–24, 2015 (pp. 213–216). Institution of Electrical Engineers (IEE). http://dx.doi.org/10.1109/Agro-Geoinformatics.2015.7248137

Mikhail, E. M., Bethel, J. S., & McGlone, J. C. (2001). *Introduction to modern photogrammetry* [Internet], Anderson, W, editor. John Wiley & Sons, Inc. https://books.google.co.za/books?hl=en&lr=&id=D4h8EAAAQBAJ&oi=fnd&pg=PA1&dq=%22Introduction+to+Modern+Photogrammetry%22+by+Edward+M.+Mikhail,+James+S.+Bethel,+and+J.+Chris+McGlone.&ots=6JGTOvIun &sig=IsqUuMGjqreugU1LTRWkCOmrc3o

Milton, S. J., Dean, W. R. J., O'Connor, T. G., & Mills, A. J. (2007). Scaling up from site-based research to a national research and monitoring network: Lessons from tierberg Karoo research centre and other design considerations: SAEON review. *South African Journal of Science* [Internet], *103*(7), 311–317. https://journals.co.za/doi/abs/10.10520/EJC96697

Milton, S. J., Dean, W. R. J., & Richardson, D. M. (2003, June). Economic incentives for restoring natural capital in southern African rangelands. *Frontiers in Ecology and the Environment* [Internet], *1*(5), 247. https://doi.org/10.1890/1540-9295(2003)001[0247:EIFRNC]2.0.CO;2

Mndela, M., Madakadze, I. C., Tjelele, J. T., Mangwane, M., Nherera-Chokuda, F., Dube, S., Ramoelo, A., & Letsoalo, N. L. (2022, March 17). Responses of grass productivity traits to bush clearing in semi-arid rangelands in North-West Province of South Africa. *The Rangeland Journal* [Internet], *44*(1), 33–45. Retrieved April 29, 2022, from https://www.publish.csiro.au/rj/RJ21053

Muavhi, N. (2021, July 29). A simple approach for monitoring vegetation change using time series remote sensing analysis: A case study from the thathe vondo area in Limpopo Province, South Africa. *South African Journal of Science* [Internet], *117*(7/8), 1–9. https://doi.org/10.17159/sajs.2021/8226

Mucina, L., & Rutherford, M. C. (2006). *The vegetation of South Africa, Lesotho and Swaziland [internet]. Kirstenbosch, NBG, Rhodes Drive, Newlands, Claremont, 7735, Cape Town, South Africa*. (1–807. South African National Biodiversity Institute. https://play.google.com/store/books/details?id=bWV1MAAACAAJ

Mutanga, O., Adam, E., & Cho, M. A. (2012, August). High density biomass estimation for wetland vegetation using WorldView-2 imagery and random forest regression algorithm. *International Journal of Applied Earth Observation and Geoinformation* [Internet], *18*(18), 399–406. https://www.sciencedirect.com/science/article/pii/S0303243412000566

Mutanga, O., & Skidmore, A. K. (2004, May). Hyperspectral band depth analysis for a better estimation of grass biomass (cenchrus ciliaris) measured under controlled laboratory conditions. *ITC J* [Internet], *5*(2), 87–96. https://doi.org/10.1016/j.jag.2004.01.001

Ndungu, L., Oware, M., Omondi, S., Wahome, A., Mugo, R., & Adams, E. (2019). Application of MODIS NDVI for monitoring Kenyan rangelands through a Web based decision support tool. *Frontiers in Environmental Science* [Internet], *7*(187), 1–12. https://doi.org/10.3389/fenvs.2019.00187

Nyamugama, A., & Kakembo, V. (2015, September 25). Estimation and monitoring of aboveground carbon stocks using spatial technology. *South African Journal of Science* [Internet], *111*(9/10), 7. 2023 May 19. https://sajs.co.za/article/view/3786

O'Connor, T. G., Puttick, J. R., & Hoffman, M. T. (2014, May 4). Bush encroachment in southern Africa: Changes and causes. *African Journal of Range & Forage Science* [Internet], *31*(2), 67–88. https://doi.org/10.2989/10220119.2014.939996

O'connor, T. G., & Roux, P. W. (1995). Vegetation changes (1949-71) in a semi-arid, grassy dwarf shrubland in the Karoo, South Africa: Influence of rainfall variability and grazing by sheep. *The Journal of Applied Ecology*, *32*(3), 612–626. https://doi.org/10.2307/2404657

Onyutha, C. (2018, September). Trends and variability in African long-term precipitation. *Stochastic Environmental Research and Risk Assessment* [Internet], *32*(9), 2721–2739. https://doi.org/10.1007/s00477-018-1587-0

Owensby, C. E. (1973, July). Modified step-point system for botanical composition and basal cover estimates. *Journal of Range Management* [Internet], *26*(4), 302. https://doi.org/10.2307/3896585

Phillips, L. B., Hansen, A. J., & Flather, C. H. (2008, December 15). Evaluating the species energy relationship with the newest measures of ecosystem energy: NDVI versus MODIS primary production. *Remote Sensing of Environment* [Internet], *112*(12), 4381–4392. https://www.sciencedirect.com/science/article/pii/S0034425708002460

Ramoelo, A., Cho, M. A., Mathieu, R., Madonsela, S., van de Kerchove, R., Kaszta, Z., & Wolff, E. (2015, December). Monitoring grass nutrients and biomass as indicators of rangeland quality and quantity using random forest modelling and WorldView-2 data. *International Journal of Applied Earth Observation and Geoinformation* [Internet], *43*, 43–54. https://doi.org/10.1016/j.jag.2014.12.010

Ramoelo, A., Cho, M., & Mathieu, R. (2015). *Potential of sentinel-2 spectral configuration to assess rangeland quality. Journal of applied* [Internet]. https://www.spiedigitallibrary.org/journals/journal-of-applied-remote-sensing/volume-9/issue-1/094096/Potential-of-Sentinel-2-spectral-configuration-to-assess-rangeland-quality/10.1117/1.JRS.9.094096.short

Ramoelo, A., Skidmore, A. K., Schlerf, M., Mathieu, R., & Heitkönig, I. M. A. (2011, July). Water-removed spectra increase the retrieval accuracy when estimating savanna grass nitrogen and phosphorus concentrations. *Isprs Journal of Photogrammetry & Remote Sensing* [Internet], *66*(4), 408–417. https://doi.org/10.1016/j.isprsjprs.2011.01.008

Rouse, J., Haas, R., Schell, J., & Deering, D. (1973). Monitoring vegetation systems in the Great Plains with ERTS. *Third ERTS Symposium, NASA*, Greenbelt, Maryland, USA (Vol. 1, pp. 309–317).

Schellberg, J., Hill, M. J., Gerhards, R., Rothmund, M., & Braun, M. (2008, August). Precision agriculture on grassland: Applications, perspectives and constraints. *The European Journal of Agronomy* [Internet], *29*(2–3), 59–71. https://doi.org/10.1016/j.eja.2008.05.005

Schumacker, R., Test, T. S. (2013). Chi-Square. *Understanding Statistics Using R* [Internet], 169–175. https://doi.org/10.1007/978-1-4614-6227-9_8

Scogings, P. F., & Mopipi, K. (2008, April 1). Effects of water, grass and N on responses of acacia karroo seedlings to early wet season simulated browsing: Aboveground growth and biomass allocation. *Journal of Arid Environments* [Internet], *72*(4), 509–522. https://www.sciencedirect.com/science/article/pii/S0140196307002236

Semenya, K., & Machete, F. (2019, September 19). Factors that influence firewood use among electrified bapedi households of Senwabarwana Villages, South Africa. *African Journal of Science, Technology, Innovation & Development* [Internet], *11*(6), 719–729. https://doi.org/10.1080/20421338.2019.1572336

Short, A. D., O'Connor, T. G., & Hurt, C. R. (2003, March). Medium-term changes in grass composition and diversity of Highland Sourveld grassland in the southern Drakensberg in response to fire and grazing management. *African Journal of Range & Forage Science* [Internet], *20*(1), 1–10. https://doi.org/10.2989/10220110309485792

Short, A., & Morris, C. (2016, January 2). The nearest-plant method is robust and powerful enough for different survey teams to monitor change in mesic grassland species composition. *African Journal of Range & Forage Science* [Internet], *33*(1), 59–65. https://doi.org/10.2989/10220119.2015.1088575

Singh, R. G., Engelbrecht, J., & Kemp, J. (2015, June 26). Change detection of bare areas in the Xolobeni region, South Africa using Landsat NDVI. *South African Journal of Geomatics* [Internet], *4*(2), 138. https://doi.org/10.4314/sajg.v4i2.6

Stanway, R. (2016a). Meat naturally initiative: Embedding sustainability into South Africa's emerging red meat sector: Research & training. *Red Meat/Rooivleis*, *7*(5), 89–91. https://journals.co.za/doi/epdf/10.10520/EJC196209

Tainton, N. M. (1988, January 1). A consideration of veld condition assessment techniques for commercial livestock production in South Africa. *Journal of the Grassland Society of Southern Africa* [Internet], *5*(2), 76–79. https://doi.org/10.1080/02566702.1988.9648114

Tainton, N. M. (1999). *Veld management in South Africa [internet]*. 472. University of Natal Press. https://play.google.com/store/books/details?id=M0MeAQAAIAAJ

Tainton, N. M., Edwards, P. J., & Mentis, M. T. (1980, January 1). A revised method for assessing veld condition. *Proceedings of the Annual Congresses of the Grassland Society of Southern Africa [Internet]*, *15*(1), 37–42. https://doi.org/10.1080/00725560.1980.9648882

Tidmarsh, C. E. M., & Havenga, C. M. (1955). The Wheel-Point Method of Survey and Measurement of Semi-Open Grasslands and Karroo Vegetation in South Africa. *Memoirs of the Botanical Survey of South Africa* (29th ed., p. 53). Government Printer. https://www.cabidigitallibrary.org/doi/full/10.5555/19560700910

Tjelele, J. T., Dziba, L. E., & Pule, H. T. (2012, January). Recovery and germination of dichrostachys cinerea seeds fed to goats (Capra hircus). *Rangeland Ecology & Management* [Internet], *65*(1), 105–108. https://doi.org/10.2111/rem-d-09-00161.1

Trollope, W. S. W. (1980, January 1). Controlling bush encroachment with fire in the savanna areas of South Africa. *Proceedings of the Annual Congresses of the Grassland Society of Southern Africa [Internet]*, *15*(1), 173–177. https://doi.org/10.1080/00725560.1980.9648907

Trollope, W. S. W., Trollope, L. A., & Bosch, O. J. H. (1990, March 1). Veld and pasture management terminology in southern Africa. *Journal of the Grassland Society of Southern Africa* [Internet], *7*(1), 52–61. https://doi.org/10.1080/02566702.1990.9648205

Trollope, W., van Wilgen, B., Trollope, L. A., Govender, N., & Potgieter, A. L. (2014, September 2). The long-term effect of fire and grazing by wildlife on range condition in moist and arid savannas in the Kruger National Park. *African Journal of Range & Forage Science* [Internet], *31* (3), 199–208. https://doi.org/10.2989/10220119.2014.884511

Ulrich, W., Matthews, T. J., Biurrun, I., Campos, J. A., Czortek, P., Dembicz, I., Essl, F., Filibeck, G., Del Galdo, G. P. G., Güler, B., Naqinezhad, A., Török, P., & Dengler, J. (2022, April 13). Environmental drivers and spatial scaling of species abundance distributions in Palaearctic grassland vegetation. *Ecology* [Internet], *103*(8), e3725. https://doi.org/10.1002/ecy.3725

van Oudtshoorn, F. (2012). *Guide to grasses of Southern Africa: An identification manual with keys, descriptions and distributions [internet]. Van Wyk, E, editor*. Briza Publications. https://doi.org/10.2989/10220119.2016.1264482.

Vetter, S. (2013). Development and sustainable management of rangeland commons – aligning policy with the realities of South Africa's rural landscape. *African Journal of Range & Forage Science*, *30*(1–2), 1–9. https://doi.org/10.2989/10220119.2012.750628

Vorster, M. (1982, January). The development of the ecological index method for assessing veld condition in the Karoo. *Proceedings of the Annual Congresses of the Grassland Society of Southern Africa* [Internet], *17*(1), 84–89. https://doi.org/10.1080/00725560.1982.9648962

Wang, Z., Ma, Y., Zhang, Y., & Shang, J. (2022, June 17). Review of remote sensing applications in grassland monitoring. *Remote Sensing* [Internet], *14*(12), 2903. https://doi.org/10.3390/rs14122903

Ward, D. (2005). Do we understand the causes of bush encroachment in African savannas? *African Journal of Range & Forage Science*, *22*(2), 101–105. https://doi.org/10.2989/10220110509485867

Whitford, W. G., De Soyza, A. G., Van Zee, J. W., Herrick, J. E., & Vegetation, H. K. (1998, June 1). Soil, and animal indicators of rangeland health. *Environmental Monitoring and Assessment* [Internet], *51*(1), 179–200. https://doi.org/10.1023/A:1005987219356

Xu, H., Wang, Y., Guan, H., Shi, T., & Hu, X. (2019, October 10). Detecting ecological changes with a remote sensing based ecological index (RSEI) produced time series and change vector analysis. *Remote Sensing* [Internet], *11*(20), 2345. https://scholar.google.co.za/scholar_url?url=https://www.mdpi.com/2072-4292/11/20/2345/pdf&hl=en&sa=X&ei=9EGlZMrDFfSV6rQPoJ6EiAU&scisig=ABFrs3yv0AjDIvDRCL-kzsW_gmmD&oi=scholarr