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Review

Anthropogenic impacts and implications for ecological restoration in the Karoo, South Africa

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ABSTRACT

Arid regions globally have suffered ecological damage as European colonists have displaced virtually all nomadic cultures over the past 300 years, exploiting grazing, fauna and water unsustainably in creating permanent settlements. The Karoo is one such arid region that covers about one third of South Africa. In common with arid regions globally, this sparsely-populated shrubland was historically used mainly for ranching, but is now becoming increasingly important for renewable energy generation (wind and sun), for adventure tourism, and potentially for mining. Current and future land users in the Karoo face challenges posed by damage caused by past land use, particularly overgrazing and impoundments. Land users of the future will probably experience additional challenges caused by the combined impacts of damaging land use and climate change. This review synthesizes the bodies of literature on the archaeology, ecology, land use history, environmental change and development planning. In doing so, we address the effects of historical land use on biodiversity and ecosystem goods and services in the region. We also identify avenues for future research, including mitigation and restoration actions required to make continued human occupation of the Karoo sustainable. Insights on the sustainability of the Karoo region are relevant when considering the socio-ecological futures of arid regions elsewhere.

1. Introduction

Arid regions have limited and fluctuating productivity and grazing capacity (Noy-Meir, 1973). For this reason, most arid regions supported nomadic hunter-gatherers or herders prior to European colonialism (Veth et al., 2005). Colonial expropriation and extermination of local cultural practices in arid regions inevitably led to ecological disasters (Holleman, 2018). The combination of human population growth and use of such areas for settled pastoralism, mining or crop production supported by aquifers or damming of seasonal rivers led to soil erosion, salinization, extinctions of indigenous species, and invasions by introduced pathogens, fauna and flora (Reynolds et al., 2007; Fernández-Cirelli et al., 2009; Milton and Dean, 2010; Stafford Smith and Cribb, 2009; Busso and Fernandez, 2018). As global climates become hotter and in many cases more extreme, there is a growing awareness and concern about environmental damage and losses of ecosystem services to dry lands in Australia (Stafford Smith and Cribb, 2009), Brazil (Ventura and Andrade, 2013), Peru (Caramanica et al., 2020), Argentina and Patagonia (Torres et al., 2015; Busso and Fernandez, 2018), Chile (Fernández-Cirelli et al., 2009), China (Feng et al., 2015), the Middle East (Nielsen and Adriansen, 2005) and the USA (Reynolds et al., 2007). Arid areas are often under-valued, leading to failure to restore mining and other damage, and deserts have been viewed as appropriate places for military training (Gilewitch et al., 2014) and storage of nuclear waste because human population densities are low (Westermann, 2020). Currently, development impacts in these fragile and damaged regions are rapidly increasing with the growing demand for low carbon energy generated by sun and wind (Hernandez et al., 2014) and rare minerals such as lithium for energy storage (Wagner, 2011). Given the low productivity of arid areas, vegetation is very slow to recover from damage or clearing, and restoration to enable sustainable use and retain biodiversity is a considerable challenge (Shackelford et al., 2021).

The Karoo region of southern Africa is an arid to semi-arid region originally occupied by nomadic people, damaged and altered by colonialism between the 18th and 20th C., and which is now increasingly the focus of energy, mining and tourism developments. Although population

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density is low there are high levels of unemployment and poverty in the region. The Karoo extends across one third of South Africa and the southern part of Namibia, covering a total of 380,000 sq km. It comprises two biomes (Fig. 1), the biodiverse, succulent-dominated Succulent Karoo (104,000 sq km) in the lowlands, and the less diverse, grassy Nama Karoo (277,000 sq km) on the inland plateau (Mucina and Rutherford, 2006). Rainfall ranges from around 100 mm/yr in the west to 400 mm/yr in the east. Interannual rainfall variability is greater in the summer-rainfall Nama Karoo than in the more westerly winter-rainfall Succulent Karoo (Desmet and Cowling, 1999). The region is affected by El Ninõ/La Ninǎ rainfall cycles (Tyson, 1987) as well as longer wet and dry cycles lasting 20–50 years (Du Toit et al., 2018). The Succulent Karoo, although arid, has a fairly reliable winter rainfall and seldom experiences frost. It is thought that rainfall predictability associated with cold fronts, together with moderate winters (Desmet and Cowling, 1999) explains the extraordinary diversity of leaf succulents endemic to this biome (Cowling and Hilton-Taylor, 1999). The Nama Karoo, which occurs at higher altitudes, has a greater range of annual and diurnal temperatures as well as greater inter-annual rainfall variability and non-seasonal to summer rainfall. This biome supports low shrublands with a grass component that oscillates with rainfall quantity and seasonality (O'Connor and Roux, 1995; Hoffman et al., 2019). The endemic fauna of the Karoo is arid-adapted and rich in reptiles and arachnids with few endemic mammals (Vernon, 1999). Large herbivores and their predators were largely nomadic, moving into the nutrient-rich grazing lands of Succulent and Nama Karoo after rain and returning to better watered areas or adjacent biomes during times of drought (Skead, 2011). Most of the avifauna of the Karoo biomes occurs in at least one other biome and only eight of the 160 South African endemic bird species are confined to the Karoo (Vernon, 1999).

Hominids have inhabited the Karoo region for more than a million years (Beaumont et al., 1995; Horwitz and Chazan, 2015). However, it would appear that people had little impact on this environment until around 250 years before present when European settlers arrived in the Karoo (Penn, 1986). A combination of population growth, cultural and technological change then drove massive changes in land cover, hydrology, sedimentology and biodiversity. The past decade has seen very rapid changes in land use in the Karoo and other arid regions of the world such as expansion of mining (Erickson et al., 2017; Pauw et al., 2018), fossil fuel extraction (Busso and Perez, 2018), and the installation of vast energy generation facilities (Komoto et al., 2009; Hernandez et al., 2014). These new developments are likely to exacerbate existing environmental damage caused by ranching. Where arid lands occur in poor countries with high population densities, failure to repair damage will negatively affect local livelihoods (UN, 2019), particularly under a scenario of climate change (Ripple et al., 2021).

This review synthesizes the literature on the cumulative effects of agricultural and other development impacts on cultures, biota, ecological processes and services, and the potential for restoration in dry lands, not only in the Karoo. In doing so, we address the effects of human activity on biodiversity and ecosystem functioning in the Karoo and the cumulative and accumulating impacts affecting ecosystem services. We also identify the priorities for research and capacity building in the field of ecological restoration in order to sustain livelihoods in the long term. Finally, we derive lessons from the Karoo for application to the restoration and sustainable management of other arid and semi-arid regions.

2. Environmental impacts of human activity in Karoo

The actions and decisions of land-users and policy makers largely determine the state of the environment through operations such as ploughing, grazing, mining, development of roads and industries (Wheeler et al., 2019), all of which affect production, regulating and cultural services. In the Karoo, where approximately 95 % of the land is privately owned (Walker et al., 2018), decisions by a single land user over a few decades may have long-term consequences for thousands of hectares of land. Particularly in arid systems, the effects of environmental alteration by overgrazing (Beinart, 2003; Seymour et al.;, 2010; Boardman et al., 2015), ploughing, dam building (Keay-Bright and Boardman, 2006), removals and additions of species and pathogens (Van Sittert, 1998, 2002a), erection of fences and other barriers (Dean et al., 2018), and the pollution of soil or water (Dennis and Dennis, 2013), may persist over decades or even centuries (Wiegand et al., 1995; Hoffman et al., 2007; Boardman et al., 2015). Depending on the resilience of the socioecological system (Vetter, 2009), climate change may exacerbate many of these other man-made environmental problems and have massive ecological, social and economic costs and making life more difficult for future generations.. The major impacts of the human activities on the fauna, vegetation and geohydrology and ecosystem services in the Karoo *sensu lato* are summarised in Table 1.

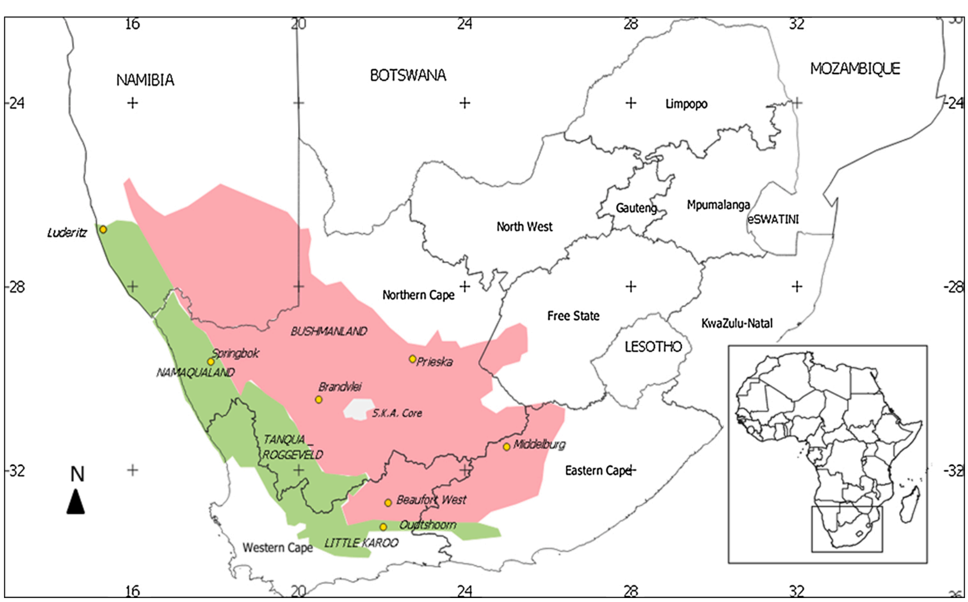

Fig. 1. Distribution of the Succulent Karoo (green) and Nama Karoo (pink) biomes within southern Africa. Also shown are names of Karoo regions mentioned in the text as well as the position of the Square Kilometre Array astronomy area (S.K.A. Core), and Karoo towns (yellow dots).

Table 1
Anthropogenic drivers of ecological change in the Karoo. Drivers are grouped into three time periods, namely (1) precolonial, (2) colonial and (3) current. The 2nd column lists human activities or drivers of change during that period. The 3rd column lists ecosystem goods and services affected by people, and the 4th column indicates the direction of change in goods and services. Sources of information are cited in the last column.

Time period	Anthropogenic drivers and ecological effects	Ecosystem goods and services affected	Trend	Information sources
1 > PRECOLONIAL 300,000–3,000 YBP Nomadic hunter-gatherers	1.01 Hunting of fauna, making of stone flake tools, small-scale us of plant resources for food, shelter, fire and poison	Fauna and flora local abundance	▼▲	Beaumont et al., 1995; Horwitz and Chazan, 2015; De Prada-Sampa, 2017
3000–400 YBP Local migrations (arrival of herders)	1.02 Herders compete with hunters for grazing, scars of kraals and settlements, deepening of water holes. Small scale soil erosion and deflation hollows.	Grazing resources (local scale) Soil stability (<1 ha)	▼ ▼	Smith, 1983; Deacon, 2014; Sampson, 1986
	2.01 Hunting and reduction of large predators and large herbivores Subsistence crop production ploughing of river terraces Introduction of small stock for meat and large stock for transport Introduction of human and ungulate diseases	Grazing resources Faunal diversity Soil stability Flood control	▼ ▼ ▼ ▼	Shaw, 1875; Acocks, 1953; Christopher, 1982; Guelke, 1976; Guelke and Shell, 1992; Van Sittert, 2004
	2.02 Hunting for cheap meat and to reduce wildlife competing with livestock for grazing. Most large wild herbivores eliminated from the Karoo by the early 1900s, Quagga *Equus quagga* extinct.	Faunal diversity	▼	Beinart, 1998; Skead, 2011; Dean and Roche, 2007
	2.03 Fencing terminated faunal migrations	Regulating services Cultural services	▼ ▼	Beinart, 2003; Dean, 2000; Dean and Roche, 2007
2> COLONIAL 1600–1994 European colonialism 1600–1800 AD 1800 –1930 YBP	2.04 Predator control caused local extinctions of large predators, and killed non-target species that control insects or generate germination microsites. Avian scavengers (vultures) locally exterminated or reduced Elimination of large predators leads to an increase in smaller predators changing the breeding success in ground birds	Predators Scavengers Ecosystem engineers Cultural services Disease regulation Avifauna Pest control	▼ ▼ ▼ ▼ ▼ ▼ ▼	Beinart, 1998; Macdonald, 1992; Van Sittert, 2016; Nattrass et al., 2017; Louw et al., 2017; Dean and Milton, 1991; Dean, 2000; Dean and Milton, 2004; Skead, 2007, 2011; SANParks, 2019; Lloyd, 2007
Settled farming Fencing technology	2.05 Cultivation of wheat and lucerne on pans and alluvial soils in the Succulent Karoo and Nama-Karoo	Biodiversity Soil stability Vegetation cover	▼ ▼ ▼	Angeler et al., 2008; Dean and Milton, 1995; Duthie et al., 1989; Hoffman et al., 2018
Global markets Ground water technology	2.06 Deep drilling for water led to a change from nomadic to settled livestock farming, which caused vegetation change and soil erosion.	Surface water Ground water and springs	▼ ▼	Archer, 2000; Boardman et al., 2017
Wool boom Ostrich feather boom	2.07 Overgrazing led to loss of vegetation cover, resulting in soil erosion, and siltation of dams.	Soil stability Landscape aesthetics	▼ ▼	Damm and Hagedorn, 2009; Snyman, 2000; Keay-Bright and Boardman, 2006
Civil war Wool boom	2.08 Overgrazing led to persistent vegetation change, and a decrease in ratio of palatable to unpalatable forage plants.	Grazing resources	▼	Dean and Macdonald, 1994; Milton and Hoffman, 1994, Milton et al., 1994, Hoffman and Ashwell, 2001; Seymour et al., 2010; Rutherford and Powrie, 2013
	2.09 Ostrich feather industry in the Little Karoo developed in response to European fashion markets. Resulted in trampling, overgrazing and soil erosion, degradation of region rich in endemic plants	Grazing Soil stability Landscape aesthetics	▼ ▼ ▼	Herling et al., 2009; O'Farrell et al., 2008
	2.10 Bare ground increases soil temperature and reduces infiltration, exacerbating droughts	Grazing resources	▼	Snyman and Van Rensburg, 1986; Snyman, 2000
	2.11 Import of horse feed during war brought weed species further spread by road and rail development	Crop production Wool production	▼ ▼	Van Sittert, 2000
	2.12 Alien forage plants introduced to (A)supplement grazing, (B) decorate gardens or (C) as sources of building materials led to thickets of alien invasive plants in water courses and rangeland (A) *Opuntia ficus-indica, Prosopis* spp., *Atriplex* spp., (B)*Tamarix ramossissima, Nerium oleander*, (C) *Arundo donax, Populus* spp.	Grazing resources Ground water availability	▼ ▼	Van Sittert, 2002a; Moran et al., 1993; Milton et al., 1999; Le Maitre et al., 2007; Milton and Dean, 2010; Shackleton et al., 2017
1930–1994	2.13 Government funded public works programmes including afforestation, irrigation schemes, soil erosion control and alien vegetation clearing to create rural employment during economic depression	Surface water, Soil stability	▼ ▲	Seekings, 2006
Recession, Apartheid, Economic incentives	2.14 Government funded fencing, predator control, locust spraying, no research on impacts on non-target species	Regulating services	▼	Coaton, 1962; Henschel, 2015; Dean and Williams, 2004; Brown, 1988
Public Works programmes	2.15 Government funded promotion of alien drought fodder crops	Biodiversity Groundwater Grazing	▼ ▼ ▼	Poynton, 1987; Milton et al., 1999; Moran et al., 1993; Shackleton et al., 2017
Mining Livestock reduction	2.16 Most mines remain unrehabilitated. Dust from exposed tailings, and slimes dams contaminate water	Grazing Aesthetics Biodiversity	▼ ▼ ▼	Desmet, 2013; Mhlongo et al., 2020; Van Rooyen et al., 2018; Erdogan et al., 2018
	2.17 Government subsidies and incentives to reduce livestock.	Grazing resources Soil stability	▲ ▲	Du Toit and O'Connor, 2014; Hoffman et al., 2019
3>CURRENT LAND USE Agricultural	3.01 Declining agricultural economy, job losses, grant dependency, demographic change, farm consolidation, land redistribution, stock theft increase, shift from	Aesthetics Biodiversity	▼ ▼ ▼	Jones and Inggs, 2003; Walker et al., 2018; Kirsten and Schöffman, 2020

(*continued on next page*)

Table 1 (*continued*)

Time period	Anthropogenic drivers and ecological effects	Ecosystem goods and services affected	Trend	Information sources
economy declines Tourism Game Farms	livestock to game, declining local food production, decreasing municipal service capacity, dependence on rangelands for fuel.	Grazing Carbon sequestration		
National parks expansion Globalisation Mining and fracking Renewable energy	3.02 Game farms, ecotourism roads, internet, life style farms, poor game management, electrified game fences, electrocution of tortoises, genetic pollution of game. Potential for privately-funded restoration of vegetation seldom realised.	Grazing resources Soil stability Biodiversity	▼▲ ▼▲ ▼▲	Conradie, 2019; Conradie et al., 2019a,b
Climate change Land restitution 2010 to future Risks to ecological infrastructure	3.03 Increased land under formal protection. Potential for restoration. More tourism facilities, roads and water extraction. Outcome will depend on management, which in turn depends on tourism revenue potentially reduced by global warming.	Water resources Vegetation cover Aesthetics Biodiversity Soil stability	▼ ▲ ▲ ▲ ▲▼	Ament et al., 2017; SANParks, 2019; Coldrey and Turpie, 2020; Toerien et al., 2016
Socio-economic risks	3.04 Big science: Square Kilometre Array radio telescope, landscape protection from grazing and water extraction, potential for restoration of vegetation through resting and alien clearing or bad management leading to overgrazing by game and further invasion of alien plants.	Grazing resources Soil stability Biodiversity	▲ ▲ ▲▼	Milton et al., 2021
	3.05 Potential miningwith more roads, roadkill, water extraction, water pollution vegetation damage, dust, overhead infrastructure.	Water quality Vegetation cover Aesthetics Biodiversity	▼ ▼ ▼ ▼	Crookes et al., 2013; Lee et al., 2019; Scholes et al., 2016; Stroebel et al., 2019
	3.06 Renewable energy installations, bats and large birds killed on powerlines and wind farms, more roads on steep slopes, vegetation clearing, alien invasive plants. Potential for land protection and rehabilitation within installation areas.	Aesthetics Biodiversity Soil stability	▼ ▼ ▼	Doty and Martin, 2012; Ralston Paton et al., 2017
	3.07 Increased atmospheric CO2, global warming, extreme drought, floods, heat waves, water shortages, vegetation change. Loss of biological crusts and soil stability, dust storms. Faunal species range contractions and extinctions.	Grazing resources Biodiversity Carbon sequestration Air quality Cultural services	▼ ▼ ▼ ▼ ▼	Ripple et al., 2021; Duniway et al., 2019; Erasmus et al., 2002; Kruger and Sekele, 2013; MacKellar et al., 2014; Stroebel et al., 2019; Van Wilgen and Herbst, 2017; Weber et al., 2018; Conradie et al., 2019a,b
	3.08 River flow reduction, reduced aquifer recharge, groundwater depletion, exacerbated by reduction in water resources through invasion by Prosopis and other alien plant species	Soil stability Water quantity and quality	▼ ▼	Shackleton et al., 2017
	3.09 Land redistribution to emerging and subsistence farmers. In the absence of extension officers and stocking rate control there is a high risk of livestock management mistakes and a repeat of the overgrazing problems of the 19th and 20th centuries. Reduced land suitability caused by climate change.	Grazing resources Biodiversity Carbon sequestration	▼ ▼ ▼	Conradie et al., 2019a,b; Walker et al., 2018
	3.10 A combination of ground water and natural resources dependence and high risk that climate change will reduce ground water and agricultural production, increased economic risk particularly in densely populated areas around towns. Revenue from tourism for protected areas may decrease.	Water quality and quantity Agricultural production Regulating services Cultural services	▼ ▼ ▼ ▼	Bourne et al., 2015; Van Wilgen and Herbst, 2017; Coldrey and Turpie, 2020

2.1. Pre-colonial land use

The effects of people on the Karoo landscape have changed and accumulated over time. Early and Middle Stone Age occupation appears to have been sparse, patchy and determined by the distribution of surface water and mammalian fauna (Beaumont et al., 1995). Variation in the abundance of archaeological artefacts that can be dated suggest that hunter-gatherers used the Central Karoo only intermittently during the mid-Holocene, but increased thereafter as temperatures cooled and rainfall increased (Deacon, 2014). They lived in small nomadic family groups without permanent settlements, moving within 'territories', repeatedly returning to waterholes, hunting lookouts and campsites over many generations, maintaining the sites by clearing vegetation and cleaning waterholes (De Prada-Sampa, 2017). This repeated use would explain why such sites remain visible in the landscape some 250 years after the San lifestyle ceased and their descendants became integrated into settler and Baster populations (Deacon, 1986). Their ecological footprint was small, and apart from some scars left at waterholes and paintings on the walls of rock shelters and etchings on boulders, their presence in the Karoo was hardly noticeable (Table 1,1.1). Indigenous pastoralists (Khoikhoin or Khoekhoen) arrived in South Africa about 3000 years ago (Table 1,1.2) and had a semi-nomadic lifestyle, moving livestock according to rainfall, and hunting and gathering natural resources (Klein, 1986; Deacon, 2014). Their ecological footprint was consequently larger, and the remains of settlement sites and kraals (corrals) can be clearly seen today as patches of bare ground and deflation hollows (Sampson, 1986). Transformation was not at landscape level and neither the San nor the Khoikhoin planted crops.

2.2. Colonial land use 18th C – mid 20th C

European settlers arrived in the Western Cape in the mid-1600s and gradually moved into the interior Karoo region (Table 1, 2.1), bringing with them Small Pox that decimated indigenous communities in the early 1700s making it easier for colonial settlers to occupy land (Hoffman et al., 2007). By 1760 much of the Karoo had been colonised (Guelke and Shell, 1992).These settlers displaced indigenous hunters and herders from their traditional land and access to water (Penn, 1986;

Hoffman and Rohde, 2007) eventually resulting in their incorporation as servants into European production-orientated farming systems that included subsistence crop production (Table 1, 2.1).

During the initial phases of colonial occupation of the Karoo, and concomitant with increasing numbers of livestock (Table 1, 2.02), large herbivores were shot for food, for 'sport' (MacKenzie, 1988), or because they competed with livestock for grazing (Acocks, 1979). The development of mining in the late 1800s and the civil war in 1899–1901, led to a large market for meat and this encouraged harvesting of game (Talbot, 1961). Springbok were probably the most abundant herbivores in the Karoo in precolonial times; the population fluctuated widely, probably in response to drought cycles and veld condition, and in some years thousands congregated and trekked across the region, and eventually ceased as a result of increases in livestock, fencing and hunting (Roche, 2004). By 1860, as a result of hunting and persecution, both quagga and lion had disappeared from the Cape Colony south of the Orange River (Bryden, 1889). Large herbivores including eland, hartebeest, mountain zebra and gemsbok had virtually been eliminated from the Karoo by the early 1900s, and one species, the Quagga *Equus quagga*, a Karoo endemic, had already gone extinct (Skead, 2007).

Accumulation of livestock by the settlers was rapid (Beinart, 1998). By the late 1700s, there was concern that livestock were transforming the environment, and by the late 1800s, the concerns that the natural capital of the Karoo was being eroded had become more serious (Shaw, 1875; Acocks, 1953, 1979; Macdonald, 1989; Archer, 2000; Beinart, 2003). Early colonial pastoralists managed their flocks by herding and enclosure of flocks in kraals at night. For several reasons, including the difficulty of managing large numbers of sheep on open range, the trampling in the kraals that caused soil erosion (Beinart, 2018), and the spread of contagious diseases among penned sheep, fencing of farms became a legal requirement (Van Sittert, 2002b). Fencing began in the late 1800s, and soon was widespread in Karoo districts (Archer, 2000) preventing any large scale nomadic movements of most of the remaining large herbivores (Table 1, 2.03).

Predator control in Karoo areas (Table 1, 2.04) began with settled livestock farming (Beinart, 1998); Van Sittert, 2016). In 1814, a bounty system was introduced to encourage predator control and promote the growth of the wool industry. This was phased out in the late 1950s, and the government assisted by training farmers to control predators, through the use of hunting dogs, baited traps and poisons that killed many non-target species including vultures, bat-eared foxes and monitor lizards (Nattrass et al., 2017). The present rarity and disappearance of some of the avian scavengers from the Karoo was caused not only by the loss of large predators that left the uneaten remains of prey for scavengers, but also by poisoning (Table 1, 2.04). Locusts, termites and caterpillars were viewed as competitors for grazing in Karoo rangelands and were controlled in the 1930s with arsenic baits (Mally, 1923; Price and Brown, 1999), and from the 1940s to the 1980s with organochlorines and organophosphates and later with pyrethroids (Brown, 1988), sometimes in large quantities (Henschel, 2015), despite the mortality of non-target invertebrates and their predators such as birds and concern over the persistence of the poisons.

The early European settlers needed wheat, so most arable land (Table 1, 2.05), which is largely confined to river terraces, was cultivated (Van Sittert, 2004) and rivers or runoff water diverted for irrigation (Acocks, 1976; Denison and Wotshela, 2009). Threshing floors and stone-built grain silos dating from the 19th C are still visible on Karoo river terraces (Keay-Bright and Boardman, 2006; Boardman et al., 2017). The introduction of deep drilling technology and pumps (Table 1, 2.06), that gave access to aquifers and other ground water sources (Talbot, 1961; Archer, 2000; Van Sittert, 2004) led to further expansion of cultivation until the mid 20th C when >120 000 ha were under cultivation, and then declined until 2007 when <20 000 ha were cultivated (Hoffman et al., 2018). Cultivation on alluvium and colluvium caused massive soil erosion, siltation of dams (Keay-Bright and Boardman, 2006) and destruction of much of the alluvial habitat of the now Endangered Riverine Rabbit *Bunolagus monticularis* (Duthie et al., 1989; Macdonald, 1989). Species-poor vegetation and disturbance tolerant, generalist invertebrates dominated old lands for decades after abandonment (Dean and Milton, 1995; Nchai, 2008). Ploughing of pans in the Bushmanland area of the Northern Cape destroyed habitat for ephemeral invertebrates such as the brachiopod crustaceans (Angeler et al., 2008), a primary food source for nomadic water birds (De Necker et al., 2016; Dube et al., 2020).

The management of livestock and the rangelands was not based on prescribed grazing systems, and the numbers of livestock on the land was always high (Talbot, 1961). About 1.5 million sheep, mainly Merinos, but also fat-tailed sheep, were present in the Karoo in the early 1800s, rising over the next 100 years or so to 23 million sheep in 1930 (Beinart, 2018). Mules and oxen for transport of goods, and horses for personal transport further depleted the available grazing (Table 1, 2.01, 2.07). This early overgrazing led to the near extinction of indigenous ryegrass (*Secale africanum*) in the Roggeveld and Tanqua Karoo (Raimondo et al., 2008), and to the decimation of a shrub (*Cliffortia arborea*) preferred as firewood (Oliver and Fellingham, 1994). The potential for exporting wool to Europe and the rising wool price from the 1830s to 1880 (Table 1, 2.07, 2.08), provided an incentive to livestock farmers in the inland part of the Karoo to maintain large flocks (Beinart, 2003). Another wool boom in the 1950s provided a new incentive for over-stocking and by the 1950s there had been major shifts in the plant species composition and a reduction in cover in Karoo shrublands (Acocks, 1953).

The ostrich feather industry (Table 1, 2.09), largely confined to the Little Karoo, developed in the 1800s in response to lucrative European fashion markets (Herling et al., 2009; O'Farrell et al., 2008) and ostrich numbers soared in the late 1900s and first decade of the 21st C in response to the global demand for ostrich meat and leather. Stocking of ostriches at unsustainable densities has resulted in vegetation change, cover loss and accelerated soil erosion throughout the Little Karoo (Wheeler et al., 2015), such that 24 % of the area is now considered as severely degraded (Thompson et al., 2009). In the north-western Karoo (Namaqualand), about half the population of 60,000 people live in 14, 000 sq. km. of communal reserves established in the early 19th C to protect indigenous people from dispossession by colonial farmers (Hoffman et al., 2007). Inhabitants keep some livestock as part of a mixed livelihood strategy and as a result of overcrowding, communal rangelands tend to be overgrazed (Todd and Hoffman, 2009).

Grazing value and animal production has declined in the Karoo since early colonial times (Table 1, 2.08). Since overgrazing keeps palatable plants small and reduces their seeding, but has little effect on the competitive abilities or seed outputs of unpalatable or toxic plant species (Milton and Dean, 1990; Todd and Hoffman, 2009), the less palatable species are more likely to succeed in the rare event of a sequence of favourable rainfall events (Wiegand et al., 1995). Summer grazing favours shrubs over grasses (Van der Walt, 1971; O'Connor and Roux, 1995; Du Toit et al., 2018), and in winter-rainfall Karoo, continuous grazing favours annuals and geophytes over long-lived shrubs (Todd and Hoffman, 2009). Grazing-induced changes in vegetation, often in combination with drought or burning, may be fast or slow to manifest themselves (Vetter, 2009; Fleury et al., 2020), but recovery of the long-lived, palatable plants is generally slow (Milton et al., 1997; Van der Merwe and Milton, 2019) and once established the unpalatable shrub species may persist for many decades (Wiegand and Milton, 1996; Van der Merwe and Milton, 2019). Reduction of vegetation cover increases soil temperatures (Snyman, 2000) and accelerates rainwater runoff (Snyman and Van Rensburg, 1986; Boardman et al., 2015), causing aridification, soil erosion and gully formation, which may take more than one farming generation to become obvious (Boardman et al., 2010; Table 1, 2.10).

Vegetation change caused by over-grazing (Milton et al., 1994; Milton and Hoffman, 1994) decreases diversity in invertebrate communities (Seymour and Dean, 1999) including assemblages of cicadas

(Homoptera: Cicadidae) (Milton and Dean, 1992), grasshoppers (Bekele, 2001), ants (Hymenoptera: Formicidae) (Milton and Dean, 1993) and spiders (Henschel and Lubin, 2018). Reduction in vegetation cover changes the species diversity and abundance of birds (Dean et al., 1995) because there are less suitable nest sites, less food for the insectivorous birds (Dean and Milton, 1995; Seymour and Dean, 1999) and more food at times for granivorous birds (Dean, 2004) due to dominance of plant communities by annual and ephemeral species that produce abundant seed in some years (Dean and Milton, 2001).

Invasive alien plants that now pose a threat to grazing and water resources in the Karoo were introduced in the 1800s and 1900s, either accidentally (Table 1, 2.11) or with the intention of improving forage resources in the depleted rangelands and during droughts (Table 1, 2.10, 2.15). Agronomic weeds introduced with animal feed include *Xanthium spinosum* and *Argemone mexicana* which then spread onto disturbed land (Van Sittert, 2000). Prickly pear (*Opuntia ficus-indica*) from the Americas, established as living fences, or drought feed for cattle, was considered a threat to the farming economy by 1880 (Van Sittert, 2002a) and by the 1930s had invaded 900,000 ha, reducing grazing value of the land and precluding access by livestock. Chemical control (Mally, 1923; Van der Merwe, 1930) had limited success, but biocontrol eventually achieved 90 % control of this weed between 1932 and 1970 (Annecke and Moran, 1978). American tree legumes (mainly *Prosopis* sp) were introduced for fodder and firewood, then became invasive after inter-specific hybridization some 60 years later (Moran et al., 1993), spreading 3.5–18 % per annum (Wise et al., 2011). Although the trees provide some benefits, the costs of the invasions, in terms of shading out grazing and water use on shallow aquifers, exceed the benefits, particularly in floodplains (Wise et al., 2011). Additional agricultural escapees are Australian forage plants in the genus *Atriplex* (Milton et al., 1999) and North African fountain grass *Pennisetum setaceum* (Rahlao et al., 2014).

The decline in condition of Karoo grazing land was exacerbated by the droughts in the 1930s and 1960s, leading to the development of government incentives to boost the economy with public works programmes that included erosion control, weed control and dam building (Table 1, 2.13). The government subsidised locust spraying and predator control (Table 1, 2.14) and sponsored widespread introductions of drought fodder crops (Table 1, 2.15) that probably had negative rather than positive effects on ecosystem services, as did the lack of rehabilitation requirements for mining for diamonds, asbestos and heavy metals (Table 1, 2.16). Livestock numbers declined after the 1950s in response to a combination of land degradation, government incentives and interventions to improve management, such as a free agricultural advisory service, and changes in demand (Dean and Macdonald, 1994; Hoffman et al., 2018). Reduced stocking rates and rotational grazing systems (Du Toit, 1923; Hoffman and Ashwell, 2001) initiated recovery in rangeland productivity and reduced soil erosion (Table 1, 2.17).

2.3. Current land use late 20th C to early 21st C

The economy of South Africa declined towards the end of the apartheid period (1980s) as a result of international sanctions and social unrest (Jones and Inggs, 2003). Economic decline continued after apartheid ended (1994) as a result of rapid population growth that flooded the job market with people poorly educated under apartheid education policies. Labour laws introduced by the new ANC government reduced the profitability of farming and small businesses (Jones and Inggs, 2003), and government support for agricultural research and extension to commercial farmers was greatly reduced (Davis and Terblanche, 2016). The result was loss of banks and agricultural service industries in small Karoo towns, job losses, crime and a wide range of other poverty-linked social problems including use of recreational drugs and the spread of HIV-AIDS (Table 1, 3.01). Economic problems in Karoo rural areas were exacerbated during the global recession that started in 2008, and again during the pandemic of 2020−2021.

The combination of economic, political (Brandt and Spierenburg, 2014; Snijders, 2015; Manyani, 2020) and climatic (B. Conradie et al., 2019; S.R. Conradie et al., 2019) changes in the late 20th C resulted in conversion of about 20 % of Karoo farms from stock farming to game farming (Beinart, 2018). During the early 2000s more than half the purchases of farms in the Central Karoo extensive farming area were for lifestyle reasons (Table 1, 3.02) rather than for production of fibre or meat (Reed and Kleynhans, 2009). Game farming may offer a better economic return where landowners combine trophy hunting, game lodges and ecotourism (Snijders, 2015; Van der Merwe and Saayman, 2003). Income from hunting is an incentive for the introduction of extra-limital species, however, which landowners believe attract more tourists and hunters (Smith and Wilson, 2002). Game farming is no more or less sustainable than other forms of livestock ranching in the Karoo (Manyani, 2020), but game is more difficult to manage than domestic livestock (Carruthers, 2008; Snijders, 2015). Early concerns about overgrazing on game farms (Jooste, 1983) seem justified almost 40 years later, and many game farms are degraded by a combination of overstocking and lack of rotational grazing (Cowell and Ferreira, 2015). Game farms blend seamlessly into lifestyle farms and private nature reserves where tax benefits may accrue to landowners who protect poorly conserved vegetation types, habitats and species (Paterson, 2005; Van Wyk, 2010). The possibility of working remotely makes rural life more appealing; and crime makes city life less comfortable, resulting in movement of wealthy professionals to rural areas (Snijders, 2015) a trend apparently increased by the Covid pandemic. A combination of rising labour prices, declining veld productivity and increased predation has reduced farm efficiency in the past decade (Conradie, 2019; B. Conradie et al., 2019; S.R. Conradie et al., 2019) and increased the sale of marginal commercial farms to those whose income is not dependent on farming (Reed and Kleynhans, 2009; Conradie et al., 2019a,b). The danger of lifestyle farming to the environment lies in the lack of management of herbivore densities and consequent overgrazing (Hyvärinen et al., 2019).

National and Provincial protected areas have greatly expanded over the past 20 years (Table 1, 3.03); to meet national biodiversity targets and contribute to the state agenda for socio-economic transformation that highlights job creation and rural development driven mainly by tourism (SANParks, 2019). Many of the parks include privately-owned contractual parks that may be overstocked or include extra-limital herbivores (Cowell and Ferreira, 2015) but some have made a substantial contribution to biodiversity conservation by linking fragmented formal conservation areas. Land reform could reverse recent gains in biodiversity conservation if these areas revert to commercial or subsistence livestock farms (Seymour et al., 2020). The Meerkat National Park was proclaimed in 2020 in the Northern Cape primarily as a buffer around the international Square Kilometer Array (Table 1, 3.04), and will differ from all other parks in that wildlife will not be reintroduced and no tourists will be allowed. In addition to National Parks there are a number of Provincial Nature Reserves that aim to protect habitats for endemic flora and fauna. All of these protected areas were once livestock farms (Van Wilgen and Herbst, 2017) and include areas of degraded vegetation. All are fenced and therefore require some form of herbivore management including culling and predator reintroductions to prevent overgrazing. They require revenue for management, so there are trade-offs between maintaining fauna for tourist enjoyment and protection of habitats (Cowell and Ferreira, 2015).

Fencing that encloses game farms, lifestyle farms and protected areas is usually high, often incorporating mesh or electrified strands (Beck, 2010; Macray, 2017) that restrict movement of most larger animals, leading, in drought years, to local over-exploitation of food and subsequent damage to vegetation (Ben-Shahar, 1993; Archer, 2000; Woodroffe et al., 2014). Fences have fragmented the Karoo, preventing nomadism, disrupting seed dispersal, increasing risk of local extinction, causing mortality through collisions with fences, and decreasing habitat quality through overgrazing (Ben-Shahar, 1993; Boone and Hobbs, 2004; Hayward and Kerley, 2009; Seymour et al., 2020). Mesh fences and electrified fences are lethal for small mammals and reptiles, particularly chelonians, that can get lodged between the lowest strand and the ground (Burger and Branch, 1994; Beck, 2010; Macray, 2017; Dean et al., 2018; Holt et al., 2021).

Mining in the Karoo takes the form of extensive open cast excavations for mineral sands, alluvial diamonds, gypsum and asbestos, and below-ground mining for heavy metals and uranium (Table 1, 3.05). Below-ground mining has a smaller footprint but destroys specialised plant communities as well as leaving toxic tailings and slimes dams that threaten local water supplies (Desmet, 2013). Shale gas extraction (fracking) has potential to contaminate ground and surface water (Scholes et al., 2016; Stroebel et al., 2019). The direct effects of mining in arid areas generally includes local destruction of vegetation, loss of fauna, alteration of soil structure, extraction and pollution of ground or surface water, alteration of the view and sense of place, as well as adverse effects of dust or fumes on crops and people in surrounding areas (Scholes et al., 2016). Storage of polluted water has the potential to be hazardous for wildlife such as arid zone birds dependent on surface water for drinking (Lee et al., 2019).

Renewable energy infrastructure (Table 1, 3.06), namely of solar and wind farms with new roads and powerlines, has expanded rapidly in the Karoo over the past decade. Wind turbines are widely spaced and their installation does not usually require total clearing of vegetation, access roads on hill tops are needed for their erection and maintenance, and turbine blades are hazardous to bats (Doty and Martin, 2012) and large birds (Ralston Paton et al., 2017). With solar infrastructure, comprising large photovoltaic panels, natural vegetation is sometimes cleared, but is generally left relatively undisturbed. However, the panels alter the distribution of sunlight and water, thereby changing the composition of the vegetation and favouring the establishment of invasive alien plants and agricultural weeds (Tanner et al., 2020). The effects of altered microsites and vegetation management between panels may be particularly disadvantageous to succulents in arid areas (Grodsky and Hernandez, 2020).

The hottest years on record globally occurred between 2015 and 2020 and despite the global lockdown and reduction of travel caused by the Covid pandemic in 2020, atmospheric concentrations of carbon dioxide (CO^2) reached a record high in September 2020 (Ripple et al., 2021). Global climate change (Table 1, 3.07) is apparently exacerbating the effects of El Niño events during the austral summer in many regions but most notably in the northern and central interior of South Africa. The average maximum daily temperatures were respectively 1.1 °C and 0.73 °C, higher in 1979–2016 than they were in 1940–1978 (Lakhraj-Govender and Grab, 2019).) Increases in high temperatures and decreases in cold spells are most marked in the central inland area of the Karoo (Kruger and Sekele, 2013). Increases in daily temperature have taken place over the past 20 years (MacKellar et al., 2014). Even without a decline in rainfall, the increased evapotranspiration resulting from higher temperatures is likely to increase the frequency and severity of drought (Vicente-Serrano et al., 2010). Climate change damages biological crusts that stabilise soils, absorb water and fix nitrogen, particularly in the winter rainfall Succulent Karoo, and this will have potentially adverse effects on soil stability and fertility (Weber et al., 2018). Global warming is likely to have a major impact on the fauna (Cunningham et al., 2021). Models of distribution ranges under a scenario of a 2 °C temperature increase resulted in range contractions for 78 % of species, as well as range changes and extinctions (Erasmus et al., 2002). Conradie et al. (2019a,b) predict that higher temperatures will reduce the reproductive outputs of arid zone birds eventually leading to species losses.

Surface water bodies have decreased in area throughout South African over the past 20–30 years (Van Deventer, 2021) and surface flow and the rate of recharge of aquifers in the Karoo are predicted to decline under climate change (Stroebel et al., 2019) which will reduce water supply for most Karoo towns and farms (Table 1, 3.08). Maintaining water supplies will become more costly because deeper boreholes will be needed, causing salinity to increase. Increasing droughts and floods will also accelerate soil erosion and have potential to pollute ground water (Dennis and Dennis, 2013). Higher temperatures that exacerbate the effects of drought on rangeland, are thought to be one of the major drivers of the shift from commercial livestock farming to game and lifestyle farming that is currently taking place in the Karoo (Conradie, 2019). Agriculturally unproductive farms, such as lifestyle farms in marginal farming areas, will have a greater probability of being expropriated without compensation under new legislation designed to accelerate land reform (Conradie et al., 2019a,b). Although this would be a cost effective way of meeting target numbers of land beneficiaries in the short term (Table 1, 3.09), these emerging farmers might fail or become permanently dependent on drought relief funds because of climate change (Conradie et al., 2019a,b).

Effects of climate change on vegetation and water supplies in the Karoo will also influence social security and the viability of villages and protected areas (Table 1, 3.10). Depending on the degree of warming, large parts of Nama Karoo could become desert (Van Wilgen and Herbst, 2017). Villages in marginal farming areas could face increasing poverty and water shortages (Bourne et al., 2015). The discomfort and danger caused by heat and flooding might make the region less attractive for lifestyle farming and for tourism (Coldrey and Turpie, 2020). Warming associated with climate change is expected to reduce tourism in the summer months in six of the 19 National Parks in South Africa, including three parks in the Karoo (Coldrey and Turpie, 2020). Moreover a desire to reduce the carbon footprint of travel may decrease conservation tourism (Seymour et al., 2020), diminishing revenue available for park management (Van Wilgen and Herbst, 2017).

3. Recuperation and restoration

Climate change and new forms of land use in the Karoo are superimposed on older, unhealed damage causing overgrazing, faunal decimation and alien plant invasion. These impacts accumulate over time as a result of aridity, low productivity, and slow recovery rates. The accumulation of impacts (Fig. 2) is likely to have a cumulative effect because past and present impacts interact. For example, overgrazing causes soil erosion which silts rivers, facilitating invasion by alien plants (Le Maitre et al., 2007). Cars using roads that intercept patches of invasive alien plants may transport seed (Rahlao et al., 2010) that can establish in the competition-free road verges and adjacent disturbed areas (Milton and Dean, 1998). The risks to biodiversity, ecosystem services, the economy and human welfare in the agriculturally marginal Karoo will increase (Bourne et al., 2015) if the temperature continues rise as it has done over the past 40 years (Jury, 2018), droughts become more frequent (Otto et al., 2018), water sources decrease (Van Deventer, 2021) and the human population maintains its current rapid growth rate (Jones and Inggs, 2003). The combined and interacting impacts (Fig. 2) can reduce the diversity and the flow of services (Table 1) provided by Karoo ecosystems. Understanding how ecosystems services are affected by human activities can provide a framework for planning and implementation of mitigation and restoration under a scenario of climate change that includes ongoing warming and intense but less frequent rainfall.

Ecological restoration, embracing damage mitigation, recovery through better land management, rehabilitation of essential ecosystem services and return to a near natural state, is now being recognised as essential for sustaining social-ecological systems (Ziervogel et al., 2014; UN, 2019), and is particularly necessary in arid lands such as the Karoo (Table 2). A paradigm shift in government, industry and the public will be needed to support and value these activities (Aronson et al., 2017).

3.1. Policy and organisations driving restoration projects in the Karoo

The benefits to society of maintaining and restoring natural capital and ecosystem services are many, but inadequately quantified or valued (Farley and Brown Gaddis, 2007). The rate of recovery and the costs of restoration are far higher in arid than in mesic areas and greatly exceed land values (Crookes et al., 2013). Despite this, there are large and small scale restoration initiatives in the Karoo driven by national legislation, public works programmes, non-profit organisations, businesses, payments for ecosystems services and individual initiatives.

3.1.1. National legislation

The numerous unrehabilitated mines in the Karoo (Cornelissen et al., 2019)), vast areas invaded by alien plants (Wise et al., 2011; Shackleton et al., 2017) or left cleared, eroded and overgrazed (Keay-Bright and Boardman, 2006; Hoffman et al., 2018) attest to the need for national environmental policy that enforces damage limitation and ecological restoration, particularly in arid areas where restoration benefits may not be cost effective within a human lifetime (Blignaut et al., 2010; Crookes et al., 2013). Since 1998, restoration of areas cleared or damaged by mining and other activities, has been required by law in South Africa. The National Environmental Management Act (NEMA Act 107 of 1998) seeks to make development socially, environmentally and economically sustainable, requiring that the costs of environmental damage are borne by the developer. Moreover the Act endeavours to limit damage, particularly in areas mapped as Critical Biodiversity Areas, Ecological Support Areas and Freshwater Protection areas (SANBI, 2017) by requiring a basic ecological assessment report and management plan before development can proceed. The developer, whether a crop farmer, miner, road builder, renewable energy company or waste management operator, needs to demonstrate that the activity will be sustainable, or if unsustainable as in the case of a mining operation, how damage will be mitigated and the land restored to its former capacity. For large development projects there is a requirement for public participation and access to all impact assessment reports (see for example NRF and SARAO, 2018). For phased developments such as extending surface mining, permission to proceed is dependent on the progress of on-going restoration described in management plans (Minerals and Petroleum Resources Development Act 28 of 2002). The enforcement of this legislation has resulted in large-scale restoration work on phosphate, diamond and mineral sands surface mines in the Namaqualand area of the Succulent Karoo (Carrick and Kruger, 2007; Van Eeden et al., 2007; Pauw et al., 2018). Enforcement of the Ecological Reserve concept in the National Water Act (Table 2, row 1) might similarly ensure persistence of riparian ecosystems currently threatened by water extraction.

3.1.2. Public works programmes

The Working for Water (WfW) Programme is a long-standing public works programme that aims to build capacity and create jobs through the clearing of invasive alien vegetation to protect freshwater catchment areas and biodiversity (Turpie et al., 2008). Within the Karoo the efforts of the WfW have focussed on the control of deep-rooted *Prosopis* sp. that threaten ground water security. In the Northern Cape Province alone there are 167,000 ha of dense stands of this tree using 2800 m^3 of water/ha/year, *ca* 20 % of the annual rainfall (Versfeld et al., 1998; Dzikiti et al., 2018). The Extended Public Works Programme (EPWP) designed to provide income through temporary work for the unemployed to carry out socially useful activities has not been as successful as it could have been, possibly because of inadequate supervision and the short-term contracts (Maphanga and Mazenda, 2019). Projects are usually managed by the National Parks, Departments of Agriculture, Water Affairs and Sanitation or by local Municipalities that usually outsource them to contractors. Projects have included ecological infrastructure projects (Table 2, row.2) such as extensive rangeland rehabilitation and soil erosion control works in the Camdeboo, Karoo, Mokala and Tankwa National Parks (EPWP, 2006; SANParks, 2015) as well as a number of erosion control and alien clearing projects in Namaqualand managed collaboratively by Conservation South Africa, Working for Water and SANParks (https://mbgecologicalrestoration.wordpress.com/tag/namaqualand/).

3.1.3. Business and science ventures

Payments for ecosystems services such as carbon sequestration and water production have potential to drive restoration; however, in the arid lands this is currently limited by high costs and low vegetation productivity (Crookes et al., 2013). The restoration of *Portulacaria afra*, a large and relatively fast-growing, long-lived, evergreen, succulent shrub that can be established by truncheon cuttings, has potential for earning carbon credits (Table 2, row 3), and is currently the target of a number of nationally and internationally-funded projects in the eastern Cape and Little Karoo (Mills and Cowling, 2006; Mills et al., 2007, https://gouritz.com/portfolio/jobs-for-carbon/). The implementation of ecological restoration and the supply of resources such as knowledge, labour, seeds, plants and specialised equipment for such work, have potential to become business ventures and to generate employment in the Karoo (Table 2, row 3) as they are doing in Western Australia (Carrick et al., 2015). At present only two Karoo-based nursery businesses specialise in contract growing of Karoo plants and supply of regionally appropriate indigenous grass and shrub seed for Karoo restoration (Van Eeden et al., 2007; Brouwer, 2012) and a few specialist consulting businesses advise on indigenous game management in the area (Coetzee, 2005; Esler et al., 2006). However, the demand for advice and materials for ecological restoration is growing as owners of livestock and game ranches, lifestyle farms, retreats and private and provincial nature reserves seek to improve rangeland productivity or to make degraded environments more attractive for their clients (Esler et al., 2006; Felmore, 2019).

A landscape scale restoration plan would be needed to revitalise ecological processes such as large scale nomadic movements by herbivores, high herbivore diversity and fluctuations in abundance (Dean and Roche, 2007). This is probably beyond the scale of most National Parks and private game reserves. The cost of taking large areas out of agricultural production would be high and probably not substituted by ecotourism revenue because of limited water supplies and landscape fragility. The internationally-funded Square Kilometre Array radio telescope project that covers 1350 sq km in the Northern Cape offers potential for achieving such landscape-scale restoration because the land will be managed as a National Park that excludes visitors, however in addition to allowing for rewilding of a vast area, the roads and telescope infrastructure will cause intensive, local-scale damage (Van der Merwe et al., in press).

3.1.4. Non-profit and University-linked organisations

There are a number of international and national non-profit organisations (NPOs) that partner with university departments and government agencies such as South African National Biodiversity Institute (SANBI) and SANParks to fund and manage research and implement projects dealing with conservation and ecological restoration in the Karoo. The Critical Ecosystem Partnership Fund (CEPF) in collaboration with the World Wildlife Fund (WWF-SA) and Lesley Hill Succulent Karoo Trust, funded the establishment of the Succulent Karoo Ecosystem Programme (SKEP) in South Africa and Namibia. Managed in partnership with Conservation International and SANBI, this project is assessing risks to biodiversity in the Succulent Karoo (Table 2, row 4). The programme produced guidelines for restoration in the southern Namib Succulent Karoo (Burke, 2005) as well as funding the Namaqualand Restoration Initiative to develop regional protocols for ecological restoration required by mining operations and engaging the local community in restoration in the Central Namaqualand Coast and the Knersvlakte priority regions of the biodiverse Succulent Karoo. The project endeavoured to encourage mining operators and other land users to change the way they understood their responsibilities concerning biodiversity conservation and restoration (Table 2, row 5; Carrick, 2008). Students from a number of German and South African universities contributed to research on ecological restoration of degraded rangelands in southern Namibia and Namaqualand as part of the

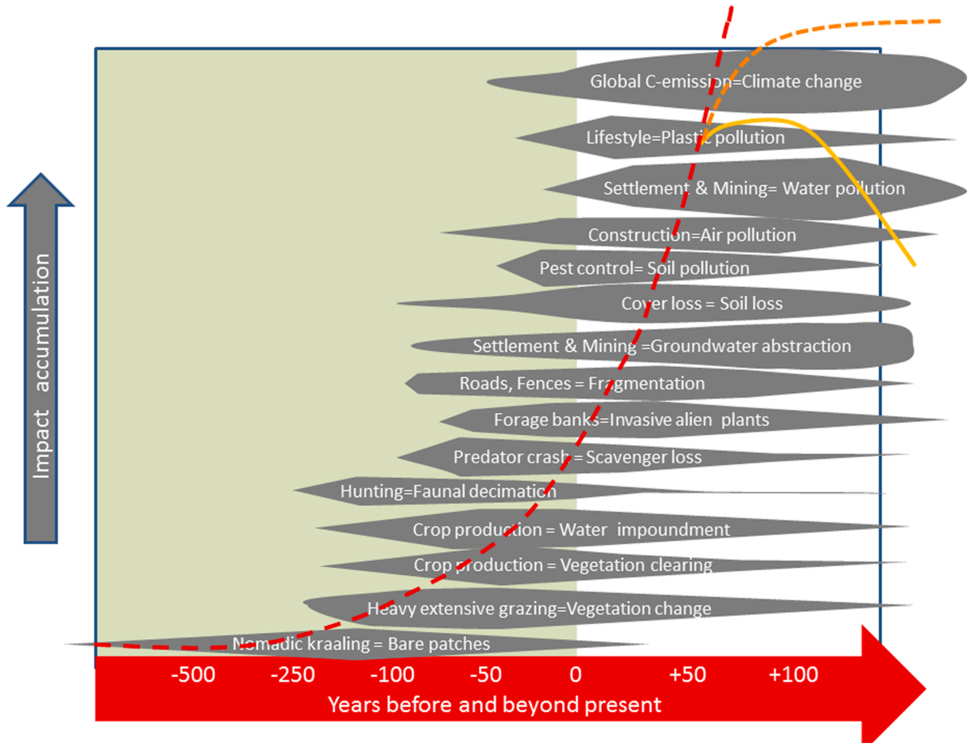

Fig. 2. Human activities have had diverse and cumulative impacts on biota, resources and physical processes in the Karoo over time. Some impacts are more persistent than others. The cumulative effects on ecosystem services may 'increase (red dash), stabilise (orange dash), decrease (yellow line)' over time.

Biota-Africa project that ran for 10 years funded by the German Ministry of Education and Research (BMBF), (Schmiedel and Jürgens, 2010; Hanke et al., 2015). This was succeeded by a programme focussing on climate change and adaptive management (Revermann et al., 2018).

In the Nama Karoo, the Drylands Conservation Programme of the Endangered Wildlife Trust is developing techniques for restoring the habitat of the Critically Endangered Riverine Rabbit and working with farmers to improve rangeland management and reduce the negative impact of predator control on wildlife (https://www.ewt.org.za/fs-july-2020-farming-for-the-future/). The Wilderness Foundation is carrying out restoration in privately-owned protected areas, such as Plains of Camdeboo in the eastern Karoo, as well as collaborating with WWF-SA to find new ways to fund conservation and restoration including tax incentives, offsets (money paid in compensation for damage done by development) and investment that can be used to fund natural resource management interventions (https://www.wildernessfoundation.co.za/projects/innovative-finance). Gouritz Cluster Biosphere Reserve that incorporates riparian corridors and the coastal, fynbos, Succulent and Nama Karoo ecosystems that they intersect, funds research and training for implementation of ecological restoration in all these habitats (https://gouritz.com/).

Decision support systems (e.g. EcoRestore) to assist in designing appropriate restoration approaches for Karoo areas are being developed by the North West University (https://www.ecorestore.co.za/), and the non-profit Asset Research (Blignaut and Aronson, 2020). In partnership with the South African Environment Observation Network *(SAEON)* and the Department of the Environment, Forestry and Fisheries, Asset Research has released interactive models to assess the likelihood for market investment in various ecological restoration projects (https://assetresearch.org.za/econrestoration/).

3.2. *Passive restoration: sustainable management practices*

Vegetation recovery from overgrazing, ploughing and clearing is most challenging under arid conditions where the annual rainfall is insufficient in most years for recruitment of new plants (Wiegand et al., 1995). The general improvement in cover and composition of Karoo veld over the past 50 years (Kraaij and Milton, 2006; Van der Merwe et al., 2018; Hoffman et al., 2018, 2019, 2020) suggests that the Karoo rangelands are recovering from early overgrazing; periods of above-average rainfall may be needed to facilitate this recovery (Hoffman et al., 2020; Saaed et al., 2020). Moreover, recovery of vegetation to the state where runoff and sediment loss is controlled is slow; even in the higher rainfall uplands of the Karoo where it is estimated to take a century or more (Boardman et al., 2010). Better management systems can reduce erosion rates but the positive effects of improved management could be offset by an increase in rainfall intensity that is predicted to be part of climate change (Boardman et al., 2010). Cover and some palatable plant species returned to Succulent Karoo areas that had been protected from grazing for 20 years (Seymour et al., 2010). At Carnarvon in the Nama Karoo, during 27 years of above average rainfall, vegetation cover increased from 25.2–31.4%, but the increase was suppressed at higher stocking rates (Van der Merwe et al., 2018). These long-term studies agree with modelling time scales for Karoo vegetation change (Wiegand and Milton, 1996) suggesting that decades are required for passive recovery of vegetation cover; species composition changes may take much longer without active interventions and adequate rainfall.

Cover of biological soil crusts, which contribute to water retention, flood control and maintenance of air and water quality as well as nitrogen fixation and carbon sequestration on fine soils, can regenerate within eight months on small-scale disturbances <1.0 m^2 (Dojani et al., 2011). However, the early successional crusts, that lack the texture and complexity of mature crusts, dominate disturbed patches for at least two years before colonisation by lichens and mosses begin. Extensive damage to biological crusts by land use that disturbs the soil will require active restoration to prevent soil erosion and fertility loss, particularly under a scenario of continued global warming (Weber et al., 2018).

The benefits of passive restoration through resting the land from grazing, include reproduction of palatable plants, soil stabilization, improved water infiltration and carbon sequestration, but are slow to

Table 2
Restoring resilience in the Karoo socio-ecological systems.

Anthropogenic drivers	Ecosystem good and Services affected	Trend	Information sources
1 Enforcement of environmental, water and agricultural legislation to prevent further land clearing, implement ecological reserve to maintain aquatic systems, sort waste to recycle as much as possible and minimise pollution and carbon emissions	Biodiversity Carbon sequestration Water quality	▲ ▲ ▲	Mander et al., 2017;' Shippey et al., 2018; Bourne et al., 2015
2 National job creation initiatives in rural areas including improved waste sorting, recycling, composting, investments in ecological infrastructure to manage land and water sustainably: control of invasive riparian plants, protect altitudinal gradients, alien clearing, erosion control (management dependent)	Water quality Aesthetics Air quality	▲ ▲ ▲	Western Cape Treasury, 2020
3 Government facilitated small business initiatives removing waste from roadsides combined with seed collection, seed banking and seed industry serving mining, renewable energy and engineering restoration needs (management dependent)	Biodiversity Carbon sequestration Air quality	▲ ▲ ▲	Putative
4 NGO and privately-funded small-scale rewilding, restoration and alien clearing, restoration business opportunities, citizen science monitoring (management dependent)	Biodiversity	▲	Putative
5 Changes in behaviour and values including limitations of travel, revised interest in local food production, emigration from cities, revival of small-town economies, improved pollution and waste disposal problems, family planning, social responsibility. (management dependent)	Carbon sequestration Air and water quality	▲▼ ▲▼	Rogers, 2020

The 1st column describes restoration activities required to reverse damage to karoo socio-ecological ecosystems, the 2nd column lists ecosystem goods and services affected by people, and the 3rd column indicates the direction of change in goods and services. Sources of evidence, where available, are cited in the last column.

manifest themselves and do not always benefit the current landowner who bears the cost of lost production. For this reason, improved land management will probably only be achieved through a combination of state, industry and non-profit interventions (Table 2, rows 2, to 4). The state is able to prepare and implement biodiversity and land use planning (SANBI, 2016), provide incentives through tax relief (Van Wyk, 2010) or payments for ecological services (Turpie et al., 2008), and disincentives such as fines for unsanctioned vegetation clearing (NEMA Act 107 of 1998). The carrying capacity of land allocated as part of restitution should be assessed and agricultural extension officers appointed to assist inexperienced farmers (Davis and Terblanche, 2016), and monitor vegetation condition. In addition to state funded extension services, industry incentives for sustainable management through certification of meat and fibre products and provision of standards and best practice guidelines (Todd et al., 2009; Cape Wools, 2020) can contribute to better land management, as does training, research and information offered by a number of non-profit organisations. The "Fairgame" initiative uses upmarket consumer preferences for ethically-produced meat to subsidise the costs of herding and kraaling (McManus et al., 2018), rather than using fencing and predator control to manage grazing resources and protect livestock (Anon, 2018), so predators, such as jackals and leopards, and the services they provide, can co-exist with livestock farmers in rangelands (www.fairgame.org.za).

3.3. Active ecological restoration interventions

The environmental diversity of the dryland Karoo means that no single suite of restoration interventions can be recommended for the whole region, or every degraded situation. Where both the physical environment and the living component has been damaged or lost, as in the case of mining, both abiotic and biotic barriers to recovery of functional ecosystems will need to be considered when planning restoration (Milton et al., 1994; Aronson et al., 2017). Most arid land restoration interventions have, in common, the need to capture and retain water, organic matter and propagules (Milton, 2001) and to restore at least productivity and regulating services to the landscape, but others require species additions of indigenous species or removals of invasive alien species.

3.3.1. Mine site restoration

Environmental damage caused by surface mining (Mhlongo et al., 2020), deposition of subsurface tailings and roadmaking involves removal of vegetation and removal, or chemical and physical alteration, of topsoil. All the barriers to recovery of functional ecosystems therefore need to be considered when planning restoration (Aronson et al., 2017). Salvage of plants, seeds, bulbs and other organic components of a mining or construction site should be the first priority before development begins (Milton, 2001). Where the site to be developed has been invaded by alien vegetation, there may be few if any indigenous plants to salvage, but cut brush can be stored and used for protection of restoration sites (Van Eeden et al., 2007). Most restoration plans require removal and storage of topsoil prior to mining or construction, so the return of topsoil to a site facilitates vegetation establishment (Carrick and Kruger, 2007; Burke, 2008). Where rocky ground is mined, or tailings from deep mines need to be revegetated, available substrates need to be amended with organic matter and slopes should be angled to optimise soil stability (Liebenberg et al., 2013). Mixing of subsoil and topsoil, or topsoil storage for many years, limits the potential of salvaged soil for returning microbes and propagules to the site (Van Eeden et al., 2007). In coastal areas, landscaping and use of nets, fences or brush packing to control wind and prevent soil movement may be required for establishment of vegetation (Carrick and Kruger, 2007). Surface heterogeneity needs to be re-established on reshaped landscapes to provide diverse microsites that contribute eventually to diverse vegetation (Milton, 2001). Rocks and dead shrubs salvaged prior to mining can be reintroduced to protect emerging plants from wind and sun (Avis et al., 2014).

The pre-mining vegetation of extensive mining areas may not always be the ideal reference for restoring vegetation cover because of changes in the landscape and soil chemistry and texture after mining (Carrick and Kruger, 2007), and because the mining may have homogenised a number of habitat types and vegetation units. Nevertheless restoration should seek to establish indigenous and self-sustaining vegetation rather than non-indigenous species that may require irrigation, die out or form low-value, potentially invasive monocultures (Carrick and Kruger, 2007; Liebenberg et al., 2013). Restoration targets that specify only vegetation cover or a percentage of the original number of species on site are less useful than those that require the full complement of functional plant types to be re-introduced, for example geophytes, grasses, annuals, succulents, woody plants, and species producing nectar or berries that are food for various vertebrates and invertebrates. Topsoil is likely to return only short-lived plants to the mine site as most long-lived Karoo plants do not maintain soil-stored seed banks (Esler, 1999; De Villiers et al., 2001). Seeds and plants for reintroduction to mined areas should include those salvaged on site and maintained in an on-site nursery, nursery-propagated plants, and plants established from seeds collected, preferably, within the local area (Burke, 2005; Van Eeden et al., 2007).

Regardless of the investment in restoration of highly disturbed arid sites, biodiversity cannot be expected to recover within a few decades. Rehabilitation trials involving landscaping, topsoil addition, soil amendment, seeding and wind control were successful in establishing vegetation cover on an open cast sand mine in Namaqualand (Pauw et al., 2018) and on mine tailings slopes in Bushmanland (Liebenberg et al., 2013), but were unable to return species richness and diversity to reference levels within two to three decades.

3.3.2. *Restoration of abandoned fields and natural grazing land*

Rehabilitation following damage to natural vegetation by ploughing and grazing usually requires a combination of interventions to curtail soil erosion, improve water, organic matter and seed retention, protect sites from herbivory and alien vegetation, and to reintroduce plant species (Coetzee, 2005; Van den Berg and Kellner, 2005; Esler et al., 2006; Saayman and Botha, 2010). Patches of bare ground, sometimes extending over a hectare or more, develop in sites that were once ploughed for subsistence crops (Keay-Bright and Boardman, 2006), or else were trampled or overgrazed around water points or supplementary feeding areas, and may remain devoid of perennial vegetation for decades unless actively restored. The reasons that vegetation fails to recover spontaneously is that such areas shed or evaporate, rather than retaining, water, and wind erodes loose soil. The mainly wind-dispersed seeds of Karoo plants blow across such bare areas because there are no living or dead plants to trap seed or protect seedlings (Esler et al., 2006). Whereas lichen soil crusts recover within a year on small disturbances (<1 m^2) they do not do so on large disturbances (Dojani et al., 2011). The interventions used to revegetate bare areas all focus on resource retention, usually starting with control of soil erosion caused by rapid runoff of rain water (Coetzee, 2005). This may involve the reshaping of erosion gullies (dongas) and the reduction of the rate of runoff using a combination of gabions, geotextile fences and brush-packing (Coetzee, 2005; Esler et al., 2006). The next step is the retention of water achieved by hand or mechanically-dug hollows, with or without the addition of mulch, brush-packing and seeding (Matthee, 2015; Jackson, 2016). The use of mulch and added gypsum improves water infiltration (Beukes and Cowling, 2003) and reduces sealing of soil caused by dispersion of clay particles. The optimal depth for hollows appears to differ among soil types as seedlings drown in deep hollows on poorly-drained soil types (Snyman, 2003; Jackson, 2016), whereas very shallow hollows are rapidly filled by silt. Mulching retains moisture in the soil for longer, but when too densely applied reduces emergence of small seeds such as those of most succulents endemic to the Karoo (de Abreu, 2011). In denuded arid winter rainfall rangeland in Namaqualand, Hanke et al. (2015) found that application of manure mulch 30 mm thick and covering 90 % of the soil surface was as effective as translocation of mature plants in reducing soil erosion and establishing vegetation on bare ground, but manured patches were dominated by a dung-dispersed alien saltbush (*Atriplex semibaccata*). Brush packing and hollows also reduced soil erosion whereas fertiliser addition stimulated only growth of annual plants that died in dry years (Hanke et al., 2015). Ripping was generally more successful on sandy soils and produced a greater number and diversity of plants establishing from seed (Van der Merwe and Kellner, 1999). A combination of tilling, brush packing and seeding was more successful than single interventions in arid Nama Karoo ten years after treatment (Saayman and Botha, 2010), whereas merely adding seeds to degraded rangeland without surface preparation is generally unsuccessful (Snyman, 2003; Saayman and Botha, 2010).

Selective grazing, and perhaps ploughing, trampling or burning, sometimes leads to an increase in long-lived toxic or unpalatable shrubs as more palatable species decline (Wiegand and Milton, 1996). This problem is common in Succulent Karoo, and attempts to restore the palatable component of the vegetation by reseeding are generally unsuccessful because of competition for water from well-established shrubs (Milton, 1994). To increase the ratio of palatable to unpalatable shrubs it is necessary to reduce competition by partial clearing before reseeding (Milton, 1994; Saayman et al., 2009). Clearing or brush cutting alone does not lead to regeneration of forage plants because most long-lived shrubs in these ecosystems rely on frequent production of fresh seed, rather than long-lived seedbanks, for regeneration (Esler, 1999; Saayman et al., 2009). Restoration to return grazing value rangeland dominated by toxic plants is costly (about five times the cost of grazing land) and sometimes unsuccessful (Saayman et al., 2017). In arid event-driven ecosystems, disturbances such as unusually prolonged drought events that kill many long-lived shrubs may prove to be an opportunity for a change in state (Westoby et al., 1989; Milton and Hoffman, 1994); the ongoing drought (2015–2021) in large parts of the Karoo presents an opportunity for reseeding restoration to bring about positive change.

The timing, intensity, quantity and frequency of rainfall following restoration interventions largely determine the outcome of rehabilitation interventions (Beukes and Cowling, 2003; Snyman, 2003; Matthee, 2015; Bourne et al., 2017), but as rainfall patterns are unpredictable, sowing or planting more than once in regions where high rainfall seasons may be frequent is probably the best approach, but is costly. Herbivores can damage restoration efforts in their early stages (Van der Merwe and Kellner, 1999; de Abreu, 2011; Saayman and Botha, 2010; Matthee, 2015) and in most cases wild and domestic herbivores should be excluded for at least three years from sites where restoration interventions such as reseeding or replanting are being carried out.

3.3.3. *Alien invasive vegetation control restoration*

Clearing of invasive alien vegetation in the Karoo has been focussed on *Prosopis* species in valley bottoms and riparian areas, and mainly in the Prieska, Douglas, Hopetown, Van Wyksvlei, Britstown, Calvina, Williston and Beaufort West where deep-rooted phraeatophytes are depleting aquifers or are a threat to grazing land. Felling and stump painting with herbicide (Ndhlovu et al., 2011), is complemented by release of biocontrol agents including seed feeding and galling insects to reduce the rate of spread and regeneration of *Prosopis* (Zachariades et al., 2011). Felling and herbicide stump treatment is also used for control of two other problem plants in the Karoo, *Tamarix ramosissima* and *Nerium oleander* (Milton and Dean, 2010); follow-up clearing is recommended (Zachariades et al., 2011). Attempted control of dense stands of Spanish reed *Arondo donax* that have invaded eutrophic rivers in the Little Karoo is mainly by brush-cutting and burning but is ineffective, and the control is controversial because of the value of the reeds in the construction industry (Guthrie, 2007). Invasions of cactus species in Karoo grazing land, particularly *Cylindropuntia pallida, C. fulgida* var. *mamillata, C. imbricata, Echinopsis schickendantzii, Myrtillocactus geometrizans, Tephrocactus articulatus* and *Opuntia* species are usually spot sprayed with herbicides (Walters et al., 2011; Klein, 2012). Species-specific biocontrol agents recently released in the Karoo are successfully controlling *C. fulgida* var. *mamillata, Harrisia martinii, H. balansae*, *Opuntia aurantiaca* and *O. humifusa* (Klein, 2002; Walters et al., 2011).

Clearing of woody vegetation on alluvial plains and riverbeds exposes soil to erosion and exacerbates the risk of flash floods, and also releases sequestrated carbon when cleared woody plants are used for firewood (Göswein et al., 2021). In arid areas where damaged vegetation takes many decades to establish, rehabilitation interventions that improve infiltration and microclimateic conditions and increase indigenous seed availability are the only way to hasten recovery, reduce rates of re-invasion and return ecosystems services to land users (Coetzee, 2005; Milton, 2010). Costs of such labour-intensive interventions are generally beyond the reach of individuals, but because they are in the national interest and generate jobs and skills, are appropriate projects for state funding.

3.4. Climate change mitigation

The mitigation of the negative impact of climate change on habitats, biodiversity and water resources in the Karoo will depend on the political will to carry out both population and land use planning for the nation and the region, because warming will continue to increase over the next few decades. International treaties, such as the Kyoto Protocol that require signatories to reduce the burning of fossils fuels, do not meet goals and CO^2 levels in the atmosphere continue to rise (Ripple et al., 2021). The global human population is growing by more than 200,000 people per day, and it is unlikely that CO^2 emissions and warming can be controlled unless the population size gradually decreases (Ripple et al., 2021). Since overpopulation exacerbates environmental and human health problems, driven by climate change, biodiversity loss and pandemics, Greguš and Guillebaud (2020) urge that medical doctors should educate people about the dangers of overpopulation, make health and family planning more easily available to women (Table 2.5). Simply, ensuring that girls receive schooling may be the best solution to the population explosion problem since better-educated women have fewer children than less-educated women (Kim, 2016). Continued growth of the human population in South Africa by 1.9 % per annum will likely result in considerable land transformation that will exacerbate effects of climate change particularly in the arid regions (Erasmus et al., 2002). Expansion of protected areas has been proposed as an approach to reduce loss of biodiversity in South Africa under climate change, but as land will probably be too costly for the state to purchase, this would need to be done through conservation agreements with landowners (Wise et al., 2012). Land use planning that protects rivers and wetlands, and aquifers in South Africa urgently needs better enforcement particularly in arid areas (Van Deventer, 2021).

4. Future perspectives

Multiple interacting factors at different scales, including past mismanagement driven by market demands, social changes and population growth, have degraded arid ecosystems globally. Moreover prohibitive costs of, and failure to implement effective ecological restoration (Reynolds et al., 2007; Feng et al., 2015), has resulted in a loss of ecosystem services, particularly those affecting production of goods and retention of carbon, soil, water and biodiversity (Le Maitre et al., 2007; Turpie et al., 2008; Ziervogel et al., 2014; Busso and Pérez, 2018; UN, 2019). Climate change, in combination with political expediency and the quest for cheap energy, is likely to cause further land degradation in the Karoo in the future, unless restoration becomes part of the culture of development (Cross et al., 2019). Restoration costs in arid areas typically exceed the current marketable value of the land and its services, and recovery of vegetation takes decades (Ntshotsho et al., 2011), whereas in mesic areas restoration of ecosystem services is often economically viable over the medium term (Crookes et al., 2013). Consequently there is little economic incentive for investment either in better land management or ecological restoration in arid environments (Crookes et al., 2013; Bourne et al., 2017). Quantification of the long-term benefits of restoration and its contribution to achieve sustainability is therefore a challenge and priority for economic, social and ecological research particularly in arid areas.

Synthesis of the literature covered in this review suggest that law enforcement, public works programmes, facilitation of large and small businesses, changed attitudes towards social and environmental responsibility, and private investment in conservation can all play a part in restoring the Karoo and contributing towards protection of biodiversity, resources and livelihoods in this region (Table 2). However, much uncertainly remains as to how to prioritise and manage public works programmes, how to change public attitudes towards the use and protection of natural resources such as land and water, how to achieve family planning and reduce urban sprawl, and how to make it economically feasible for large and small business to supply skills and materials for ecological restoration.

An urgent need exists for research on techniques for ecological restoration across the altitudinal and rainfall seasonality gradients spanned by the Nama and Succulent Karoo. Important issues for research are when, where and how to ameliorate soils, whether there are trade-offs between achieving rapid cover and stabilization of soil, and bringing back diverse communities with sufficient redundancy to maintain ecosystem services during drought and grazing (Pauw et al., 2018), and whether restoration interventions should include extra-limital species more suitable for warmer drier climates. There is also a need to understand the role of dosage in restoration – for example, a global meta-analysis of reseeding restoration in arid area shows that higher seeding rates increase the probability of species re-introductions (Shackelford et al., 2021). Improved seed storage, dormancy manipulation and pelleting have increased seeding success on Australian mine sites (Erickson et al., 2017), but methods remain to be developed for Karoo species. Irrigation accelerates vegetation development under arid conditions (Bainbridge, 2002), but long-term trials are necessary to determine whether initial irrigation reduces plant resilience to drought and grazing.

Economic models evaluating benefit-cost outputs of restoration activities are usually based on single sites or projects. A challenging field for ecological and economic research is the investigation of the possible synergies among multiple restoration activities within a landscape that may produce cumulative benefits (Diefenderfer et al., 2021). So for example the alien clearing, soil erosion control, improved rangeland management and plant species reintroductions on different properties may cumulatively improve biodiversity, productivity and water regulation in the landscape in such a way that the whole is greater than the sum of the parts. In mesic environments agricultural intensification and diversification is a promising way of increasing productivity while maintaining natural diversity (Kremen, 2020). In arid areas this approach might be applicable in altered environments such as solar infrastructure installations that create a range of light and hydrological conditions. In addition to the need for research into the most cost effective techniques for restoring cover, ecosystem services and biodiversity, solutions are required for social, political and economic problems that constrain restoration activities, such as limited training, funding and data-sharing. Finding effective ways to repair the damage and maintain biodiversity and ecosystem services must surely be more valuable for earthlings than discovering new galaxies and putting boots on the moon. As Bourne et al. (2017) point out, investment in restoration, even where costs are high, is likely to be the only real option for sustaining livelihoods in the Karoo over the longer term.

The Karoo is not unique in the ways that social history, global economics and climate change have cumulatively contributed to land degradation. Drivers of land degradation have widely been attributed to complex interactions between government policy, human population growth, and local land use practices, in combination with climate change. In arid regions from China to Patagonia, urgent repairs to the environment are now needed in order to return and sustain essential ecosystem services (Shackelford et al., 2021). Despite differences in culture, scale and economies of the affected regions, understanding the challenges that past, present and future land use developments, combined with climate change pose, and why ecological restoration is critical for ecological and economic sustainability, is relevant to development planning in arid regions in many other parts of the world.

Declaration of Competing Interest

The authors declare no competing interests.

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References

Acocks, J.P.H., 1953. Veld types of South Africa. Mem. Bot. Surv. S. Africa 28. Government Printer, Pretoria.

Acocks, J.P.H., 1976. Riverine vegetation of the semi-arid and arid regions of South Africa. J. S. Afr. Biol. Soc. 17, 21–35.

Acocks, J.P.H., 1979. The flora that matched the fauna. Bothalia 12, 673–709.

Ament, J.M., Moore, C.A., Herbst, M., Cumming, G.S., 2017. Cultural ecosystem services in protected areas: understanding bundles, trade-offs, and synergies. Cons. Letters 10, 440–450.

Angeler, D.G., Viedma, O., Sánchez-Carrillo, S., Alvarez-Cobelas, M., 2008. Conservation issues of temporary wetland Branchiopoda (Anostraca, Notostraca: crustacea) in a semiarid agricultural landscape: what spatial scales are relevant? Biol. Conserv. 141, 1224–1234.

Annecke, D.P., Moran, V.C., 1978. Critical reviews of biological pest control in South Africa. 2. The prickly pear, *Opuntia ficus-indica* (L.) Miller. J. Entomol. Soc. S. Africa 41, 161–188.

Anon, 2018. Landmark victory for farming and wildlife. The Gremlin: Online Newspaper for the Garden Route and Klein Karoo 14 November 2018. https://www.thegremlin.co.za/2018/11/14/landmark-victory-for-farming-wildlife/.

Archer, S., 2000. Technology and ecology in the Karoo: a century of windmills, wire and changing farming practice. J. Sth. African Studies 26, 675–696. https://doi.org/10.1080/03057070020008224.

Aronson, J., Blignaut, J.N., Aronson, T.B., 2017. Conceptual frameworks and references for landscape-scale restoration: reflecting back and looking forward. Ann. Mo. Bot. Gard. 102, 188–200.

Avis, A.M., Lubke, R.A., Van Eeden, D., 2014. Zirco Roode Heuwel Kamiesberg Project, Northern Cape, South Africa. Rehabilitation Strategies Recommended Rehabilitation Programme. Coastal and Environmental Services (CES), Grahamstown.

Bainbridge, D.A., 2002. Alternative irrigation systems for arid land rehabilitation. Ecol. Restor. 20, 23–30.

Beaumont, P.B., Smith, A.B., Vogel, J.C., 1995. Before the Einiqua: the archaeology of the frontier zone. In: Smith, A.B. (Ed.), Einiqualand: Studies of the Orange River Frontier. University of Cape Town, Cape Town, pp. 236–264.

Beck, A., 2010. Electric Fence Induced Mortality in South Africa. MSc Thesis. School of Animal, Plant and Environmental Sciences, University of the Witwatersrand, Johannesburg.

Beinart, W., 1998. The night of the jackal: sheep, pastures and predators in the Cape. Past Present 158, 172–206.

Beinart, W., 2003. The Rise of Conservation in South Africa: Settlers, Livestock and the Environment 1770–1950. Oxford University Press, Oxford.

Beinart, W., 2018. An overview of themes in the agrarian and environmental history of the Karoo since C.1800. Afr. J. Range Forage Sci. 35 (3-4), 191–202.

Bekele, S.G., 2001. Grasshopper Ecology and Conservation in the Nama karoo. PhD Thesis. University of KwaZulu-Natal, Pietermaritzburg.

Ben-Shahar, R., 1993. Does fencing reduce the carrying capacity for populations of large herbivores? J. Trop. Ecol. 9, 249–253.

Beukes, P.C., Cowling, R.M., 2003. Evaluation of restoration techniques for the succulent Karoo, South Africa. Restor. Ecol. 11, 308–316.

Blignaut, J., Aronson, J., 2020. Developing a restoration narrative: a pathway towards system-wide healing and a restorative culture. Ecol. Econ. 168, 106483.

Blignaut, J., De Wit, M.P., Esler, K., Le Maitre, D., Milton, S., Mitchell, S., Van der Elst, L., 2010. Restoration in South Africa. Quest 6, 26–30.

Boardman, J., Foster, I., Rowntree, K., Mighall, T., Gates, J., 2010. Environmental stress and landscape recovery in a semi-arid area, the Karoo, South Africa. Scottish Geogr. Journ. 126, 64–75.

Boardman, J., Favis-Mortlock, D., Foster, I., 2015. A 13-year record of erosion on badland sites in the Karoo, South Africa. Earth Surf. Process. Landf. 40, 1964–1981.

Boardman, J., Foster, I.D.L., Rowntree, K.M., Favis-Mortlock, D.T., Mol, L., Suich, H., Gaynor, D., 2017. Long-term studies of land degradation in the Sneeuberg uplands, eastern Karoo, South Africa: a synthesis. Geomorphology 285, 106–120.

Boone, R.B., Hobbs, N.T., 2004. Lines around fragments: effects of fencing on large herbivores. Afr. J. Range For Sci. 21, 147–158.

Bourne, A., de Abreu, P., Donatti, C., Scorgie, S., Holness, S., 2015. A Climate Change Vulnerability Assessment for the Namakwa District, South Africa: the 2015 Revision. Conservation South Africa, Cape Town.

Bourne, A., Muller, H., De Villiers, A., Alam, M., Hole, D., 2017. Assessing the efficiency and effectiveness of rangeland restoration in Namaqualand, South Africa. Plant Ecol. 218, 7–22.

Brandt, F., Spierenburg, M., 2014. Game fences in the Karoo: reconfiguring spatial and social relations. J. Contemp. Afr. Stud. 32, 220–237.

Brouwer, M., 2012. The Ecosystem Promise. Meindert Brouwer Partner in Communicatie, Bunnik, The Netherlands.

Brown, H.D., 1988. Current pesticide application: effectiveness and persistence. In: McKenzie, B., Longridge, M. (Eds.), Proceedings of the Locust Symposium. S Afr. Inst. Ecol. Bull. Special Issue, pp. 101–117.

Bryden, H.A., 1889. Kloof and Karoo: Sport, Legend and Natural History in Cape Colony With a Notice of the Game Birds, and of the Present Distribution of the Antelopes and Larger Game. Longmans, Green and Co, London.

Burger, M., Branch, W.R., 1994. Tortoise mortality caused by electric fences in the Thomas Baines Nature Reserve. S. Afr. J. Wildl. Res. 24, 32–37.

Burke, A., 2005. Best Practice Guidelines for Minimising Impacts on the Flora of the Southern Namib. Windhoek, EnviroScience and Namibia Nature Foundation.

Burke, A., 2008. The effect of topsoil treatment on the recovery of rocky plain and outcrop plant communities in Namibia. J. Arid Environ. 72, 1531–1536.

Busso, C.A., Fernandez, O.A., 2018. Arid and semiarid rangelands of Argentina. In: Gaur, M.K., Squires, V.R. (Eds.), Climate Variability Impacts on Land Use and Livelihoods in Drylands. Springer International Publishing, pp. 261–291. https://doi.org/10.1007/978-3-319-56681-8.

Busso, C.A., Pérez, D.R., 2018. Opportunities, limitations and gaps in the ecological restoration of drylands in Argentina. Ann. Arid Zone 57, 191–200.

Cape Wools, S.A., 2020. Sustainable Cape Wool Standard: Good Practice Principles for Sustainable Wool Production in South Africa. https://www.capewools.co.za/content/sustainable-cape-wool-standard.

Caramanica, A., Mesiab, L.H., Morales, C.R., Huckleberry, G., Castillo, L.J., Quilter, J., 2020. El Niño resilience farming on the north coast of Peru. PNAS 117, 24127–24137.

Carrick, P., 2008. Namaqualand Restoration Initiative: Bringing Mining, Biodiversity, and Local Communities Together. CEPF, Final project completion report. https://www.cepf.net/grants/grantee-projects/namaqualand-restoration-initiative-bringing-mining-biodiversity-and-local.

Carrick, P.J., Kruger, R., 2007. Restoring degraded landscapes in lowland Namaqualand: lessons from the mining experience and from regional ecological dynamics. J. Arid Environ. 70, 767–781.

Carrick, P., Erickson, T.E., Becker, C.H., Mayence, C.E., Bourne, A.R., 2015. Comparing ecological restoration in South Africa and Western Australia: the benefits of a' travelling workshop. Ecol. Manag. Restor. 16 (5), 86–94.

Carruthers, J., 2008. Wilding the farm or farming the wild? The evolution of scientific game ranching in South Africa from the 1960s to the present. Trans. R. Soc. South Africa 63, 160–181.

Christopher, A.J., 1982. Towards a definition of the nineteenth century south african frontier. S. Afr. Geogr. J. 64, 97–113.

Coaton, W.G.H., 1962. Control of hodotermitid harvester termites in the Karoo. J. Ent. Soc. S. Africa 25, 318–327.

Coetzee, K., 2005. Caring for Natural Rangelands. Pietermaritzburg, University of KwaZulu-Natal Press, Pietermaritzburg.

Coldrey, K.M., Turpie, J.K., 2020. Potential impacts of changing climate on nature-based tourism: a case study of South Africa's national parks. Koedoe 62, a1629. https://doi.org/10.4102/koedoe.v62i1.1629.

Conradie, B., 2019. Land use and redistribution in the arid west: the case of Laingsburg Magisterial district. Agrekon 58, 281–291.

Conradie, B., Piesse, J., Stephens, J., 2019a. The changing environment: efficiency, vulnerability and changes in land use in the South African Karoo, 2012-2014. Environ. Dev. 32, 100453.

Conradie, S.R., Woodborne, S.M., Cunningham, S.J., McKechnie, A.E., 2019b. Chronic, sublethal effects of high temperatures will cause severe declines in southern African arid-zone birds during the 21st century. PNAS 116, 14065–14070.

Cornelissen, H., Watson, I., Adamc, E., Malefetsea, T., 2019. Challenges and strategies of abandoned mine rehabilitation in South Africa: the case of asbestos mine rehabilitation. J. Geochem. Explor. 205, 106354.

Cowell, C., Ferreira, S., 2015. Challenges managing herbivores in the contractual Postberg section of West Coast National Park. Afr. J. Wildl. Res. 45, 28–54.

Cowling, R.M., Hilton-Taylor, C., 1999. Plant biogeography, endemism and diversity. In: Dean, W.R.J., Milton, S.J. (Eds.), The Karoo: Ecological Patterns and Processes. Cambridge University Press, Cambridge, pp. 42–56.

Crookes, D.J., Blignaut, J.N., De Wit, M.P., Esler, K.J., Le Maitre, D.C., Milton, S.J., Mitchell, S.A., Cloete, J., De Abreu, P., Fourie, H., Gull, K., Marx, D., Mugido, W., Ndhlovu, T., Nowell, M., Pauw, M., Rebelo, A., 2013. System dynamic modelling to assess economic viability and risk trade-offs for ecological restoration in South Africa. J. Environ. Manag. 120, 138–147.

Cross, A.T., Nevill, P.G., Dixon, K.W., Aronson, J., 2019. Time for a paradigm shift towards a restorative culture. Restor. Ecol. 27, 24–928.

Cunningham, S.J., Gardner, J.L., Martin, R.O., 2021. Opportunity costs and the response of birds and mammals to climate warming. Front. Ecol. Environ. 2021 https://doi.org/10.1002/fee.2324.

Damm, B., Hagedorn, J., 2009. Holocene floodplain formation in the southern cape region, South Africa. Geomorphology 122, 213–222.

Davis, K.E., Terblanche, S.E., 2016. Challenges facing the agricultural extension landscape in South Africa, quo vadis? A. Afr. J. Agri. Ext. 44, 231–247.

De Abreu, P., 2011. The Effect of Rehabilitation on Ecosystem Services in the Semi-arid Succulent Karoo Lowlands of the Little Karoo, South Africa. MSc Dissertation. University of Cape Town.

De Necker, L., Ferreira, M., Van Vuuren, J.H.J., Malherbe, W., 2016. Aquatic invertebrate community structure of selected endorheic wetlands (pans) in South Africa. Inland Waters 6, 303–313.

De Prada-Samper, J.M., 2017. 'I have hgubbo': kabbo's maps and place-lists and the !xAm concept of !xoe. S. Afr. Archaeol. Bull. 72, 116–124.

De Villiers, A.J., Van Rooyen, M.W., Theron, G.K., 2001. Seedbank phytosociology of the Strandveld Succulent Karoo, South Africa: a pre-mining benchmark survey for rehabilitation. Land Degrad. Devel. 12, 119–130.
Deacon, J., 1986. 'My place is the Bitterpits': the home territory of Bleek and Lloyd's /XAM San informants. Afr. Stud. 45, 135–155.
Deacon, J., 2014. The holocene archaeology of the karoo. In: Ntsebeza, L., Saunders, C. (Eds.), Papers from the Precolonial Catalytic Project. Vol 1. Centre for African Studies. University of Cape Town, pp. 10–21.
Dean, W.R.J., 2000. Factors affecting bird diversity patterns in the Karoo, South Africa. S. Afr. J. Sci. 96, 609–616.
Dean, W.R.J., 2004. Nomadic Desert Birds. Springer, Berlin.
Dean, W.R.J., Macdonald, I.A.W., 1994. Historical changes in stocking rates of domestic livestock as a measure of semi-arid and arid rangeland degradation in the Cape Province, South Africa. J. Arid Environ. 26, 281–298.
Dean, W.R.J., Milton, S.J., 1991. Disturbances in semi-arid shrubland and arid grassland in the Karoo, South Africa: mammal diggings as germination sites. Afr. J. Ecol. 29, 11–16.
Dean, W.R.J., Milton, S.J., 1995. Plant and invertebrate assemblages on old fields in the arid southern Karoo, South Africa. Afr. J. Ecol. 33, 1–13.
Dean, W.R.J., Milton, S.J., 2001. Responses of granivorous birds to rainfall and seed abundance in the southern Karoo, South Africa. J. Arid Environ. 47, 101–121.
Dean, W.R.J., Milton, S.J., 2004. Pre-1950 breeding records for vultures (Acciptridae) in southern Africa. Vulture News 51, 54–59.
Dean, W.R.J., Roche, C., 2007. Setting appropriate restoration targets for changed ecosystems in the semiarid Karoo. In: Aronson, J.A., Milton, S.J., Blignaut, J.N. (Eds.), Restoring Natural Capital – Science, Business and Practice. Island Press, Washington DC, pp. 57–63.
Dean, W.R.J., Williams, J.B., 2004. Adaptations of birds for life in deserts with particular reference to larks (Alaudidae). Trans. R. Soc. South Africa 59, 79–91.
Dean, W.R.J., Milton, S.J., Du Plessis, M.A., Siegfried, W.R., 1995. Dryland degradation: symptoms, stages and hypothetical cures. In: Roundy, B.A., McArthur, E.D., Haley, J. S., Mann, D.K. (Eds.), Proceedings: Wildland Shrub and Arid Land Restoration Symposium. General Technical Report INT-GTR-315. U.S. Dept of Agriculture, Forest Service, Intermountain Research Station, Ogden, Utah, pp. 178–182.
Dean, W.R.J., Seymour, C.L., Joseph, G.S., 2018. Linear structures in the Karoo, South Africa, and their impacts on biota. Afr. J. Range Forage Sci. 35, 223–232.
Denison, J., Wotshela, L., 2009. Indigenous water harvesting and conservation practices: historical context, cases and implications. WRC Report No. TT 392/09. Water research Commission, Pretoria.
Dennis, E., Dennis, I., 2013. Potential climate climate change impacts on Karoo Aquifers. WRC Report No. KV 308/12. Water research Commission, Pretoria, 96 pp.
Desmet, P.G., 2013. Gamsberg zinc project: vegetation baseline and impact assessment report draft 5. Report for ERM Southern Africa on Behalf of Black Mountain Mining (Pty) Ltd/Vedanta Zinc International, 19 April 2013.
Desmet, P.G., Cowling, R.M., 1999. The climate of the karoo – a functional approach. In: Dean, W.R.J., Milton, S.J. (Eds.), Eds.), The Karoo, Ecological Patterns and Processes. Cambridge University Press, Cambridge, pp. 3–16.
Diefenderfer, H.L., Steyer, G.D., Harwell, M.C., LoSchiavo, A.J., Neckles, H.A., Burdick, D.M., Johnson, G.E., Buenau, K.E., Callaway, J.C., Thom, R.M., Ganju, N.K., Twilley, R.R., 2021. Applying cumulative effects to strategically advance large-scale ecosystem restoration. Front. Ecol. Environ. 19, 108–117.
Dojani, S., Budel, B., Deutschewitz, K., Weber, B., 2011. Rapid succession of biological soil crusts after experimental disturbance in the succulent Karoo, South Africa. Agric., Ecosyst. Environ., Appl. Soil Ecol. 48, 263–269.
Doty, A.C., Martin, A.P., 2012. Assessment of bat and avian mortality at a pilot wind turbine at Coega, Port Elizabeth, Eastern Cape, South Africa. N. Z. J. Zool. 40, 75–80.
Du Toit, H.S.D., 1923. Final Report of the Drought Investigation Commission. Government Printer, Pretoria.
Du Toit, J.C.O., O'Connor, T.G., 2014. Changes in rainfall pattern in the eastern Karoo, South Africa, over the past 123 years. Water SA 40, 453–460.
Du Toit, J.C.O., Ramaswiela, T., Pauw, M.J., O'Connor, T.G., 2018. Interactions of grazing and rainfall on vegetation at Grootfontein in the eastern Karoo. Afr. J. Range For. Sci. 35, 267–276.
Dube, T., De Necker, L., Wepener, V., Smit, N.J., Pinceel, T., Mwaijengo, G.N., Lemmens, P., Brendonck, L., 2020. A comparison of aquatic macroinvertebrate and large branchiopod community composition between temporary pans of a conservation area and surrounding communal area in South Africa. Afr. Zool. 55, 67–77.
Duniway, M.C., Pfennigwerth, A.A., Fick, S.E., Nauman, T.W., Belnap, J., Barger, N.N., 2019. Wind erosion and dust from US drylands: a review of causes, consequences, and solutions in a changing world. Ecosphere 10, e02650.
Duthie, A.J., Skinner, J.D., Robinson, T.J., 1989. The distribution and status of the Riverine Rabbit *Bunolagus monticularis*, South Africa. Biol. Conserv. 47, 195–202.
Dzikiti, S., Bugan, R., le Maitre, D., Ntshidi, Z., Ramoelo, A., Gush, M., Jovanovic, N., Schachtschneider, K., 2018. Comparison of water use by *Prosopis*spp and the co-occurring Vachelia karroo trees before and after clearing the invasions: implications in groundwater. WRC Report No 2256/1/18. Water Research Commission, Pretoria.
EPWP, 2006. Expanded Public Works Programme 1 April to 31 December 2005: Project Report List of Projects Per Department. www.epwp.gov.za.
Erasmus, B.F.N., Van Jaarsveld, A., Chown, S.L., Kshatriya, M., Wessels, K.J., 2002. Vulnerability of South Africa animal taxa to climate change. Glob. Change Biol. Bioenergy 8, 679–693.
Erdogan, I.G., Fosso-Kankeua, E., Ntwampe, S.K.O., Waanders, F.B., Hoth, N., Rand, A., 2018. Potential toxic elements contamination of soils in O'Kiep, an Arid Region of Namaqualand, South Africa. In: 10th International Conference on Advances in Science, Engineering, Technology and Healthcare (ASETH-18). Nov. 19-20, 2018 Cape Town, pp. 137–142.
Erickson, T.E., Muñoz-Rojas, M., Kildisheva, O.A., Stokes, B.A., White, S.A., Heyes, J.L., Dalziell, E.L., Lewandrowski, W., James, J.J., Madsen, M.D., 2017. Benefits of adopting seed-based technologies for rehabilitation in the mining sector: a Pilbara perspective. Austr. J. Bot. 65, 646–660.
Esler, K.J., 1999. Plant reproductive ecology. In: Dean, W.R., Milton, S.J. (Eds.), The Karoo: Ecological Patterns and Processes. Cambridge University Press, Cambridge, pp. 123–144.
Esler, K.J., Milton, S.J., Dean, W.R.J., 2006. Karoo Veld - Ecology and Management. Briza Press, Pretoria, pp. 224.
Farley, J., Brown Gaddis, E.J., 2007. Restoring natural capital: an ecological economics assessment. In: Aronson, J.A., Milton, S.J., Blignaut, J.N. (Eds.), Restoring Natural Capital – Science, Business and Practice. Island Press, Washington DC, pp. 17–27.
Felmore, T., 2019. Restoring the Great Karoo one reintroduction at a time. Africa Geographic Stories. Issue 246. https://africageographic.com/stories/samara-rewilding-great-karoo/.
Feng, Q., Ma, H., Jiang, X., Wang, X., Cao, S., 2015. What has caused desertification in China? Sci. Rep. 5, 15998. https://doi.org/10.1038/srep15998.
Fernández-Cirelli, A., Arumí, J.L., Rivera, D., Boochs, P.W., 2009. Environmental effects of irrigation in arid and semi-arid region. Chilean J. Agri. Res. 69 (Suppl. 1), 27–40.
Fleury, G.S., Hoffman, M.T., Todd, S.W., 2020. Land reform and its impact on the arid South African environment: riemvasmaak as a case study. Afr. J. Range Forage Sci. https://doi.org/10.2989/10220119.2020.1783700.
Gilewitch, D.A., King, W.C., Palka, E.J., Harmon, R.S., McDonald, E.V., Doe, W.W., 2014. Characterizing the desert environment for Army operations. Geol. Soc. America Rev. Engin. Geol. 22, 57–68.
Göswein, V., Dinis Silvestre, J., Lamb, S., Gonçalves, A.B., Pittau, F., Freire, F., Oosthuizen, D., Lord, A., Habert, G., 2021. Invasive alien plants as an alternative resource for concrete production – multi-scale optimization including carbon compensation, cleared land and saved water runoff in South Africa. Resour. Conserv. Recycl. 167 https://doi.org/10.1016/j.resconrec.2020.105361.
Greguš, J., Guillebaud, J., 2020. Doctors and overpopulation 48 years later: a second notice. Eur. J. Contracept. Reprod. Health Care 25, 409–416.
Grodsky, S.M., Hernandez, R.R., 2020. Reduced ecosystem services of desert plants from ground-mounted solar energy development nature research. Nat. Sustain. 3, 1036–1043.
Guelke, L., 1976. Frontier settlement in early Dutch South Africa. Ann. Assoc. Am. Geogr. 66, 25–42.
Guelke, L., Shell, R., 1992. Landscape of conquest: frontier water alienation and Khoikhoi strategies for survival, 1652-1780. J. South. Afr. Stud. 18, 803–824.
Guthrie, G., 2007. Impacts of the Invasive Reed *Arundo donax* on Biodiversity at the Community-ecosystem Level. MSc Thesis. University of the Western Cape.
Hanke, W., Wesuls, D., Münchberger, W., Schmiedel, U., 2015. Tradeoffs in the rehabilitation of a succulent Karoo rangeland. Land Degrad. Develop. 26, 833–842.
Hayward, M.W., Kerley, G.I.H., 2009. Fencing for conservation: restriction of evolutionary potential or a riposte to threatening processes? Biol. Conserv. 142.
Henschel, J.R., 2015. Locust times – monitoring populations and outbreak controls in relation to Karoo natural capital. Trans. R. Soc. South Africa 70, 135–143.
Henschel, J.R., Lubin, Y., 2018. Web spider abundance is affected by sheep farming in the Karoo. Afr. J. Range Forage Sci. 35, 319–324.
Herling, M.C., Cupido, C.F., O'Farrell, P.J., Du Plessis, L., 2009. The financial costs of ecologically non-sustainable farming practices in a semi-arid system. Restor. Ecol. 17, 827–836.
Hernandez, K.R.R., Easter, S.B., Murphy-Mariscal, M.L., Maestre, F.T., Tavassoli, M., Allen, E.B., Barrows, C.W., Belnap, J., Ochoa-Hueso, R., Ravi, S., Allen, M.F., 2014. Environmental impacts of utility-scale solar energy. Renewable Sustainable Energy Rev. 29, 766–779.
Hoffman, M.T., Ashwell, A., 2001. Nature divided. Land Degradation in South Africa. University of Cape Town Press, Cape Town.
Hoffman, M.T., Rohde, R.F., 2007. From pastoralism to tourism: the historical impact of changing land use practices in Namaqualand. J. Arid Environ. 70, 641–658.
Hoffman, M.T., Allsopp, N., Rohde, R.F., 2007. Sustainable land use in Namaqualand, South Africa: key issues in an interdisciplinary debate. J. Arid Environ. 70, 561–569.
Hoffman, M.T., Skowno, A., Bell, W., Mashele, S., 2018. Long-term changes in land use, land cover and vegetation in the Karoo drylands of South Africa: implications for degradation monitoring. Afr. J. Range Forage Sci. 35, 209–221.
Hoffman, M.T., Rohde, R.F., Gillson, L., 2019. Rethinking catastrophe? Historical trajectories and modelled future vegetation change in southern Africa. Anthropocene 25, 100189.
Hoffman, M.T., Rohde, R.F., Gillson, L., 2020. Further comments on analysing trajectories of vegetation and landscape change in southern Africa from historical field photographs. Anthropocene 32, 100274.
Holleman, H., 2018. Dust Bowls of Empire. Imperialism, Environmental Politics, and the Injustice of "Green" Capitalism. Yale Agrarian Studies Series. Yale University Press, New Haven and London.
Holt, S., Horwitz, L.K., Wilson, B., Codron, D., 2021. Leopard tortoise *Stigmochelys pardalis* (Bell, 1928) mortality caused by electrified fences in central South Africa and its impact on tortoise demography. Afr. J. Herpetol. https://doi.org/10.1080/21564574.2020.1860140.
Horwitz, L.K., Chazan, M., 2015. Past and present at Wonderwerk cave (Northern Cape Province, South Africa). Afr. Archaeol. Rev. 32, 595–612.
Hyvärinen, O., Hoffman, M.T., Reynolds, C., 2019. Vegetation dynamics in the face of a major land-use change: a 30-year case study from semi-arid South Africa. Afr. J. Range Forage Sci. 36, 141–150.

Jackson, A.S., 2016. Investigating the effectiveness of microcatchments at enhancing transplant performance in Nama-karoo riparian ecosystem restoration. Dissertation, M.Tech. Nature Conservation. Mandela University, Port Elizabeth.

Jones, S., Inggs, J., 2003. The South African economy in the 1990s. S. Afr. J. Econ. Hist. 18, 1–15.

Jooste, J.F., 1983. Game farming as a supplementary farming activity in the Karoo. Proc. Grassl. Soc. South. Afr. 18, 46–49.

Jury, M., 2018. Climate trends across South Africa since 1980. Water SA 43, 297–307.

Keay-Bright, J., Boardman, J., 2006. Changes in the distribution of degraded land over time in the central Karoo, South Africa. Catena 67, 1–14.

Kim, J., 2016. Female education and its impact on fertility. Iza World Labor 2016, 228. https://doi.org/10.15185/izawol.228.

Kirsten, J., Schöffman, I., 2020. How civil society is stepping in when small-town Karoo municipalities fail. Maverick Citizen, 15 December 2020. https://www.dailymaverick.co.za/article/2020-12-15-how-civil-society-is-stepping-in-when-small-town-karoo-municipalities-fail/.

Klein, R.G., 1986. The prehistory of stone age herders in the Cape Province of South Africa. In: Hall, M., Smith, A.B. (Eds.), Prehistoric Pastoralism in Southern Africa. South African Archaeological Society Goodwin Series 5, pp. 5–12.

Klein, H., 2002. Harrisia cactus mealybug (*Hypogeococcus pungens*). PPRI Leaflet Series: Weeds Biocontrol 2.5. Plant Protection research Institute, Pretoria.

Klein, H., 2012. Focus on cacti in South Africa. SAPIA News 24, 1–9.

Komoto, K., Ito, M., van der Vleuten, P., Faiman, D., Kurokawa, K., 2009. Energy From the Desert: Very Large Scale Photovoltaic Systems: Socioeconomic, Financial, Technical and Environmental Aspects. Earthscan Publications, London.

Kraaij, T., Milton, S.J., 2006. Vegetation changes (1995–2004) in semi-arid Karoo shrubland (South Africa): effects of rainfall, wild herbivores and change in land use. J. Arid Environ. 64, 174–192.

Kremen, C., 2020. Ecological intensification and diversification approaches to maintain biodiversity, ecosystem services and food production in a changing world. Emerg. Top. Life Sci. 4, 229–240.

Kruger, A.C., Sekele, S.S., 2013. Trends in extreme temperature indices in South Africa: 1962–2009. Int. J. Climatol. 33, 661–676.

Lakhraj-Govender, R., Grab, S.W., 2019. Assessing the impact of El Niño–Southern Oscillation on South African temperatures during austral summer. Int. J. Climatol. 39, 143–156.

Le Maitre, D.C., Milton, S.J., Jarmain, C., Colvin, C.A., Saayman, I., Vlok, J.H.J., 2007. Linking ecosystem services and water resources: landscape-scale hydrology of the Little Karoo. Front. Ecol. Environ. 5, 261–270.

Lee, A.T.K., Geary, C., Wright, D.R., Dean, W.R.J., 2019. Vulnerability of birds to contaminated water sources in the Karoo region of South Africa. Ostrich 90, 1–10.

Liebenberg, D., Claassens, S., Van Rensburg, L., 2013. Insights and lessons learned from the long-term rehabilitation of an iron ore mine. Int. J. Environ. Res. 7, 633–644.

Lloyd, P., 2007. Predator control, mesopredator release, and impacts on bird nesting success: a field test. Afr. Zool. 42, 180–186.

Louw, M.A., le Roux, P.C., Meyer-Milne, E., Haussmann, N.S., 2017. Mammal burrowing in discrete landscape patches further increases soil and vegetation heterogeneity in an arid environment. J. Arid Environ. 141, 68e75.

Macdonald, I.A.W., 1989. Man's role in changing the face of southern Africa. In: Huntley, B.J. (Ed.), Biotic Diversity in Southern Africa. Oxford University Press, Cape Town, pp. 53–77.

Macdonald, I.A.W., 1992. Vertebrate populations as indicators of environmental change in southern Africa. Trans. R. Soc. South Africa 48, 87–122.

MacKellar, N., New, M., Jack, C., 2014. Observed and modelled trends in rainfall and temperature for South Africa: 1960–2010. S. Afr. J. Sci. 110, 2013-0353.

MacKenzie, J.M., 1988. The empire of nature. Hunting, Conservation and British Imperialism. Manchester University Press, Manchester and New York.

Macray, M.B., 2017. Tortoise mortalities along fences in the southeastern Karoo, South Africa. MSc thesis, Conservation Biology. University of Cape Town.

Mally, C.W., 1923. Arsenite of soda as a locust poison. J. Dep. Agric. 6, 220–223.

Mander, M., Jewitt, G., Dini, J., Glenday, J., Blignaut, J., Hughes, C., Marais, C., Maze, K., Van der Waal, B., Mills, A., 2017. Modelling potential hydrological returns from investing in ecological infrastructure: case studies from the Baviaanskloof-Tsitsikamma and uMngeni catchments, South Africa. Ecosyst. Serv. 27, 261–271.

Manyani, C.R.S., 2020. From Livestock to Game Farming: Farmers' Understandings of Land Use Changes, Sustainable Agriculture and Biodiversity Conservation in the Ubuntu Municipality, South Africa. PhD, Thesis. Stellenbosch University, Stellenbosch.

Maphanga, M., Mazenda, A., 2019. The effectiveness of the Expanded Public Works Programme as a poverty alleviation strategy. J. Dent. Pract. Adm. 27, 7–26.

Matthee, W., 2015. Factors Affecting the Success of Reseeding Rehabilitation in the Semi-arid Karoo, South Africa. MSc Thesis. Mandela University, Port Elizabeth.

McManus, J., Goets, S.A., Bond, W.J., Henschel, J.R., Smuts, B., Milton, S.J., 2018. Effects of short-term intensive trampling on Karoo vegetation. Afr. J. Range Forage Sci. 35, 311–318.

Mhlongo, S.E., Amponsah-Dacosta, F., Kadyamatimba, A., 2020. Appraisal of strategies for dealing with the physical hazards of abandoned surface mine excavations: a case study of Frankie and Nyala Mines in South Africa. Minerals 10, 145.

Mills, A.J., Cowling, R.M., 2006. Rate of carbon sequestration at two Thicket restoration sites in the Eastern Cape, South Africa. Rest. Ecol. 14, 38–49.

Mills, A.J., Turpie, J., Cowling, R.M., Marais, C., Kerley, G.I.H., Lechmere-Oertel, R.G., Sigwela, A.M., Powell, M., 2007. Assessing costs, benefits and feasibility of restoring natural capital in subtropical thicket in South Africa. In: Aronson, J., Milton, S.J., Blignaut, J.N. (Eds.), Restoring Natural Capital: Science, Business, and Practice. Society for Ecological Restoration International, Island Press, Washington, pp. 179–189.

Milton, S.J., 1994. Small-scale reseeding trials in arid rangeland: Effects of rainfall, clearing and grazing on seedling survival. Afr. J. Range Forage Sci. 11, 54–58.

Milton, S.J., 2001. Rethinking ecological rehabilitation in arid and winter rainfall regions of southern Africa. S. Afr. J. Sci. 97, 47–48.

Milton, S.J., 2010. Feasibility and benefits of veld rehabilitation following control of invasive Prosopis in the Calvinia area. Working for Water: Namaqua District Municipality. 2010.01.10. Unpublished Report.

Milton, S.J., Dean, W.R.J., 1990. Seed production in rangelands of the southern Karoo. S. Afr. J. Sci. 86, 231–233.

Milton, S.J., Dean, W.R.J., 1992. An underground index of rangeland degradation: cicadas in arid southern Africa. Oecologia 91, 288–291.

Milton, S.J., Dean, W.R.J., 1993. Selection of seeds by harvester ants (Messor capensis) in relation to rangeland condition. J. Arid Environ. 23, 63–74.

Milton, S.J., Dean, W.R.J., 1998. Alien plant assemblages near roads in arid and semi-arid South Africa. Divers. Distrib. 4, 175–188.

Milton, S.J., Dean, W.R.J., 2010. Plant invasions in arid areas: special problems and solutions: a South African perspective. Biol. Invasions 12, 3935–3948.

Milton, S.J., Hoffman, M.T., 1994. The application of state-and-transition models to rangeland research and management in arid succulent and semi-arid grassy Karoo, South Africa. Afr. J. Range Forage Sci. 11, 18–26.

Milton, S.J., Dean, W.R.J., Du Plessis, M.A., Siegfried, W.R., 1994. A conceptual model of arid rangeland degradation: the escalating cost of declining productivity. BioScience 44, 70–76.

Milton, S.J., Gourlay, I.D., Dean, W.R.J., 1997. Shrub growth and demography in arid Karoo, South Africa: inference from wood rings. J. Arid Environ. 37, 487–496.

Milton, S.J., Gasser, S., Bortenschlager, S., Dean, W.R.J., 1999. Invertebrates and leaf damage on alien *Atriplex lindleyi* Moq. and the indigenous *A. vestita* (Thunb.) Ael. (Chenopodiaceae) in the southern Karoo, South Africa. Afr. Entomol. 7, 298–301.

Milton, S.J., Henschel, J.R., Van der Merwe, H., Dean, W.R.J., Meyer-Milne, E., Gerber, H., 2021. Environmental baseline review of the core area and surrounds of the square kilometre array (SKA). SAEON Technical Report - February 2021. https://doi.org/10.15493/saeon.arid.10000001.

Moran, V.C., Hoffmann, J.H., Zimmermann, H.G., 1993. Objectives, constraints, and tactics in the biological control of mesquite weeds (Prosopis) in South Africa. Biol. Control 3, 80–83.

Mucina, L., Rutherford, M.C., 2006. The vegetation of South Africa, Lesotho and Swaziland. Strelitzia 19. South African National Biodiversity Institute, Pretoria.

Nattrass, N., Conradie, B., Drouilly, M., O'Riain, M.J., 2017. A brief history of predators, sheep farmers and government in the Western Cape, South Africa. CSSR Working Paper No. 398. Centre for Social Science Research, University of Cape Town, Cape Town.

Nchai, M.C., 2008. The Impact of Land Use on Invertebrate Assemblages in the Succulent Karoo, South Africa. MSc Thesis. Stellenbosch University, Stellenbosch.

Ndhlovu, T., Milton, S.J., Esler, K.J., 2011. Impact of Prosopis (mesquite) invasion and clearing on the grazing capacity of semiarid Nama Karoo rangeland, South Africa. Afr. J. Range Forage Sci. 28, 129–137.

Nielsen, T.T., Adriansen, H.K., 2005. Government policies and land degradation in the Middle East. Land Degrad. Develop. 16, 151–161.

Noy-Meir, I., 1973. Desert ecosystems: environment and producers. Ann. Rev. Ecol. Syst. 4, 25–51.

NRF, SARAO, 2018. Integrated Environmental Management Plan (IEMP) for SKA Phase 1 Mid-frequency Array (SKA1_MID) in South Africa. First version published in 2017 and prepared by Council for Scientific and Industrial Research (CSIR), 2nd version published 2018 by Gaea Enviro (Pty) Ltd., Stellenbosch. https://www.sarao.ac.za/about/strategic-environmental-assessment/.

Ntshotsho, P., Reyers, B., Esler, K.J., 2011. Assessing the evidence base for restoration in South Africa. Restor. Ecol. 19, 578–586.

O'Connor, T.G., Roux, P., 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. J. Appl. Ecol. 32, 612–626.

O'Farrell, P.J., Le Maitre, D.C., Gelderblom, C., Bonora, D., Hoffman, M.T., Reyers, B., 2008. Applying a resilience framework in the pursuit of sustainable land-use development in the Little Karoo, South Africa. In: Burns, M., Weaver, A. (Eds.), Exploring Sustainability Science - A Southern African Perspective. Sun Media, Stellenbosch, pp. 383–432.

Oliver, E.G.H., Fellingham, A.C., 1994. A new serotinous species of *Cliffortia* (Rosaceae) from the southwestern Cape with notes on *Cliffortia arborea*. Bothalia 24, 153–162.

Otto, F.E.L., Wolski, P., Lehner, F., Tebaldi, C., Van Oldenborg, G.J., Hogesteeger, S., Singh, R., Holden, P., Fučkar, N.S., Odoulami, R.C., New, M., 2018. Anthropogenic influence on the drivers of the Western Cape drought 2015–2017. Environ. Res. Lett. 13, 124010.

Paterson, A., 2005. Tax incentives - valuable tools for biodiversity conservation in South Africa. S. Afr. Law J. 122 (182), 216.

Pauw, M.J., Esler, K.J., Le Maitre, D.C., 2018. Assessing the success of experimental rehabilitation on a coastal mineral sands mine in Namaqualand, South Africa. Afr. J. Range Forage Sci. 35, 363–373.

Penn, N.G., 1986. Pastoralists and pastoralism in the Northern Cape frontier zone during the eighteenth century. S. Afr. Archaeol. Soc., Goodwin Series 5, 62–68.

Poynton, R.J., 1987. Tree planting in southern Africa. In: Prosopis L., Vol. 3. South African Forestry Research Institute, Pretoria, pp. 51.

Price, R.E., Brown, H.D., 1999. A century of locust control in South Africa. In: Cheke, R. A., Rosenberg, L.J., Kieser, M.E. (Eds.), Workshop on Research Priorities for Migrant Pests of Agriculture in Southern Africa. Plant Protection Research Institute, Pretoria, South Africa, 24-26 March 1999. Natural Resources Institute Chatham, pp. 37–49.

Rahlao, S.J., Milton, S.J., Esler, K.J., Barnard, P., 2010. The distribution of invasive Pennisetum setaceum along roadsides in western South Africa: the role of corridor interchanges. Weed Res. 50, 537–543.
Rahlao, S.J., Milton, S.J., Esler, K.J., Barnard, P., 2014. Performance of invasive alien fountain grass (Pennisetum setaceum) along a climatic gradient through three South African biomes. S. Afr. J. Bot. 91, 43–48.
Raimondo, D., Manning, J.C., Fish, L., 2008. *Secale Strictum* (J. Presl) J. Presl Subsp. Africanum (Stapf) K. Hammer. National Assessment: Red List of South African Plants Version 2020.1. Accessed on 2021/06/08.
Ralston Paton, S., Smallie, J., Pearson, A., Ramalho, R., 2017. Wind energy's impacts on birds in South Africa: a preliminary review of the results of operational monitoring at the first wind farms of the renewable energy independent power producer procurement programme in South Africa. BirdLife South Africa Occasional Report Series No. 2. BirdLife South Africa, Johannesburg.
Reed, L.L., Kleynhans, T.E., 2009. Agricultural land purchases for alternative uses – evidence from two farming areas in the Western Cape province, South Africa. Agrekon 48, 323–342.
Climate change and adaptive land management in southern Africa – assessments, changes, challenges, and solutions. In: Revermann, R., Krewenka, K.M., Schmiedel, U., Olwoch, J.M., Helmschrot, J., Jürgens, N. (Eds.), 2018. Biodiv. Ecol, 6. Klaus Hess Publishers, Göttingen and WindhoekGTZ.
Reynolds, J.F., Stafford Smith, D.M., Lambin, E.F., Turner, B.L., Mortimore, M., Batterbury, S.P., Downing, T.E., Dowlatabadi, H., Fernández, R.J., Herrick, J.E., Huber-Sannwald, E., Jiang, H., Leemans, R., Lynam, T., Maestre, F., Ayarza, M., Walter, B., 2007. Global desertification: building a science for dryland development. Science 316, 84–851. https://doi.org/10.1126/science.1131634.
Ripple, W.J., Wolf, C., Newsome, T.M., Barnard, P., Moomaw, W.R., 2021. The Climate Emergency: 2020 in Review. Scientific American, 6 January 2021.
Roche, C.J., 2004. Ornaments of the desert" springbok treks in the Cape Colony, 1774-1908. MA thesis, Historical Studies. University of Cape Town, Cape Town.
Rogers, G., 2020. Post Covid Karoo: a Powerhouse in the Making. Herald Live. https://www.heraldlive.co.za/weekend-post/your-weekend/2020-05-17.
Rutherford, M.C., Powrie, L.W., 2013. Impacts of heavy grazing on plant species richness: a comparison across rangeland biomes of South Africa. S. Afr. J. Bot. 87, 146–156.
Saaed, M.W., Jacobs, S.M., Masubelele, M.L., Samuels, M.I., Muncha, Z., Khomo, L., 2020. Fifteen-year resilience against further degradation of Succulent Karoo vegetation in South Africa. J. Arid Environ. 178, 104152.
Saayman, N., Botha, H., 2010. Is soil disturbance really necessary to ensure the success of bare patch restoration in sandy soils in the Nama Karoo? Grassroots 10, 12–17.
Saayman, N., Morris, C.D., Hardy, M.B., Botha, J.C., 2009. Can brushcutting of *Pteronia paniculata* improve the composition and productivity of veld in the Succulent Karoo, South Africa? Afr. J. Range Forage Sci. 26, 181–190.
Saayman, N., Cupido, C., Botha, J.C., Swart, R., 2017. Possible rehabilitation methods of *Galenia africana*-dominated old lands in the Cederberg Mountains, South Africa. Afr. J. Range Forage Sci. 34, 167–171.
Sampson, C.G., 1986. Veld damage in the Karoo caused by its pre-Trekboer inhabitants: preliminary observations in the Seacow Valley. The Naturalist 30, 37–40.
SANBI, 2016. Lexicon of Biodiversity Planning in South Africa, beta version, 2016. South African National Biodiversity Institute, Pretoria. pp 72.
SANBI, 2017. Technical Guidelines for CBA Maps: Guidelines for Developing a Map of Critical Biodiversity Areas and Ecological Support Areas Using Systematic Biodiversity Planning, first edition (beta version). South African National Biodiversity Institute, Pretoria. Compiled by Driver, A., Holness, S., Daniels, F.
SANParks, 2015. Annual Report 2014.2015. Downloaded 2021.01.17 from. South African National Parks, Pretoria. https://www.sanparks.org/.
SANParks, 2019. Five-Year Strategic Plan 2019/20–2023/24 Annual Performance Plan. Downloaded 2021.01.17 from. South African National Parks, Pretoria. https://www.sanparks.org/.
Schmiedel, U., Jürgens, N. (Eds.), 2010. Biodiversity in Southern Africa, Vol. 2: Patterns and Processes at Regional Scale.. Klaus Hess Publishers, Göttingen and Windhoek, p. 348.
Scholes, R., Lochner, P., Schreiner, G., Snyman-Van der Walt, L., De Jager, M. (Eds.), 2016. Shale Gas Development in the Central Karoo: A Scientific Assessment of the Opportunities and Risks. CSIR/IU/021MH/EXP/2016/003/A, ISBN 978-0-7988-5631-77. CSIR, Pretoria. Available at. http://seasgd.csir.co.za/scientific-assessment-chapters/.
Seekings, J., 2006. The Carnegie Commission and the Backlash Against Welfare State-building in South Africa, 1931-1937 Centre for Social Science Research (CSSR) Working Paper 159. University of Cape Town, Cape Town.
Seymour, C.L., Dean, W.R.J., 1999. Effects of heavy grazing on invertebrate assemblages in the Succulent Karoo, South Africa. J. Arid Environ. 43, 267–286.
Seymour, C.L., Milton, S.J., Joseph, G.S., Dean, W.R.J., Ditlhobolo, T., Cumming, G.S., 2010. Twenty years of rest returns grazing potential, but not palatable plant diversity, to Karoo rangeland, South Africa. J. Appl. Ecol. 47, 859–867.
Seymour, C.L., Gillson, L., Child, M.F., Tolley, K.A., Curie, J.C., da Silva, J.M., Alexander, G.J., Anderson, P., Downs, C.T., Egoh, B.N., Ehlers Smith, D.A., Ehlers Smith, Y.C., Esler, K.J., O'Farrell, P., Skowno, A.L., Suleman, E., Veldtman, R., 2020. Horizon scanning for South African biodiversity: a need for social engagement as well as science. Ambio 49, 1211–1221.
Shackelford, N., Paterno, G.B., Winkler, D.E., Erickson, T.E., Leger, E.A., Svejcar, L.N., Breed, M.F., Faist, A.M., Harrison, P.E., Curran, M.F., Guo, Q., Kirmer, A., Law, D.J., Mganga, K.Z., Munson, S.M., Porensky, L.M., Quiroga, R.E., Török, P., Wainwright, C.E., 2021. Drivers of seedling establishment success in dryland restoration efforts. Nat. Ecol. Evol. https://doi.org/10.1038/s41559-021-01510-3.
Shackleton, R.T., Le Maitre, D.C., Van Wilgen, B.W., Richardson, D.M., 2017. Towards a national strategy to optimise the management of a widespread invasive tree (*Prosopis* species; mesquite) in South Africa. Ecosyst. Serv. 27, 242–252.
Shaw, J., 1875. On the changes going on in the vegetation of South Africa through the introduction of the merino sheep. Bot. J. Linn. Soc. 14, 202–208.
Shippey, K., Mukanya, R., Van Staden, F., 2018. . State of Environment Outlook Report for the Western Cape Province | Executive Summary. Department of Environmental Affairs and Development Planning (DEAandDP), Cape Town.
Skead, C.J., 2007. In: Boshoff, A.F., Kerley, G.I.H., Lloyd, P.H. (Eds.), Historical Incidence of the Larger Land Mammals in the Broader Eastern Cape, 2nd edn., Vol. 1. Port Elizabeth, Centre for African Conservation Ecology, Nelson Mandela Metropolitan University, Port Elizabeth.
Skead, C.J., 2011. In: Boshoff, A.F., Kerley, G.I.H., Lloyd, P.H. (Eds.), Historical Incidence of the Larger Land Mammals in the Broader Northern and Western Cape, 2nd edn., Vol. 2. Port Elizabeth, Centre for African Conservation Ecology, Nelson Mandela Metropolitan University, Port Elizabeth.
Smith, A.B., 1983. Prehistoric pastoralism in the Southwestern Cape, South Africa. World Archaeol. 15, 79–89.
Smith, N., Wilson, S., 2002. Changing land use trends in the thicket biome: pastoralism to game farming. Report No. 38. Terrestrial Ecology Research Unit, University of Port Elizabeth, Port Elizabeth.
Snijders, D., 2015. Shifting Species in South Africa - Wildlife Policy, Rural Consequences. PhD Thesis. Vrije Universiteit, Amsterdam.
Snyman, H., 2000. Soil-Water Utilisation and Sustainability in a Semi-arid Grassland Water SA 26, pp. 333–341.
Snyman, H.A., 2003. Revegetation of bare patches in a semi-arid rangeland of South Africa: an evaluation of various techniques. J. Arid Environ. 55, 417–432.
Snyman, H.A., Van Rensburg, W.L.J., 1986. Effect of slope and plant cover on run-off, soil loss and water use efficiency of natural veld. J. Grassl. Soc. South. Afr. 3, 153–158.
Stafford Smith, M., Cribb, J., 2009. Dry Times. Blueprint for a Red Land. CSIRO Publishing, Collingwood, Victoria.
Stroebel, D.H., Thiart, C., De Wit, M., 2019. Towards defining a baseline status of scarce groundwater resources in anticipation of hydraulic fracturing in the Eastern Cape Karoo, South Africa: salinity, aquifer yields and groundwater levels. In: Ofterdinger, U., Macdonald, A.M., Comte, J.-C., Young, M.E. (Eds.), Groundwater in Fractured Bedrock Environments: Managing Catchment and Subsurface Resources., vol. 479. Geol. Soc. Spec. Publ., pp. 129–145
Talbot, W.J., 1961. Land utilization in the arid regions of southern Africa. Part I: South Africa. In: Stamp, L.D. (Ed.), A History of Land Use in Arid Regions, vol. 17. Arid Zone Res., pp. 299–338
Tanner, K.E., Moore-O'Leary, K.A., Parker, I.M., Pavlik, B.M., Hernandez, R.R., 2020. Simulated solar panels create altered microhabitats in desert landforms. Ecosphere 11 (4), e03089. https://doi.org/10.1002/ecs2.308.
Thompson, M., Vlok, J., Rouget, M., Hoffman, M.T., Balmford, A., Cowling, R.M., 2009. Mapping grazing-induced degradation in a semi-arid environment: a rapid and cost effective approach for assessment and monitoring. Environ. Manage. 43, 585–5596.
Todd, S.W., Hoffman, M.T., 2009. A fence line in time demonstrates grazing-induced vegetation shifts and dynamics in the semiarid Succulent Karoo. Ecol. Appl. 19, 897–908.
Todd, S., Milton, S., Dean, R., Carrick, P.J., Meyer, A., 2009. Ecological Best-Practice Livestock Production Guidelines for the Namaqua District. Arid Zone Ecology Forum. Accessed 2021.03.15. http://www.azef.co.za/pdf/Grazing_Guidelines_Draft.pdf.
Toerien, D., Du Rand, G., Gelderblom, C., Saayman, M., 2016. Impacts on tourism in the Karoo. In: Scholes, R., Lochner, P., Schreiner, G., Snyman-Van der Walt, L., De Jager, M. (Eds.), Shale Gas Development in the Central Karoo: A Scientific Assessment of the Opportunities and Risks. CSIR/IU/021MH/EXP/2016/003/A, ISBN 978-0-7988-5631-7. CSIR, Pretoria. Available at. http://seasgd.csir.co.za/scientific-assessment-chapters/.
Torres, L., Abraham, E.M., Rubio, C., Barbero-Sierra, C., Ruiz-Pérez, M., 2015. Desertification research in Argentina. Land Degrad. Develop 26, 433–440.
Turpie, J.K., Marais, C., Blignaut, J.N., 2008. The working for water programme: evolution of a payments for ecosystem services mechanism that addresses both poverty and ecosystem service delivery in South Africa. Ecol. Econ. 65, 788–798.
Tyson, P.D., 1987. Climatic Change and Variability in Southern Africa. Oxford University Press, Cape Town.
UN, 2019. United Nations General Assembly, Resolution 73/284 United Nations Decade on Ecosystem Restoration (2021-2030). https://undocs.org/A/RES/73/284.
Van den Berg, L., Kellner, K., 2005. Restoring degraded patches in a semi-arid rangeland of South Africa. J. Arid Environ. 61, 497–511.
Van der Merwe, C.R., 1930. Eradication of prickly pear. Farming S. Afr. 5, 165–168.
Van der Merwe, J.P.A., Kellner, K., 1999. Soil disturbance and increase in species diversity during rehabilitation of degraded arid rangelands. J. Arid Environ. 41, 323–333.
Van der Merwe, H., Milton, S.J., 2019. Growth in three Karoo shrub species under various grazing treatments: the tracking of marked individuals over 25 years. Afr. J. Range Forage Sci. 36, 61–66.
Van der Merwe, P., Saayman, M., 2003. Determining the economic value of game farm tourism. Koedoe 46, 103–112.
Van der Merwe, H., Du Toit, J.C.O., Van den Berg, L., O'Connor, T.G., 2018. Impact of sheep grazing intensity on vegetation at the Arid Karoo Stocking Rate Trial after 27 years, Carnarvon, South Africa. J. Arid Environ. 155, 36–45.
Van der Merwe, H., Milton, S.J., Dean, W.R.J., O'Connor, T.G., Henschel, J.R. in press. Developing an environmental research platform in the Karoo at the Square Kilometre Array (SKA). South African Journal of Science.

Van der Walt, J.L., 1971. Voorlopige verslag oor die reaksie van dorre karooveld op beweiding gedurende spesifieke jaargetye: boesmangrasveld. Proc. Ann. Congr. Grassl. Soc. South. Afr. 6, 82–85.
Van Deventer, H., 2021. Monitoring changes in South Africa's surface water extent for reporting Sustainable Development Goal sub-indicator 6.6.1.a. S. Afr. J. Sci. 117. Art. #8806.
Van Eeden, J.D., Lubke, R.A., Haarhoff, P., 2007. Return of natural, social and financial capital to the hole left by mining. In: Aronson, J., Milton, S.J., Blignaut, J.N. (Eds.), Restoring Natural Capital: Science, Business, and Practice. Society for Ecological Restoration International. Island Press, Washington, pp. 198–207.
Van Rooyen, M.W., Le Roux, A., Van der Merwe, H., Van Rooyen, N., Geldenhuys, C., 2018. Long-term vegetation change (&20 years) in the plains habitat on the Goegap Nature Reserve, Succulent Karoo, South Africa. Afr. J. Range Forage Sci. 35, 289–302.
Van Sittert, L., 1998. "Keeping the enemy at bay": the extermination of wild Carnivora in the Cape Colony, 1889-1910. Environ. Hist. 3, 333–356.
Van Sittert, L., 2000. The seed blows in every breeze: noxious weed eradication in the Cape Colony 1860-1909. J. South. Afr. Stud. 26, 655–674.
Van Sittert, L., 2002a. Our irrepressible fellow-colonist: the biological invasion of prickly pear (*Opuntia Ficus-indica*) in the Eastern Cape c.1890±c.1910. J. Hist. Geogr. 28, 397–419.
Van Sittert, L., 2002b. Holding the line: the rural enclosure movement in the Cape Colony, c. 1865-c. 1910. J. Afr. Hist. 43, 95–118.
Van Sittert, L., 2004. The Supernatural State: water divining and the Cape underground water rush, 1891-1910. J. Soc.Hist. 37, 915–937.
Van Sittert, L., 2016. Routinising genocide: the politics and practice of vermin extermination in the Cape Province c.1889–1994. J. Contemp. Afr. Stud. 34, 111–128.
Van Wilgen, N.J., Herbst, M. (Eds.), 2017. Taking Stock of Parks in a Changing World: The SANParks Global Environmental Change Assessment. SANParks, Cape Town.
Van Wyk, E., 2010. Tax incentives for biodiversity conservation in the Western Cape. Meditari Account. Res. 18, 58–75.
Ventura, A.C., Andrade, J.C., 2013. Polyculture in the semi-arid regions of Brazil. Field Actions Science Reports [Online], Special Issue 3 | 2011, Online since 19 April 2013, connection on 30 April 2019. URL: http://journals.openedition.org/factsreports/2557.
Vernon, C.J., 1999. Biogeography, endemism and diversity of animals In the Karoo. In: Dean, W.R.J., Milton, S.J. (Eds.), The karoo – Patterns and Processes. Cambridge University Press, Cambridge, pp. 57–86.
Versfeld, D.B., Le Maitre, D.C., Chapman, R.A., 1998. Alien invading plants and water resources in South Africa: a preliminary assessment. WRC Report No. TT 99/98, CSIR No. ENV/S-C 97154. Water Research Commission, Stellenbosch.
Veth, P., Smith, M., Hiscock, P., 2005. Desert Peoples: Archaeological Perspectives. Blackwell, Malden, USA.
Vetter, S., 2009. Drought, change and resilience in South Africa's arid and semi-arid rangelands. S. Afr. J. Sci. 105, 29–33.
Vicente-Serrano, S.M., Beguerias, S., Lopez-Moreno, J.I., 2010. A multiscalar drought index sensitive to global warming: the Standardized Precipitation Evapotranspiration Index. J. Climate 23, 1696–1718.
Wagner, T.C., 2011. The Lithium future - resources, recycling, and the environment. Conserv. Lett. 4, 202–206.
Walker, C., Milton, S.J., O'Connor, T.G., Maguire, J.M., Dean, W.R.J., 2018. Drivers and trajectories of social and ecological change in the Karoo, South Africa. Afr. J. Range Forage Sci. 35, 157–177.
Walters, M., Figueiredo, E., Crouch, N.R., Winter, P.J.D., Smith, G.F., Zimmermann, H. G., Mashope, B.K., 2011. Naturalised and invasive succulents of southern Africa. ABC Taxa 11. SANBI, Pretoria.
Weber, B., Tamm, A., Maier, S., Rodríguez-Caballero, E., 2018. Biological soil crusts of the Succulent Karoo: a review. Afr. J. Range Forage Sci. 35, 335–350.
Westermann, A., 2020. Enrichment and dilution in the Atacama mining Desert. Writing History from an Earth-Centered Perspective. Geschichte und Gesellschaft 46, 634–661. https://doi.org/10.13109/gege.2020.46.4.634. Published Online:Feb 2021.
Western Cape Treasury , Provincial Economic Review and Outlook. Report PR242/2020. 2020; ISBN: 978-0-621-48657-2.
Westoby, M., Walker, B., Noy-Meir, I., 1989. Opportunistic management for rangelands not at equilibrium. J. Range Manage. 42, 266–274.
Wheeler, A., Knight, A.T., Vetter, S., 2015. Examining the evidence for ecologically sustainable ostrich breeding practices on natural veld in the Little Karoo, South Africa. Afr. J. Range Forage Sci. 32, 233–241.
Wheeler, A., Knight, A.T., Difford, M., Vetter, S., 2019. Ostrich farmer characteristics predict conservation opportunity. S. Afr. J. Sci. 115, 5540.
Wiegand, T., Milton, S.J., 1996. Vegetation change in semiarid communities - simulating probabilities and time scales. Vegetatio 125, 169–183.
Wiegand, T., Milton, S.J., Wissel, C., 1995. A simulation model for a shrub-ecosystem in the semi-arid Karoo, South Africa. Ecol. 76, 2205–2221.
Wise, R.M., Van Wilgen, B.W., Le Maitre, D.C., 2011. Costs, benefits and management options for an invasive alien tree species: the case of mesquite in the Northern Cape, South Africa. J. Arid Environ. 84, 80–90.
Wise, R.M., Reyers, B., Guo, C., Midgley, G.F., De Lange, W., 2012. Costs of expanding the network of protected areas as a response to climate change in the Cape Floristic Region. Conserv. Biol. 26, 397–407.
Woodroffe, R., Hedges, S., Durant, S.M., 2014. To fence or not to fence. Science 344, 46–48.
Zachariades, C., Hoffmann, J.H., Roberts, A.P., 2011. Biological control of mesquite (*Prosopis* species) (Fabaceae) in South Africa. Afr. Ent. 19, 402–415.
Ziervogel, G., New, M., Archer Van Garderen, E., Midgely, G., Taylor, A., Hamann, R., Stuart-Hill, S., Myers, J., Warburton, M., 2014. Climate change impacts and adaptation in South Africa. WIREs Climate Change 2014. www.10.1002/wcc.295.