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Repairing compound damage in arid ecosystems – challenges and controversies

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Using the Karoo as an example, we discuss past agricultural damage to the arid ecosystems, which is currently being followed by environmental changes and biodiversity losses associated with the new role of desert ecosystems as power factories (gas, uranium, wind and sun energy), mineral resources or retreats from the city. Development-related damage includes road building, vegetation clearing, soil compaction, water extraction and pollution. We present our views on prospects for ecologically and socially appropriate rehabilitation to rebuild complex and resilient ecosystems where recovery rate is constrained by aridity and rainfall unpredictability. We conclude that, to achieve intergenerational equity and conserve unique ecosystems, considerable investment in arid zone rehabilitation is needed to keep pace with the demands of a rapidly growing human population.

Keywords: **Karoo, land degradation, mining, ecological restoration, biodiversity conservation, development.**

INTRODUCTION

Characterized by high inputs of solar energy, shortage of fresh water and low agricultural productivity, the arid regions of the world are mostly sparsely inhabited, of low value in national economies, and are low priorities for government investment in solutions to human or ecological problems. Many of the world's arid and semi-arid regions, including parts of Australia, southern Africa, China, and North and South America, have been damaged over the past 200 years by interactions of domestic livestock management practices with climate and soil processes in these fragile regions (Illius & O'Connor, 1999; Hoffman & Todd, 2000; Reynolds *et al.*, 2007). Future threats to the integrity of arid land landscapes, their natural capital and endemic fauna and flora may be unrelated to farming, but driven by the growing global need for minerals and energy. In desert areas of Australia, Bolivia, Chile, China, India, Israel, Mongolia, Peru, north Africa and North America, there is rapidly growing investment in hydrocarbon (US Energy Information Administration, 2013) and mineral resources (Gratzfeld, 2003; Asian Development Bank, 2014), and in the renewable energy sectors (Levitan, 2013; Shahan, 2014; Desertec Foundation, 2014). In South Africa there are many pending applications for the development of wind and photo-voltaic power stations, for mining of copper, titanium, phosphate, gypsum and uranium, and for prospecting for natural gas in the arid Karoo region. This paper briefly describes the semi-desert Karoo region of southern Africa, land degradation caused by past and present landuse, and the risks posed by new energy-related developments, before making the case for ecological rehabilitation in this and other unproductive but biodiverse ecosystems.

LANDSCAPE, CLIMATE AND BIODIVERSITY

The vast, rugged, sparsely-populated landscapes of the Karoo have tremendous emotional and aesthetic appeal. In the absence of highways and industrial developments, the only sounds are those of birds, insects and wind – in fact the greatest asset of the region has sometimes been described as "die niks" or nothingness (Le Maitre *et al.*, 2009). The Karoo is an arid to semi-arid inland area making up about one third of the area of South Africa. It comprises two distinct biomes (Figures 1 and 2), namely Succulent Karoo and Nama Karoo (Cowling & Hilton-Taylor, 1999; Vernon, 1999). Succulent Karoo is restricted to narrow, inter-montane valleys 200–600 m above sea level (a.s.l.). The Nama Karoo comprises stony and sandy plains and small igneous inselbergs, mainly on an inland plateau 800–1600 m a.s.l. There is a gradient in rainfall amount (100–450 mm), variability and seasonality from the more arid winter rainfall Succulent Karoo in the southwest of the region north eastward through the Nama Karoo that receives mostly summer rainfall (Desmet & Cowling, 1999).

The flora of the Succulent Karoo is exceptionally rich with 40% endemicity (Table 1), and holds one third of the world's succulent plant species (Cowling & Hilton-Taylor, 1999; Cowling 2002). Diversity of miniature succulents (435 spp.) and geophytes (630 spp.) is unusually high (Figure 3). The Succulent Karoo is classified as an "Endangered" ecosystem because only 3% of the area is formally protected and transformed by high levels of grazing disturbance, and development is a threat to biodiversity (Cowling, 2002). By contrast, the colder Nama Karoo region is characterized by grasses and dwarf, small-leaved evergreen shrubs, particularly Asteraceae (Table 1). The biodiversity of the Nama Karoo region is considered vulnerable because <1% of the area is formally protected (Seymour, 2002). Endemic succulent plants and bulbs are associated with sheltered stable microsites such as cracks and ledges in mudstone outcrops or ephemeral pans (Seymour, 2002, Figure 4).

The Succulent and Nama Karoo have a diverse reptile fauna rich in endemic species of tortoises, lizards, chamaeleons and snakes (Table 1). High levels of diversity and endemism are found in some invertebrate groups including scorpions, spiders, solifuges, flightless grasshoppers, as well as pollinating flies, bees and wasps with life-histories closely linked with

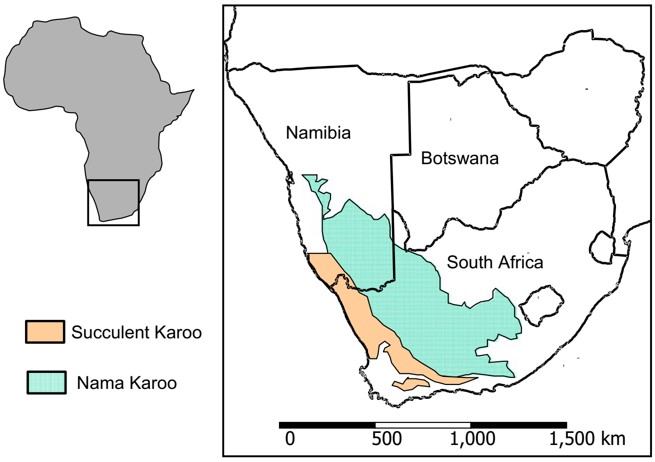

Figure 1. Geographical distribution of Succulent Karoo and Nama Karoo (from Dean, 1995).

those of annual and geophytic plants that flower in response to rain. Whereas many birds and some mammals escape harsh physical conditions and drought by nomadism (Dean, 2004), most small mammals, reptiles and invertebrates survive waterless times and temperature extremes through aestivation and use of burrows or rock crevices (Lovegrove, 1999). The Aardvark *Orycteropus afer*, a large (60 kg) ant and termite-feeding mammal that digs deep burrow systems, is a keystone species in Karoo areas, facilitating the survival and breeding of many species of reptiles, foxes, cats, porcupines, providing nest sites for the endemic South African Shelduck *Tadorna cana* and hive sites for honeybees.

HOW PASTORALISM AND SETTLED AGRICULTURE CHANGED THE KAROO

In common with arid areas on other continents, the Karoo was prehistorically grazed by nomadic game. Around 2000 years ago, game were supplemented by sheep flocks of transhumant pastoralists (Sampson, 1986; Smith, 1999). In the C18th, colonization by Europeans with guns, crops, ox-drawn vehicles and a tradition of settlement and commercial farming, soon resulted in the loss of nomadic grazers, large predators, mammalian and avian scavengers (vultures) and hunter-gatherer cultures (Dean & Milton, 2003). The advent of wire fencing, technology for extracting underground water and markets for wool in Europe led to a boom in sheep farming and the development of rural villages, mostly dependent on ground-water, serving the farming economy (Beinart, 2003). Within a century, in an environment characterized by droughts, flash floods and shallow, fine-textured soils, high stocking densities, in combination with clearing of alluvium for subsistence cropping, had caused soil erosion (Keay-Bright & Boardman, 2006), salinization and widespread, persistent changes in vegetation composition (Milton *et al*., 1994; Decker *et al*., 2011). Drought-tolerant forage plants (*Opuntia ficus-indica, Prosopis* spp., *Atriplex nummularia*) introduced from other continents to replace lost forage plants became invasive, forming impenetrable thickets that excluded forage grasses (Van Sittert, 2000; Milton & Dean, 2010).

Passive recovery of vegetation following overgrazing, ploughing, invasive vegetation clearing and other forms of land degradation, fails to take place within human life-spans because of demographic inertia, rare recruitment events, loss of seed banks or changes in the biophysical environment (shade, soil surface roughness, infiltration rate). In some areas overgrazing leads to dominance of very long-lived indigenous unpalatable shrubs that exclude other species for decades or centuries. Recruitment of perennial plant seedlings is uncommon in the drier parts of the Karoo as it depends on a coincidence of rain events that promote flowering, seeding, germination and seedling survival.

Perennial vegetation may take centuries to re-establish on exposed soil surfaces because water runs off bare ground too rapidly to infiltrate, and seeds and organic matter blow away where there are no existing plants to reduce wind speed and trap resources (Milton *et al*., 1994). Excellent examples of slow recovery from vegetation loss in Karoo landscapes, even for areas of 250 m^2 or less, are the pre-European sheep kraal sites of indigenous herders (Sampson, 1986). Despite abandonment for some 250 to 300 years, these sites remain unvegetated and eroded (Figure 5).

SOCIO-ECONOMIC DRIVERS OF NEW DEVELOPMENTS IN THE KAROO

Changes in the global economy, including the falling wool price and the widespread economic recession, together with national trends such as a rapid increase in the human population, unemployment and rising costs of fuel and electricity, are currently driving changes in landuse in the Karoo (Atkinson, 2008, 2009, undated; Western Cape Government, 2014). Sheep farms that are no longer economically viable are being consolidated and converted to game farms for hunting and tourism, often with absentee owners. With the demise of the farming economy rural villages are losing services (banks, schools, hospitals) despite growing populations (Toerien & Seaman, 2010). Unemployment is on the increase and most rural families depend on government

Figure 2. Typical landscapes of Succulent Karoo (left) and Nama Karoo (right) biomes.

Table 1. Biodiversity attributes of the Succulent and Nama regions of the Karoo.

Attribute	Nama Karoo	Succulent Karoo	Source
Area (km^2 x10)	198.5	112.2	Cowling & Hilton-Taylor (1999)
Plant species (% endemic)	~2200 (18%)	~5000 (40%)	Cowling & Hilton-Taylor (1999)
Dominant families	Asteraceae Poaceae Liliaceae	Asteraceae Aizoaceae Liliaceae	Cowling & Hilton-Taylor (1999)
Mammal species (% endemic)	83 (3.6%)	78 (10%)	Vernon (1999)
Bird species (% endemic)	186 (4.3%)	226 (2%)	Vernon (1999)
Reptile species (% endemic)	91 (6.6%)	115 (35%)	Vernon (1999)
Scorpion species (% endemic)		50 (44%)	
Percent in protected areas	<1%	2.5%	http://www.worldwildlife.org/ecoregions/at1314 http://www.worldwildlife.org/ecoregions/at1322
WWF Vulnerability rating	Vulnerable	Critical/endangered	http://www.worldwildlife.org/ecoregions/at1314 http://www.worldwildlife.org/ecoregions/at1322
Threats	Overgrazing, mining (gas, uranium), invasive alien plants, renewable energy facilities	Overgrazing, arable agriculture, mining (heavy metals, gypsum), settlements, succulent collection, climate change	http://www.worldwildlife.org/ecoregions/at1314 http://www.worldwildlife.org/ecoregions/at1322

grants (Atkinson 2009, Western Cape Government, 2014). Such socioeconomic problems are not unique to the Karoo, but characteristic of many arid regions (Reynolds *et al*., 2007).

THE KAROO AS A SOURCE OF RENEWABLE AND NON-RENEWABLE ENERGY

Given this bleak social scenario, the rising oil price, and the national need for foreign revenue and the supply of cheaper energy for industrial and urban development, many nations are exploring solar, wind, nuclear, oil and gas, hydraulic and thermal energy alternatives. Deserts are often targeted for the production of solar and wind energy because of their low human population density, and high frequency of windy and cloudless days (Levitan 2013, Desertec Foundation 2014). The damage caused by grazing and ploughing will therefore soon be compounded by infrastructure development. As West (1982) pointed out "…. deserts and semi-deserts are regarded as wasteland or at least a sacrifice area in terms of placement of 'nuisance' activities." In its latest strategy document, the South African Department of Energy (2012) is encouraging the development of energy resources to supplement existing, but inadequate, coal burning power stations and issuing new regulations for proposed gas and nuclear energy developments. Many solar and wind energy plants are already under construction in the Karoo, uranium prospecting is under way, and gas prospecting is set to begin in 2015 (De Wit, 2011). Within the next decade, Karoo landscapes will have been transformed by solar and wind farms, uranium mines and hydraulic fracturing to extract shale gas, of which South Africa apparently has the largest reserve on the African continent (US Energy Information Administration, 2013).

All development activities would involve vegetation clearing, compaction and linear infrastructure such as roads, power lines and cables. Such infrastructure will change the sense of place of the Karoo, as well as having negative effects on plant and animal species. Compaction and levelling permanently removes specialized habitats such as rock crevices, cracks and pebble patches that are habitat for specialized succulents, geckos, tortoises, scorpions and trapdoor spiders in Karoo landscapes. Roads and increased traffic of heavy vehicles increase the roadkill risk for many slow-moving animals, including tortoises and the Riverine Rabbit (*Bunolagus monticularis*), a Critically Endangered species. Wind turbines and overhead cables are responsible for mortality of bats and birds – especially large threatened species such as Blue Crane *Anthropoides paradisea*, Kori Bustard *Otis kori*, Black Stork *Ciconia nigra*, Secretary Bird *Sagittarius serpentarius* and Marshall Eagle *Polemaetus bellicosus* (Bevanger, 1998; Barnes, 2000).

Mining options would additionally necessitate ground water extraction, storage of "produced" or extracted water contaminated with radioactivity or heavy metals from deep geological strata as well as with mining additives, and disposal of such water with concomitant risks for aquifer and surface water pollution (De Wit, 2011, Council of Canadian Academies, 2014, Warner *et al*., 2014). The high cost and inadequate outcomes of land rehabilitation in arid areas (Crookes & Blignaut, 2012), together with the groundwater dependency of the human population, forces the government and international companies into the moral dilemma of deciding whether future Karoo landuse options, such as livestock and wildlife ranching or tourism (Atkinson,

Figure 3. Diversity of Mesembryanthemum (Aizoaceae) species in Succulent Karoo.

2009, Le Maitre *et al*., 2009), should be traded for quick solutions to the national energy crisis based on uranium and gas deposits that may last for only a few decades.

THE CASE FOR BASELINE RESEARCH, MONITORING, MITIGATION AND ECOLOGICAL RESTORATION IN THE KAROO

Some degree of repair of the physical and biological components of natural environments damaged by engineering activities is essential both for retaining biodiversity and for restoring the ecosystem services that control floods and dust storms, recharge aquifers and maintain the productivity, resilience and aesthetic qualities of the Karoo. Although the words "rehabilitation" and "restoration" are generally used to refer to environmental repair interventions, they refer to different intentions or endpoints. The intention of rehabilitation is the return of ecosystem processes, productivity and services, whereas the goal of restoration is the return of both ecosystem services and the composition of plant and animal communities to the pre-disturbance state or facilitate their recovery over time (Society of Ecological Restoration, 2004). To achieve inter-generational equity, natural capital must be rebuilt fast enough to keep pace with current human development needs (Aronson *et al.*, 2007). This is particularly challenging economically in arid areas where the rate of ecosystem recovery is limited by rainfall (Tinley & Pringle, 2014), so that the cost of restoration may greatly exceed the

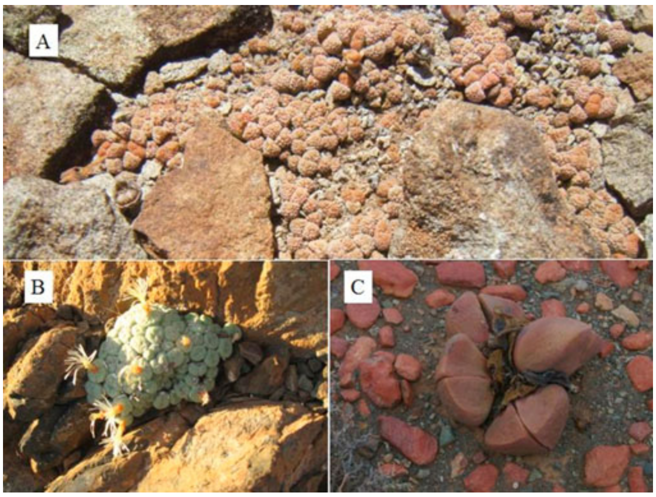

Figure 4. Nama Karoo succulents protected by surrounding rocks from frost, desiccation and herbivory.

Figure 5. Khoekhoen sheep kraal abandoned around 250 ybp.

Figure 6. Approaches to improving water infiltration and reducing windspeed during rehabilitation of bare soil in the Karoo (A) pits and mulch (Photo W. Matthee), (B & C) Pits and water barriers, (D) ripping and sowing of grass seed, and (E) topsoiling with wind barriers.

current value of the land or its annual production (Blignaut *et al.*, 2013).

An annual rehabilitation plan, monitoring and progress reports towards a stated closure vision are requirements under new regulations for financial provisions for rehabilitation after mining or prospecting is proposed (South African National Environmental Management Act, proposed amendment in November 2014). Closure visions are often difficult to set realistically because the Karoo is poorly researched. Although there are broad-scale vegetation (Mucina & Rutherford, 2006) and groundwater maps (Murray *et al.*, 2012), there is a need for spatially explicit, fine scale, environmental baseline data. For example, there is very limited information on vegetation composition, cover and grazing capacity at farm scale. There are few data on densities and population dynamics of apparent keystone animals such as ants, termites and the aardvark, whose sheltering burrows may enable numerous other species to survive in the Karoo. Data on surface and ground-water quality, fluctuations in groundwater depth, recharge rates, and aquifer connections are based on broad scale extrapolations (Murray *et al.*, 2012). In addition, there is no database that documents the effects of various rehabilitation interventions on recovery of function or composition of Karoo ecosystems under differing edaphic, climatic conditions and topographic conditions. Such data, essential for guiding mitigation and restoration, are scarce for all aspects of the physical, biological, cultural or aesthetic landscape likely to be impacted by mining and energy developments. The immediate challenges are to collect, store and make accessible appropriate baseline data to inform mitigation and restoration targets, to establish meaningful impact monitoring approaches and to develop effective rehabilitation for fragile but unproductive ecosystems with complex biodiversity.

There is no fool-proof recipe for returning sustainable landscape function and biodiversity to arid areas within a matter of decades. International and local reviews concur that recovery of sustainable natural vegetation under arid conditions depends on the use of fresh topsoil, and maximizing the effectiveness of rainfall and using locally adapted plant species (Coetzee, 2005; Carrick & Kruger, 2007; Bainbridge, 2007; Tinley & Pringle, 2014). Documented revegetation trials in the Karoo (Snyman, 2003; Visser *et al.*, 2004; van den Berg & Kellner, 2005; Simons & Allsopp, 2007; Burke, 2008) have attempted to maximize water infiltration and retention through ripping, digging of hollows, brush or stone packing, mulching, use of erosion mesh and vegetation “sieves” to retard runoff water and trap seed (Figure 6). Gypsum and hydrogels may be added to soils (Beukes & Cowling, 2003). Reseeding is sometimes supplemented by replanting and is used to facilitate the return of local species and processes (Anderson *et al.*, 2004). Even in relatively low diversity plant communities, and with considerable corporate investment in soil restoration and reseeding, rehabilitated areas may lack key functional plant groups, particularly late successional species which may need to be reintroduced using propagated plants (Pauw, 2011).

Faunal return to degraded and mined landscapes in the Karoo has barely been investigated. Ant species that depend on a narrow range of food resources are slower to return to rehabilitated mine sites than are omnivores (Netshilaphala *et al.*, 2005), and flightless locusts are slow to recolonize areas treated with insecticide during locust extermination operations (Stewart, 1998). Fauna that depend on stable soil surfaces, rock crevices or other special substrates (tortoises, geckos, scorpions, trapdoor spiders), or have close links with a narrow suite of plant species (specialized bees, wasps and pollinating flies) are also vulnerable to vegetation change (Gess, 2001) and are likely to be slow to return to rehabilitated sites.

Despite sound environmental legislation (Van der Linde, 2006), rehabilitation and restoration is not always effectively implemented, and there are no incentives for companies to exceed minimum requirements. Leaving restoration until project closure will certainly result in failure. Restoration toward resilient ecosystems takes decades under arid conditions so that endpoints should be phased and informed by adaptive management approaches (Pauw, 2011, 2012).

HOW NEW DEVELOPMENT COULD HELP REPAIR PAST DAMAGE

In our opinion, there should be an additional rehabilitation requirement for companies extracting non-renewable resources (minerals, uranium, gas, rock, gypsum, diamonds) from the Karoo, namely, that they should mitigate past environmental damage caused by livestock management by purchasing and maintaining a buffer around the mine or drill pad. During the grazing rehabilitation period (at least two decades under arid conditions) domestic livestock should be excluded from the buffer area, soil erosion works should be built if necessary, invasive alien plant species should be removed and seeds of lost forage species could be reintroduced. Good condition rangeland in buffer areas would not only fix carbon, but would function as a refuge and seed reserve, facilitating vegetation and faunal recovery after closure of mining or drilling activities in the core area. Such buffer areas should be large enough to support viable populations of key animal species (i.e. at least 2000 ha in the most arid parts of the Karoo).

CONCLUSION

Deserts are fragile environments. Vegetation and substrate damage initiates a cascade of events including dust storms, flooding, gully formation, salinization of soil, losses of plant and animal species. This cascade is difficult and costly to contain or reverse. And yet few governments can afford to leave the energy resources (sun, wind, uranium, gas) of deserts untapped because of the demands of rapid growth in human populations and consumption levels. Working in harmony or at odds, today's developers, policy makers, conservation planners, restoration practitioners and law enforcement officials will influence the future face of the Karoo.

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REFERENCES

ANDERSON, P., HOFFMAN, M.T. & HOLMES, P.M. 2004. The potential of *Cephalophyllum inaequale* (L. Bolus) for the restoration of degraded arid landscapes in Namaqualand, South Africa. *Restoration Ecology* 12: 343–351.

ARONSON, J., MILTON, S.J. & BLIGNAUT, J.N. (Eds) 2007. *Restoring Natural Capital: Science, business and practice*. Washington, DC, Island Press.

ASIAN DEVELOPMENT BANK 2014. *Demand in the Desert: Mongolia's water–energy–mining nexus*. Mandaluyong City, Philippines, Asian Development Bank.

ATKINSON, D. 2008. A Review of International Arid Areas Research Agencies. The implications for investment in the Karoo, Kalahari and Namaqualand. Eastern Cape Socio-Economic Consultative Council (ECSECC).

ATKINSON, D. 2009. Towards cross-border collaboration in desert areas – lessons for the Karoo. Karoo Development Conference, 26–27 March 2009, Graaff-Reinet.

ATKINSON, D. (undated). A multi-causal analysis of local economic development: The example of Graaff-Reinet, Eastern Cape. Unpublished paper available from http://www.aridareas.co.za/publishedarticles.html

BAINBRIDGE, D.A. 2007. *A Guide for Desert and Dryland Restoration: New Hope for Arid Lands*. Washington, DC, Island Press.

BARNES, K.N. (Ed.) 2000. *The Eskom Red Data book of birds of South Africa, Lesotho and Swaziland*. Avian Demography Unit, University of Cape Town.

BEINART, W. 2003. *The Rise of Conservation in South Africa – Settlers, livestock and the environment 1770–1950*. New York, Oxford.

BEUKES, P.C. & COWLING, R.M. 2003. Evaluation of restoration techniques for the succulent Karoo, South Africa. *Restoration Ecology* 11: 308–316.

BEVANGER, K. 1998. Biological and conservation aspects of bird mortality caused by electricity power lines: a review. *Biological Conservation* 86(1): 67–76.

BLIGNAUT, J., DE WIT, M., MILTON, S.J.; ESLER, K. J., LE MAITRE, D., MITCHELL, S. & CROOKES, D. 2013. A market for ecosystem goods and services following the restoration of natural capital: Volume 1: Main Report. Water Research Commission Report 1803/1/13, ISBN No. 978-1-4312-0435-9. www.wrc.org.za (accessed 20 February 2015).

BURKE, A. 2008. The effect of topsoil treatment on the recovery of rocky plain and outcrop plant communities in Namibia. *Journal of Arid Environments* 72: 1531–1536.

CARRICK, P.J. & KRUGER, R. 2007. Restoring degraded landscapes in lowland Namaqualand: Lessons from the mining experience and from regional ecological dynamics. *Journal of Arid Environments* 70: 767–781.

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

COUNCIL OF CANADIAN ACADEMIES, 2014. *Environmental Impacts of Shale Gas Extraction in Canada*. The Expert Panel on Harnessing Science and Technology to Understand the Environmental Impacts of Shale Gas Extraction, Council of Canadian Academies, Ottowa. http://www.scienceadvice.ca/uploads/eng/assessments%20and%20publications%20and%20news%20releases/Shale%20gas/ShaleGas_fullreportEN.pdf

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*. Pp 42–56. Cambridge, Cambridge University Press.

COWLING, S. 2002. Succulent Karroo. In Olson, D.M. & Dinerstein, E., The Global 200: Priority eco-regions for global conservation. *Annals of the Missouri Botanical Garden* 89(2): 199–224. http://www.worldwildlife.org/ecoregions/at1322 (accessed 20 February 2015).

CROOKES, D.J. & BLIGNAUT, J.N. 2012. Market challenges for the restoration of the natural environment. Trade and Industry Policy Strategies. http://www.tips.org.za (accessed 20 February 2015).

DE WIT, M.J. 2011. The great shale debate in the Karoo. *South African Journal of Science* 107(7/8): 1–9.

DEAN, W.R.J. 1995. Where birds are rare or fill the air: the protection of the endemic and the nomadic avifaunas of the Karoo. Unpublished PhD thesis, University of Cape Town. 298 pp.

DEAN, W.R.J. 2004. *Nomadic desert birds. Adaptations of Desert Organisms series*. Berlin, Springer Verlag.

DEAN, W.R.J. & MILTON, S.J. 2003. Did the flora match the fauna? Acocks and historical changes in Karoo biota. *South African Journal of Botany* 69(1): 68–78.

DECKER, J.E., NIEDERMANN, S. & DE WIT, M.J. 2011. Soil erosion rates in South Africa compared with cosmogenic 3He-based rates of soil production. *South African Journal of Geology* 114: 475–488.

Desertec Foundation. 2014. http://www.desertec.org/ (accessed 10 February 2015).

Desmet, P.G. & Cowling, R.M. 1999. The climate of the karoo – a functional approach. In Dean, W.R.J. & Milton, S.J. (Eds), *The Karoo – Ecological Patterns and Processes*. Pp. 3–16. Cambridge, Cambridge University Press.

Gess, S.K. 2001. The Karoo, its insect pollinators and the perils which they face. International Pollinator Initiative (IPI) Case Study. www.ecoport.org/EP.exe$EAFull?ID=35 (accessed 17 November 2014)

Gratzfeld, J. (Ed.) 2003. Extractive Industries in Arid and Semi-Arid Zones: Environmental Planning and Management. IUCN, Gland, Switzerland. https://portals.iucn.org/library/efiles/documents/CEM-001.pdf (accessed 21 February 2015).

Hoffman, M.T. & Todd, S. 2000. A national review of land degradation in South Africa: the influence of biophysical and socioeconomic factors. *Journal of Southern African Studies* 26: 743–758.

Illius, A.W. & O'Connor, T.G. 1999. On the relevance of nonequilibrium concepts to arid and semi-arid grazing systems. *Ecological Applications* 9(3): 798–813.

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.

Le Maitre, D., O'Farrell, P., Milton, S.J., Atkinson, D., De Lange, W., Egoh, B., Reyers, B., Colvin, C., Maherry, A. & Blignaut, J. 2009. Assessment and evaluation of ecosystem services in the Succulent Karoo biome. Report prepared for the Succulent Karoo Ecosystem Programme (SKEP) Coordination Unit. Report CSIR/NRE/ECO/ER/2009/0043/B available from CSIR, Stellenbosch.

Levitan, D. 2013. Is anything stopping a truly massive build-out of desert solar power? *Scientific American*, 1 July 2013. http://www.scientificamerican.com/article/challenges-for-desert-solar-power/ (accessed 20 February 2015).

Lovegrove, B.G. 1999. Animal form and function. In Dean, W.R.J. & Milton, S.J. (Eds), *The Karoo – Ecological Patterns and Processes*. Pp. 145–163. Cambridge, Cambridge University Press.

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

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(2): 70–76.

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

Murray, R., Baker, K., Ravenscroft, P., Musekiwa, C. & Dennis, R. 2012. A groundwater-planning toolkit for the main Karoo basin: Identifying and quantifying groundwater-development options incorporating the concept of wellfield yields and aquifer firm yields. *Water SA* 38: 407–416.

National Environmental Management Act: Regulations (2014). Financial provision for rehabilitation, closure and post closure of prospecting, exploration, mining or production operations. South African Government Gazette No. 38145. http://www.gov.za/documents/national-environmental-management-act-regulations-financial-provision-rehabilitation (accessed 15 February 2015).

Netshilaphala, N.M., Milton, S.J. & Robertson, H.G. 2005. Response of an ant assemblage to mining on the arid Namaqualand coast, South Africa. *African Entomology* 13: 162–167.

Pauw, M.J. 2011. Monitoring Ecological Rehabilitation on a Coastal Mineral Sands Mine in Namaqualand, South Africa. Unpublished MSc thesis, Stellenbosch University.

Pauw, M. 2012. Policy Brief ASSET Research TIPS 5 – Implications of the regulatory landscape for the restoration of natural capital. Trade and Industrial Policy Strategies. http://www.tips.org.za (accessed 17 November 2014).

Reynolds, J.F., Stafford Smith, D.M., Lambin, E.F., Turner, B.L. II, Mortimore, M., Batterbury, S.P.J., Downing, T.E., Dowlatabadi, H., Fernandez, R.J., Herrick, J.E., Huber-Sannwald, E., Jiang, H., Leemans, R., Lynam, T., Maestre, F.T., Ayarza, M. & Walker, B.. 2007. Global desertification: building a science for dryland development. *Science* 316: 847–851.

Sampson, C.G. 1986. Veld damage in the Karoo caused by its pre-trekboer inhabitants: preliminary observations in the Seacow Valley. *The Naturalist* 30: 37–42.

Seymour, C. 2002. Nama Karroo. In Olson, D.M. & Dinerstein, E. 2002. The Global 200: Priority ecoregions for global conservation. *Annals of the Missouri Botanical Garden* 89(2):199–224. http://www.worldwildlife.org/ecoregions/at1314 (accessed 20 February 2015).

Shahan, C. 2014. Chile Solar Power Plant Is Now Latin America's Largest. Clean Technica. http://cleantechnica.com/2014/06/09/chile-solar-power-plant-latin-america-largest-solar-power-plant/ (accessed 20 February 2014).

Simons, L. & Allsopp, N. 2007. Rehabilitation of rangelands in Paulshoek, Namaqualand: Understanding vegetation change using biophysical manipulations. *Journal of Arid Environments* 70: 755–766.

Smith, A. 1999. Hunters and herders in the karoo landscape. In Dean, W.R.J. & Milton, S.J. (Eds), *The Karoo – Ecological Patterns and Processes*. Pp. 243–256. Cambridge, Cambridge University Press.

Snyman, H.A. 2003. Revegetation of bare patches in a semi-arid rangeland of South Africa: an evaluation of various techniques. *Journal of Arid Environments* 55: 417–432.

Society for Ecological Restoration (SER) 2004. Society for Ecological Restoration International Science & Policy Working Group. 2004. The SER International Primer on Ecological Restoration. http://www.ser.org.

South African Department of Energy. Revised Strategy 2011/12–2015/16. http://www.energy.gov.za

Stewart, D.A.B. 1998. Non-target grasshoppers as indicators of the side-effects of chemical locust control in the Karoo, South Africa. *Journal of Insect Conservation* 2: 263–276.

Tinley, K. & Pringle, H. 2014. *Rangeland Rehydration 1: Field Guide*. Printline Graphics, Freemantle, Western Australia.

Toerien, A.F. & Seaman, M.T. 2010. The enterprise ecology of towns in the Karoo, South Africa. *South African Journal of Science* 106: 25–34.

United States Energy Information Administration. 13 June 2013. *Technically Recoverable Shale Oil and Shale Gas Resources: An Assessment of 137 Shale Formations in 41 Countries Outside the United States*. http://www.eia.gov/analysis/studies/worldshalegas/ (accessed 17 November 2014).

van den Berg, L. & Kellner, K. 2005. Restoring degraded patches in a semi-arid rangeland of South Africa environments. *Journal of Arid Environments* 61: 497–511.

Van der Linde, M. (Ed.) 2006. Compendium of South African Environmental Legislation. Pretoria University Law Press, Pretoria.

Van Sittert, L. 2000. The seed blows about in every breeze: noxious weed eradication in the Cape Colony, 1860–1909. *Journal of Southern African Studies* 26(4): 655–674.

Vernon, C.J. 1999. Biogeography, endemism and diversity of animals. In Dean, W.R.J. & Milton, S.J. (Eds), *The Karoo – Ecological Patterns and Processes*. Pp 57–85. Cambridge, Cambridge University Press.

Visser. N., Botha, J.C. & Hardy, M.B. 2004. Re-establishing vegetation on bare patches in the Nama Karoo, South Africa. *Journal of Arid Environments* 57: 15–37.

Warner, N.R., Darrah, T.H., Jackson, R.B., Millot, R., Kloppmann, W., & Vengosh, A. 2014. New tracers identify hydraulic fracturing fluids and accidental release from oil and gas operations. *Environmental Science & Technology* 20 October 2014. dx.doi.org/10.1021/es5032135

West, N.E.1982. Comparisons and contrasts between the temperate deserts and semi-deserts of three continents. In: West, N.E. (Ed.), *Ecosystems of the World. 5. Temperate Deserts and Semideserts*. Pp. 461–471. Amsterdam, Elsevier.

Western Cape Government Provincial Treasury. 2014. Socio-economic Profile Central Karoo District. www.westerncape.gov.za (accessed 20 February 2015).