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Long-term changes in land use, land cover and vegetation in the Karoo drylands of South Africa: implications for degradation monitoring§

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We used several large data sets at a range of temporal and spatial scales to document the land-use/land-cover change (LULCC) dynamics of the semi-arid Succulent Karoo and Nama-Karoo biomes of South Africa. More than 95% of the Karoo is comprised of land classified as Natural, which has been relatively stable since 1990. Over the last 100 years cultivation, as well as the number of domestic livestock, has declined significantly in both biomes. Protected areas have increased since 1980 to comprise nearly 8% of the Succulent Karoo biome, although they only cover 1.6% of the Nama-Karoo biome. There has been a significant recent increase in renewable energy installation applications, which cover 4% of the Karoo drylands. The trend in vegetation productivity (NDVI; 1982–2015) is unchanged over 90% of both biomes, while nearly 10% of the Karoo has shown a significant increase in NDVI trend. An analysis of repeat photographs shows that vegetation cover has either remained unchanged or has increased at most locations. Although the Karoo drylands appear less degraded than they were in the mid-twentieth century, on-going monitoring at different temporal and spatial scales is essential to evaluate the future impact of LULCC on these semi-arid environments.

Keywords: desertification, land cover change, NDVI, remote sensing, repeat photography

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Introduction

The world's drylands represent an important terrestrial biome. They cover 41% of the Earth's surface and provide critical ecosystem goods and services for 38% of the world's population (Maestre et al. 2016). Drylands are also subject to severe land degradation with significant consequences for the environment and for the development of its inhabitants (Maestre et al. 2012). Furthermore, they are expected to increase in area during the twenty-first century in response to an increase in global aridity (Schlaepfer et al. 2017) as well as inappropriate land-use practices, particularly overgrazing.

The drylands of southern Africa mirror the global situation in terms of their national and regional importance. For example, the Succulent Karoo and Nama-Karoo biomes (Mucina and Rutherford 2006) cover nearly one-third of South Africa and support an important sheep-farming industry. Although they sustain a relatively small proportion of the country's population they possess several key mineral resources as well as a supply of potentially recoverable shale gas reserves (de Kock et al. 2017). They are also used increasingly for the establishment of renewable energy installations (Department of Environmental Affairs 2013) and large, internationally-funded scientific observatories, such as the Square Kilometre Array (SKA; Bhogal 2018).

As is the case in other drylands of the world, the two Karoo biomes have been the subject of considerable debate concerning the impact of climate and land use on the vegetation of the region. Some have argued that they are significantly degraded compared with their historical condition (Acocks 1953), while some have suggested that Karoo rangelands are no longer able to support the same number of domestic livestock that they once did (Dean and Macdonald 1994). Others, however, have proposed that environmental conditions in the Karoo have improved significantly during the course of the twentieth century (Hoffman and Cowling 1990), primarily as a result of a reduction in grazing pressure (Masubelele et al. 2015) or a change in climate (du Toit and O'Connor 2018). Although considerable uncertainty exists, most future projections suggest that the Karoo will become more arid and that desert-like environments will expand into more mesic areas (Rutherford et al. 1999; Engelbrecht and Engelbrecht 2016).

An understanding of the nature, extent and rate of change in the drylands of South Africa at multiple spatial and temporal scales, therefore, is important for policy development and to inform management decisions. The accessibility of remotely sensed imagery, particularly from satellites, together with the availability of large integrated

§ This article is from the 'Karoo Special Issue: Trajectories of Change in the Anthropocene'.

data sets have made this increasingly possible (Willis 2015). Such analyses have been used to assess the long-term changes in other dryland areas, such as the Sahel, where up-to-date information is important for decisions made by both international health agencies as well as local land users (Ahmed et al. 2017). Studies such as these are also being used increasingly to assess changes at global or continental scales to address environmental problems, such as deforestation (Wheeler et al. 2018) and desertification (Albalawi and Kumar 2013). While several local studies exist for the Karoo on the impact of climate or land use on ecosystem structure and function (e.g. O'Connor and Roux 1995; Arena et al. 2018), few biome-wide analyses provide information over decadal time scales to monitor the state of these drylands and to assess the trend in key indicators of environmental change.

The purpose of this analysis was to use some of the relatively large data sets and monitoring tools that have recently become available to document long-term changes in land cover, land use and vegetation cover in the Succulent Karoo and Nama-Karoo biomes. Even though these data sets extend over a range of spatial and temporal scales, we hypothesised that the state or condition of Karoo environments can be inferred from the trajectories of change in each of the measured variables (Duveiller et al. 2018). For example, a loss in area classified as natural vegetation, an increase in grazing pressure, and a decline in vegetation productivity and cover over time would imply that Karoo environments are more degraded than they were in the past (Eldridge et al. 2016). Alternatively, a decrease in grazing pressure and an increase in vegetation productivity and cover would suggest that the Karoo is less degraded than it was previously. Agreement between different measures of change at multiple temporal and spatial scales would add support for a particular degradation or recovery narrative, while differences between indicators would help to clarify interpretations and suggest new directions for research.

Methods

Land cover change (1990–2014)

Land cover data were derived from the habitat modification layer used in South Africa's National Biodiversity Assessment 2018. This layer has been created by the South African National Biodiversity Institute (SANBI) and draws on the 1990 and 2013/14 national land-cover products developed in 2015 by GEOTERRAIMAGE (GTI). In addition to GTI's land-cover products, the habitat modification layer also includes a class comprised of secondary natural areas. This layer has been created from the historical boundaries of field crops that were mapped from 1:50 000 topographical maps published over the period 1955 to 1990. Secondary natural areas pre-1990, therefore, consist of areas that were ploughed before 1990 but have not been ploughed subsequently. Skowno (2018) provides a detailed account of the development of each of these layers, how they were created, their technical specifications and an assessment of their main limitations.

The following land-cover classes available in the habitat modification layer were used for the purposes of this analysis: Cropland (irrigated and not irrigated), Secondary Natural, Natural, Mine, Built-up and Other. The latter class includes all of the remaining land-cover classes, such as Plantation, Artificial Water Body and Erosion, which were generally poorly represented in the Succulent Karoo and Nama-Karoo biomes.

The extent of each land-cover class in 1990 and 2014 was determined separately for each bioregion (Mucina and Rutherford 2006) in the Succulent Karoo and Nama-Karoo biomes. The change in each class in each bioregion over the 24-year time step was calculated and summed for each biome.

Land-use change

Changes in three different land-use practices in the Succulent Karoo and Nama-Karoo biomes were assessed. These included an assessment of (1) the change in the main agricultural practices of crop cultivation and livestock production, (2) the change in protected area status and (3) the extent of land designated for use by the emerging renewable energy sector (primarily wind farms and solar photovoltaic [PV] installations).

Change in agricultural practices (1911–2007)

The South African government has maintained a census of key agricultural indicators at irregular intervals since the mid-nineteenth century. This includes a census of important land-use practices, such as the number of hectares that are cultivated for the growing of different crops as well as the number of animals kept on commercial farms. Values are collated and reported by Statistics South Africa (e.g. Statistics South Africa 2010) for each of the 367 magisterial districts in the country. The boundaries of the magisterial districts have remained relatively constant in the agricultural census record since the establishment of the Union of South Africa in 1910. While data are available for some of the communal areas for some of the years, the focus of the census reporting is on the commercial agricultural sector.

Data for the two most important crops grown in the Karoo (wheat and lucerne) were compiled from the 19 published agricultural censuses carried out over the period 1911 to 2007, when the last major agricultural census was undertaken. The number of cattle, sheep, goats and equines (i.e. horses, mules and donkeys) were also extracted from the census records for the same period. All breeds of different animal types are included in the census data. For example, cattle numbers include beef and dairy cattle, sheep include wool and mutton sheep, and goats include Boer goats as well as Angora goats. The magisterial districts used for this analysis were aligned broadly with the bioregions outlined by Mucina and Rutherford (2006) and then grouped into the Succulent Karoo and Nama-Karoo biomes for purposes of reporting (see Supplementary Table S1). While the correspondence between magisterial district boundaries and those of the bioregions is imperfect, the association is close enough to provide a general indication of how important agricultural land-use practices have changed over time within each of the bioregions and the biomes examined in this study.

Change in the extent of protected areas (1960–2017)

The extent of protected areas in the Karoo was calculated using a database developed in 2017 by SANBI's Threatened Species Unit. This is based on the South African Protected Areas Database (SAPAD), which is published by the Department of Environmental Affairs each quarter (https://egis.environment.gov.za/?q=protected_areas_database). The total area within each bioregion in the Succulent Karoo and Nama-Karoo biomes was summed separately for each of the following protected area designations: Private Nature Reserve, Provincial Nature Reserve, National Park as well as areas given World Heritage Site Buffer status. Areas that were designated as a Nature Reserve, Protected Environment, Wilderness Area or Mountain Catchment were grouped as 'Other'. SAPAD also contains designation dates for each protected area providing information on how a biome's protected area status has changed over time. Using this information the change in the area under some level of environmental protection (i.e. inclusive of all designations) was calculated for the Succulent Karoo and Nama-Karoo biomes from 1960 to the present.

Renewable energy installations

Applications for the establishment of renewable energy installations (primarily wind, PV or concentrated solar power [CSP]) are submitted on a regular basis to the South African Department of Environmental Affairs who maintain an online database of all applications designated as being in review, approved or withdrawn (https://egis.environment.gov.za/?q=renewable_energy; Department of Environmental Affairs 2013). The most recent shape files available (17 January 2018) were downloaded (website was accessed on 18 June 2018) and mapped in ArcMap 10.3 (ESRI, Redlands, CA, USA). Installations were grouped broadly into whether they are being used for solar (PV and CSP) or wind energy. In some instances a polygon contained both a solar and wind installation designation, in which case it was classified as such. The area covered by the outer boundaries of each application designated as being either in review or approved (i.e. applications that have been withdrawn were excluded) was calculated and expressed as a percentage of the area of each bioregion and for the entire biome. Given that the area covered is aligned with farm boundaries, it is larger than the actual footprint of each installation.

Vegetation change

Two approaches were used to determine the extent and direction of vegetation change in the Karoo. These included an assessment of (1) the trends in the Normalised Difference Vegetation Index (NDVI) and (2) the change in vegetation cover as determined from an analysis of 280 repeat photograph sites in the two Karoo biomes.

Trends in the NDVI (1982–2015)

The NDVI is related to net primary productivity (Bai and Dent 2009) and some measures of NDVI, such as the annual integral, can also be used as a proxy for biomass (Helldén and Tottrup 2008). Long-term changes in the slope of the trend line as well as its direction (positive or negative) have also been used to indicate whether vegetation cover and biomass have improved or declined over time (Higginbottom and Symeonakis 2014).

The NDVI values for the Succulent Karoo and Nama-Karoo biomes for the period 1982–2015 were determined from the TRENDS.EARTH tool using QGIS 2.18.19. TRENDS.EARTH has been created by Conservation International as a tool for analysing key indicators of land change at multiple scales to assess and monitor land degradation (http://trends.earth/docs/en/index.html). It has been designed to calculate three subindicators of land degradation: productivity, land cover and soil organic carbon. The land cover and soil organic carbon tools were not used here, however, as the underlying global data sets employed in the tool were not considered useful for this context. The productivity subindicator measures the performance and state of primary productivity in an area as well as its trajectory. For this analysis, only the trajectory was used and was calculated separately for the Succulent Karoo and Nama-Karoo biomes, and their respective bioregions.

The trajectory measures the rate of change in primary productivity over time at the pixel level. It does this by computing a time series of the annual integral of NDVI for each pixel, applying a linear regression to the time series, and performing a Mann–Kendall, non-parametric significance test to determine whether the observed trends are significant (http://trends.earth/docs/en/background/understanding_indicators.html#indicator-productivity-trajectory). The two NDVI data sets that are available within the TRENDS.EARTH tool are the AVHRR/GIMMS and MODIS data sets. The AVHRR data set was chosen here for its higher temporal resolution allowing for the calculation of NDVI trends between 1982 and 2015. The TRENDS.EARTH tool produces two raster images. The first image represents the value of the trend, regardless of significance, while the second image has been classified according to whether there has been a significant change in NDVI or not. This image was subsequently analysed in ArcMap 10.3 to determine the number of pixels within each class for each biome, and its bioregions. The three classes chosen were (1) a significant ($p < 0.05$) decrease, (2) no change ($p > 0.05$) and (3) a significant ($p < 0.05$) increase in the annual integral of NDVI values in a pixel over the period 1982–2015.

Vegetation change from analysis of repeat photograph pairs

The Plant Conservation Unit at the University of Cape Town maintains an archive of repeat photographs from more than 1 800 sites across southern Africa. From this collection, 203 sites from the Succulent Karoo biome and 77 from the Nama-Karoo biome were analysed. The locations of the repeat photograph pairs used in this analysis are shown in Supplementary Figure S1.

Following the approach of Rohde and Hoffman (2012), total vegetation cover at each time step was estimated within three generalised landforms (slopes, plains or ephemeral rivers) in each photograph. Some photographs contained views of more than one land form, in which case each land form was evaluated separately. For the Succulent Karoo biome, estimates of the change in total vegetation cover were made for 103 slopes, 113 plains and 16 ephemeral rivers. In the Nama-Karoo biome, estimates of the change in vegetation cover were made for 51 slopes, 45 plains and five ephemeral rivers. The latter were considered too few to be meaningful and were not included in the final assessment.

Estimates of the change in total vegetation cover within a land form and between the two periods when the photographs were taken were assessed according to the same five-point Vegetation Cover Change Index used by Hoffman and Rohde (2011). The index values are related to the percentage change in total vegetation cover within a landform as follows: −2 = >25% decrease in cover in the repeat photograph when compared against the original; −1 = >5% to 25% decrease in cover; 0 = −5% to +5% difference in cover; +1 = >5% to 25% increase in cover; and +2 = >25% increase in vegetation cover. The number of photographs within each of the Vegetation Cover Change Index values was calculated for each of the land forms assessed in the different biomes and expressed as a percentage of the total for the land form. This approach provides a general overview of the direction of change in vegetation cover over time for each of the different land forms in a biome.

Results

Land-cover change

Natural land was the dominant land cover class in both the Succulent Karoo and Nama-Karoo biomes in 2014 and comprised more than 95% of the area of both biomes with the remaining land-cover classes together comprising less than 5% (Table 1). The proportion of cropping area was higher in 2014 in the Succulent Karoo biome than in the Nama-Karoo biome with more than 4% of the Namaqualand Sandveld and Knersvlakte bioregions under cultivation. Irrigated croplands on the margins of these bioregions, especially around Vredendal, comprised a significant proportion of the cultivated lands. The proportion of area mined was greatest in the Namaqualand Sandveld bioregion and reflects the legacy of the diamond mining industry, which operated along the coastal environments of Namaqualand for much of the twentieth century.

The land-cover classes were generally stable over the 24 years between 1990 and 2014 and none changed by more than 1% over this period (Table 1). The area of Cropland increased slightly in the Knersvlakte and in the Upper Karoo largely as a result of the increase in irrigated fields. However, the Secondary Natural land-cover class also increased in several bioregions, suggesting that areas that were once cultivated have since been abandoned and have now reverted to a state that resembles natural vegetation. The Natural land-cover class decreased in all bioregions, although the greatest decrease (in the Namaqualand Sandveld bioregion) was only by −0.82%.

Land-use change

Change in agricultural practices (1911–2007)

The number of hectares sown to wheat in the Succulent Karoo biome was greatest between 1946 and 1976 when more than 70 000 ha were cultivated on a regular basis (Figure 1). In the most recent agricultural census in 2007 less than 10 000 ha were cultivated for the production of wheat. Although slightly lower, the pattern for wheat cultivation in the Nama-Karoo biome mirrored that of the Succulent Karoo biome for the first half of the twentieth century but declined rapidly after 1950. There has been a slight increase in the number of hectares sown to wheat in the Nama-Karoo biome in the 2002 and 2007 agricultural census record largely as a result of the increase in irrigated fields in the more mesic magisterial districts (e.g. Philipstown and Hopetown), which fall within the Upper Karoo bioregion and utilise water from perennial rivers such as the Orange River. The number of hectares sown to lucerne is very similar for both biomes and increased from 1911 to the 1970s but has declined steadily to 2002 when the last complete census for this crop is available.

In both Karoo biomes the number of cattle has remained relatively stable following an initial decline from the peak value in 1923 (Figure 2). Higher values and greater fluctuations are evident in the number of cattle in the more grassy Nama-Karoo biome compared with that of the Succulent Karoo biome where the trend has generally been downward since the middle of the twentieth century.

Table 1: Percentage cover of each land-cover class in the bioregions of the Succulent Karoo and Nama-Karoo biomes in 2014. The area (km^2) of the bioregions and biomes is also provided. Land-cover classes that increased (or decreased) by between 0.2% and 1% over the period 1990–2014 are indicated in bold (or italics)

Biome and bioregion	Land-cover class (%)						Total area (km^2)
	Cropland	Secondary Natural	Natural	Mine	Built-up	Other	
Richtersveld	0.1	0.5	99.3	0.0	0.0	0.0	6.237
Namaqualand Hardeveld	2.3	2.3	*95.1*	0.1	0.1	0.0	19.486
Namaqualand Sandveld	4.2	**1.9**	*90.0*	3.6	0.1	0.2	9.519
Knersvlakte	**4.6**	**0.9**	*94.2*	0.2	0.0	0.1	5.289
Trans-escarpment Succulent Karoo	1.7	1.2	*96.8*	0.0	0.1	0.2	15.959
Rainshadow Valley Karoo	2.0	**0.8**	*96.7*	0.0	0.1	0.4	30.511
Succulent Karoo biome	2.3	**1.3**	*95.7*	0.4	0.1	0.2	87.001
Bushmanland	0.5	0.2	99.1	0.1	0.1	0.1	100.924
Upper Karoo	**2.0**	**0.8**	*96.2*	0.1	0.1	0.8	124.646
Lower Karoo	0.7	0.3	98.5	0.0	0.1	0.4	34.725
Nama-Karoo biome	1.2	0.5	*97.6*	0.1	0.1	0.5	260.295

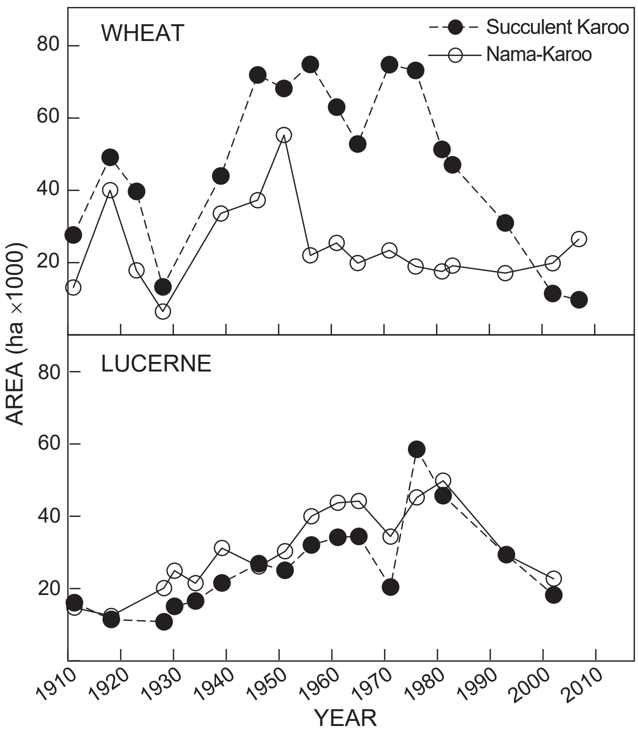

Figure 1: Number of hectares of wheat and lucerne cultivated in the Succulent Karoo and Nama-Karoo biomes over the period 1911–2007 as recorded in the Agricultural Censuses (e.g. Statistics South Africa 2010)

Sheep totals were greatest in both biomes over the period 1928–1976 (Figure 2). If values for both biomes are combined, the number of sheep in the wider Karoo region has declined from a peak of more than 11 million animals in 1939 to just over 4 million animals in 2007. Between 1956 and 2007 the number of sheep in the Nama-Karoo biome declined by more than 60%. For the Succulent Karoo biome this decline is closer to 70%.

The number of goats in the two biomes has declined significantly from pre-1930 levels when their combined totals were close to 3 million animals or more (Figure 2). In 2007 the number of goats in the two biomes was less than 10% of this value. A brief spike in the number of goats in the Nama-Karoo between 1976 and 1993, brought about by the boom in Angora goat mohair production, has not been sustained into the twenty-first century.

At their peak in 1923, the combined number of horses, mules and donkeys (equines) in the two biomes was close to 300 000 (Figure 2). Their number declined significantly after 1946. In 2002, when the last complete census of equines took place, there were fewer than 4 500 animals in the Karoo.

Change in the extent of protected areas (1960–2017)

The current protected area estate of the Succulent Karoo biome is 404 508 ha (7.7% of the biome). The Nama-Karoo biome has 668 430 ha under some form of protection, but this constitutes a far smaller proportion of the biome (1.6%) (Table 2). The Richtersveld has the greatest level of conservation protection in the Karoo drylands as a result of the establishment of the Richtersveld National Park as well as

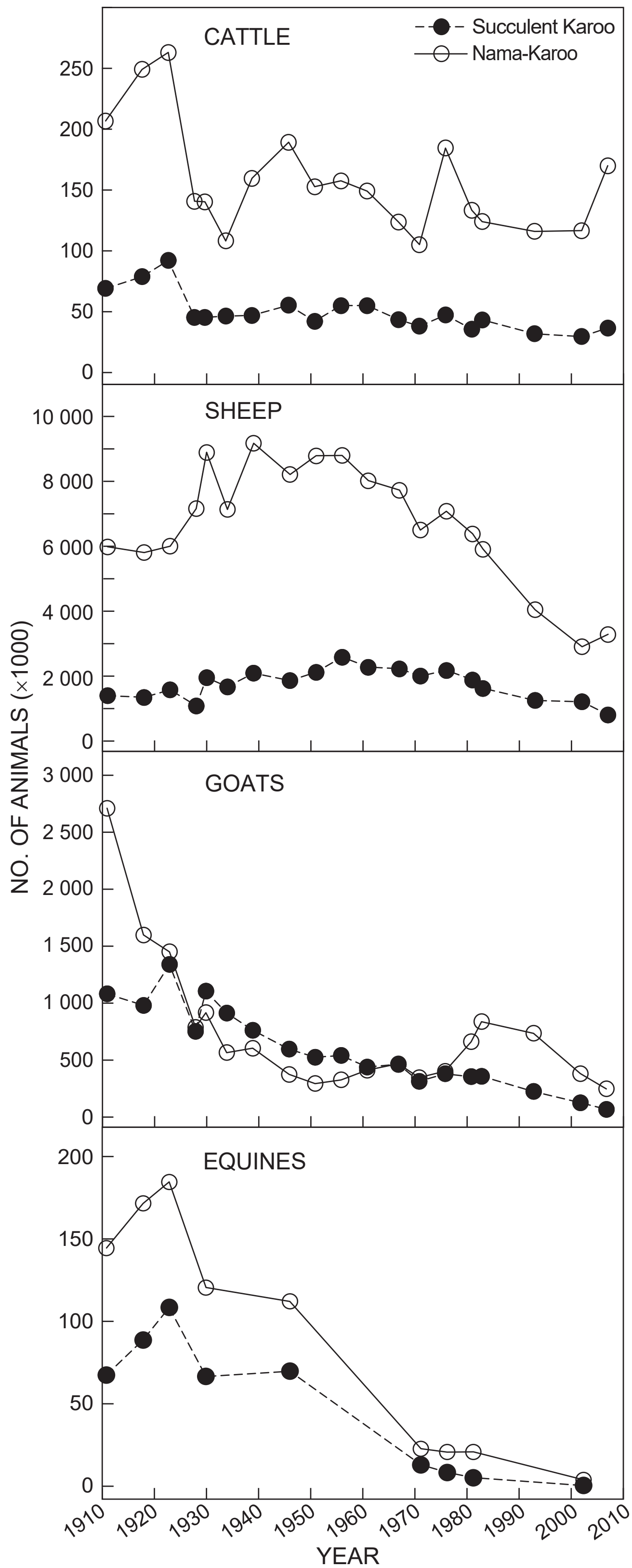

Figure 2: Changes in the number of cattle, sheep, goats and equines (horses, mules and donkeys) in the magisterial districts of the Succulent Karoo and Nama-Karoo biomes over the period 1911–2007 as recorded in the Agricultural Censuses (e.g. Statistics South Africa 2010) for commercial farming areas

Table 2: Percentage cover of different types of protected areas in the bioregions of the Succulent Karoo biome and the Nama-Karoo biome in 2017. The total percentage of each bioregion that has some form of protected area status is also provided. 'Other' refers to protected areas designated as a Nature Reserve, Protected Environment, Wilderness Area or Mountain catchment

Biome and bioregion	Type of protected area (%)					Proportion of total area (%)
	Private Nature Reserve	Provincial Nature Reserve	National Park	World Heritage Site Buffer	Other	
Richtersveld	0	0.1	9.7	15.0	0	24.8
Namaqualand Hardeveld	0	1.1	3.3	0	0.1	4.5
Namaqualand Sandveld	0	0.6	9.7	0	0	10.3
Knersvlakte	1.2	14.8	0	0	0	15.9
Trans-escarpment Succulent Karoo	0	0.1	0.2	0	0	0.2
Rainshadow Valley Karoo	1.3	1.8	4.5	0	0.3	7.9
Succulent Karoo biome	0.5	1.9	4.1	1.1	0.1	7.7
Bushmanland	0	0.1	0.5	0	0	0.5
Upper Karoo	0.2	0.3	0.5	0	1.1	2.0
Lower Karoo	0.2	0.2	0.6	0	0.6	2.8
Nama-Karoo biome	0.2	0.6	1.7	0.4	0.5	1.6

its World Heritage Site Buffer status. The Trans-escarpment Succulent Karoo bioregion in the Succulent Karoo biome is the least protected bioregion in the Karoo (0.2%). While the level of conservation protection is generally low in the Nama-Karoo biome, the Bushmanland bioregion is particularly poorly protected, with only 0.5% of its vast area under some form of conservation protection.

Between 1960 and 2016 the protected area estate of the Succulent Karoo biome increased substantially, from being completely unprotected (0 ha) to 7.7% protected (668 430 ha). The extent of protected areas has also increased in the Nama-Karoo over the last 57 years, from 0.03% (6 483 ha) to 1.6% (668 430 ha) (Figure 3). In 1960 none of the Succulent Karoo and only 6 483 ha in the Nama-Karoo was protected. However, from the mid-1980s onwards this changed significantly for the Succulent Karoo biome, especially in the Richtersveld, Knersvlakte and Namaqualand Sandveld bioregions as a result of the declaration of several Provincial Nature Reserves and National Parks (Table 2). The same pattern of increase is not as obvious in the Nama-Karoo biome due to the sheer size of the bioregions, but significant protected area expansions have occurred through the expansion of national parks and the development of protected environments, which is a form of biodiversity stewardship protection.

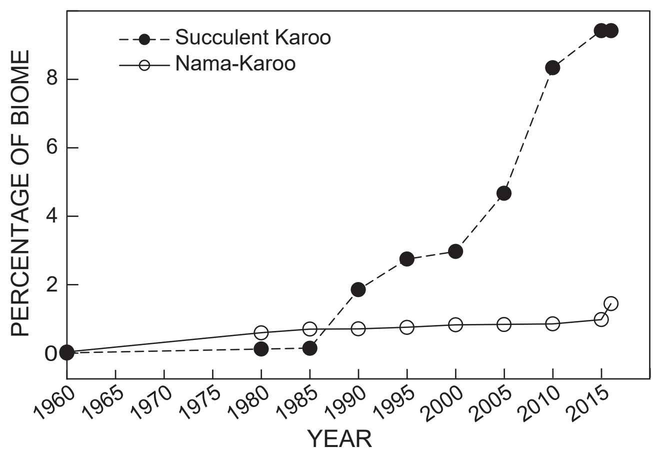

Figure 3: Change in the Protected Area status for the Succulent Karoo and Nama-Karoo biomes over the period 1960–2016. The values reflect the percentage of the total area of the biome having some level of protected area status

Renewable energy installations

Renewable energy installations, which have been designated as either being in review or approved, cover 5.2% and 3.6% of the Succulent Karoo and Nama-Karoo biomes, respectively, or 4.0% of the combined area of both biomes (Table 3, Figure 4). All of the bioregions are affected to some extent, although some significantly more than others. The Namaqualand Sandveld and the Namaqualand Hardeveld bioregions in the Succulent Karoo biome have the largest percentage of their areas earmarked for renewable energy installations. However, because of the relatively large area covered by the bioregions of the Nama-Karoo biome, the total area that could potentially contain wind and solar energy installations in this biome is more than twice that designated for the Succulent Karoo biome (9 506 km^2 vs 4 538 km^2).

Vegetation change

Trends in the NDVI (1982–2015)

An analysis of changes in the annual integral of NDVI shows that about 90% of the area of both biomes has not changed significantly between 1982 and 2015 (Table 4). Less than 1% of the combined area has shown a significant decrease in NDVI over time, while nearly 10% of the area reflects a significant increase in NDVI.

The decrease in NDVI in the Succulent Karoo biome is associated exclusively with the Rainshadow Valley Karoo bioregion and with the Lower Karoo bioregion of the Nama-Karoo biome (Table 4, Figure 5). Areas where NDVI has increased significantly are associated with the Rainshadow Valley Karoo, the Namaqualand Sandveld and, to a lesser extent, the Knersvlakte. For the Nama-Karoo biome a significant increase in NDVI has occurred in locations adjacent to the higher rainfall grassland and savanna environments towards the eastern, north-eastern and northern margins of the biome, respectively.

Table 3: Percentage of each bioregion and biome earmarked for different types of energy installations and which are designated as either having been approved or are currently in the process of review

Biome and bioregion	Area covered by installation type (%)			
	Solar	Wind	Solar and Wind	Proportion of total area (%)
Richtersveld	1.0	1.1	0.7	2.8
Namaqualand Hardeveld	5.0	0.8	0.1	5.9
Namaqualand Sandveld	10.5	14.0	0	24.5
Knersvlakte	0.2	0.6	0	0.8
Trans-escarpment Succulent Karoo	0.1	0.1	0.3	0.5
Rainshadow Valley Karoo	0.1	2.3	0.1	2.5
Succulent Karoo biome	2.4	2.6	0.2	5.2
Bushmanland	3.1	0.3	1.4	4.7
Upper Karoo	1.1	1.0	0.7	2.9
Lower Karoo	1.1	2.0	0	3.1
Nama-Karoo biome	1.9	0.9	0.9	3.6

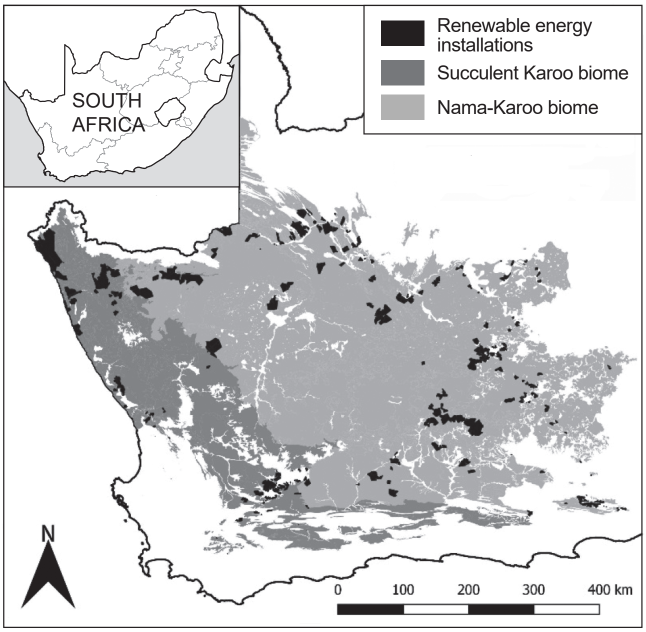

Figure 4: Location of solar and wind renewable energy installations in the Succulent Karoo and Nama-Karoo biomes that have either been approved or are under review

Vegetation change from analysis of repeat photograph pairs
In both biomes, the majority of comparisons between photograph pairs on slopes and plains showed little change in vegetation cover over time (i.e. changes in cover were estimated to lie between −5% and +5%) (Figure 6). Vegetation cover on slopes of the Succulent Karoo biome was especially stable over time with two-thirds of the comparisons showing little change. However, on the plains and slopes in both biomes far more comparisons between repeat photograph pairs reflected an increase in vegetation cover than a decrease (Figures 7–10). Fewer than 10% of the sites showed a decrease in vegetation cover greater than −5% within all land forms of both biomes.

Table 4: Percentage of pixels for each bioregion and for the Succulent Karoo and Nama-Karoo biomes as a whole showing a significant decrease ($p < 0.05$), no change or significant increase ($p < 0.05$) in the annual integral of NDVI using the AVHRR for the period 1982–2015

Biome and bioregion	NDVI trend		
	Significant decrease ($p < 0.05$)	Stable (no significant change)	Significant increase ($p < 0.05$)
Richtersveld	0	100	0
Namaqualand Hardeveld	0	97.4	2.6
Namaqualand Sandveld	0	89.6	10.4
Knersvlakte	0	93.7	6.3
Trans-escarpment Succulent Karoo	0	100	0
Rainshadow Valley Karoo	1.9	77.2	21.0
Succulent Karoo biome	0.7	89.4	9.9
Bushmanland	0	94.9	5.1
Upper Karoo	0	86.8	13.1
Lower Karoo	0.2	90.4	9.5
Nama-Karoo biome	0.1	90.2	9.6

The pattern of vegetation change in ephemeral rivers of the Succulent Karoo biome (Figure 6) showed a general increase in cover over time. Half of the repeat photographs taken of this land form showed an increase in cover of between 5% and 25%, while three of the 16 images of ephemeral rivers in the Succulent Karoo biome showed an increase in cover of greater than 25% between the sampling periods (Figure 11).

Discussion

Land-use and land-cover change (LULCC)

A relatively complex and potentially contradictory pattern emerges from this examination of LULCC in the Karoo, which is influenced both by the type of analysis used as well as by the temporal and spatial scale of investigation. For example, an analysis of land-cover change suggests that the region is dominated by Natural land, the area of which has changed remarkably little since 1990. In fact, there appears to have been almost no change in any of the major land-cover classes over the 24-year period of analysis. This stands in contrast to the findings of other land-cover change studies for more mesic parts of South Africa, such as those of Jewitt et al. (2015) for KwaZulu-Natal. Their analysis indicated that since 1994, an average of 1.2% of the natural habitat of the province had been transformed each year, primarily as a result of human activities such as agriculture, plantations, settlements and mines. Part of the reason for this difference between the Karoo drylands and KwaZulu-Natal, however, lies in the land-cover class categories used in the national land-cover products database for South Africa (e.g. Fairbanks et al. 2000). While they might be useful for understanding the dynamic interactions that occur over time between people and the environment in more densely populated, higher rainfall areas, they appear unable to reflect the impact that people might have had on Karoo environments. Other measures at different spatial and temporal scales are needed to understand the dynamic

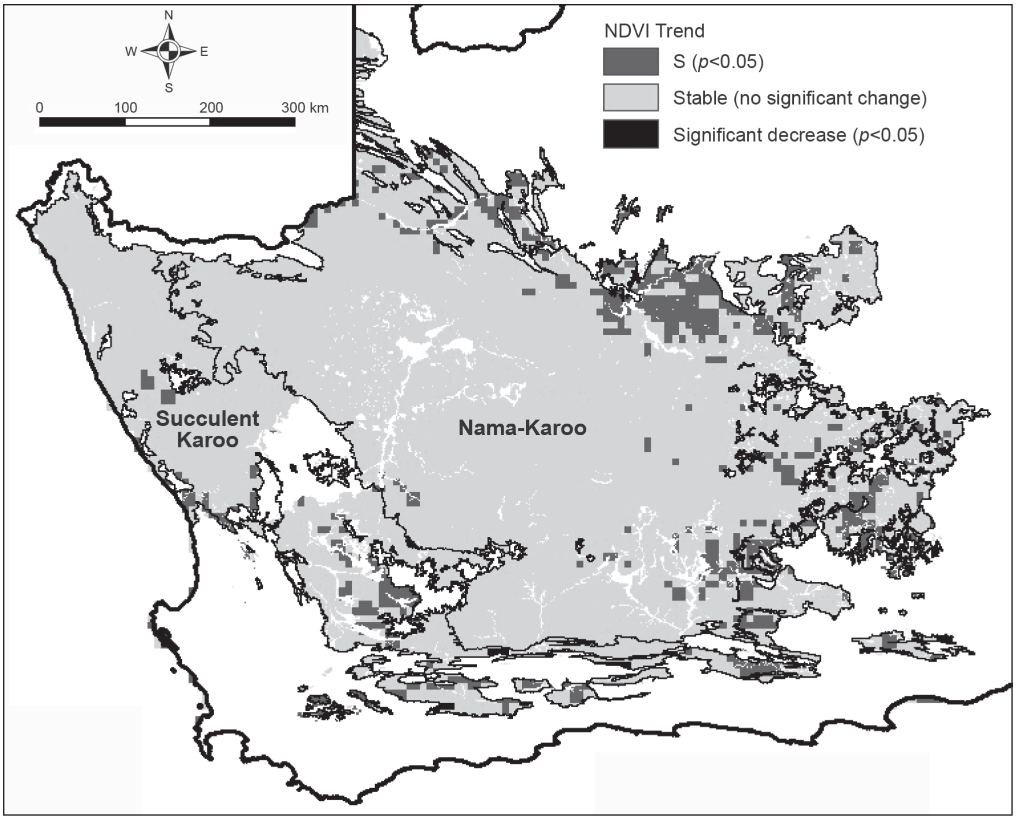

Figure 5: Location of areas within the Succulent Karoo and Nama-Karoo biomes where the change in the annual integral of NDVI has been stable, where it has decreased or where it has increased significantly ($p < 0.05$) over the period 1982–2015

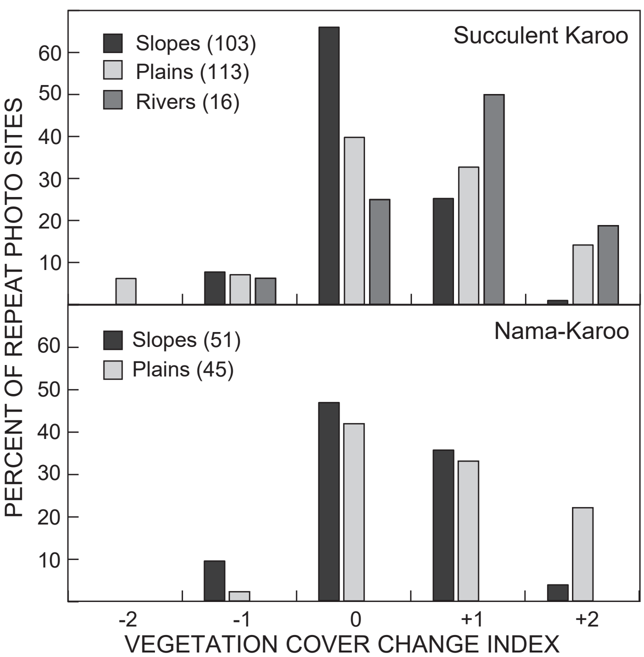

Figure 6: Percentage of repeat photograph sites within each of five Vegetation Cover Change Index classes in the Succulent Karoo (top) and Nama-Karoo (bottom) biomes. Changes in vegetation cover in the different major landforms (slopes, plains and rivers) are shown separately

nature of the Karoo and how it might have changed over time in response to anthropogenic influences.

An analysis of changes in land use, as opposed to land cover, goes some way to helping in this regard. What emerges from an investigation of land-use change is quite different to the pattern observed from an assessment of land-cover change only. Rather than being stable, land-use change in the Karoo has been highly dynamic in both space and time. Some land-use practices that were dominant throughout the drylands in the past have declined in intensity and importance, while new developments, unforeseen just a few decades ago, have emerged rapidly to influence the Karoo's social and ecological environments.

In terms of the main agricultural practices, for example, our findings show that there has been a fundamental shift in agricultural practices over the last 100 years. Areas used for the cultivation of rain-fed crops, such as wheat and lucerne, have declined significantly since the middle of the twentieth century, as has the number of domestic livestock that utilise privately-owned Karoo rangelands (Hoffman and Rohde 2007; Masubelele et al. 2014). Stocking rates have continued to decline even further since 1994 when Dean and Macdonald (1994) first brought attention to the widespread decrease in livestock numbers in the Karoo. Livestock have a profound and largely negative influence on ecosystem structure and function (Eldridge et al. 2016) and their decline in number has implications for the composition and productivity of the Karoo today (Rutherford

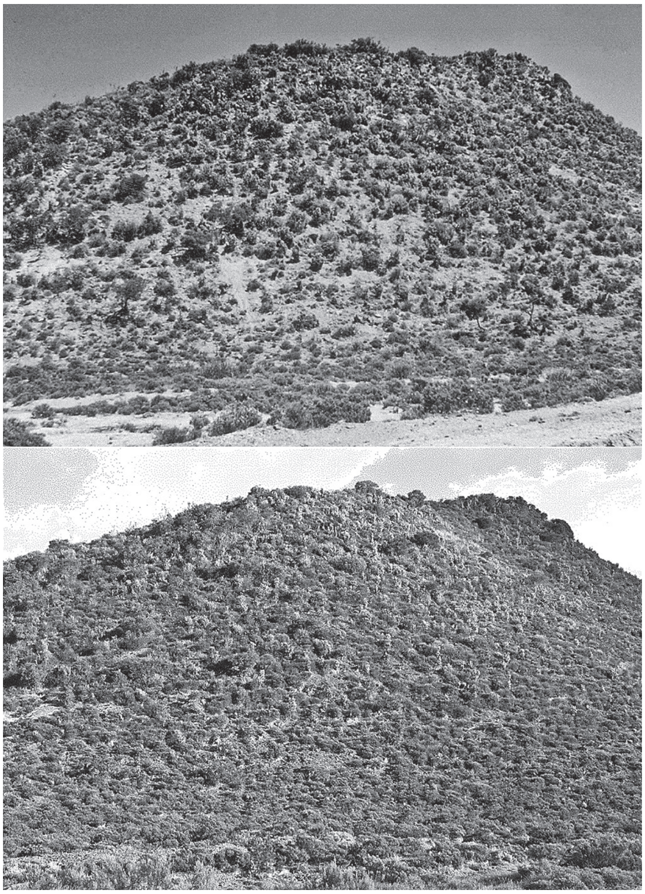

Figure 7: Perennial vegetation cover has increased on this slope and now covers many of the open areas evident in the original photograph, which was taken by John Acocks on 20 October 1959 and repeated by Amy Murray and Timm Hoffman on 27 June 2014. The site (No. 88) is located in the Succulent Karoo biome about 14 km north-west of Vanwyksdorp at 33.69178° S, 21.33545° E

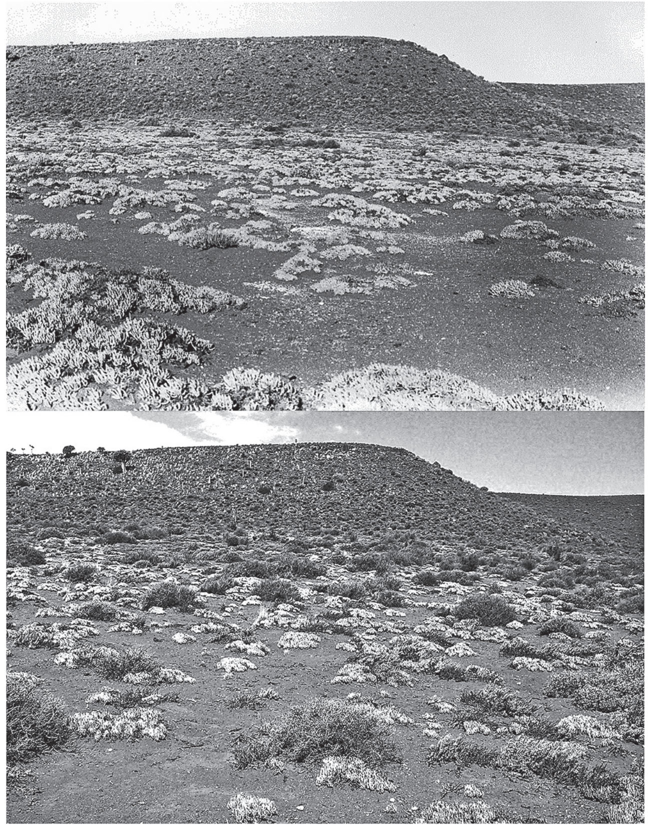

Figure 8: The overall cover of the vegetation in the foreground plains is relatively similar in both photographs although there has been an increase in the cover of low shrubs (e.g. *Roepera microphyllum*) and a decrease in the cover of prostrate, succulent-leaved shrubs (e.g. *Cephalophyllum* sp.). There has also been a notable increase in the number of individuals of *Aloidendron dichotomum* on the distant slope. The original photograph was taken by IB Pole Evans in 1920 and the repeat was taken by Rick Rohde and Timm Hoffman on 27 October 2005. The site (No. 144) is located in the Succulent Karoo biome about 30 km south of Loeriesfontein at 31.204556° S, 19.45258° E

and Powrie 2010). What the agricultural census record does not document, however, is the number of indigenous ungulates that are now kept on farms that have been converted to wildlife or game ranches. This practice has been widespread in southern Africa (Lindsey et al. 2009), although no biome-wide census of indigenous ungulate numbers is available for the Karoo drylands.

One of the more important changes in land use that has affected the Succulent Karoo biome in particular has been the significant increase in the amount of land that has been set aside for conservation purposes. The global recognition of the unique biodiversity of the Succulent Karoo biome (Myers et al. 2000) has mobilised substantial investment from the state, non-governmental organisations and private sector to expand the conservation estate across the biome. From having almost no land set aside for conservation in the mid-1980s to there being nearly 8% of the Succulent Karoo biome conserved today is a major achievement for the conservation and private land-owner community. The same pattern has not occurred in the Nama-Karoo biome, probably because it lacks the unique plant and animal lineages and high levels of biodiversity and endemism that are to be found in the Succulent Karoo biome (Mucina and Rutherford 2006) and as a result has not attracted the same level of national and international interest. However, the recent establishment of the Square Kilometre Array astronomical installation in the Nama-Karoo could potentially add more than 2.4% to the area under formal conservation protection in the Nama-Karoo biome (CSIR 2016).

The absence of any formal conservation protection for over 98% of the Nama-Karoo biome should be viewed in the context of the recent expansion or threat of expansion of a significant number of new, energy-related developments in the biome. The impact that the renewable energy sector might have on the people and environment of the Karoo could hardly have been imagined just a decade ago and, perhaps because of this, has barely been researched at all. Much of the research effort in the region to date has focused on the impact of grazing or climate on Karoo ecosystem structure and function (Arena et al. 2018). There has been very little investigation into the impact of wind turbines, transmission lines or

Figure 9: The paddock on the left of the fence line has been grazed continuously since 1967 and shows an increase in the number of large shrubs, whereas the paddock on the right has not been grazed over this period and indicates little change. The original photograph of this slope was taken by Piet Roux in 1967 and repeated by Mmoto Masubelele and Timm Hoffman on 12 October 2010. The site (No. 586) forms part of the Department of Agriculture's Bergkamp experiment and is located in the Nama-Karoo biome about 7 km north of Middelburg at 31.43249° S, 24.98027° E

Figure 10: Grass cover has increased on the plains over much of the eastern margins of the Nama-Karoo biome as shown in this matched pair of photographs taken on the farm Corndale (Site No. 512) about 12 km south-west of Graaff-Reinet (32.33115° S, 24.44106° E) in the Nama-Karoo biome. The top photograph was taken by John Acocks on 6 December 1968, whereas the lower photograph was taken by Zander Venter and Samantha Venter on 27 May 2018

extensive fields of solar PV panels or CSP installations on the region's biota (Rudman et al. 2017; Dean et al. 2018). Work done elsewhere, however, suggests that the impacts could be considerable, especially in terms of habitat loss and the effects experienced by birds and bats resulting from their collision with wind turbines and transmission lines (Gasparatos et al. 2017). Although not yet a reality in the Karoo, knowledge of the impact of shale gas extraction on these dryland environments is equally scant (Todd et al. 2016). These recent and emerging developments pose significant threats to the region's biodiversity and greater focus on the accumulated impact of the renewable energy sector on the Karoo is urgently needed.

Vegetation change

While an assessment of LULCC is important for environmental monitoring purposes, such measures do not record direct changes in vegetation cover and composition. To do this, other approaches are needed, preferably at a range of spatial and temporal scales. Our assessment, which has adopted this strategy, shows that vegetation cover over the Karoo has either increased or has remained relatively stable over time scales of several decades to even a century. The results from both remote sensing and repeat photography provide little support for an on-going degradation narrative for the region (Acocks 1953), although at local scales this has undoubtedly occurred in the past (Keay-Bright and Boardman 2006; Nenzhelele et al. 2018) and continues in the present. Of particular concern throughout the Karoo is the threat posed by the increase in alien invasive species such as *Prosopi*s spp. (Shackleton et al. 2015). While invaded areas reflect an increase in biomass and vegetation cover, such species pose considerable threats to the biodiversity of the Karoo as well as to its scarce water resources. The increase in cover of some indigenous species, such as *Senegalia mellifera*, particularly in areas that border on the arid savanna biome (Ward et al. 2014), is also perceived as being negative for many farming practices because the cover of grasses is often reduced under dense stands of this species. The

Figure 11: The ephemeral river systems of the Succulent Karoo biome have either shown little change in cover (such as in this view of the Buffels River) or have exhibited an increase in cover, particularly of the low tree, *Vachellia karroo*. This location (No. 305) is about 20 km south-east of Komaggas in Namaqualand (29.911444° S, 17.67181° E). The top photograph was taken by John Acocks on 27 August 1957 and repeated by Rick Rohde and Timm Hoffman on 25 November 2004

impact of woody-cover change in the Karoo is therefore often context-specific and some caution should be undertaken when interpreting its significance.

The trend for an increase in vegetation productivity and cover is supported by other studies in the Karoo. For example, Davis et al. (2017) used AVHRR satellite data for Namaqualand to show that productivity of the region, as measured by the small and large integral of NDVI, had increased over the period 1982–2011. Numerous repeat photography studies also confirm the findings presented here, namely that vegetation cover of the slopes, plains and rivers of the Karoo drylands has not declined in recent decades but has either remained stable or in some cases has increased considerably relative to earlier periods (Hoffman and Rohde 2007, 2011). In some parts of the Karoo, such as in the eastern margins of the Nama-Karoo biome, there has even been a complete shift in growth form dominance, for example from dwarf shrubs to perennial grass since the 1960s (Masubelele et al. 2014). This contrasts with several global analyses of arid and semi-arid regions, which report a loss of cover, especially of perennial grasses, as a direct result of an increase in land-use intensity (Schlesinger et al. 1990; Eldridge et al. 2016).

We have not examined the main reasons for the changes observed in vegetation cover, although rainfall is clearly a main driver of rangeland dynamics in the Karoo (O'Connor and Roux 1995). The number and type of animals as well as the grazing treatment are also important as indicated by the results from several long-term grazing trials in the region (O'Connor and Roux 1995; van der Merwe et al. 2018). While the rising concentration of CO_2 in the atmosphere could also influence vegetation cover and composition, its effect on dwarf shrubs and perennial grasses is poorly understood at present (Scheiter et al. 2012).

Du Toit and O'Connor (2018) have argued that rainfall is the primary determinant of the switch in growth form from shrubs to grasses observed in the eastern Nama-Karoo biome, with changes in stocking rates providing an additional, secondary influence. They present clear evidence for their study area near Middelburg of a significant increase in annual rainfall as well as a shift in rainfall seasonality. While this explanation might apply to several other parts of the eastern Karoo, its utility as a general explanation for an increase in vegetation cover will need to be evaluated for the rest of the Karoo drylands, where changes in rainfall seasonality and annual amounts have not occurred (Hoffman et al. 2009; MacKellar et al. 2014; Davis et al. 2016). What has happened across the entire region, in every magisterial district, however, is a significant reduction in the number of livestock. In 2007 the Karoo supported 35.4%, or about one-third, of the number of cattle, sheep and goats that were sustained on the rangelands of the two biomes in 1930 when the total number of animals reached its peak in the Karoo. This reflects a difference of more than 8.4 million animals or a shift from 16.1 ha per large stock unit (LSU) in 1930 to 40.4 ha LSU^{-1} in 2007. This means that 2.5 times the area was available for each LSU equivalent in 2007 as compared with 1930. Any explanation for the patterns observed in vegetation cover of the Karoo should consider the effect that this decline in livestock numbers might have had on ecosystem structure (cover and composition) and function (soil carbon, biomass and productivity) at both local and regional scales (Eldridge et al. 2016) and over decadal time scales.

Implications for degradation monitoring

An understanding of the basic patterns of LULCC in the Karoo as well as the response of the region's vegetation is important if this vast semi-arid environment is to be managed sustainably. This analysis has highlighted four issues worth considering in this regard. Firstly, a range of different approaches at multiple spatial and temporal scales are needed to fully appreciate the trajectories of change in the Karoo drylands (Sommer et al. 2011). We have shown, for example, that an analysis of land cover is a useful exercise when comparing change in the Karoo with other biomes but does not characterise the dynamic nature of the region, nor is it intended to. Similarly, remote sensing is being used increasingly to monitor degradation with useful outcomes. However, interpreting the trends in NDVI is complicated (Easdale et al. 2018) and the ground truthing of the results of remotely-sensed productivity measures is a critical part of the validation process (Higginbottom and Symeonakis 2014). The need for local-level studies that provide additional data and insights is also critical (Albalawi and Kumar 2013), especially in the Karoo, where the recent and rapid rise of the renewable energy sector has the potential to impact heavily on several taxa. Baseline studies together with long-term, local-level monitoring programmes are needed to measure the impact that these installations and others in the future might have on the biota of the Karoo.

Secondly, it is essential that the long-term data sets that are currently in place are maintained and updated but also that new information is included in future assessments of change. An up-to-date and accurate agricultural census record is an essential aid for any interpretation of land-use change in the region and more than a decade has passed since the last country-wide census was undertaken (Statistics South Africa 2010). The focus of the agricultural census is also exclusively on the commercial farming sector and no collated information is available for the communal areas of Namaqualand, which cover 25% of that region. The switch from livestock production to wildlife ranching has already been mentioned. This reflects a major shift in land-use practices about which very little is known but which has important consequences for environmental health (Clements and Cumming 2017).

Thirdly, the results presented here portray the Karoo as a region in recovery from the significantly higher intensity of land use, especially livestock grazing, that characterised the first half of the twentieth century and possibly much of the nineteenth century as well (Dean and Macdonald 1994). However, climate-change projections suggest that the Karoo will become hotter and drier in the future by as much as 4 °C (Engelbrecht and Engelbrecht 2016) with significant consequences for Karoo ecosystems. Appropriate indicators that can be used to identify tipping points and thresholds of change (Sommer et al. 2011) need to be identified and monitored as a matter of urgency.

Finally, nothing is presented here of the change in Karoo society that has occurred as a result of the change in land-use practices over time or how this in turn could have impacted on Karoo environments. An understanding of the coupled socio-ecological system and its impact on land degradation and social change is a rich area of study (Stringer et al. 2017) that has barely been touched on in the Karoo.

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