Journal of Arid Environments 70 (2007) 767–781

Journal of Arid Environments

www.elsevier.com/locate/jaridenv

Restoring degraded landscapes in lowland Namaqualand: Lessons from the mining experience and from regional ecological dynamics

P.J. Carrick*, R. Krüger

Department of Botany, Institute for Plant Conservation, University of Cape Town, Private bag, Rondebosch 7701, South Africa

Received 28 September 2005; received in revised form 25 July 2006; accepted 16 August 2006
Available online 9 November 2006

Abstract

Three-quarters of a century ago diamond mining was added to livestock grazing and cereal cropping as a serious cause of landscape degradation in the north-western semi-arid region of South Africa, Namaqualand. Since that time the activities of diamond mine operators and prospectors have eclipsed all other land uses as a cause of degradation in this region. Discontinuous patches along virtually all of the 400 km of the Namaqualand coastline have been, or are currently, being mined or prospected. Prior to 1992 little was done to restore the landscapes and ecosystems to their pre-mining state, but since then legislation has placed a clear responsibility for restoration on mining operators. Implementation of ecological restoration was initially slow, but has recently gained momentum, in line with a growing awareness of environmental responsibilities amongst the global mining industry. In general, autogenic recovery of the perennial vegetation does not take place. The low annual rainfall and prevailing strong windy conditions present the greatest climatic challenges to the restoration of the flora. While the unique vegetation, and its features (e.g. poor representation of perennial species in the seedbank) present challenges to understanding the interventions that are critical in achieving ecological restoration. At the same time, climatic conditions such as the strong seasonality and low variability of rainfall, together with floristic features such as the high incidence of succulence, and the extraordinary drought tolerance of many seedlings, present opportunities for restoration. Perhaps the greatest challenges to restoration derive from the unsuitability of much of the mined overburden soils for plant growth. The nature and importance of climatic conditions, mined soils, topsoils, soil nutrients, landscaping, seedbanks, seeding, transplantation, and the

*Corresponding author. Tel.: +021 650 5789; fax: +021 650 4046.
E-mail addresses: carrick@botzoo.uct.ac.za (P.J. Carrick), Rkruger@botzoo.uct.ac.za (R. Krüger).

0140-1963/$ - see front matter
doi:10.1016/j.jaridenv.2006.08.006

interactions between these and other factors are evaluated in the context of this semi-arid environment and the prevailing mining practices.

Keywords: Soils; Wind erosion; Seedbanks; Patch dynamics; Succulent karoo; Semi-arid

1. A brief history of mining and restoration in Namaqualand

People have derived their livelihoods from the Namaqualand region for millennia. Approximately 2000 years ago, hunter-gathering started to give way to the widespread herding of sheep and goats (Webley, 2007). The impact of these activities on the ecosystems of Namaqualand is unknown, but the impacts are likely to have increased dramatically in the early 1800s when both the indigenous people of Namaqualand, and the newly arrived farmers of European descent, began clearing and ploughing patches of land in order to plant grain crops (Jowell and Folb, 2004). It is the unusual mineral wealth of Namaqualand, however, that led to the most intense human impact on its ecosystems.

High grade copper was discovered at Springbok in 1850, and the residents of Namaqualand, together with new immigrants, began mining in earnest in 1852 (Jowell and Folb, 2004). Copper deposits were later mined at a number of sites in the uplands of Namaqualand (Jowell and Folb, 2004). In 1925, as the era of copper mining was drawing to a close, diamonds were discovered in marine terraces at Oubeep, near Port Nolloth. A number of discoveries along the west coast, both north and south of Oubeep, followed in 1926 (Carstens, 2001). Since that time the landscape of the west coast of Namaqualand has been altered extensively in search of diamonds. Discontinuous patches along virtually all of the 400 km between the Olifants River in the south, and the Gariep (Orange) River in the north, have been, or are currently being mined or prospected. This represents about half of the 800 km of coastline along the west coast of South Africa (from Cape Point to the Gariep River). However, public access is restricted to most of this area. Similar degradation continues north of Namaqualand, along the west coast of Namibia as far as Luderitz, which has a slightly longer history of diamond mining (diamonds were first discovered there in 1907; Cornell, 1986). While terrestrial diamond mining (there are also marine diamond mining operations), has taken place almost exclusively within a few kilometres of the coast and the major rivers, gypsum and heavy mineral mining (primarily for titanium) have, more recently, extended the degradation of the Namaqualand lowlands further inland (de Villiers et al., 1998; Schmidt, 2002). In this paper we will focus on past and current degradation, and the potential restoration of the ecologically distinct Namaqualand lowlands, an area that stretches inland from the west coast 100 km or more to the base of the escarpment (Namaqualand uplands).

While there has been a relatively long history of degradation of Namaqualand's ecosystems, there has been a very short history of restoration of these ecosystems. Only since the Minerals Act 50 of 1991 came into effect has there been legislation that expressly requires the holders of mining and prospecting permits to restore the land surface to its natural state. Legislation has been further strengthened by the Mineral and Petroleum Resources Development Act 28 of 2002 which is more comprehensive and explicit than the previous act. Although the implementation of ecosystem restoration practices among mining operators was initially slow, it has recently gained momentum, in line with a growing awareness amongst the global mining industry of their environmental responsibilities (Hobbs and Harris, 2001; Mining and Minerals Sustainibility Survey, 2001).

The aim of ecological restoration is to ''repair ecosystems with respect to their health, integrity, and self-sustainability'' (Society for Ecological Restoration International Science and Policy Working Group, 2004). With the exception of early copper mining, virtually all the major operations in Namaqualand are surface mining operations. This inevitably involves the destruction of ecological communities over a large area. Part of the difficulty in advancing restoration techniques lies in the lack of adequate documentation of past efforts. It is therefore very difficult to assess what was been done before and whether it was successful or not. On the other hand, in the past two decades an ever-increasing number of scientifically rigorous ecological studies have been conducted in the region with the aim of understanding the underlying ecosystem functioning. Certain aspects of these studies are directly applicable to restoration, which together with environmental reports for mining operators, and lessons from the international experience of areas with similar conditions, allow us to begin a detailed discussion of the dynamics involved in each stage of restoration. While low rainfall is frequently considered a primary obstacle to the ecological restoration of the vegetation of lowland Namaqualand, strong and persistent winds, extreme soil conditions, and features of the unique vegetation are likely to be at least as important. Challenges and opportunities that relate to these four factors are discussed in the sections that follow.

2. Flora, rainfall and autogenic recovery

Although tailings dumps that result from the processing of mineral deposits may reach very large proportions (Fig. 1), the majority of the landscape degradation takes place at the mining surface. Current mining practice is to use new overburden to backfill recently mined areas (Desmet, 1996; Mahood, 2003). In the past backfilling was not the norm and the land surface along most of the Namaqualand coast is scarred by mine blocks (areas, frequently many hectares in size that have been systematically mined), and more frequently by numerous prospecting trenches that may be 10–500 m or more in length, and 2–30 m or more in depth. In the past, mined excavations and dumps were usually either left as is, or were simply flattened, and were left to natural devices of recovery, without intervention. On most soil types, with the exception of the partially mobile dune sands immediately adjacent to the coast, the result was little or no natural vegetation establishment and little long-term recovery (le Roux and Odendaal, 1992; Lanz, 1997).

The notion that insignificant autogenic recovery occurs in lowland Namaqualand is supported by a number of research studies. le Roux and Odendaal (1992) surveying overburden dumps from diamond mining in the coastal regions concluded that autogenic recovery is insufficient for the natural vegetation to re-establish on its own. Schmidt (2002) analysed gypsum mined sites further inland and concluded that the recovery of mined areas was not correlated with the time since mining was terminated.

The poor establishment success of plants, and hence the poor recovery of the vegetation is frequently blamed on the very low annual rainfall of lowland Namaqualand. The Namaqualand lowlands receive less than 200 mm mean annual rainfall, and most of the northern parts, less than 100 mm, falling predominantly in winter, with hot dry summers

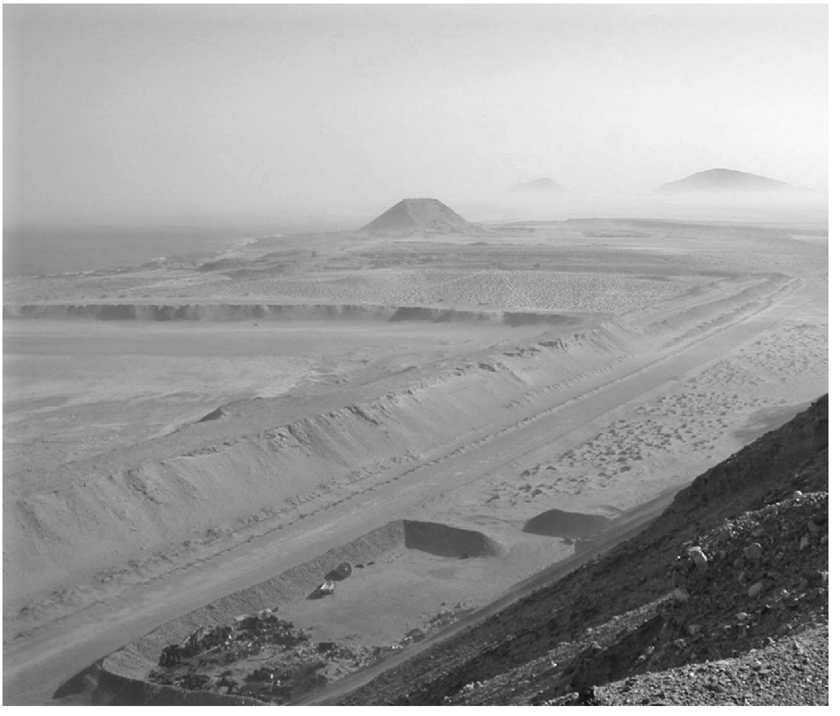

Fig. 1. Coarse residue, or gravel, dumps (near and far distance) and fine residue, or slimes, holding dams (middle distance) resulting from diamond strip-mining operations on the northern Namaqualand coast can reach extremely large proportions.

(Desmet and Cowling, 1999). While there is considerable variation in the timing and quantity of rainfall from year to year, relative to other semi-arid environments both the season and quantity of rainfall between years is unusually consistent (Hoffman and Cowling, 1987). Another factor that militates against the extremeness of the climatic conditions is that the winter temperatures are relatively mild, and are usually not low enough to prohibit plant growth during the wet winter season (Cowling et al., 1999).

The floristically diverse Namaqualand lowlands comprises two major vegetation types: Strandveld forms a narrow strip that may extend inland of the beach and coastal dunes up to 10 km (or more in the north), and consists mainly of succulent and non-succulent shrubs from a variety of families; Succulent Karoo (Sandveld) extends 50–100 km (and more in the south) inland to the Namaqualand uplands at the escarpment, and consists predominantly of leaf-succulent shrubs in the Mesembryanthemaceae/Aizoaceae (Acocks, 1988). Both lowland Namaqualand vegetation types have been described in more detail elsewhere (e.g. Boucher and le Roux, 1981; Acocks, 1988; Cowling et al., 1994; Milton et al., 1997).

In the past rehabilitation was attempted with exotic agricultural plants (and techniques), e.g. rye and sorghum (Halbich, 2003). It is a basic tenet of biology that the relative severity of the environmental conditions experienced by any organism depends on the adaptations of that organism to the prevailing environmental conditions (Darwin, 1890). The environmental conditions facing exotic species in Namaqualand are undoubtedly extreme, and as a result their survival has frequently been dependent on additional interventions e.g. irrigation (Halbich, 2003). The same environmental conditions are likely to be far less extreme for plants that are indigenous to this area.

The unique flora of Namaqualand is dominated in terms of abundance by shallow-rooted leaf-succulent shrubs (principally Mesembryanthemaceae), which are specifically adapted to the prevailing environmental conditions (Cowling et al., 1994; Cowling et al., 1999). Two key adaptations are the ability to optimally benefit from the unusually high number of small rainfall events in Namaqualand by accessing water available in very shallow soil (Carrick, 2001, 2003), and the exceptional drought tolerance of seedlings which facilitates establishment under low-rainfall conditions (Esler and Phillips, 1994; Carrick, 2001). In contrast, the seedlings of many of Namaqualand's non-succulent shrubs are less drought tolerant (Esler and Phillips, 1994; Carrick, 2001), require the right sequence of rainfall for successful establishment, and may fail to establish in most years (Milton, 1995). The opportunities to develop restoration methods specifically for the prevailing environmental condition, using the indigenous flora, have only just begun to be explored.

There are numerous physical factors that influence vegetation establishment and recovery. The mean annual rainfall the northern end of the Namaqualand coastline is well below 100 mm, yet Alexander Bay, in the north, receives a mean of 67 fog days a year, and Port Nolloth around 100 km to the south receives 148 (data from the South African Weather Service). Since this fog penetrates only a short distance inland, proximity to the coast and therefore moisture in the form of fog, greatly influences the total amount of water available to establishing plants (Desmet and Cowling, 1999).

The scale of degradation is another factor that greatly affects the probability of recovery. Smaller areas of degradation, e.g. roads, are more likely to recover naturally as a result of reduced wind erosion, greater input of seeds from surrounding vegetation, and a greater edge-to-area ratio. Large degraded areas have a relatively small contact zone with the surrounding vegetation, and wind speeds are greater due to lack of resistance from vegetation. Greater wind speeds result in greater erosion rates and also mean that the few seeds that blow into the area are not readily trapped, and therefore the chances of establishing are very low (Harvey, 2000; Dong et al., 2001; Anderson et al., 2004).

3. Soil relocation, landscaping and wind

The most obvious sign of landscape degradation is an alteration in the topography of the mined area. As a consequence of the huge scale of earth removal and relocation that occurs during surface mining, the first step in attempting to restore the area to its natural state is to landscape the topography so that it matches that of the surrounding areas. While backfilling mining areas adds aesthetic value by blending in with the surrounding landscape, the correct topography is also necessary for the long-term stability of slopes as well as for vegetation to establish successfully (Schor and Gray, 1995). The long-term stability of a slope usually depends on its ability to reduce the impact of maximum water flow, and therefore erosion (Nicolau, 2003). Even in Namaqualand's low-rainfall climate occasional bursts of heavy rain can cause considerable damage to bare slopes. However, the primary erosive force in lowland Namaqualand is wind. The prevailing wind is a very strong southerly wind, and is most intense nearest the coast where it is experienced on most days of the year. A strong easterly, or 'berg wind', caused by high pressure systems on the inland plateau blows only intermittently, usually during winter and spring. Berg winds are most intense inland and dissipate to some extent by the time they reach the coast. However, berg winds have a great ecological impact as the dynamic warming of the subsiding air is responsible for the highest maximum temperatures in lowland Namaqualand (Desmet and Cowling, 1999). The long-term stability of bare slopes therefore will depend primarily on their ability to reduce the impact of maximum wind speed, and thus wind erosion.

Landscaping to the natural topography can reduce the impact of wind. Before vegetation can establish, however, bare surfaces are particularly vulnerable to wind erosion, and it is therefore important to incorporate preventative measures during the initial stages of restoration. A number of techniques have been tried, including the use of straw bales, but rows of shade-cloth placed at perpendicular angles to the prevailing wind have proved most successful in lowland Namaqualand (Halbich, 2003). Systematic trials have achieved the optimum reduction in wind erosion from 40% density shade-cloth erected at a height of 750 mm perpendicular to the prevailing wind direction at intervals of 6 m (Halbich, 2003). Wind-breaks decrease the wind-speed at ground level, thus trapping sand blown in from adjacent patches, as well as seeds and light organic matter (Harvey, 2000; Dong et al., 2001; Anderson et al., 2004). This provides a sheltered microhabitat where seeds can germinate in soils with a higher organic content, which can lead to the development of a 'fertile-island' and patch dynamics that concentrate resources and are vital to ecological functioning in semi-arid environments (Garcia-Moya and McKell, 1970; Aguiar and Sala, 1999). These wind-breaks are also incidentally beneficial in that they act as fog-traps, the increased condensation thereby concentrating the water input along wind-breaks (Halbich, 2003).

Soil surface topography at a smaller scale (microtopography) also plays an important ecological role (Fig. 2). Uneven microtopography is a feature of the natural environment, and it creates crucial small-scale concentrating and dispersing dynamics for water, nutrients and seeds (Burke, 2003). Creating furrows perpendicular to the slope reduces

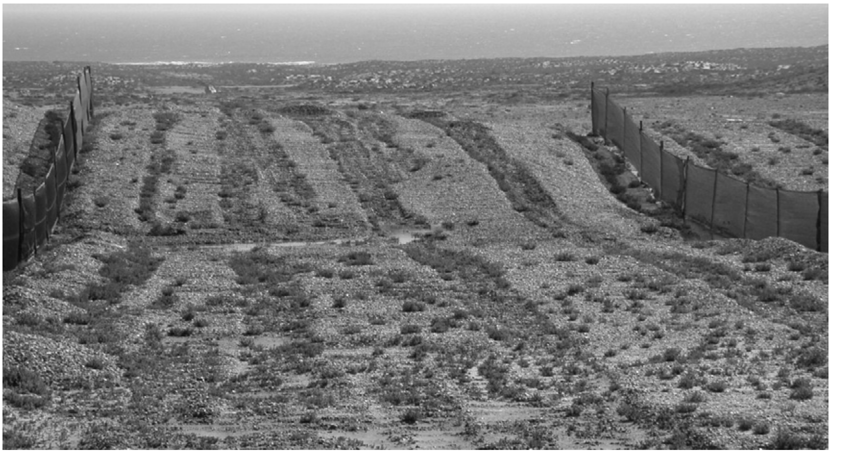

Fig. 2. Restoration trials at a diamond mining operation on the Namaqualand coast make use of shade-netting to limit wind erosion, and the microtopography created by the spreading of coarse-tailings (gravel) and the tracks of bulldozers enhance the establishment of early-succession plants on overburden soils.

water and wind erosion, as well as providing depressions where water, organic matter and seeds can accumulate (Tongway and Hindley, 2004). Tilling the soil additionally ameliorates compaction of the soil that has been subject to heavy mining machinery, and improves soil aeration (Burke, 2003). In experiments conducted in the neighbouring summer-rainfall Nama Karoo, tilled soils provided a more suitable environment for the establishment of vegetation. Establishment was further enhanced by seeding and brush-packing, which reduces wind erosion and creates a more sheltered micro-climate (Visser et al., 2004). On balance it seems most beneficial to till immediately after relocating and landscaping a mined area with overburden soils. There are some benefits to tilling the soil after the re-application of topsoil, but these are offset by the risk of mixing soil layers, and their associated conditions.

4. Topsoils, mined soils and soil processes

Overburden soils can be excavated from depths of 30 m or deeper, and such soils comprise a sterile growth medium, devoid of nutrients, and depending on the clay content, are of high salinity and often phytotoxic (Desmet, 1996). Even shallow overburden soils are largely depleted of nutrients, and all soils that have been through processing plants are greatly depleted of nutrients and, at least initially, are of a high salinity. All of these soils constitute unsuitable media for the establishment of plants, except in some cases for a few salt-tolerant species (de Villiers et al., 1992). These soils require either the re-application of suitable growth media, i.e. topsoils, or intensive and dramatic soil amelioration.

The interactions between salinity, soils and plants are complex. de Villiers et al. (1992) found that germination on saline mined soils was high for salt-tolerant species such as *Atriplex lindleyi* (62%) and *Cheiridopsis* sp. (81%), but lower than 50% for the other 18 species in the study (mostly under 15%). Germination and biomass production was negatively influenced by watering with saline water in all species, except *A. lindleyi* (de Villiers et al., 1992). Various methods for ameliorating saline soil conditions have been tried. Of these, the application of gypsum and mulches has received the most attention. On Nama Karoo soils with a fairly high clay fraction, Beukes and Cowling (2003) found that gypsum (at $5\,\mathrm{t\,ha^{-1}}$) and gypsum-plus-mulching treatments produced the highest germination of seeds over 4 years in a randomized seeding experiment. However, survival was lower in the gypsum only treatment than in the gypsum-plus-mulching treatment. Infiltration was increased by mulching, and even more so by gypsum, thus further assisting in the leaching of salts. Scott and Johnston (1995) working on Namaqualand coastal sands, found that gypsum and sulphuric acid were good soil ameliorates, and that gypsum reduced surface sealing or crust formation, but that they were less effective than simply leaching with fresh water. Leaching with 100 mm of water was effective in reducing the sodium concentration and the sodium absorption ratio, which implies that soils leach well with the equivalent of one season's rainfall. The efficacy of leaching is determined principally by the clay fraction of the soil. Where there is very little fine-texture material in the sands phytotoxic concentrations of salt can be leached within 1–2 years, even under the prevailing semi-arid conditions (Scott and Johnston, 1995). However, it appears that even a moderate fine-texture fraction within the soil (e.g. clay $>10\%$) will bind the salts within the soils and are likely to require the application of gypsum, or some other substance with high sodium affinity that will preferentially bind the salts, before they can be leached (Lanz, 1997). In general the shallow soils immediately adjacent to the coast have an insignificant clay fraction and are easily leached, but inland overburden soils may contain levels of clay that bind salts forming a chemical crust that prevents plant establishment, and erodes rapidly under wet conditions (Scott and Johnston, 1995). The benefits of gypsum need to be weighed against the financial costs, and the environmental costs associated with mining gypsum elsewhere. Moreover, by far the most important factor in successful restoration is the application of topsoil (Guidelines for Mining in Arid Environments, 1996; Rokich et al., 2000; Schmidt, 2002).

Apart from containing the seedbank of the plant community, topsoil contains communities of micro-organisms, fungi and soil fauna that are responsible for soil processes (e.g. nutrient cycling) and function in a range of facultative and obligatory interactions with the vegetation and other organisms. The biologically active upper layer of soil is fundamental in the development of soils, and the sustainability of the entire ecosystem (Guidelines for Mining in Arid Environments, 1996; Tongway and Hindley, 2004). On the soil surface fungi, algae, cyanobacteria and non-vascular plants form a 'living crust' that influences the retention of resources (principally nutrients and water), as well as reducing the potential for soil erosion. The ability of a landscape to retain and recycle existing resources within the system is correlated with the health and sustainability of that system (Tongway and Hindley, 2004).

While the time since termination of mining was not correlated with measures of vegetation recovery at inland lowland Namaqualand sites, the time since application of topsoil was correlated with recovery in terms of plant cover, species richness and species diversity (Schmidt, 2002).

The two most important aspects to consider in removing topsoil are the depth of soil to remove as topsoil, and the conditions for storing topsoil. Studies on the Namaqualand coast indicate that the top 5 cm of soil contains 90% of the seed bank (de Villiers et al., 1994; de Villiers, 2000). However, there are difficulties in mechanically removing such shallow layers of soil. Moreover, the biologically active and nutrient enriched layer extends well beyond 5 cm. Since the soils in semi-arid areas contain very little organic matter (Whitford, 1999), and there is little stratification in the sandy soils of lowland Namaqualand, delineating the topsoil layer with precision is not always easy (Lanz, 1997). There is a trade-off between losing too much of the nutrient enriched, biologically active soil, and diluting and irretrievably burying much of the seedbank. A solution that has been used with much initial success by one mining operator on the Namaqualand coast is to remove both a shallow seedbank topsoil layer, and a deeper biologically active 'subsoil' layer separately, and re-apply them in the corresponding order. This method has enhanced restoration success in the semi-arid regions of Australia (Guidelines for Mining in Arid Environments, 1996).

Ideally, removed topsoil should be re-applied immediately (Sweeting and Clark, 2000). This requires careful planning and co-ordination from mining operators to ensure that sufficient mined areas are backfilled and prepared for the application of topsoil in advance of the removal of new topsoil and the opening up of new areas to mining. However, there are situations in which this is not possible. Storing topsoil for long periods leads to seedbank depletion following germination during storage, and anoxic conditions develop inside large storage heaps (Strohmayer, 1999). Even in small storage heaps it is likely that a high proportion of the micro-organisms, fungi and soil biota are killed. Allied with the loss of biological communities is a significant depletion in soil nutrients. Both at inland and coastal lowland Namaqualand sites, any relocation or stockpiling of topsoil reduced the concentrations of a range of nutrients (Schmidt, 2002; Mahood, 2003). These reductions appear to progress further over the first few months of stockpiling, and are reflected in the reduced productivity of bio-assay plants on these soils (Schmidt, 2002; Mahood, 2003). Recommendations for minimizing topsoil depletion are based on the experiences of British coal mines and mines of various types in Australia, which are broadly in keeping with the limited analyses that have been conducted in Namaqualand, i.e. that soil should be stored less than 1 m deep and for less than 1 month (Strohmayer, 1999; Schmidt, 2002).

The role of nutrients, particularly nitrogen, remains poorly prioritized in South African semi-arid regions (Whitford, 1999), and in semi-arid regions generally (Garcia-Moya and McKell, 1970; Goldberg and Novoplansky, 1997). The addition of nutrients without additional water increased the growth rates of the two most common species in the Namaqualand uplands (Carrick, 2001), and four out of five species common on the Namaqualand coast (de Villiers et al., 1992). Where topsoils have been stored for a long period of time, slow release fertilizers can be added to partially allay the effect of leaching that occurs during storage (Anderson, 1995).

Patch dynamics within the soil, particularly the 'fertile-islands' that are built up beneath perennial plants, are an integral feature of semi-arid systems (Garcia-Moya and McKell, 1970; Aguiar and Sala, 1999), and have been found in Namaqualand wherever communities have been examined, including Namaqualand upland communities that have been severely degraded by clearing and excessive grazing, and little perturbed communities in the Namaqualand uplands (Allsopp, 1999; Carrick, 2001) and along the Namaqualand coast (Stock et al., 1999).

Fertile-islands develop by the concentrating action of long-lived plants or a succession of plants that occupy the same clump. The roots of semi-desert plants typically extend well beyond their canopies into the open spaces between plant canopies (e.g. Cannon, 1911; Carrick, 2001). Nutrients absorbed from this wide soil area are concentrated in the plant canopies and ultimately collect beneath plants in the form of litter, where the nutrients are recycled locally enriching the soil beneath the canopies (Garcia-Moya and McKell, 1970). Enrichment is also a consequence of perennials and clumps reducing wind speed and surface water flow trapping sediment and organic material (Aguiar and Sala, 1999; Tongway and Hindley, 2004).

Throughout the Succulent Karoo, with the exception of the coarsest sandy soils, a second and unique concentrating mechanism operates at a larger scale. The action of termites that may occupy the same nest area for millennia has served to concentrate nutrients within the soils of the shallow subterranean nest sites, as the termites gather organic material from an area significantly larger than the nest area (Dean and Yeaton, 1993). The nest area mounds may be 30 m or more in diameter, 1 m high, and are known in the region as 'heuweltjies' (Midgley and Musil, 1990; Dean and Yeaton, 1993). The soils of heuweltjies have significantly increased water holding capacity, pH, micro- and macro-nutrients, especially nitrogen, and are habitats that are frequently disturbed, particularly by fossorial animals. As a result, plant communities on heuweltjies are distinct from those of the surrounding vegetation (Midgley and Musil, 1990; Dean and Yeaton, 1993).

While heuweltjies do not occur in coarse Strandveld sands, clumping is extremely pronounced in this vegetation type. Long-lived shrubs are not dispersed regularly or randomly within the landscape but are strongly aggregated, with little specific affinity among species within clumps (Eccles et al., 1999). Protection from wind abrasion and trampling by herbivores are the speculative drivers of this pattern (Eccles et al., 2001).

Concentrated patches of organic material and nutrients within the soil are often necessary for the successful establishment and growth of many species, but these fertile-islands are homogenized within the soil when the topsoil is removed (Schmidt, 2002; Mahood, 2003). Methods of recreating these patches when distributing topsoil have been little explored in restoration practices to date. Simple techniques, e.g. not spreading topsoil evenly, may improve restoration. The new physical and biotic concentrating dynamics that develop with restoration contribute to the development of new plant and animal communities. However, alteration of the fine-scale aggregation patterns within soil is likely to be primary among the reasons that post-restoration communities do not exactly resemble the pre-mining communities (Carrick and Desmet, 2004).

5. Seedbanks, seeding and transplantation

We have stressed the importance of topsoil in conserving the seedbank. In this variable environment plants with short life-histories are likely to be reliant on spreading the risk of establishment through time and space (Esler, 1999). Dispersal spreads the risk through space, while seed dormancy spreads the risk through time.

Understanding of seedbank dynamics on the Namaqualand coast has been greatly advanced in the last 10 years. There is a high predictability that the top 5 cm of soil will contain the majority of the seed bank (de Villiers et al., 1994; de Villiers, 2000), but simply applying this topsoil to a well prepared restoration site does not result in the same species richness and diversity as the surrounding areas (de Villiers et al., 2001). A primary reason for this is that not all plants produce dormant (i.e. soil stored) seeds. A study in coastal Namaqualand indicated that the seedbank represents only about 50% (108 out of 230) of the species in standing vegetation (de Villiers et al., 2001). The four most abundant species in the seedbank were annuals, while the most abundant species in the standing vegetation were perennials (de Villiers et al., 2001). The tendency for annuals and pauciennials to exhibit seed dormancy, while perennials do not, has been well established for Namaqualand (von Willert et al., 1992; Esler, 1999). The seedbank is thus dominated by short-lived species, while the standing vegetation mostly consists of perennial species (Esler, 1999; de Villiers et al., 2001). Post-mining recruitment from the seedbank would therefore be biased in favour of short-lived species, which does not necessarily facilitate long-term vegetation recovery.

The tendency also is for short-lived, early-succession species to have effective long distance dispersal mechanisms and to produce large numbers of seeds (von Willert et al., 1992). Seed dispersal distances for Namaqualand's perennial species are typically short (Esler, 1999), further contributing to the difficulties in re-establishing diverse perennial communities. The Asteraceae and Mesembryanthemaceae are the two largest families of plants in lowland Namaqualand, and together dominate most communities in terms of composition and structure (Cowling et al., 1999). These two families reflect a general pattern in the flora as a whole. Seeds of most of the Asteraceae are dispersed by wind, yet appear usually to travel only a few metres before they are trapped beneath other shrubs (Esler, 1999). Wind dispersed seeds will travel greater distances across bare ground, but natural establishment is likely to only be effective on small degraded areas near a good seed source, and the degraded areas will have to contain some wind barriers. The seeds of Mesembryanthemaceae and other species that are not wind dispersed travel even shorter distances. Around 98% of Mesembryanthemaceae species have hygrochastic capsules that only release their canopy-stored seeds when wet (Esler, 1999). This is effective at releasing seeds at times that are conducive for establishment, and explains their lack of soil-dormancy. Rain provides the mechanism for dispersal, but it is unlikely that this effects dispersal beyond 2 m (Esler, 1999).

Restoration ecologists in Namaqualand cannot rely solely on the seedbank and seed dispersal. In order for restored sites to achieve similar species richness, composition, vegetation structure and ecosystem functioning as the undisturbed sites, many perennial species need to be introduced in some way. The most cost-effective and least labour-intensive way of doing this is likely to be by seeding.

Obtaining seeds from the vegetation in close proximity to the rehabilitation site (or from the site itself prior to mining), ensures that the right combination of seeds are available for the site (Burke, 2003). Moreover, locally adapted genotypes are likely to be better suited to the conditions, and conserve the genetic integrity of local populations and the genetic diversity of the entirety of populations (Lesica and Allendorf, 1999).

In a strongly seasonal environment the timing at which seeding takes place is important. A 4-year field-study in the southern Succulent Karoo demonstrated that seed germination and emergence on degraded rangelands are principally affected by soil moisture during the cool season (autumn to spring), while plant survival is principally affected by follow-up rainfall (Beukes and Cowling, 2003). Ideally seeding should therefore pre-empt the rainy season (Burke, 2003), which would optimize the number of sown seeds that are available for germination, since there would be less opportunity for granivory by rodents, ants or birds, and a smaller likelihood of mechanical removal by wind. Seed loss due to germination following an atypical summer rainfall event would also be minimized, although many species (both annual and perennial) have after-ripening physiological dormancy that lasts about 6 months, in order to avoid out-of-season germination (van Rooyen and de Villiers, 2004).

The fantastic richness and abundance of succulent species in Namaqualand (about 10% of the world's succulents occur in Namaqualand; Van Jaarsveld, 1987) provides opportunities for restoration. Many succulents respond well to transplantation, and ideally plants could be relocated from pre-mined sites to post-mined sites to avoid unnecessary damage to natural populations (Mahood, 2003; Burke, 2005). The benefits of transplantation include greater compositional and structural diversity, greater soil stability, and attaining later-successional community structure more rapidly (Mahood, 2003). The greater soil stability offered by larger plants may reduce the effect of mobile sand which prevents seedlings from establishing, as well as providing a seed source for the area (de Villiers et al., 2001). Assuming pollinator interactions are functioning on restoration sites, transplantation will be particularly beneficial in the case of species that do not have seed dormancy, since a fresh supply of viable seeds would be provided periodically by the mature transplants. The large plants increase the diversity of microhabitats, act as nurse plants for seedlings, and provide nodes for the development of 'fertile islands' and other patch dynamics within the community (Aguiar and Sala, 1999). In addition to transplantation trials on the Namaqualand coast (e.g. Mahood, 2003), considerable experience has been gained of the suitability of southern Namib plant groups to transplantation that can be readily applied in lowland Namaqualand (Burke, 2005).

Transplantation requires fairly intensive labour and time commitments, which increases the expense of restoration considerably. Bulking-up seedlings and cuttings, using horticultural techniques, and planting these into restoration sites provide further options for carrying out restoration, but are likely to be associated with even larger demands on labour and finances (Anderson et al., 2004). In some instances the benefits of intensive interventions (e.g. transplantation and planting seedlings) may not be greater than those of cheaper methods (e.g. seeding), and thus the inflated costs cannot be justified. In other instances, intensive interventions may be the only way to effect restoration of longer-lived species that ensure the continuity of late-successional communities, and therefore the costs assume a lesser relative importance. Some circumstances may call for a combination of methods of restoration, and ideally an optimum should be reached where expenses are minimized and restoration success is maximized. This can be achieved by categorizing plant species according to their most successful method of restoration, as well as identifying species on which initial restoration efforts should be focussed (i.e. easily re-established, perennial species; Burke, 2005). Most importantly, restoration should not be regarded as a once-off intervention. A phased approach over time, often involving a number of methods is likely to provide the key to the restoration of a high proportion of the original species richness and ecosystem functioning. The feasibility of restoration methods are necessarily influenced by finances as well as by natural limitations, yet it should be borne in mind that the costs incurred in establishing vegetation are likely to be a fraction of those incurred in relocating overburden soils and landscaping.

6. Hopes for the future

There are a number of avenues of research that will particularly facilitate ecological restoration in Namaqualand. Research that contributes to a mechanistic understanding of the dynamics of Strandveld and Succulent Karoo ecosystems will make it possible to more accurately predict vegetation change under a variety of circumstances and interventions. Although restoration must necessarily begin with the primary producers, the assumption that the autogenic recovery of animals and other groups will follow vegetation recovery has not been adequately tested. Conditions for the restoration of herbivore and higher trophic communities remain largely unknown, while soil and non-vascular plant communities remain almost entirely unstudied. Restoration in Namaqualand is likely to be greatly facilitated by taking advantage of the specific adaptations of indigenous organisms to the prevailing environmental conditions. Moreover, the patchy nature of mining in Namaqualand can be used to advantage in restoration as this frequently results in degraded patches occurring within relatively pristine undisturbed areas that can act as reference sites and a source of propagules.

Easily measured criteria need to be identified to asses the success and extent of restoration, without which control cannot be exercised by the governing authorities (Hobbs and Harris, 2001). Internationally few standards have been set for restoration, and few mining operators have committed themselves to meeting measurable goals. One proactive mining operator in Namaqualand has set itself the goal of re-establishing communities with at least 60% of the original plant species richness after mining is completed, a goal that may only be met through new innovations in restoration methods (de Villiers et al., 1998, 2001).

Ecological restoration needs to be proactive. A closer partnership between research institutions that are working to gain a mechanistic understanding of the underlying ecology of lowland Namaqualand and those with management responsibilities for restoration within this region is likely to offer insights to both parties, and can facilitate an improved understanding of the ecological forces that dominate, and improved ecological restoration on the ground.

Acknowledgements

Contributions by Susan Botha and three reviewers improved this paper. Funding for this project was provided by the Critical Ecosystem Partnership Fund through the Succulent Karoo Ecosystem Programme. The Mazda Wildlife Fund provided a courtesy vehicle for field use.

References

Acocks, J.P., 1988. Veld types of South Africa. Memoirs of the Botanical Survey of South Africa 57, 1–146.
Aguiar, M.R., Sala, O.E., 1999. Patch structure, dynamics and implications for the functioning of arid ecosystems. Trends in Ecology and Evolution 14, 273–277.
Allsopp, N., 1999. Effects of grazing and cultivation on soil patterns and processes in the Paulshoek area of Namaqualand. Plant Ecology 142, 179–187.
Anderson, P., 1995. Ecological restoration and creation: a review. Biological Journal of the Linnean Society 56, 187–211.
Anderson, P., Hoffman, M.T., Holmes, P.M., 2004. The potential of *Cephalophyllum inaequale* (L. Bolus) for the restoration on degraded arid landscapes in Namaqualand, South Africa. Restoration Ecology 12, 343–351.
Beukes, P.C., Cowling, R.M., 2003. Evaluation of restoration techniques for the Succulent Karoo, South Africa. Restoration Ecology 11, 308–316.
Boucher, C., le Roux, A., 1981. South African west coast strand vegetation. In: van der Maarel, E. (Ed.), Ecosystems of the World, vol. 2B: Dry Coastal Ecosystems. Elsevier, Amsterdam, pp. 75–88.
Burke, A., 2003. Practical measures in arid land restoration after mining—a review for the southern Namib. South African Journal of Science 99, 413–417.
Burke, A., 2005. Best Practice Guidelines for Minimising Impacts on the Flora of the Southern Namib. EnviroScience and Namibia Nature Foundation, Windhoek.
Cannon, W.A., 1911. The Root Habits of Desert Plants. Carnegie Institution, Washington.
Carrick, P.J., 2001. Shrub Community Dynamics in a South African Semi-Desert. Ph.D. Thesis, University of Cambridge, Cambridge.
Carrick, P.J., 2003. Competitive and facilitative relationships among three shrub species, and the role of browsing intensity and rooting depth in the Succulent Karoo, South Africa. Journal of Vegetation Science 14, 761–772.
Carrick, P.J., Desmet, P., 2004. Comments on Namakwa Sands Brand-se-Baai Mine-Site Rehabilitation Process. Report for Namakwasands mine, Brand-se-Baai.
Carstens, P., 2001. In the Company of Diamonds. Ohio University Press, Athens.
Cornell, F.C., 1986. The Glamour of Prospecting. David Philip, Cape Town.
Cowling, R.M., Esler, K.J., Midgley, G.F., Honig, M.A., 1994. Plant functional diversity, species diversity and climate in arid and semi-arid southern Africa. Journal of Arid Environments 27, 141–158.
Cowling, R.M., Esler, K.J., Rundel, P.W., 1999. Namaqualand, South Africa—an overview of a unique winter-rainfall desert ecosystem. Plant Ecology 142, 3–21.
Darwin, C., 1890. The Origin of the Species by Means of Natural Selection. John Murray, London.
Dean, W.R., Yeaton, R.I., 1993. The effects of harvester ant Messor capensis nest-mounds on the physical and chemical properties of soils in the southern Karoo, South Africa. Journal of Arid Environments 25, 249–260.
Desmet, P.G., 1996. The phytosociology and restoration potential of the vegetation of the Namaqualand coastal belt between Port Nolloth and Alexander Bay. M.Sc. Thesis, University of Cape Town, Cape Town.
Desmet, P.G., Cowling, R.M., 1999. The climate of the Karoo—a functional approach. In: Dean, W.R., Milton, S.J. (Eds.), The Karoo: Ecological Patterns and Processes. Cambridge University Press, Cambridge, pp. 3–16.
de Villiers, A.J., 2000. Seed bank dynamics of the Strandveld Succulent Karoo. Ph.D. Thesis, University of Pretoria, Pretoria.

de Villiers, A.J., van Rooyen, M.W., Theron, G.K., 1992. Studies of the revegetation of saline mined soil at Namaqua sands. Report for Anglo American Corporation.
de Villiers, A.J., van Rooyen, M.W., Theron, G.K., 1994. Comparison of two methods for estimating the size of the viable seed bank of two plant communities in the Strandveld of the west coast, South Africa. South African Journal of Botany 60, 81–84.
de Villiers, A.J., van Rooyen, M.W., Theron, G.K., van Rooyen, N., 1998. Vegetation diversity of the Brand-se-Baai coastal dune area, West Coast, South Africa: a premining benchmark survey for rehabilitation. Land Degradation and Development 10, 207–224.
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 Degradation and Development 12, 119–130.
Dong, Z., Shangyu, G., Fryrear, D.W., 2001. Drag coefficients, roughness length and zero-plan displacement height as disturbed by artificial standing vegetation. Journal of Arid Environments 49, 485–505.
Eccles, N.S., Esler, K.J., Cowling, R.M., 1999. Spatial pattern analysis in Namaqualand desert plant communities: evidence for general positive interactions. Plant Ecology 142, 71–85.
Eccles, N., Lamont, B., Esler, K., Lamont, H., 2001. Relative performance of clumped vs. experimentally isolated plants in a South African winter-rainfall desert community. Plant Ecology 155, 219–227.
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., Phillips, N., 1994. Experimental effects of water stress on semi-arid Succulent Karoo seedlings: implications for field seedling survivorship. Journal of Arid Environments 26, 325–337.
Garcia-Moya, E., McKell, C.M., 1970. Contribution of shrubs to the nitrogen economy of a desert-wash plant community. Ecology 51, 81–88.
Goldberg, D., Novoplansky, A., 1997. On the relative importance of competition in unproductive environments. Journal of Ecology 85, 409–418.
Guidelines for Mining in Arid Environments, 1996. Department of Minerals and Energy Western Australia, Perth.
Halbich, T.F.J., 2003. Mine rehabilitation in the arid Succulent Karoo vegetation zone on the South African west coast, Namakwa Sands—case study. In: Heavy Minerals, South African Institute of Mining and Metallurgy, pp. 113–118.
Harvey, C.A., 2000. Windbreaks enhance seed dispersal into agricultural landscapes in Monteverde, Costa Rica. Ecological Applications 10, 155–173.
Hobbs, R.J., Harris, J.A., 2001. Restoration ecology: repairing the earth's ecosystems in the new millennium. Restoration Ecology 9, 239–246.
Hoffman, M.T., Cowling, R.M., 1987. Plant physiognomy, phenology and demography. In: Cowling, R.M., Roux, P.W. (Eds.), The Karoo Biome: A Preliminary Synthesis. Part 2—Vegetation and History. South African National Scientific Programmes Report 142, pp. 1–34.
Jowell, P., Folb, A., 2004. Into Kokerboom Country: Namaqualand's Jewish Pioneers. Fernwood, Cape Town.
Lanz, J., 1997. An evaluation of revegetation at Namaqualand Mines with an emphasis on soil conditions. Report for De Beers Namaqualand Mines, Kleinzee.
le Roux, A., Odendaal, F.J., 1992. Report on the study of natural recovery of overburden dumps on DBCM properties in Namaqualand. Report for De Beers Namaqualand Mines, Kleinzee.
Lesica, P., Allendorf, F.W., 1999. Ecological genetics and the restoration of plant communities: Mix or match? Restoration Ecology 7, 42–50.
Mahood, K., 2003. Strip mining rehabilitation by translocation in arid coastal Namaqualand, South Africa. M.Sc. Thesis, University of Stellenbosch, Stellenbosch.
Midgley, G.F., Musil, C.F., 1990. Substrate effects of zoogenic soil mounds on vegetation composition in the Worcester-Robertson valley, Cape Province. South African Journal of Botany 56, 158–166.
Milton, S.J., 1995. Spatial and temporal patterns in the emergence and survival of seedlings in arid Karoo shrubland. Journal of Applied Ecology 32, 145–156.
Milton, S.J., Yeaton, R.I., Dean, W.R., Vlok, J.H.J., 1997. Succulent Karoo. In: Cowling, R.M., Richardson, D.M., Pierce, S.M. (Eds.), Vegetation of Southern Africa. Cambridge University Press, Cambridge, pp. 131–166.
Mining & Minerals Sustainability Survey, 2001. PriceWaterhouseCoopers and Mining. Minerals and Sustainable Development, London.
Nicolau, J.M., 2003. Trends in relief design and construction in opencast mining reclamation. Land Degradation & Development 14, 215–226.

Rokich, D.P., Dixon, K.W., Sivasithamparam, K., Meney, K.A., 2000. Topsoil handling and storage effects on woodland restoration in Western Australia. Restoration Ecology 8, 196–208.

Schmidt, A., 2002. Strip-mine rehabilitation in Namaqualand. M.Sc. thesis, University of Stellenbosch, Stellenbosch.

Schor, H.J., Gray, D.H., 1995. Landform grading and slope evolution. Journal of Geotechnical Engineering 121, 729–734.

Scott, D.F., Johnston, M.A., 1995. Soil leaching trials on overburden soil from Kleinzee and Koingnaas. Report for De Beers Namaqualand Mines, Kleinzee.

Society for Ecological Restoration International Science & Policy Working Group, 2004. The SER International Primer on Ecological Restoration. www.ser.org & Tucson, Society for Ecological Restoration International.

Stock, W.D., Dlamini, T.S., Cowling, R.M., 1999. Plant induced fertile islands as possible indicators of desertification in a succulent desert ecosystem in northern Namaqualand, South Africa. Plant Ecology 142, 161–167.

Strohmayer, P., 1999. Soil stockpiling for reclamation and restoration activities after mining and construction. Restoration and Reclamation Review 4, 1–4.

Sweeting, A.R., Clark, A.P., 2000. Lightening the Lode: A Guide to Responsible Large-Scale Mining. Conservation International, Washington, DC.

Tongway, D., Hindley, N.L., 2004. Landscape Function Analysis: Procedures for Monitoring and Assessing Landscapes. With Special Reference to Minesites and Rangelands. CSIRO Australia, Canberra.

Van Jaarsveld, E., 1987. The succulent riches of South Africa and Namibia. Aloe 24, 45–92.

van Rooyen, M.W., de Villiers, A.J., 2004. Germination patterns in the Succulent Karoo Biome, South Africa. Transactions of the Royal Society of South Africa 59, 31–38.

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.

von Willert, D.J., Eller, B.M., Werger, M.J.A., Brinckmann, E., Ihlenfeldt, H.-D., 1992. Life Strategies of Succulents in Deserts: with Special Reference to the Namib Desert. Cambridge University Press, Cambridge.

Webley, L., 2007. Archaeological evidence for pastoralist land-use and settlement in Namaqualand over the last 2000 years. Journal of Arid Environments 70 (4), 629–640.

Whitford, W.G., 1999. Comparisons of ecosystem processes in the Nama Karoo and other deserts. In: Dean, W.R., Milton, S.J. (Eds.), The Karoo: Ecological Patterns and Processes. Cambridge University Press, Cambridge, pp. 291–302.