# Monitoring Ecological Rehabilitation on a Coastal Mineral Sands Mine in Namaqualand, South Africa

by
Marco Johann Pauw

Thesis presented in partial fulfilment of the requirements for the degree Master of Science in Conservation Ecology at the University of Stellenbosch
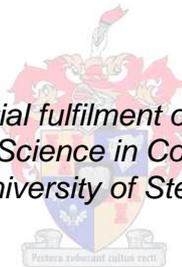
Supervisor: Prof Karen J Esler
Co-supervisor: Dr David le Maitre
Faculty of AgriSciences
Department of Conservation Ecology and Entomology

December 2011

Declaration

By submitting this thesis/dissertation electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

December 2011

i

Abstract

The Exxaro Namakwa Sands heavy mineral sands mine at Brand-se-Baai, on the west coast of South Africa, is an important source of income, development and job-creation in the region. However, this comes at a great environmental cost, as strip mining causes large scale destruction of ecosystems through the complete removal of vegetation and topsoil. This is particularly problematic in an environment, such as Namaqualand, where the arid and windy climate, as well as saline and nutrient-poor soils, hamper rehabilitation. These environmental constraints create the need to develop a site-specific rehabilitation program. At Namakwa Sands the objective of rehabilitation is to "rehabilitate and re-vegetate disturbed areas and establish a self-sustaining Strandveld vegetation cover in order to control dust generation, control wind and water erosion, as well as restore land capability. In general, vegetation will be rehabilitated to a minimum grazing standard capable of supporting small stock (sheep) grazing." In order to achieve this Namakwa Sands conducted rehabilitation experiments with topsoil replacement, seeding of indigenous species and translocation of mature plants.

Monitoring is an important part of the rehabilitation process as it allows rehabilitation practitioners to evaluate success and to adapt their management strategies and rehabilitation methods, as well as to evaluate and, if necessary, change their rehabilitation objectives. This study forms part of the monitoring process at Namakwa Sands. It assesses the success of sites that were experimentally rehabilitated in 2001 and a site that was rehabilitated in 2008, using current practice, in order to identify possible management requirements on rehabilitated sites as well as improvements on rehabilitation objectives, methods and monitoring. This study also tests the Landscape Function Analysis (LFA) as rehabilitation monitoring tool by correlating LFA indices with traditional measurements of biophysical variables or their surrogates.

Results showed that experimental sites were not successful in returning vegetation cover and plant species richness to the required levels, but did achieve the grazing capacity objective. These sites will need adaptive management to achieve the vegetation cover and plant species richness objectives. The recently rehabilitated site achieved the three-year vegetation cover and plant species richness objectives, as well as the grazing capacity objective, within two years after rehabilitation. Namakwa Sands should therefore continue using the current rehabilitation method. However, rehabilitation should be done in multiple stages in future to decrease the mortality of nursery cuttings and to facilitate the return of late successional species to rehabilitated sites. The

sustainability of small stock farming on rangeland with the grazing capacity that is identified as the minimum objective is questionable and this merits further investigation. LFA can be a useful tool to monitor nutrient cycling and soil stability at Namakwa Sands, provided that enough replicates are used. However, LFA cannot be used as is to assess water infiltration at Namakwa Sands, due to assumptions in the calculation of this index that do not hold for the Namaqualand environment. Landscape functioning should be monitored annually to complement vegetation surveys.

Opsomming

Die *Exxaro Namakwa Sands* swaarminerale-sandmyn by Brand-se-Baai, aan die weskus van Suid-Afrika, is 'n belangrike bron van inkomste, ontwikkeling en werkskepping in die streek. Daar is egter negatiewe omgewingsimpakte aan verbonde, aangesien die strookmyntegniek grootskaalse vernietiging van ekosisteme veroorsaak deur die algehele verwydering van die plantegroei en bogrond. Dit is veral problematies in 'n omgewing, soos Namakwaland, waar die droë en winderige klimaat, asook die souterige en voedingstof-arme grond, rehabilitasie belemmer. Hierdie beperkings wat deur die omgewing veroorsaak word skep die behoefte om 'n rehabilitasieprogram te ontwikkel wat spesifiek is tot die terrein. Die doel van rehabilitasie by *Namakwa Sands* is om te rehabiliteer en herplant op versteurde gebiede en om self-onderhoudende Strandveld plantbedekking te vestig om sodoende stofgenerering te beheer, om wind- en watererosie te beheer, en om grondgebruik-vermoë te herstel. In die algemeen sal plantbedekking gerehabiliteer word tot 'n minimum weidingskapasiteit wat kleinveeweiding (skaapweiding) kan onderhou. Om dit te bereik het *Namakwa Sands* rehabilitasie-eksperimente uitgevoer met terugplasing van bogrond, saai van inheemse spesies en oorplanting van volwasse inheemse plante.

Monitering is 'n belangrike deel van die rehabilitasieproses, aangesien dit rehabilitasie-praktisyns in staat stel om sukses te evalueer en om bestuurstrategieë en rehabilitasiemetodes aan te pas, sowel as om rehabilitasiedoelwitte te evalueer en, indien nodig, aan te pas. Hierdie studie vorm deel van die moniteringsproses by *Namakwa Sands*. Dit assesseer die sukses op persele wat eksperimenteel gerehabiliteer is in 2001 en 'n perseel wat in 2008 gerehabiliteer is, volgens die huidige praktyk, om moontlike bestuursbehoeftes op gerehabiliteerde persele en verbeteringe aan rehabilitasiedoelwitte, -metodes en –monitering te identifiseer. Hierdie studie toets ook die geskiktheid van die *Landscape Function Analysis* (LFA) as 'n rehabilitasie-moniteringsinstrument deur LFA-indekse met tradisionele metings van biofisiese veranderlikes of hul surrogate te korreleer.

Resultate dui daarop dat eksperimentele persele nie suksesvol was om plantbedekking en plantspesies-rykdom tot die vereiste vlakke te herstel nie, maar wel die weidingskapasiteit-doelwit bereik het. Hierdie persele benodig aanpassingsbestuur om plantbedekking- en plantspesiesrykdom-doelwitte te bereik. Die perseel wat onlangs gerehabiliteer is, het binne twee jaar na rehabilitasie die drie-jaar plantbedekking- en plantspesiesrykdom-doelwitte, sowel as die

weidingskapasiteitdoelwit bereik. Daarom moet *Namakwa Sands* voortgaan om die huidige rehabilitasiemetode te gebruik. Rehabilitasie moet egter in die toekoms in veelvoudige stadiums gedoen word om die mortaliteit van kwekery-steggies te verminder en om die terugkeer van laat-suksessionele spesies na gerehabiliteerde persele te fasiliteer. Die volhoubaarheid van kleinveeboerdery op weiveld met die minimum vereiste weidingskapasiteit word betwyfel en vereis verdere ondersoek. LFA kan 'n bruikbare instrument wees om siklering van voedingstowwe en grondstabiliteit te monitor by *Namakwa Sands* indien genoeg repliserings gebruik word. LFA kan egter nie in die huidige vorm gebruik word om waterinfiltrasie by *Namakwa Sands* te assesseer nie, aangesien daar aannames in die berekening van die indeks is wat nie juis is in die Namakwaland omgewing nie. Landskapfunksionering behoort jaarliks gemoniteer te word om plantopnames aan te vul.

Acknowledgments

Table of Contents

List of Figures

List of Tables

List of Appendices

Chapter 1: General Introduction

1.1. Background

Rehabilitation after mining can prove difficult, especially in an arid environment, such as Namaqualand, with its unique set of environmental constraints. As part of the continuous development of their site-specific rehabilitation methods, Exxaro Namakwa Sands has supported a number of research studies. This, being the most recent study, investigates the success of past rehabilitation experiments as well as current practice. It also tests the Landscape Function Analysis (Tongway & Hindley, 2004) as a monitoring tool at Namakwa Sands. This study also forms part of a country-wide, multi-disciplinary research project on the restoration of natural capital in South Africa, initiated and funded by the Water Research Commission, which is described later in this chapter.
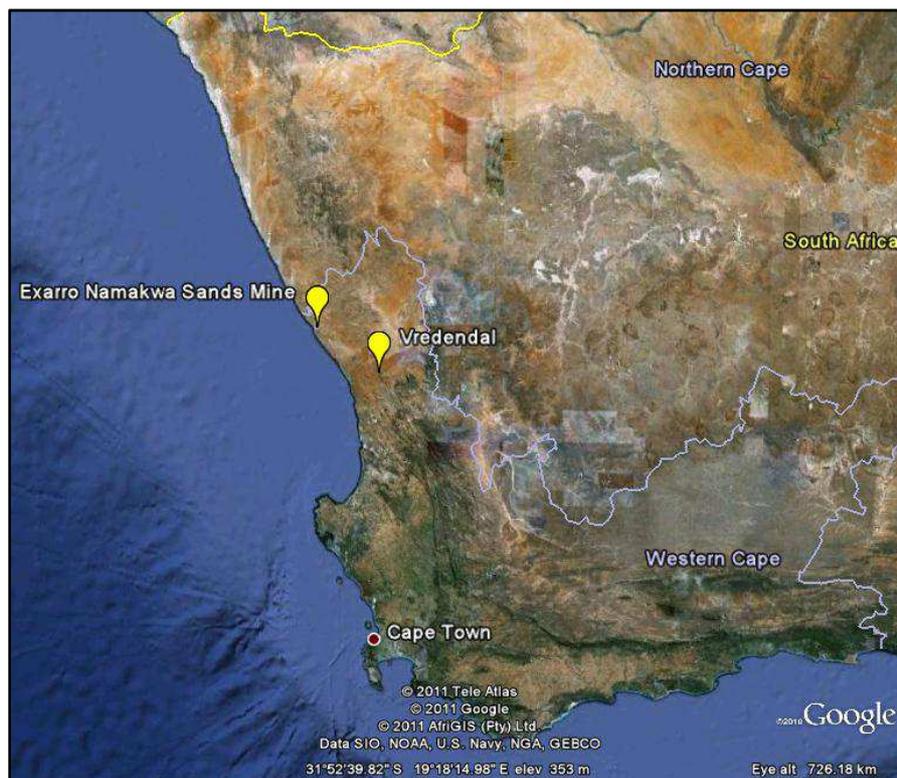
Figure 1.1: Map showing the location of the Exxaro Namakwa Sands mine (source: Google Earth).

The Exxaro Namakwa Sands heavy minerals mining and beneficiation business consists of two operational sectors. The smelter and associated structures at Saldanha Bay are known as the

Southern operations, while the mine and the Primary and Secondary Concentration Plants, located at Brand-se-Baai, and the Mineral Separation Plant (MSP), located just outside Koekenaap are collectively known as the Northern operations (Golder Associates, 2008). The map below (Figure 1.1) shows the location of the Exxaro Namakwa Sands mine. This study will focus on the heavy minerals mining operation that is situated at Brand-se-Baai (31° 18' S, 17° 54' O), northwest of Vredendal, on the west coast of South Africa. The mine has been in operation since 1992 (Mahood, 2003; Golder Associates, 2008).

1.2. Study Area

1.2.1. Succulent Karoo

The largest part of the Succulent Karoo receives between 20 and 290 mm rain per year (Milton *et al.*, 1997). The rainfall is very predictable (Milton *et al.*, 1997; Desmet & Cowling, 1999b), with more than 40 % of this falling in winter (Milton *et al.*, 1997). However, the southern part of the Succulent Karoo receives a significant portion of its rainfall in summer (Desmet & Cowling, 1999b; Esler *et al.*, 1999). Winter rainfall is mostly brought by cold fronts (Milton *et al.*, 1997; Desmet & Cowling, 1999b). Advective sea fog is an important additional source of moisture along the west coast of the Succulent Karoo (Desmet & Cowling, 1999b). The Atlantic current has a significant moderating effect on the temperature in the western part of the Succulent Karoo (Desmet & Cowling, 1999b).

The Succulent Karoo is a globally recognized biodiversity hotspot (Mittermeier *et al.*, 2000; Myers *et al.*, 2000), one of only two arid areas in the world to have this status (Desmet, 2007). It is considered to be very species rich, as it contains 6 356 species of vascular plants in an area of only 112 000 km^2 (Desmet, 2007). Of these, about 40 % are endemic (Hilton-Taylor, 1996; Desmet & Cowling, 1999a) and 17 % are IUCN Red Data list species (Driver *et al.*, 2003). The vegetation is dominated by leaf-succulent dwarf shrubs (Cowling *et al.*, 1999; Esler & Rundel, 1999; Mucina *et al.*, 2006). This is thought to be because of the low, but reliable winter rainfall in the region (Cowling & Hilton-Taylor, 1999; Cowling *et al.*, 1999; Esler & Rundel, 1999).

1.2.2. Namaqualand

The Namaqualand region is situated on the west coast of South Africa (Anderson & Hoffman, 2007), and includes the strongly winter rainfall part of the Succulent Karoo biome (Milton *et al.*, 1997; Cowling *et al.*, 1999). Namaqualand covers approximately 45 000 km² between the Olifants

River in the South and the Gariep River in the North, and between the Atlantic coast in the West and the edge of the escarpment in the East (Desmet, 2007). The proximity of the Atlantic Ocean, and in particular the cold Benguela Current, significantly affects the climate of Namaqualand (Desmet & Cowling, 1999a). The greatest part of Namaqualand receives less than 150 mm of rainfall annually, but this low rainfall is augmented along the coast by the occurrence of fog (Cowling *et al.*, 1999; Hälbich, 2003; Carrick & Kruger, 2007), which greatly increases the amount of water available to plants (Desmet & Cowling, 1999a). Namaqualand has one of the strongest wind regimes in the world, with south and south-easterly winds prevailing in summer and north and north-westerly winds in winter (Hälbich, 2003; Mahood, 2003).

The soils found in Namaqualand are typical of arid environments (Francis *et al.*, 2007) and have certain characteristics that have a major effect on hydrological processes. Soil crusts and the naturally hydrophobic, sandy topsoils cause fingering water infiltration, which enables water to penetrate deeper into the soil, where it cannot be lost through evapotranspiration (Francis *et al.*, 2007). Subsurface soil horizons that are cemented with silica, calcite, fibrous clays or gypsum, such as the dorbank layer at Namakwa Sands, inhibit deeper penetration of water, creating an aquifer below the plant root layer, where water may be stored temporarily (Francis *et al.*, 2007). Nocturnal distillation occurs when differences between atmospheric and soil temperature cause soil water vapour to move towards the surface. This is thought to have a significant impact on the water availability for plants, especially shallow rooted species (Prinsloo, 2005; Francis *et al.*, 2007). Soluble salts slow the uptake of plant water, decreasing the rate of evapotranspiration (Francis *et al.*, 2007). Clay minerals (sepiolite and palygorskite) that are unique to arid environments and have an exceptionally high water-absorbing capacity are common in the clay fraction of Namaqualand soils (Singer *et al.*, 1995; Francis *et al.*, 2007). This provides soils with better water retention than expected for a given clay content.

The Namaqualand region, which forms part of the Succulent Karoo, is very species rich (Cowling *et al.*, 1999; Cowling & Hilton-Taylor, 1999), containing about 3500 species of vascular plants (Desmet, 2007). Approximately 25 % of plant species found in Namaqualand are endemic (Desmet, 2007). The vegetation is dominated by leaf succulent dwarf shrubs (Milton *et al.*, 1997; Desmet & Cowling, 1999a), but a large number of geophytes also occur in the region (Milton *et al.*, 1997; Cowling & Hilton-Taylor, 1999; Cowling *et al.*, 1999; Esler *et al.*, 1999). Most succulents have shallow root systems that enable them to effectively absorb moisture during the frequent small rainfall events in winter, which they store in leaves and stems, however, this dependence on reliable rainfall leave them vulnerable to prolonged periods of drought (Esler & Rundel, 1999; Esler *et al.*, 1999, Cowling *et al.*, 1999).

3

The dominant agricultural activity in the Namaqualand region is sheep and goat farming (Anderson & Hoffman, 2007). Domestic livestock were introduced into Namaqualand around 2 000 years ago, but commercial farming only emerged in the 1750's, when colonial settlers moved into the region (Hoffman & Rohde, 2007). It is presumed that historic overgrazing has caused a decline in the carrying capacity, reflected by a greater than 60 % reduction of the recommended carrying capacity in the magisterial district (Esler *et al.*, 2006; Hoffman & Rohde, 2007). The recommended carrying capacity for domestic livestock in the Succulent Karoo is more than 50 ha / LSU (Hälbich, 2003; Esler *et al.*, 2006). There has been a decline in commercial farming in recent years (Hoffman & Rohde, 2007), and it is being replaced by mining and tourism as the most important economic activities. There has been a great increase in strip mining operations in particular on the west coast of South Africa (Milton, 2001). Cultivation, mostly of wheat, has been practiced since colonial settlers moved into the region, but has declined significantly because it is no longer economically viable (Hoffman & Rohde, 2007).

1.2.3. Brand-se-Baai

The average annual rainfall at Brand-se-Baai, calculated from data collected by CSIR between 1996 and 2009 (CSIR, 2011), is 150 mm. Fog occurs on approximately 100 days per year (Mahood, 2003), adding more than 120 mm to the average annual precipitation. Wind is the primary erosion factor in the area and has been cited as a major constraint to restoration in these systems (Botha *et al.*, 2008). The prevailing winds from September to March are strong south and south-easterly winds, while the prevailing winds from June to August are strong north to north-westerly winds (Hälbich, 2003; Mahood, 2003).

Mounds of the termite *Microhodotermes viator*, that are known as "heuweltjies" (Midgley & Musil, 1990; Moore & Picker, 1991; Dean & Yeaton, 1993), occur throughout the Succulent Karoo, but not on very coarse sandy soils (Carrick & Kruger, 2007). The soil composition of *heuweltjies* differs from that of the surrounding areas and *heuweltjies* have increased water holding capacity and nutrients (Midgley & Musil, 1990; Carrick & Kruger, 2007). Due to this the plant communities on *heuweltjies* also differ from that on the surrounding area (Midgley & Musil, 1990; Dean & Yeaton, 1993; Carrick & Kruger, 2007). Although Carrick and Kruger (2007) claim that *heuweltjies* do not occur in Strandveld vegetation, which grows on coarse, sandy soils, Blood (2006) reports a large number of *heuweltjies* in and around the mining area at Brand-se-Baai. *Heuweltjies* can also be observed on neighbouring farms (personal observation). As strip mining disturbs the soil, these termite mounds are destroyed (Blood, 2006). These ancient mounds will not return after mining as

4

they are no longer active. Therefore, this important source of landscape and microsite heterogeneity can be considered as permanently lost on the mine.

There are five vegetation types, as defined by Mucina *et al.* (2006), which occur in the vicinity of the mine. Namaqualand Strandveld is a shrubland dominated by erect and creeping succulents. It usually has low species richness. The mine at Brand-se-Baai has been listed as one of the threats to this vegetation type (Mucina *et al.*, 2006). Namaqualand Klipkoppe Shrubland occurs on granite and gneiss domes and koppies. It is dominated by dwarf and medium sized shrubs. Scattered shrubs occur in Namaqualand Sand Fynbos, but it is dominated by Restoids. This is the driest of Fynbos vegetation types and it occurs at the northern distribution boundary of Fynbos. Namaqualand Salt Pans are flats or depressions that are sparsely populated by salt-tolerant plant species. Namaqualand Seashore Vegetation occurs on beaches and coastal rock formations. It is sparsely covered by hummock-forming and spreading succulent dwarf shrubs.

1.3. Mining

1.3.1. Mining Process and Products

The mine is divided into the West Mine and East Mine. At the East mine, only the layer of Aeolian sand is mined to a maximum depth of five metres. At the West mine, the Aeolian sand is also mined but, in addition, the underlying dorbank and feldspathic sand layers are mined to a maximum depth of 45 m (Golder Associates, 2008). The depth to which mining takes place has important implications for, amongst others, water infiltration, water holding capacity and leaching, and therefore affects the outcome of rehabilitation. Approximately 18 million metric tons of ore is extracted annually (Golder Associates, 2008). The rehabilitated sites studied are all located on the East Mine.

The mining process (see Figure 1.2) can be seen as a cycle that continuously advances: as the subsoil is removed from the mining front, it is taken back to mined-out areas to be used for back-filling. The strip mining process starts with the removal of vegetation with a bulldozer. The topsoil is then removed to a minimum depth of 50 mm and either stored (stockpiled on site), or immediately transported to a mined-out and back filled area to be used in the restoration process. A digger loader excavates the subsoil and loads it onto a haul truck. The haul truck tips its load into a tip bin, from where it is transported to the Primary Concentration Plant (PCP) on a conveyor system.

At the PCP, the ore is mixed with sea water to form a slurry. The fine particles (clay) are separated and pumped into a slimes dam, while tailings (oversize material and vegetation) are transported to mined-out areas to be used in the restoration process. The concentrate, consisting of 90 % Total Heavy Minerals (THM), is pumped to the Secondary Concentration Plant (SCP). At the SCP, the remaining oversize is separated and silica coatings are removed from the minerals. The THM concentrate is then separated into magnetic and non-magnetic fractions. These fractions are dried and then trucked to the MSP. The MSP produces zircon and rutile final products from the non-magnetic fraction and ilmenite form the magnetic fraction. Products are transported by rail to the smelter at Saldanha, although some zircon products are transported to Cape Town harbour for export. Ilmenite is processed into pig iron and titania slag and exported together with the rutile products and the rest of the zircon products, which are stored at Saldanha.
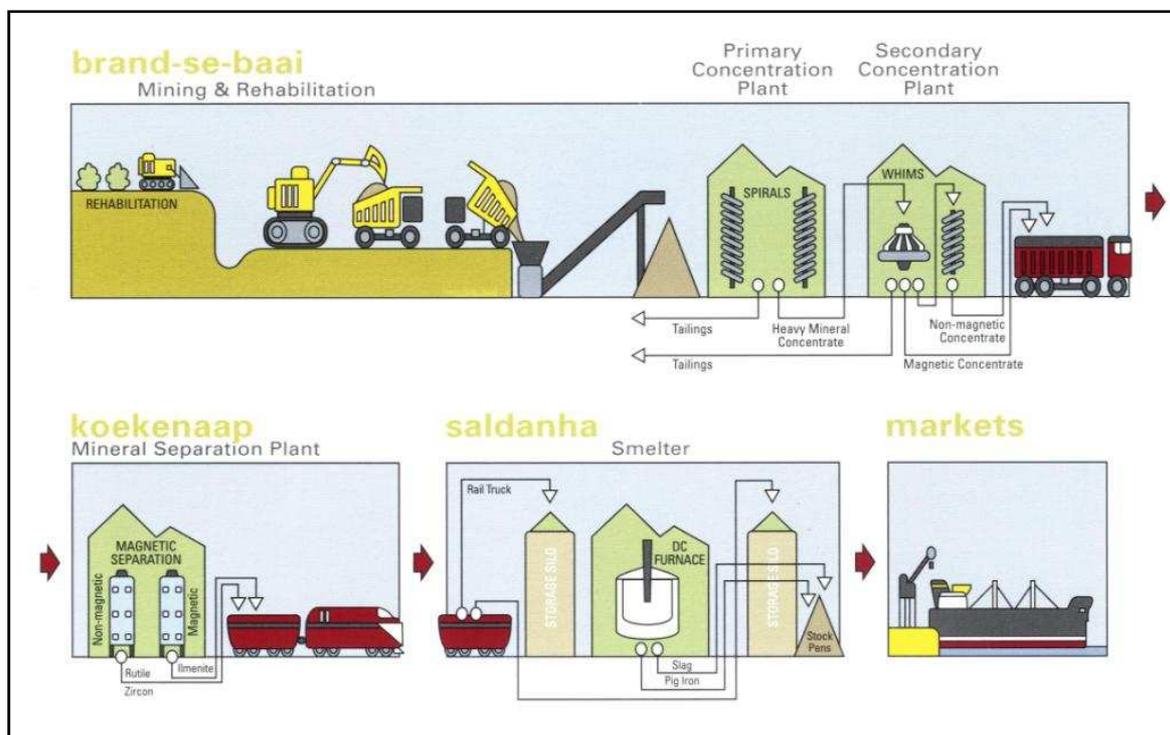
Figure 1.2: Diagram, copied from Namakwa Sands (2008), of the mining, treatment and production processes that take place at the Northern and Southern Operations of Exxaro Namakwa Sands.

The Namakwa Sands mine and MSP produces 125 000 tons of zircon and 25 000 tons of rutile annually, while ilmenite is also produced and sent to the smelter, which produces 200 000 tons of titania slag and 120 000 tons of pig iron annually (Golder Associates, 2008). Globally, South Africa is the second largest producer of titanium and zircon, and also has the second largest reserves of

6

both heavy minerals (Robinson *et al.*, 2005). Namakwa Sands has a global market share of about 10 % of zircon production and 7 % of rutile and titania slag production (Namakwa Sands, 2008).

1.3.2. Impacts of the Mine

Namakwa Sands exports more than 95 % of its products, earning more than R 1 billion in foreign exchange annually (Namakwa Sands, 2008). The mine and MSP are also economically important in a regional context, since there are very few job opportunities in the Namaqualand, and livestock farming is the primary economic activity. According to Namakwa Sands (2008), the mine and MSP contributed more than 280 million Rand to the regional economy in 2007. This consists of tax and utility payments, salaries, as well as educational, health and economic development projects. Almost 80 % of Namakwa Sands employees come from communities in the surrounding municipalities (Namakwa Sands, 2008).

It has to be recognised that these socio-economic benefits come at a great environmental cost. It is believed that the mining operation at Brand-se-Baai has had a major impact on the vegetation communities in the area (Mucina *et al.*, 2006; Manning, 2008). Strip mining completely disrupts natural ecosystems over a large area, because the vegetation is removed, as is the soil (Bradshaw, 1997; Cooke & Johnson, 2002; Mahood, 2003; Hälbich, 2003; Carrick & Kruger, 2007). This is of great concern, particularly when considering the unique vegetation of the area and the difficulties of rehabilitation in an environment with very low rainfall, strong winds and soils with low nutrient levels (Milton, 2001; Carrick & Kruger, 2007; Botha *et al.*, 2008).

Another concern is that the mining operation causes the formation of saline sand tailings with very low levels of clay and organic matter (Prinsloo, 2005). This is due to the treatment of ore with sea water and the centrifugal separation of the lighter sandy material and the heavier, mineral-containing clay material (Marius Vlok, pers. comm., 2009). The salinity of tailings is reduced to near natural levels after 25 months, through natural leaching processes (Prinsloo, 2005). However, this might also decrease the fertility of tailings. The high salinity and low soil fertility is likely to impair the rehabilitation process, as is the case elsewhere (Bell, 2002).

1.4. Rehabilitation at Namakwa Sands

The first step in the rehabilitation process is when tailings are transported from the PCP to the mined-out areas, where it is bulldozed to recreate pre-mining contours (Hälbich, 2003). Topsoil is then spread over the contoured tailings. Where possible, fresh topsoil is transported to areas that are being restored shortly after it has been removed at the mining front. It has been suggested that the use of fresh topsoil increases the success of restoration efforts (Mahood, 2003; DITR, 2006), as topsoil contains the greatest fraction of nutrients, organic matter, seeds and micro-organisms that occur in the soil (Smith *et al.*, 2004; DITR, 2006). This is also the practice at some other operations where the strip mining method is used, such as Alcoa World Alumina Australia's bauxite mine at Jarrahdale, Western Australia (Smith *et al.*, 2004) and Anglo American's heavy minerals mine at Richards Bay, South Africa (Lubke & Avis, 1998). After the topsoil has been spread, rows of 40 % density shade cloth are erected perpendicular to the prevailing wind direction to act as wind-breaks. This method has been found to be the most successful in Namaqualand (Hälbich, 2003; Mahood, 2003). At Namakwa Sands the wind-breaks are approximately 0.75 m high and spaced 5 m apart. Metal droppers are inserted into pockets sown into the shade nets, and hammered into the ground to keep the net upright. Not only does the shade cloth reduce wind speed and thus wind erosion, but it also traps seed as well as fog (Hälbich, 2003; Mahood, 2003). When perennial vegetation cover is deemed suitable by the mine's environmental department, the shade cloths fences are removed.

In past rehabilitation trials, seeds of natural vegetation harvested from undisturbed veld were mixed with either seed of *Eragrostis curvula* and *Sorghum* species or with seed of *Ehrharta calycina* and spread over topsoil or tailings. However, current practice is to use seed harvested from natural vegetation that has not yet been mined and on neigbouring farms. In past rehabilitation trials *Ruschia versicolor*, *Lampranthus suavissimus*, *Othonna cylindrica*, *Zygophyllum morgsana* and *Asparagus* sp. were translocated in multi-species clumps. At one site all five species were translocated, while only the first three mentioned were translocated at another site. Namakwa Sands currently translocates plants of a number of different species from undisturbed natural veld. Some indigenous plant species such as *Asparagus africanus*, *Berkheya cuneata* and *Tetragonia fruticosa* are also transplanted from a nursery that has been established at the mine. Cuttings are made from plants in natural veld and then grown in carton boxes in the nursery. Nursery plants are transplanted, still in carton boxes, with the first rains, one at each (wind break) dropper. Paper cups, similar to the carton boxes used at Namakwa Sands, have been used in the restoration of coastal marshes in China (Zhou *et al.*, 2003). The idea is to create a favourable micro-climate and to reduce the shock of translocation (Zhou *et al.*, 2003; Marius Vlok, pers. comm., 2009). In 2007, more than 500 000 plants had been transplanted, including 660 aloes

(Namakwa Sands, 2008). Some large bulbs, which are not expected to naturally recolonize the site within an acceptable time frame (Sue Milton, pers. comm., 2009; Karen Esler, pers. comm., 2009), have also been rescued from the mining front and transplanted on restoration sites (Marius Vlok, pers. comm., 2009).

1.5. Importance of study

1.5.1. Monitoring Rehabilitation

Carrick & Kruger (2007) state that: "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." This study contributes towards the bridging of the gap that exists between researchers and environmental managers in this regard, as there is close collaboration between the researcher and the environmental staff at Namakwa Sands.

The National Environmental Management Act (Act 8 of 2004) and the Mineral and Petroleum Resources Development Act (MPRDA, Act 28 of 2002) compels mining companies to rehabilitate land on which mining activities have ceased. Mining companies must be able to show that they have successfully rehabilitated land in compliance with their Environmental Management Plan in order to obtain a closure certificate, as described in the MPRDA, releasing them from legal and financial responsibility for the mined-out land.

Monitoring is an indispensable part of the restoration process (Hobbs & Harris, 2001; Cooke & Johnson, 2002) that enables the evaluation of restoration success (Hobbs & Harris, 2001; Herrick *et al.*, 2006). It gives managers an opportunity to evaluate and, if necessary, change their restoration objectives (Herrick *et al.*, 2006). Monitoring also allows practitioners to adapt their management strategies and better their restoration practices (Cooke & Johnson 2002; Cummings *et al.*, 2005; Herrick *et al.*, 2006). This study forms part of the monitoring process at Namakwa Sands, as a follow-up to the work done by Mahood (2003) and Blood (2006) and complementary to the annual vegetation monitoring.

1.5.2. Water Research Commission Project

This thesis forms part of a Water Research Commission and ASSET Research project titled: "The impact of re-establishing indigenous plants and restoring the natural landscape on sustainable rural employment and land productivity through payment for environmental services". Data from this study feeds into a study by Worship Mugido on the economic impacts of rehabilitation at the Exxaro Namakwa Sands mine. Data from both these studies feed into a model developed by Douglas Crookes that will serve as a policy tool to direct restoration efforts and funding in South Africa.

1.6. Aims and Objectives of Study

The aims of this study are to determine whether experimental rehabilitation methods have been successful in the long-term, and whether a site rehabilitated according to the current rehabilitation method is progressing towards rehabilitation targets. This study also identifies shortcomings in the rehabilitation methods and makes recommendations on rehabilitation methods and the management and monitoring of rehabilitated areas. Another aim is to test the Landscape Function Analysis (Tongway & Hindley, 2004) as a monitoring tool at Namakwa Sands.

The objectives of this study are to determine differences in vegetation cover, plant species cover, grazing capacity, and plant species richness, diversity and evenness between rehabilitated and reference sites. Rehabilitated sites are also compared to reference sites to determine whether targets have been met or not.

In order to test the Landscape Function Analysis (LFA) method, the LFA Landscape Organisation Index is correlated with vegetation cover, the LFA Stability Index is correlated with dust collection, the LFA Nutrient Cycling Index is correlated with various soil nutrients, and the LFA Water Infiltration Index is correlated with water infiltration rate.

1.7. Thesis Structure

The remainder of this thesis is structured as follows:

- **Chapter 2** is a literature review on the impacts of mining and the restoration process, with specific reference to the restoration of mines and restoration in arid environments. Both cases present unique challenges and opportunities.

- **Chapter 3** investigates the development of plant communities on sites experimentally rehabilitated in 2001, using different combinations of treatments, and a site rehabilitated in 2008, using the current rehabilitation method, and compares it to the communities on reference sites. This chapter also investigates whether Namakwa Sands has met their rehabilitation targets.

- **Chapter 4** tests the Landscape Function Analysis as a tool for monitoring rehabilitation at Namakwa Sands. Results of LFA, dust collection, soil chemical analyses and water infiltration measurements are presented and discussed. Comments are also made on the return of landscape functioning after rehabilitation at Namakwa Sands.

- **Chapter 5** summarizes the conclusions made in chapters 3 and 4 and suggests possible improvements to the rehabilitation objectives, monitoring methods and rehabilitation methods, as well as the management of rehabilitated sites.

1.8. References

Anderson, P.M.L. & Hoffman, M.T. 2007. The impacts of sustained heavy grazing on plant diversity and composition in lowland and upland habitats across the Kamiesberg mountain range in the Succulent Karoo, South Africa. Journal of Arid Environments **70**:686–700.

Bell, R.W. 2002. Restoration of degraded landscapes: Principles and lessons from case studies with salt-affected land and mine revegetation. Chiang Mai University Journal **1**:1 – 21.

Blood, J.R. 2006. Monitoring Rehabilitation Success on Namakwa Sands Heavy Minerals Mining Operation, Namaqualand, South Africa. MSc Thesis. Stellenbosch University, Stellenbosch, South Africa.

Botha, M.S., Carrick, P.J. & Allsopp, N. 2008. Capturing lessons from land-users to aid the development of ecological restoration guidelines for lowland Namaqualand. Biological Conservation **141**:885–895.

Bradshaw, A. 1997. Restoration of mined lands – using natural processes. Ecological Engineering **8**:255–269.

Carrick, P.J. and 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.

Cooke, J.A. and Johnson, M.S. 2002. Ecological Restoration of land with particular reference to the mining of metals and industrial minerals: A review of theory and practice. Environmental Review **10**:41–71.

Council for Scientific and Industrial Research (CSIR). 2011. Exxaro Namakwa Sands weather monitoring programme biannual progress report: Spring 2010 and Summer 2010/2011. Unpublished report. CSIR, Stellenbosch, South Africa.

Cowling, R.M. & Hilton-Taylor, C. 1999. Plant biogeography, endemism and diversity. Pages 42–55 in: Dean, W.R.J. & Milton, S.J. (eds.) The Karoo: Ecological patterns and processes. Cambridge University Press, Cambridge, UK.

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.

Cummings, J., Reid, N., Davies, I. and Grant, C. 2005. Adaptive management of sand-mined areas for biological conservation. Journal of Applied Ecology **42**:160–170.

Dean, W.R.J. & Yeaton, R.I. 1992. The importance of harvester ant *Messor capensis* nest mounds as germination sites in the southern Karoo, South Africa. African Journal of Ecology **30**:335–345.

Department of Industry, Tourism & Resources. 2006. Leading practice sustainable development program for the mining industry – mine rehabilitation. DTIR, Canberra.

Desmet, P.G. & Cowling, R.M. 1999a. Biodiversity, habitat and range-size aspects of a flora from a winter-rainfall desert in north-western Namaqualand, South Africa. Plant Ecology **142**:23–33.

Desmet, P.G. & Cowling, R.M. 1999b. The climate of the Karoo – a functional approach. Pages 3–16 in: Dean, W.R.J. & Milton, S.J. (eds.) The Karoo: Ecological patterns and processes. Cambridge University Press, Cambridge.

Desmet, P.G. 2007. Namaqualand – A brief overview of the physical and floristic environment. Journal of Arid Environments **70**:570–587.

Driver, A., Desmet, P.G., Rouget, M., Cowling R.M. & Maze, K.E. 2003. Succulent Karoo Ecosystem Plan biodiversity component technical report. Cape Conservation Unit, Botanical Society of South Africa, Cape Town, South Africa.

Esler, K.J. 1999. Plant reproductive ecology. Pages 123–144 in: Dean, W.R.J. & Milton, S.J. (eds.) The Karoo: Ecological patterns and processes. Cambridge University Press, Cambridge.

Esler, K.J. & Rundel, P.W. 1999. Comparative patterns of phonology and growth form diversity in two winter rainfall deserts: The Succulent Karoo and the Mojave Desert ecosystems. Plant Ecology **142**:97–104.

Esler, K.J., Milton, S.J. & Dean, W.R.J. 2006. Karoo Veld Ecology and Management. Briza Publications, Pretoria.

Francis, M.L., Fey, M.V., Prinsloo, H.P., Ellis, F., Mills, A.J. & Medinski, T.V. 2007. Soils of Namaqualand: Compensations for aridity. Journal of Arid Environments **70**:588–603.

Golder Associates. 2008. Environmental management programme for Namakwa Sands. Unpublished report nr. 10417-5659-1-E. Golder Associates, Johannesburg, South Africa.

Hälbich, T.F.J. 2003. Mine rehabilitation in the arid Succulent Karoo vegetation zone on the South African west coast, Namakwa Sands – a case study. Pages 113 – 118 in: Heavy Minerals. South African Institute of Mining and Metallurgy, Johannesburg, South Africa.

Herrick, J.E., Schuman, G.E. and Rango, A. 2006. Monitoring ecological processes for restoration projects. Journal of Nature Conservation **14**:161–171.

Hilton-Taylor, C. 1996. Patterns and characteristics of the flora of the Succulent Karoo Biome, southern Africa. Pages 58–72 in: van der Maesen, L., van der Burgt, X. & van Medenbach de Rooy, J. (eds.) The biodiversity of African plants. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Hobbs, R.J. and Harris, J.A. 2001. Restoration Ecology: Restoring the Earth's Ecosystems in the New Millennium. Restoration Ecology **9**:239–246.

Hoffman, M.T. & Rohde, R.F. 2007. From pastoralism to tourism: The historical impact of changing land use practices in Namaqualand. Journal of Arid Environments **70**:641–658.

Lubke, R.A. & Avis, A.M. 1998. A review of the concepts and application of rehabilitation following heavy mineral dune mining. Marine Pollution Bulletin **37**:546–557.

Mahood, K. 2003. Strip Mining Rehabilitation by Translocation in Arid Coastal Namaqualand, South Africa. MSc Thesis. Stellenbosch University, Stellenbosch, South Africa.

Manning, J. 2008. Ecoguide Namaqualand. Briza Publications, Pretoria, South Africa.

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., Yeaton, R.I., Dean, W.R.J. & Vlok, J.H.J. 1997. Succulent Karoo. Pages 131–166 in: Cowling, R.M., Richardson, D.M. & Pierce, S.M. (eds.) Vegetation of South Africa. Cambridge University Press, Cambridge.

Milton, S.J. 2001. Rethinking ecological rehabilitation in arid and winter rainfall regions of southern Africa. South African Journal of Science **97**:47–48.

Mittermeier, R.A., Myers, N., Robles Gil, P. & Mittermeier, C.G. 2000. Hotspots: Earth's biologically richest and most endangered terrestrial ecoregions. CEMEX, Mexico.

Moore, J.M. & Picker, M.D. 1991. *Heuweltjies* (earth mounds) in the Clanwilliam district, Cape Province, South Africa: 4000-year-old termite nests. Oceologia **86**:424–432.

Mucina, L., Jürgens, N., le Roux, A., Rutherford, M.C., Schmiedel, U., Esler, K.J., Powrie, L.W., Desmet, P.G. & Milton, S.J. 2006. Succulent Karoo Biome. Pages 220 – 299 in: Mucina, L. & Rutherford, M.C. (eds.) The Vegetation of South Africa, Lesotho and Swaziland. South African National Biodiversity Institute, Pretoria, South Africa.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., Da Fonseca, G.A.B. & Kent, J. 2000. Biodiversity hotspots for conservation priorities. Nature **403**:853–858.

Namakwa Sands. 2008. 2007 Footprint Sustainability Report. Namakwa Sands, Vredenburg, South Africa.

Prinsloo, H.P. 2005. Alteration of the soil mantle by strip mining in the Namaqualand Strandveld. MSc Thesis. Stellenbosch University, Stellenbosch, South Africa.

Robinson, I., Van Averbeke, N., Harding, A.J., Duval, J.A.G., Mwape, P. and Perold, J.W. (eds.) 2005. South Africa's Mineral Industry 2004/2005. Directorate: Mineral Economics, Department of Minerals and Energy, Pretoria, South Africa.

Singer, A., Kirsten, W. & Bühmann, C. 1995. Fibrous clay minerals in the soils of Namaqualand, South Africa: characteristics and formation. Geoderma **66**:43–70.

Smith, M.A., Grant, C.D., Loneragan, W.A. & Koch, J.M. 2004. Fire management implications of fuel loads and vegetation structure in jarrah forest restoration on bauxite mines in Western Australia. Forest Ecology and Management **187**:247–266.

Tongway, D. & Hindley, N. 2004. Landscape function analysis: Procedures for monitoring and assessing landscapes (With special reference to Minesites and Rangelands). CSIRO Sustainable Ecosystems, Canberra.

Zhou, C.F., Qin, P. & Xie, M. 2003. Vegetating coastal areas of east China: species selection, seedling cloning and transplantation. Ecological Engineering **20**:275–286.

Personal Communications

Esler, K.J. Dept. of Conservation Ecology and Entomology. University of Stellenbosch. Private Bag X1, Matieland, 7602, South Africa. Tel: (021) 8084 005. Fax: (021) 8083 304. E-mail: kje@sun.ac.za.

Milton, S.J. Renu-karoo Veld Restoration CC. PO Box 47, Prince Albert, 6930, South Africa. Tel: (023) 5411 828. Fax: (023) 5411 828. E-mail: renukaroo@gmail.com.

Vlok, M. Safety, Health, Environmental and Quality Dept. Exarro Namakwa Sands. P.O. Box 223, Lutzville, 8165, South Africa. Tel: (027) 2173 330. Fax: (027) 2173 055. E-mail: marius.vlok@exxaro.com.

Chapter 2: Literature Review

2.1. Introduction

Exxaro Namakwa Sands is located in the region known as Namaqualand, the strongly winter rainfall part of the Succulent Karoo (Milton *et al.*, 1997; Cowling *et al.*, 1999). The Succulent Karoo is considered to be a unique environment, due to its low, but predictable rainfall (Milton *et al.*, 1997; Cowling *et al.*, 1999; Desmet, 2007; MacKellar *et al.*, 2007), high species richness and endemism (Hilton-Taylor, 1996; Milton *et al.*, 1997; Desmet & Cowling, 1999a; Desmet 2007), as well as the dominance of leaf succulent dwarf shrubs (Milton *et al.*, 1997; Cowling *et al.*, 1999; Esler & Rundel, 1999). Namaqualand is also well known for its diversity, and has a high number of endemic plant species (Cowling *et al.*, 1999; Cowling & Hilton-Taylor, 1999; Desmet, 2007).

Strip mining activities are expanding on the west coast of South Africa (Milton, 2001). Strip mining, which is also practiced at Namakwa Sands, completely disrupts ecosystems on a large scale, as vegetation is destroyed and soil is removed (Milton *et al.*, 1997; Cooke & Johnson, 2002; Hälbich, 2003; Prinsloo, 2005; Botha *et al.*, 2008). It is now considered the greatest threat to environment in the region (Carrick & Kruger, 2007; Cousins *et al.*, 2007; Botha *et al.*, 2008). However, the mining sector is an important driver of the Namaqualand economy (Mucina *et al.*, 2006; Francis *et al.*, 2007), and mining operations such as Namakwa Sands bring significant socio-economic benefits to the region (Namakwa Sands, 2008).

The need for restoration is becoming ever more evident (Aronson *et al.*, 2007). In South Africa, organizations or individuals that negatively impact on the environment are required by the National Environmental Management Act (Act 8 of 2004) to restore what they degraded. The Mineral and Petroleum Resources Development Act (Act 28 of 2002) further regulates rehabilitation in the mining sector. Unfortunately, there are many challenges to restoration, specifically in environments such as Namaqualand, where the climate is arid and windy and the soils are saline and nutrient-poor (Lubke & Avis, 1998; Milton, 2001; Hälbich, 2003; Carrick & Kruger, 2007; Botha *et al.*, 2008).

Appropriate restoration goals and objectives, which are well defined and achievable, need to be developed in order to boost the chances of success (Lubke & Avis, 1998; Johnson & Tanner, 2003; Ntshotsho *et al.*, 2010). These goals and objectives are used to evaluate restoration success.

Few international standards for restoration exist (Carrick & Kruger, 2007), although some best practice guidelines have been developed (DITR, 2006; ICMM, 2006). Monitoring forms an important part of the restoration process (Lubke & Avis, 1998; Hobbs & Harris, 2001; Cooke & Johnson, 2002), as it allows managers to evaluate their success (Lubke & Avis, 1998; Hobbs & Harris, 2001; Herrick *et al.*, 2006) and to adapt their management strategies if necessary (Cooke & Johnson 2002; Cummings *et al.*, 2005; Herrick *et al.*, 2006). Using an adaptive management approach, the restoration process should be improved as better methods are researched, and should be suited to the specific environment (Blood, 2006).

Blood (2006) evaluated the success of four experimental rehabilitation treatments at Namakwa Sands and found that some reached the final objective for vegetation cover, while none reached the final objective for species richness. Blood (2006) did not expect any of the treatments to reach the grazing capacity objective. This study follows up on Blood (2006), but is also an assessment of the success of the current rehabilitation method (described in Chapter 1).

This chapter provides an overview of the impacts of mining and of the restoration process. It also reviews the existing literature on these subjects.

2.2. Impacts of Mining

The mining sector forms an important part of the South African economy (Tanner, 2007; Chamber of Mines of South Africa, 2008), contributing 7.7 % to the national GDP in 2007 (Masetlana *et al.*, 2008) and creating nearly one million jobs (Chamber of mines of South Africa, 2009). Mining is also an important driver of the Namaqualand regional economy (Mucina *et al.*, 2006; Francis *et al.*, 2007). Namakwa Sands exports more than 95 % of its products, earning more than R 1 billion in foreign exchange annually (Namakwa Sands, 2008). The mine and MSP are also economically important in a regional context (Mucina *et al.*, 2006; Francis *et al.*, 2007), since there are very few job opportunities in the Namaqualand, and livestock farming is the primary economic activity (Anderson & Hoffman, 2007). According to Namakwa Sands (2008), the company contributed more than 280 million Rand to the regional economy in 2007. This consists of tax and utility payments, salaries, as well as educational, health and economic development projects. Almost 80 % of Namakwa Sands employees come from communities in the surrounding municipalities (Namakwa Sands, 2008).

Unfortunately, these socio-economic benefits come at a great environmental cost. It is believed that the mining operation at Brand-se-Baai has had a major impact on the vegetation communities in the area (Mucina *et al.*, 2006; Manning, 2008). Strip mining completely disrupts natural ecosystems over a large area, because the vegetation is destroyed, and the soil is removed (Lubke & Avis, 1998; Cooke & Johnson, 2002; Carrick & Kruger, 2007). Important ecological processes such as mycorrhizal symbioses are also disrupted by mining (Miller, 1979; Bradshaw, 1997). This is of great concern, particularly when bearing in mind the unique vegetation of the area and the difficulties of restoration in an environment with very low rainfall, strong winds and soils with low nutrient levels (Lubke & Avis, 1998; Milton, 2001; Hälbich, 2003; Carrick & Kruger, 2007; Botha *et al.*, 2008).

Another concern is that the mining operation causes the formation of saline sand tailings with very low levels of clay and organic matter (Prinsloo, 2005). This is due to the treatment of ore with sea water and the centrifugal separation of the lighter sandy material and the heavier, mineral-containing clay material (Marius Vlok, pers. comm., 2009). The salinity of tailings is expected to reduce to near natural levels after 25 months, through natural leaching processes (Prinsloo, 2005). However, this might also decrease the fertility of tailings. The salinity and low soil fertility is likely to impair the restoration process (Prinsloo, 2005).

2.3. Restoration

2.3.1. The Need for Restoration

The need to restore natural capital is becoming ever more evident (Aronson *et al.*, 2007), and it is the focal point of the larger WRC/ASSET Research project, in which this study is included. Humans, together with all other organisms in the biosphere, are reliant on natural ecosystems to sustain life, through the provision of ecosystem goods and services (Aronson *et al.*, 2007). The degradation of natural ecosystems thus leads to a reduction in the capability of these ecosystems to deliver life-sustaining goods and services (Aronson *et al.*, 2007). However, restoration of degraded natural capital will lead to an increase in the generation of these goods and services and ultimately to an increase in the quality of life (Aronson *et al.*, 2007). The diversity contained within intact ecosystems also increases the resilience and adaptability of critical life support systems to disturbances, which can protect the quality of life even in the face of global climate change (Aronson *et al.*, 2007).

The restoration efforts of mining companies are, however, largely driven by economic incentives. Firstly, mining companies in South Africa will not be able to obtain a closure certificate in order to be released from financial and legal liability for mined-out land unless it is successfully restored to pre-determined targets. Secondly, mining companies will not be granted further mining rights and permits if the company does not comply with legislative requirements. Thirdly, breaching the legislation on restoration as contained in the acts listed below may result in large financial penalties. The Mineral and Petroleum Resources Development Act (Act 28 of 2002) states that "the holder of a prospecting right, mining right, retention permit or mining permit must ensure that: the land is rehabilitated, as far as practicable, to its natural state, or to a predetermined and agreed standard or land use which conforms with the concept of sustainable development." The National Environmental Management Act (Act 8 of 2004), National Environmental Management: Air Quality Act (Act 29 of 2004) and National Water Act (Act 36 of 1998) also require that, where degredation or pollution cannot be avoided, it must be minimised and remedied.

Globally, the mining industry is growing more aware of its obligations towards the environment (Hobbs and Harris, 2001). This is partly due to the need for mining companies to show that the industry is socially and environmentally sustainable, in order to enhance its public image (Milton *et al.*, 2003). There is also a growing environmental awareness in international trade (Milton *et al.*, 2003), which might be a result of greater public awareness of environmental issues.

2.3.2. Restoration Goals and Objectives

To improve the chances of restoration success it is important to set clear and attainable restoration goals, and objectives that are specific, contribute to the achievement of restoration goals and that can be monitored (Lubke & Avis, 1998; Johnson & Tanner, 2003; DITR, 2006). In order to set valid restoration goals and objectives, it is important to have baseline studies conducted on the soil, fauna and flora of the region (Lubke & Avis, 1998; DITR, 2006). The restoration process is frequently divided into different stages, with suitable goals and objectives set for each of these stages. According to Lubke & Avis (1998), the first goal when rehabilitating mined land should be to create a landscape that is resistant to erosive forces such as wind and water. The next goal would be to rehabilitate the landscape to a condition that enables other forms of land use, whether it is nature conservation, agriculture, forestry, or urban development (Lubke & Avis, 1998). Objectives concerning the composition, structure and function of the ecosystem need to be developed (Hobbs & Norton, 1996). The rehabilitation process cannot be judged as successful unless all three ecosystem attributes are restored (Hobbs & Norton, 1996; Reay & Norton, 1999).

The assumption that the functioning of an ecosystem will return if the composition and structure of the ecosystem is restored does not necessarily hold true (Reay & Norton, 1999).

Exxaro Namakwa Sands' rehabilitation goal is to "rehabilitate and re-vegetate disturbed areas and establish a self-sustaining Strandveld vegetation cover in order to control dust generation, control wind and water erosion, as well as restore land capability. In general, vegetation will be rehabilitated to a minimum grazing standard capable of supporting small stock (sheep) grazing." The minimum grazing standard set in the Environmental Management Programme is 20 ha per small stock unit (Golder Associates, 2008). Vegetation cover and plant species richness objectives for rehabilitation were developed by the Environmental Evaluation Unit, who conducted the environmental impact report for the Namakwa Sands mine in 1990 (EEU report as referenced in Blood, 2006). The vegetation cover objectives were that rehabilitated sites should have 50 % of the cover at reference sites after three years and 80 % after five years, respectively. The objectives for species richness were that rehabilitated sites should have 30 % of the average number of species at reference sites after three years, and 60 % at the end of rehabilitation (EEU report, as referenced in Blood, 2006). These vegetation cover and species richness objectives are not used by Namakwa Sands at present and were not included in their updated EMP (Golder Associates, 2008). This is because a single set of objectives cannot be applied to sites which differ in environmental conditions such as slope and depth of mining and which supported different vegetation communities before mining. These objectives may not be realistic at all sites. Namakwa Sands is currently developing objectives that are specific to different sets of environmental conditions. However, because the new objectives are still in development and to enable comparison with Blood's results, the objectives developed by the Environmental Evaluation Unit are still used in this study.

2.3.3. Monitoring Restoration

Carrick & Kruger (2007) state that: "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." This study contributes towards the bridging of the gap that exists between researchers and environmental managers in this regard, as there is close collaboration between the researcher and the mine.

Monitoring is an indispensable part of the restoration process (Lubke & Avis, 1998; Hobbs & Harris, 2001; Cooke & Johnson, 2002; Ntshotsho *et al.*, 2010) that enables the evaluation of restoration success (Lubke & Avis, 1998; Hobbs & Harris, 2001; Herrick *et al.*, 2006). It gives restoration managers an opportunity to evaluate and, if necessary, change their restoration objectives (Herrick *et al.*, 2006). Monitoring also allows practitioners to adapt their management strategies and better their restoration practices (Cooke & Johnson 2002; Cummings *et al.*, 2005; Herrick *et al.*, 2006). Because restoration is very costly, especially in arid environments (Milton, 2001; Herling *et al.*, 2009), and it is a legal requirement to successfully restore mined land, researching better restoration methods can save mining companies a lot of money (Ndeinoma, 2006). A major issue in the practice of mine rehabilitation is the lack of published studies in the peer-reviewed literature. Of those studies that are published most are short-term (Blood, 2006; Herrick *et al.*, 2006) and very few are repeated in time. Therefore a potentially large and valuable body of knowledge on rehabilitation is left inaccessible to researchers and practitioners.

The methods used to monitor restoration success are diverse and depend on the site-specific restoration objectives (Hobbs & Harris, 2001; Cooke & Johnson, 2002; Johnson & Tanner, 2003; Tanner, 2007; Nthsotsho *et al.*, 2010). As restoration objectives often focus on vegetation structure and composition (Cooke & Johnson, 2002; Johnson & Tanner, 2003; Ruiz-Jean & Aide, 2005; Herrick *et al.*, 2006), plot- or transect-based vegetation surveys are frequently the main method of monitoring restoration success. Methods that measure or indicate the success of restoration of ecosystem function are used less often (Ruiz-Jean & Aide, 2005), although a number of methods have been developed. One noteworthy method is the Landscape Function Analysis that was developed by researchers in Australia to rapidly assess ecosystem function on rangelands and minesites (Tongway & Hindley, 2004b). It is a transect-based method in which soil-surface indicators are used to calculate indices of soil surface stability, nutrient cycling and water infiltration. The LFA method has been tested and successfully applied to monitor the development of restored sites in many different environments (Tongway & Hindley, 2004a). Other methods used to monitor the success of restoring ecosysem function include measuring biomass (Foster *et al.*, 2007; Grant *et al.*, 2007), examining ant communities (Majer, 1992; 1996; Majer & Nichols, 1998; Andersen *et al.*, 2002; Andersen *et* al., 2003; Netshilaphala *et al.*, 2005), and examining avian communities (Twedt *et al.*, 2002; Wood *et al.*, 2004).

2.3.4. Challenges to and Opportunities for Restoration

Arid environments, such as the west coast of South Africa, hold many challenges to restoration (Lubke & Avis, 1998). Challenges to restoration in the Namaqualand region include the low annual

rainfall, strong winds, hot and dry summers (Desmet & Cowling, 1999b; Botha *et al.*, 2008), the short dispersal distance of most perennial plant seeds (Esler, 1999), as well as the poor representation of perennial plant species in the seed bank (De Villiers *et al.*, 2001). Such environmental constraints which affect seedling survival, together with the extent of degradation (total disruption of the ecosystem over large areas in this case) increase the cost of restoration (Herling *et al.*, 2009). Other frequently overlooked challenges are the limited availability of finances and expertise to carry out restoration (Lubke & Avis, 1998). These are dependent on the mining company's financial situation and its dedication to successful rehabilitation.

There are also opportunities for restoration that should be kept in mind. The strong seasonality and low variability of rainfall (Cowling *et al.*, 1999; Desmet, 2007; MacKellar, 2007) creates a favourable period for transplantation and sowing. The low rainfall is augmented by the occurrence of fog (Cowling *et al.*, 1999; Desmet & Cowling, 1999b; Desmet, 2007; MacKellar *et al.*, 2007) on approximately 100 days per year at Namakwa Sands (Blood, 2006), which adds more than 120 mm to the average annual precipitation (De Villiers *et al.*, 1999), and thus greatly increases the amount of water available to plants (Desmet & Cowling, 1999a). Winter temperatures are mild enough to allow plants to grow while water is available (Cowling *et al.*, 1999; Desmet & Cowling, 1999b; Desmet, 2007; MacKellar *et al.*, 2007). Also, the high prevalence of succulence and drought tolerance of seedlings (Carrick & Kruger, 2007) allow plants to survive the hot and dry summer conditions.

2.3.5. Rehabilitation Methods

Different combinations of topsoil replacement, seeding and translocation of mature plants or nursery seedlings have been used during rehabilitation after bauxite, coal and mineral sands mining in different ecosystems across Australia (Lubke & Avis, 1998; Bell, 2001; Johnson & Tanner, 2003; Norman *et al.*, 2006; Koch, 2007; Herath *et al.*, 2009), on phosphate mines in the western USA (Chambers *et al.*, 1994), as well as after diamond and mineral sands mining on the west coast and east coast of South Africa (Lubke & Avis, 1998; Carrick & Kruger, 2007; Botha *et al.*, 2008). Topsoil replacement is generally regarded as crucial for rehabilitation (Milton, 2001; Johnson & Tanner, 2003; Carrick & Kruger, 2007), and has been implemented on most mines. Seeding has also been used during restoration of over-grazed rangeland, in combination with soil treatments and / or micro-site creation, in the neighbouring Nama Karoo biome (Beukes & Cowling, 2003; Visser *et al.*, 2004; van den Berg & Kellner, 2005) and seeding and seedling translocation have been tested during rangeland restoration in Namaqualand (Simons & Allsopp, 2007).

Topsoil replacement, seeding and translocation of mature plants and nursery cuttings can be justified theoretically. Topsoil contains organic matter, nutrients and soil fauna and flora such as earthworms and mycorrhiza, which contribute to the successful establishment of vegetation and the return of ecosystem functioning (Lubke & Avis, 1998; Milton, 2001 Carrick & Kruger, 2007; Koch, 2007). Topsoil also contains the greatest fraction of the soil seed bank, which supplies many of the species that establish on rehabilitation sites (de Villiers, 2000; Holmes, 2001; Hälbich, 2003; Johnson & Tanner, 2003; Koch, 2007; Tanner, 2007). Seeding is an important way of supplementing species richness by adding species that are not well represented or absent in the soil seed bank (Bell, 2001; Holmes, 2001; Hälbich, 2003; Carrick & Kruger, 2007). These are generally small seeded species and perennial, wind dispersed species (Hälbich, 2003). Seeding some time after initial rehabilitation has been recommended as an effective means of re-introducing late successional species to rehabilitation sites (Carrick & Desmet, 2003; Norman *et al.*, 2006). Seeding is also very cost-effective, as it is not a labour intensive treatment (Carrick & Kruger, 2007). Translocation of mature plants and nursery cuttings enables rehabilitation practitioners to return species which are not present in the soil seed bank or which doesn't establish well from seeds to rehabilitation sites (Bell, 2001; Hälbich, 2003), and also returns micro-organisms (Milton, 2001). Nursery cuttings can be propagated in bulk by means of horticultural methods (Carrick & Kruger, 2007), and have been found to establish better than seeds (Botha *et al.*, 2008), which increases the cost-effectiveness of this method. However, mature plants have established roots and will also set seed, and thus spread sooner in the rehabilitation site (Milton, 2001; Carrick & Kruger, 2007). Translocation is particularly effective for small seeded, succulent species in Namaqualand (Carrick & Kruger, 2007; Botha *et al.*, 2008).

2.3.6. Rehabilitation Success at Exxaro Namakwa Sands

Jeremy Blood evaluated the success of four different rehabilitation treatments at Namakwa Sands during 2004 and 2005 (Blood, 2006). The rehabilitation experiments at the time differed somewhat from the current method. Four different treatments were applied in the experiment that aimed to improve the rehabilitation method. He found that all four experimental rehabilitated sites had reached the 3-year objective for vegetation cover (50 % of cover at reference sites), while some rehabilitated sites also reached the 5-year objective (80 % of cover at reference sites) in some sampling periods. Some of the rehabilitated sites achieved the 3-year objective for species richness (30 % of richness at reference sites), but none had reached the final objective (60 % of richness at reference sites). He found it doubtful that the grazing capacity objective would have been achieved with the combinations of rehabilitation treatments used at the time. This is the first study that will evaluate the success of the current rehabilitation method.

2.4. References

Andersen, A.N., Hoffmann, B.D., Müller, W.J. & Griffiths, A.D. 2002. Using ants as bioindicators in land management: simplifying assessment of ant community responses. Journal of Applied Ecology **39**:8–17.

Andersen, A.N., Hoffmann, B.D. & Somes, J. 2003. Ants as indicators of minesite restoration: community recovery at one of eight rehabilitation sites in central Queensland. Ecological Management & Restoration **4**:S12–S19.

Anderson, P.M.L. & Hoffman, M.T. 2007. The impacts of sustained heavy grazing on plant diversity and composition in lowland and upland habitats across the Kamiesberg mountain range in the Succulent Karoo, South Africa. Journal of Arid Environments **70**:686–700.

Aronson, J., Milton, S.J. & Blignaut, J.N. (eds.) 2007. Restoring Natural Capital: Science, Business and Practice. Island Press, Washington D.C.

Bell, L.C. 2001. Establishment of native ecosystems after mining – Australian experience across diverse biogeographic zones. Ecological Engineering **17**:179–186.

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

Botha, M.S., Carrick, P.J. & Allsopp, N. 2008. Capturing lessons from land-users to aid the development of ecological restoration guidelines for lowland Namaqualand. Biological Conservation **141**:885–895.

Blood, J.R. 2006. Monitoring Rehabilitation Success on Namakwa Sands Heavy Minerals Mining Operation, Namaqualand, South Africa. MSc Thesis, University of Stellenbosch, South Africa.

Bradshaw, A. 1997. Restoration of mined lands – using natural processes. Ecological Engineering **8**:255–269.

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.

Chamber of Mines of South Africa. 2008. Annual Report. Chamber of Mines of South Africa, Johannesburg, South Africa.

Chamber of Mines of South Africa. 2009. Annual Report. Chamber of Mines of South Africa, Johannesburg, South Africa.

Chambers, J.C., Brown, R.W. & Williams, B.D. 1994. An evaluation of reclamation success on Idaho's phosphate mines. Restoration Ecology **2**:4–16.

Cooke, J.A. & Johnson, M.S. 2002. Ecological Restoration of land with particular reference to the mining of metals and industrial minerals: A review of theory and practice. Environmental Review **10**:41–71.

Cousins, B., Hoffman, M.T., Allsopp, N. & Rhode, R.F. A synthesis of sociological and biological perspectives on sustainable land use in Namaqualand. Journal of Arid Environments **70**:834–846.

Cowling, R.M. & Hilton-Taylor, C. 1999. Plant biogeography, endemism and diversity. Pages 42–55 in: Dean, W.R.J. & Milton, S.J. (eds.) The Karoo: Ecological patterns and processes. Cambridge University Press, Cambridge.

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.

Cummings, J., Reid, N., Davies, I. & Grant, C. 2005. Adaptive management of sand-mined areas for biological conservation. Journal of Applied Ecology **42**:160–170.

Department of Industry, Tourism & Resources (DITR). 2006. Leading practice sustainable development program for the mining industry – mine rehabilitation. DTIR, Canberra.

Desmet, P.G. & Cowling, R.M. 1999a. Biodiversity, habitat and range-size aspects of a flora from a winter-rainfall desert in north-western Namaqualand, South Africa. Plant Ecology **142**:23–33.

Desmet, P.G. & Cowling, R.M. 1999b. The climate of the Karoo – a functional approach. Pages 3–16 in: Dean, W.R.J. & Milton, S.J. (eds.) The Karoo: Ecological patterns and processes. Cambridge University Press, Cambridge.

Desmet, P.G. 2007. Namaqualand – A brief overview of the physical and floristic environment. Journal of Arid Environments **70**:570–587.

De Villiers, A.J. 2000. Seed bank dynamics of the Strandveld Succulent Karoo. Ph.D. Thesis, University of Pretoria, South Africa.

De Villiers, A.J., Van Rooyen, M.W. & Theron, G.K. 2001. Seed bank phytosociology of the Strandveld Succulent Karoo, South Africa: a pre-mining benchmark survey for rehabilitation. Land Degradation and Development **12**:119–130.

De Villiers, A.J., Van Rooyen, M.W., Theron, G.K. & Van Rooyen, N. 1999. Vegetation diversity of the Brand-se-Baai coastal dune area, West Coast, South Africa: A pre-mining benchmark survey for rehabilitation. Land Degradation and Development **10**:195–206.

Esler, K.J. 1999. Plant reproductive ecology. Pages 123–144 in: Dean, W.R.J. & Milton, S.J. (eds.) The Karoo: Ecological patterns and processes. Cambridge University Press, Cambridge.

Esler, K.J. & Rundel, P.W. 1999. Comparative patterns of phonology and growth form diversity in two winter rainfall deserts: The Succulent Karoo and the Mojave Desert ecosystems. Plant Ecology **142**:97–104.

Foster, B.L., Murphy, C.A., Keller, K.R., Aschenbach, T.A., Qeustad, E.J. & Kindscher, K. 2007. Restoration of Prairie community structure and ecosystem function in an abandoned hayfield: a sowing experiment. Restoration Ecology **15**:652–661.

Francis, M.L., Fey, M.V., Prinsloo, H.P., Ellis, F., Mills, A.J. & Medinski, T.V. 2007. Soils of Namaqualand: Compensations for aridity. Journal of Arid Environments **70**:588–603.

Golder Associates. 2008. Environmental management programme for Namakwa Sands. Unpublished report nr. 10417-5659-1-E. Golder Associates, Johannesburg, South Africa.

Grant, C.D., Ward, S.C. & Morley, S.C. 2007. Return of ecosystem function to restored bauxite mines in Western Australia. Restoration Ecology **15**:S94–S103.

Hälbich, T.F.J. 2003. Mine rehabilitation in the arid Succulent Karoo vegetation zone on the South African west coast, Namakwa Sands – a case study. Pages 113–118 in: Heavy Minerals, South African Institute of Mining and Metallurgy, Johannesburg.

Herath, D.N., Lamont, B.B., Enright, N.J. & Miller, B.P. 2009. Comparison of post-mine rehabilitation and natural shrubland communities in southwestern Australia. Restoration Ecology **17**:577–585.

Herling, M.C., Cupdio, C.F., O'Farrell, P.J. & Du Plesis, L. 2009. The financial costs of ecologically nonsustainable farming practices in a semiarid system. Restoration Ecology **17**:827–836.

Herrick, J.E., Schuman, G.E. & Rango, A. 2006. Monitoring ecological processes for restoration projects. Journal of Nature Conservation **14**:161–171.

Hilton-Taylor, C. 1996. Patterns and characteristics of the flora of the Succulent Karoo Biome, southern Africa. Pages 58–72 in: van der Maesen, L., van der Burgt, X. & van Medenbach de Rooy, J. (eds.) The biodiversity of African plants. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Hobbs, R.J. & Norton, D.A. 1996. Towards a conceptual framework for restoration ecology. Restoration Ecology **4**:93–110.

Hobbs, R.J. & Harris, J.A. 2001. Restoration Ecology: Restoring the Earth's Ecosystems in the New Millennium. Restoration Ecology **9**:239–246.

Holmes, P.M. 2001. Shrubland restoration following woody alien invasion and mining: effects of topsoil depth, seed source, and fertilizer addition. Restoration Ecology **9**:71–84.

International Council for Mining and Metals (ICMM). 2006. Good practice guidance for mining and biodiversity. International Council for Mining and Metals, London, UK.

Johnson, M.S. & Tanner, P.D. 2003. Mine Site Rehabilitation and Ecosystem Reconstruction for Biodiversity Gain. IUCN/ICMM Workshop, Gland, Switzerland.

Koch, J.M. 2007. Alcoa's mining and restoration process in south western Australia. Restoration Ecology **15**:S11–S16.

Lubke, R.A. & Avis, A.M. 1998. A review of the concepts and application of rehabilitation following heavy mineral dune mining. Marine Pollution Bulletin **37**:546–557.

MacKellar, N.C., Hewitson, B.C. & Tadross, M.A. 2007. Namaqualand's climate: Recent historical changes and future scenarios. Journal of Arid Environments **70**:604–614.

Manning, J. 2008. Ecoguide Namaqualand. Briza Publications, Pretoria.

Masetlana, T.R., Dlambulo, N., Themba, L.A. & Mwape, P. (eds.) 2008. South Africa's Mineral Industry 2007/2008. Directorate: Mineral Economics, Department of Minerals & Energy, Pretoria.

Majer, J.D. 1992. Ant recolonisation of rehabilitated bauxite mines of Poços de Caldas, Brazil. Journal of Tropical Ecology **8**:97–108.

Majer, J.D. 1996. Ant recolonization of rehabilitated bauxite mines at Trobetas, Pará, Brazil. Journal of Tropical Ecology **12**:257–273.

Majer, J.D. & Nichols, O.G. 1998. Long-term recolonization patterns of ants in Western Australian rehabilitated bauxite mines with reference to their use as indicators of restoration success. Journal of Applied Ecology **35**:161–182.

Manning, J. 2008. Ecoguide Namaqualand. Briza Publications, Pretoria.

Miller, R.M. 1979. Some occurrences of vesicular-arbuscular mycorrhiza in natural and disturbed ecosystems of the Red Desert. Canadian Journal of Botany **57**:619–623.

Milton, S.J., Yeaton, R.I., Dean, W.R.J. & Vlok, J.H.J. 1997. Succulent Karoo. Pages 131–166 in: Cowling, R.M., Richardson, D.M. & Pierce, S.M. (eds.) Vegetation of South Africa. Cambridge University Press, Cambridge.

Milton, S.J. 2001. Rethinking ecological rehabilitation in arid and winter rainfall regions of southern Africa. South African Journal of Science **97**:47–48.

Milton, S.J., Dean, W.R.J. & Richardson, D.M. 2003. Economic incentives for restoring natural capital in southern African rangelands. Frontiers in Ecology and the Environment **1**:247–254.

Mucina, L., Jürgens, N., le Roux, A., Rutherford, M.C., Schmiedel, U., Esler, K.J., Powrie, L.W., Desmet, P.G. & Milton, S.J. 2006. Succulent Karoo Biome. Pages 220 – 299 in: Mucina, L. & Rutherford, M.C. (eds.) The Vegetation of South Africa, Lesotho and Swaziland. South African National Biodiversity Institute, Pretoria.

Namakwa Sands. 2008. 2007 Footprint Sustainability Report. Namakwa Sands, Vredenburg.

Ndeinoma, A. 2006. Mycorrhiza re-establishment on post-mined rehabilitated areas of the Brand-se-Baai Succulent Karoo vegetation. MSc Thesis. University of Stellenbosch, South Africa.

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.

Norman, M.A., Koch, J.M., Grant, C.D., Morald, T.K. & Ward, S.C. 2006. Vegetation succession after Bauxite mining in Western Australia. Restoration Ecology **14**:278–288.

Ntshotsho, P., Reyers, B. & Esler, K.J. 2010. Assessing the evidence base for restoration in South Africa. Restoration Ecology (available early online, doi: 10.1111/j.1526-100X.2010.00753.x).

Prinsloo, H.P. 2005. Alteration of the soil mantle by strip mining in the Namaqualand Strandveld. MSc Thesis, University of Stellenbosch, South Africa.

Reay, S.D. & Norton, D.A. 1999. Assessing the success of restoration plantings in a temperate New Zealand forest. Restoration Ecology **7**:298–308.

Ruiz-Jean, M.C. & Aide, T.M. 2005. Restoration success: How is it being measured? Restoration Ecology **13**:569–577.

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

Tanner, P.D. (ed.) 2007. Guidelines for the rehabilitation of mined land. Chamber of Mines of South Africa/Coaltech, Johannesburg, South Africa.

Tongway, D. & Hindley, N. 2004a. Landscape function analysis: Procedures for monitoring and assessing landscapes (With special reference to Minesites and Rangelands). CSIRO Sustainable Ecosystems, Canberra.

Tongway, D. & Hindley, N. 2004b. Landscape function analysis: a system for monitoring rangeland function. African Journal of Range & Forage Science **21**:109–113.

Twedt, D.J., Wilson, R.R., Henne-Kerr, J.L. & Grosshuesch, D.A. 2002. Avian response to Bottomland Hardwood reforestation: the first 10 years. Restoration Ecology **10**:645–655.

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

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.

Wood, D.R., Burger, L.W. Jr., Bowman, J.L. & Hardy, C. 2004. Avian community response to pine-grassland restoration. Wildlife Society Bulletin **32**:819–828.

Personal Communications

Vlok, M. Safety, Health, Environmental and Quality Dept. Exarro Namakwa Sands. P.O. Box 223, Lutzville, 8165, South Africa. Tel: (027) 2173 330. Fax: (027) 2173 055. E-mail: marius.vlok@exxaro.com.

Chapter 3: Rehabilitation Success on a Coastal Mineral Sands Mine in Namaqualand, South Africa

Abstract

The success of different combinations of rehabilitation treatments at Exxaro's Namakwa Sands heavy mineral sands mine, on the west coast of South Africa, was assessed. Different treatment combinations were applied to experimental rehabilitation sites in 2001. These are topsoil only, seeding only, topsoil + translocation and seeding + translocation. Another site representing the current rehabilitation method at Namakwa Sands, topsoil + seeding + translocation + nursery cuttings, which was rehabilitated in 2008, was also assessed to see whether development of vegetation at this site is satisfactory. In the winter of 2009 and summer of 2010 vegetation cover, drought tolerance, species cover, species richness, diversity and evenness, and grazing capacity at these sites were compared to that of two reference sites. The similarity of rehabilitated sites to reference sites and to each other, based on vegetation cover and species richness, as well as species cover, was also assessed. Vegetation cover, species richness and grazing capacity at rehabilitated sites were also measured against the objectives that were determined by Namakwa Sands. That the vegetation cover of rehabilitated sites should be 50 % of that of reference sites after three years, and 80 % of that of reference sites after five years; that the species richness of rehabilitated sites should be 30 % of that of reference sites after three years and 60 % of that of reference sites at mine closure; and that the grazing capacity at rehabilitated sites should be a minimum of 20 ha / SSU (142.8 ha / LSU). Past rehabilitation trials were unsuccessful in returning vegetation cover and species richness, diversity and evenness to reference levels and did not resemble reference sites in vegetation cover and species richness or species composition. Late successional species were almost completely absent at all four sites. These sites did not reach the five-year vegetation cover and final species richness objectives, but maintained vegetation cover and species richness above the three-year objectives and had higher grazing capacity than the minimum objective. The current rehabilitation method at Namakwa Sands is working well and has already reached the three-year objectives for vegetation cover and species richness, as well as the minimum grazing capacity objective. Topsoil replacement, seeding and translocation of mature plants and nursery cuttings all have advantages, therefore Namakwa Sands should continue to apply all these treatments in future rehabilitation. However, rehabilitation should be done in multiple stages in future to improve seedling survival and to return late successional species to rehabilitated sites.

Key words: Rehabilitation; Topsoil; Reseeding; Strip Mining; Namaqualand

3.1.   Introduction

The mining sector forms an important part of the South African economy (Tanner, 2007; Chamber of Mines of South Africa, 2008), contributing 7.7 % to the national GDP in 2007 (Masetlana *et al.*, 2008) and creating nearly one million jobs (Chamber of Mines of South Africa, 2009).   Mining is also an important driver of the Namaqualand regional economy (Mucina *et al.*, 2006; Francis *et al.*, 2007).   Exxaro Namakwa Sands alone contributed more than 280 million rand to the regional economy in 2007 (Namakwa Sands, 2008).   Strip mining for heavy minerals is expanding in Namaqualand (Milton, 2001) and, in conjunction with diamond mining, is considered the greatest threat to the biodiversity of the region (Botha *et al.*, 2008), having overtaken other land uses as the greatest source of degradation (Carrick & Kruger, 2007; Cousins *et al.*, 2007).   Strip mining, which is also practiced at Namakwa Sands, is considered one of the most destructive mining methods as it involves the total removal of topsoil and vegetation from large stretches of land (Milton *et al.*, 1997; Cooke & Johnson, 2002; Botha *et al.*, 2008).   This is of particular concern in an environment, such as Namaqualand, where revegetation is hampered by an arid and windy climate (Lubke & Avis, 1998; Milton, 2001; Hälbich, 2003; Carrick & Kruger, 2007; Botha *et al.*, 2008), as well as saline and nutrient-poor soils (Milton, 2001; Carrick & Kruger, 2007; Botha *et al.*, 2008).

The mining industry world-wide is committing itself to sustainable development, and therefore also responsible environmental management (ICMM, 2006).   As a result, many mining companies are taking their responsibility to rehabilitate mined-out land ever more seriously.   Governments have also stepped up environmental legislation in recent decades.   A number of new acts have been proclaimed in South Africa in the past decade to ensure responsible environmental management. These include the National Environmental Management Act 107 of 1998, the National Environmental Management: Air Quality Act 29 of 2004 and the Minerals and Petroleum Resources Development Act 28 of 2002 (MPRDA).   Large mine blocks and prospecting trenches, evident by their lack of vegetation, are still visible along the Namaqualand coast and indicate that rehabilitation used to be the exception rather than the rule before the Minerals Act 50 of 1991 and subsequently the MPRDA came into effect (Milton *et al.*, 1997; Carrick & Kruger, 2007; Botha *et al.*, 2008).   The MPRDA requires that mined-out land "is rehabilitated, as far as is practicable, to its natural state, or to a predetermined and agreed standard or land use which conforms to the principles of sustainable development".

Few international standards for environmental management exist (Carrick & Kruger, 2007), although best practice guidelines have been developed by the International Council on Mining and Metals (ICMM, 2006), the Chamber of Mines of South Africa, in conjunction with Coaltech (Tanner,

31

2007) and the Australian Department of Industry, Tourism and Resources (DITR, 2006). In general, rehabilitation goals focus on ecosystem stability, as well as some form of land capability, such as grazing potential, while rehabilitation objectives normally focus on certain aspects of the structure and function of ecosystems (Cooke & Johnson, 2002; Blood, 2006; Bainbridge, 2007; Tanner, 2007). At Exxaro Namakwa Sands, the focus of this study, the rehabilitation goal is to "rehabilitate and re-vegetate disturbed areas and establish a self-sustaining Strandveld vegetation cover in order to control dust generation, control wind and water erosion, as well as restore land capability" (Golder Associates, 2008). The land capability referred to is small stock farming, which was the land use before mining started (Hälbich, 2003). The objective is to rehabilitate disturbed areas to a minimum grazing capacity of 20 ha / SSU (Golder Associates, 2008), which converts to 142.8 ha / LSU.

Every area in need of restoration has its own set of constraints and opportunities (Johnson & Tanner, 2003). Therefore, a site-specific rehabilitation method must be developed through experimentation. At Namakwa Sands, experiments were conducted in 2001, and reported on by Mahood (2003) and Blood (2006). These experiments assessed the effectiveness of different treatments, including: topsoil replacement, seeding (a mix of indigenous species and commercially available grasses) and translocating three and five indigenous species in clumps. All of the above mentioned treatments, together with transplanting of nursery cuttings, comprise the rehabilitation method currently practiced at Namakwa Sands.

Different combinations of topsoil replacement, seeding and translocation of mature plants or nursery seedlings have been used during rehabilitation after bauxite, coal and mineral sands mining in different ecosystems across Australia (Lubke & Avis, 1998; Bell, 2001; Johnson & Tanner, 2003; Norman *et al.*, 2006; Koch, 2007; Herath *et al.*, 2009), on phosphate mines in the western USA (Chambers *et al.*, 1994), as well as after diamond and mineral sands mining on the west coast and east coast of South Africa (Lubke & Avis, 1998; Carrick & Kruger, 2007; Botha *et al.*, 2008). Topsoil replacement is generally regarded as crucial for rehabilitation (Milton, 2001; Johnson & Tanner, 2003; Carrick & Kruger, 2007), and has been implemented on most mines. Seeding has also been used during restoration of over-grazed rangeland, in combination with soil treatments and / or micro-site creation, in the neighbouring Nama Karoo biome (Beukes & Cowling, 2003; Visser *et al.*, 2004; van den Berg & Kellner, 2005) and seeding and seedling translocation have been tested during rangeland restoration in Namaqualand (Simons & Allsopp, 2007).

Topsoil replacement, seeding and translocation of mature plants and nursery cuttings can be justified theoretically. Topsoil contains organic matter, nutrients and soil fauna and flora such as earthworms and mycorrhiza, which contribute to the successful establishment of vegetation and the return of ecosystem functioning (Lubke & Avis, 1998; Milton, 2001 Carrick & Kruger, 2007; Koch, 2007). Topsoil also contains the greatest fraction of the soil seed bank, which supplies many of the species that establish on rehabilitation sites (de Villiers, 2000; Holmes, 2001; Hälbich, 2003; Johnson & Tanner, 2003; Koch, 2007; Tanner, 2007). Seeding is an important way of supplementing species richness by adding species that are not well represented or absent in the soil seed bank (Bell, 2001; Holmes, 2001; Hälbich, 2003; Carrick & Kruger, 2007). These are generally small seeded species and perennial, wind dispersed species (Hälbich, 2003). Seeding some time after initial rehabilitation has been recommended as an effective means of re-introducing late successional species to rehabilitation sites (Carrick & Desmet, 2003; Norman *et al.*, 2006). Seeding is also very cost-effective, as it is not a labour intensive treatment (Carrick & Kruger, 2007). Translocation of mature plants and nursery cuttings enables rehabilitation practitioners to return species which are not present in the soil seed bank or which does not establish well from seeds to rehabilitation sites (Bell, 2001; Hälbich, 2003), and also returns micro-organisms (Milton, 2001). Nursery cuttings can be propagated in bulk by means of horticultural methods (Carrick & Kruger, 2007), and have been found to establish better than seeds (Botha *et al.*, 2008), which increases the cost-effectiveness of this method. However, mature plants have established roots and will also set seed, and thus spread sooner in the rehabilitation site (Milton, 2001; Carrick & Kruger, 2007). Translocation is particularly effective for small seeded, succulent species in Namaqualand (Carrick & Kruger, 2007; Botha *et al.*, 2008).

Monitoring is an indispensable part of the restoration process (Hobbs & Harris, 2001; Cooke & Johnson, 2002) that enables the evaluation of restoration success (Hobbs & Harris, 2001; Herrick *et al.*, 2006). It gives restoration managers an opportunity to evaluate and, if necessary, change their restoration objectives (Herrick *et al.,* 2006). Monitoring also allows practitioners to adapt their management strategies and improve their restoration practices (Cooke & Johnson 2002; Cummings *et al.*, 2005; Herrick *et al.*, 2006).

The aims of this study were to determine whether past rehabilitation efforts have been successful and whether a recently rehabilitated area is progressing towards set objectives, to identify any shortcomings in the rehabilitation method, and to make recommendations to improve the rehabilitation method or manage previously rehabilitated areas, where necessary. The effects of different rehabilitation treatments applied to experimentally rehabilitated sites are also assessed after eight to nine years. Vegetation cover and plant species richness objectives for rehabilitation

33

were developed by the Environmental Evaluation Unit, who conducted the environmental impact report for the Namakwa Sands mine in 1990 (Blood, 2006). The vegetation cover objectives were that rehabilitated sites should have 50 % of the cover at reference sites after three years and 80 % after five years, respectively. The objectives for species richness were that rehabilitated sites should have 30 % of the average number of species at reference sites after three years, and 60 % at the end of rehabilitation (Blood, 2006). These vegetation cover and species richness objectives are no longer used by Namakwa Sands and were not included in their updated EMP (Golder Associates, 2008). This is because a single set of objectives cannot be applied to sites which differ in environmental conditions such as slope and depth of mining, so these objectives may not be realistic at all sites. Namakwa Sands is currently developing objectives that are specific to different environmental conditions.   However, because the new objectives are still under development and to enable comparison with Blood's results, the objectives developed by the Environmental Evaluation Unit are still used in this study.

The overarching hypotheses tested in this chapter, are: That the sites rehabilitated in 2001 (S1 – S4) are similar to the reference sites (R1 & R2) in vegetation structure and composition, and can sustain a similar number of livestock units, while the site rehabilitated in 2008 (S5) differs from these sites in vegetation structure and composition, and can sustain less livestock units. Also, that there is strong seasonal variation in vegetation structure and composition, and grazing capacity. The specific hypotheses being tested are presented in table 3.1 below.

Table 3.1: Hypotheses concerning rehabilitation success that are tested in this chapter.

Measure	Hypotheses
Vegetation cover	Sites rehabilitated in 2001 have similar vegetation cover to reference sites
	Sites rehabilitated in 2001 have more than 80 % of the vegetation cover of reference site R2
	The site rehabilitated in 2008 has significantly lower vegetation cover than all other sites
	The site rehabilitated in 2008 has less than 50 % of the vegetation cover of reference site R2
	All sites have significantly lower vegetation cover in summer 2010 than in winter 2009
Species cover	Sites rehabilitated in 2001 have similar species cover to reference sites
	Sites rehabilitated in 2001 are dominated by the same group of species than reference sites
	The site rehabilitated in 2008 has different species cover than all other sites
	The site rehabilitated in 2008 is dominated by a different group of species than all other sites

	There are significant differences in species cover between winter 2009 and summer 2010
Plant species richness, diversity & evenness	Sites rehabilitated in 2001 have similar plant species richness, diversity and evenness to reference sites
	Sites rehabilitated in 2001 contain more than 60 % of the number of species in reference site R2
	The site rehabilitated in 2008 has significantly lower plant species richness, diversity and evenness than all other sites
	The site rehabilitated in 2008 contains less than 30 % of the number of species in reference site R2
	All sites have significantly lower species richness in summer 2010 than in winter 2009
Grazing capacity	Sites rehabilitated in 2001 have similar grazing capacity to reference sites
	The site rehabilitated in 2008 has significantly lower grazing capacity than all other sites
	The grazing capacity at all rehabilitated sites is less than 142.8 ha / LSU

3.2. Methods

3.2.1. Study Area

This study was conducted on the Exxaro Namakwa Sands heavy minerals mining operation located at Brand-se-Baai (31° 18' S, 17° 54' E), 92 km northwest of Vredendal, on the west coast of South Africa. The mine occurs in the region known as Namaqualand which is situated in the strongly winter rainfall part of the Succulent Karoo Biome (Milton *et al.*, 1997; Cowling *et al.*, 1999). The vegetation is dominated by succulents, especially dwarf leaf succulent shrubs of the Mesembryanthemaceae (Milton *et al.*, 1997; Cowling *et al.*, 1999; Desmet & Cowling, 1999a; Esler & Rundel, 1999). Because of these features, as well as the predictability of rainfall, the Succulent Karoo is considered unique among the arid areas of the world (Esler *et al.*, 1999). Annuals and geophytes, which are not as conspicuous as shrubs, are a functionally important part of the vegetation (Cowling *et al.*, 1999), providing at least short term grazing material when available (Milton *et* al., 1997; Esler *et al.*, 2006). De Villiers *et al.* (1999) mapped six vegetation communities in the vicinity of the mine. The dominant communities were *Ruschia tumidula – Tetragonia virgata* Tall Shrub Strandveld where the East Mine is now located and *Ruschia versicolor – Odyssea paucinervis* Dwarf Shrub Strandveld where the West Mine is now located.

The mean annual precipitation in Namaqualand generally ranges from 50 mm to 250 mm (Desmet, 2007), and is considered very predictable (Cowling *et al.*, 1999; Desmet, 2007; MacKellar, 2007).

35

It is supplemented by frequent coastal fog and dew (Cowling *et al.*, 1999; Desmet & Cowling, 1999b; Desmet, 2007; MacKellar *et al.*, 2007). Rainfall events are typically associated with cold fronts that form in the southern oceans and reach their northern limits during winter (Desmet & Cowling, 1999b; Desmet, 2007). Temperatures are mild, being heavily influenced by the proximity of the Atlantic Ocean, and the cold Benguala Current in particular (Cowling *et al.*, 1999; Desmet & Cowling, 1999b; Desmet, 2007; MacKellar *et al.*, 2007). Namaqualand has one of the strongest wind regimes in the world, dominated by north to north-westerly winds in winter and south to south-easterly winds in summer (de Villiers *et al.*, 1999).

The mean annual rainfall at Brand-se-Baai, calculated from data collected by CSIR (2011) between 1996 and 2009, is 150 mm. The total annual rainfall at Brand-se-Baai was far above average during 2009 (243.7 mm (CSIR, 2011)). The rainfall data for Brand-se-Baai for 2010 is not yet available, but the region also received above average rainfall in 2010 (191 mm in Vredendal, compared to the 20-year average of 159.7 mm (SAWS)). Fog occurs approximately 100 days per year, adding more than 120 mm to the mean annual precipitation (de Villiers *et al.*, 1999). According to Desmet & Cowling (1999b) fog greatly increases the amount of water available to plants. Wind is the primary erosion factor in the area and has been cited as a major constraint to restoration in these systems (Botha *et al.*, 2008). Strong south and south-easterly winds prevail from September to March and strong north to north-westerly winds from June to August (Hälbich, 2003; Mahood, 2003).

The soils found in Namaqualand are typical of arid environments (Francis *et al.*, 2007). Namaqualand soils have certain characteristics that have a major effect on hydrological processes. Soil crusts and naturally hydrophobic, sandy topsoils cause fingering water infiltration, which enables water to penetrate deeper into the soil, where it cannot be lost through evapotranspiration (Francis *et al.*, 2007). Subsurface soil horizons that are cemented with silica, calcite, fibrous clays or gypsum (such as the dorbank layer at Namakwa Sands) inhibit deeper penetration of water, creating an aquifer below the plant root layer, where water can be stored temporarily (Francis *et al.*, 2007). Nocturnal distillation occurs when differences between atmospheric and soil temperatures cause soil water vapour to move towards the surface. This is thought to have a significant impact on the water availability for plants, especially shallow rooted species (Prinsloo, 2005; Francis *et al.*, 2007). Soluble salts slow the uptake of plant water, decreasing the rate of evapotranspiration (Francis *et al.*, 2007). Clay minerals (sepiolite and palygorskite) that are unique to arid environments and have an exceptionally high water-absorbing capacity are common in the clay fraction of Namaqualand soils (Singer *et al.*, 1995; Francis *et al.*, 2007). This provides soils with better water retention than expected for a given clay content (Francis *et al.*, 2007).

36

The dominant soil type in the Brand-se-Baai area is red apedal soil, while regic sands are also quite common (Ellis, 1988; Prinsloo, 2005). Only the layer of Aeolian sand is mined to a maximum depth of 5 m (Golder Associates, 2008). Mining at Namakwa Sands results in tailings that are saline and almost entirely devoid of the clay and organic matter fraction (Prinsloo, 2005). However, the salinity of the soil is expected to lower to natural levels within 25 months, due to natural leaching. Topsoil hydrophobicity (resulting in infiltration fingering) and a cemented dorbank layer are thought to be the key factors driving the nocturnal distillation (Prinsloo, 2005). Therefore, losing these features might result in a reduction of the soil water available to plants.

3.2.2. Study Sites

Two reference sites were located in the two most widespread vegetation communities identified by de Villiers *et al.* (1999). It is important to keep in mind that mining radically alters the bio-physical template, and that the vegetation communities that develop on rehabilitated sites can therefore not be expected to be the same as those that existed prior to mining.   During the development of the rehabilitation method research was conducted on the success of different treatments.   Four experimental sites were rehabilitated in 2001 with different combinations of treatments. The lack of sites at which treatments could be replicated on a sufficient scale resulted in unavoidable pseudo-replication (Blood, 2006). These two reference sites and four rehabilitated sites were sampled by Blood (2006) and have been re-sampled in this study. In addition, a site rehabilitated in 2008, using the current method, was sampled.

At all rehabilitated sites 0.75 meter high windbreaks, consisting of polyethylene shade cloth (with a density of 40 %) and metal droppers, were placed five meters apart and perpendicular to the prevailing winds (Blood, 2006). This was done to prevent wind erosion, loss of seeds and damage to plants due to sand-blasting (Namakwa Sands, 2001; Hälbich, 2003; Mahood, 2003; Blood, 2006). These wind breaks were removed at all rehabilitated sites when the vegetation cover reached a level deemed satisfactory, except for one site (S5) where the vegetation cover is still relatively low (Marius Vlok, pers. comm., 2009)

The locations of the seven sites and the treatments applied on the rehabilitation sites are listed below:

1. Reference site R1 is located at 31°15' 85.3" S, 17°58' 41.5" E. The vegetation community at this site has been classified as *Ruschia versicolor – Odyssea paucinervis* Dwarf Shrub

Strandveld by de Villiers *et al.* (1999). Four 50 m x 50 m plots were laid out from west to east, spaced 10 m apart.

2. Reference site R2 is located at 31° 16' 45.1" S, 17° 56' 18.1" E. De Villiers *et al.* (1999) classified the vegetation community at the site as *Ruschia tumidula – Tetragonia virgata* Tall Shrub Strandveld. Four 50 m x 50 m plots were laid out from north to south, spaced 10 m apart.

3. Rehabilitation site S1 is located at 31° 15' 84. 0" S, 17° 56' 14.3" E. The restoration of this site took place in June 2001. It involved only the spreading of topsoil over tailings and no seeding or transplantations. Four 50 m x 50 m plots were laid out from north to south, spaced 10 m apart.

4. Rehabilitation site S2 is located at 31° 15' 46. 1" S, 17° 55' 54.4" E. Sometime in 2001, a mix of indigenous species with the addition of *Eragrostis curvula* and *Sorghum sp.* was seeded over bare tailings on this site. Four 50 m x 50 m plots were laid out from north to south, spaced 10 m apart.

5. Rehabilitation site S3 is located at 31° 15' 88. 9" S, 17° 56' 00.3" E. Topsoil was spread over tailings and five indigenous species (*Ruschia versicolor*, *Lampranthus suavissimus*, *Othonna cylindrica*, *Zygophyllum morgsana* and *Asparagus sp.*) were translocated on this site in multi-species clumps. The restoration of this site took place in June 2001. Four 50 m x 50 m plots were laid out from north to south, spaced 10 m apart.

6. Rehabilitation site S4 is located at 31° 15' 26. 7" S, 17° 55' 43.3" E. A mix of indigenous species with the addition of *Ehrharta calycina* was seeded onto bare tailings on this site sometime in 2001.   Three indigenous species (*Ruschia versicolor*, *Lampranthus suavissimus* and *Othonna cylindrica*) were also translocated in multi-species clumps between July and August 2002. Four 50 m x 50 m plots were laid out from north to south, spaced 10 m apart.

7. Rehabilitation site S5 has been established on an area rehabilitated in 2008. Topsoil was spread over tailings and a mix of indigenous plant species were sown in addition to transplants from natural veld. Cuttings grown in the nursery on site were also planted during the rainy season in 2008. Four 50 m x 50 m plots were laid out from south to north, spaced 10 m apart.

Reference site R2 is located on a sheep farm, and is periodically grazed at a very high stocking rate of 10 ha / SSU (Blood, 2006). In contrast, reference site R1 and rehabilitation sites S1 – S5 are only very lightly grazed by wild animals such as steenbok (*Raphicerus campestris*). Unfortunately the effects of this difference in grazing regime on parameters such as vegetation cover, species richness and grazing capacity are unknown, but this is thought to be the cause of some of the observed differences between sites R1 and R2.

3.2.3. Vegetation Sampling

Vegetation cover was sampled in August 2009 and May 2010 using the Line Intercept Method (Sutherland, 1997), as this method is effective where the vegetation cover is low and patchy. Five 50 m line transects, orientated in a zig-zag pattern as described in Blood (2006), were located in each of the four plots at each site. This was done to ensure that line transects did not run parallel to lines of translocated clumps (Blood, 2006), nursery cuttings or plants that grow along the wind breaks. The species and cover of each plant intercepting the line transect was recorded. Reference site R1 could not be sampled in August 2009 due to time constraints.

3.2.4. Data Analysis

Overlap between individual plants was taken into account when total vegetation cover was calculated, but not when calculating species cover. The Shannon-Wiener Diversity Index was used to calculate the diversity for each site in winter 2009 and summer 2010, using the software package Species Diversity & Richness 2.64 (Pisces Conservation 2001). Evenness (equitability) was also calculated using the same software package. Randomization tests were conducted to test for significant differences in both diversity and evenness between sites.

Bayer's method of veld condition assessment (Bayer, 1990), which is essentially an adapted version of the Ecological Index Method of Vorster (1982), was used to calculate grazing capacity in hectares per large stock unit (ha / LSU). A large stock unit (LSU) is defined as the equivalent of one steer of 450 kg (Meissner *et al.*, 1983). As there is no universal definition of a small stock unit, a conversion rate of 7.14 was used in this study (Clement Cupido, pers. comm., 2010). Initially, an attempt was made to calculate grazing capacity using du Toit's Objective Grazing Capacity Assessment (OGCA) (du Toit, 1995; 2000). However, this was abandoned for two reasons: due to the lack of grazing index values for many plant species which occur in the study site, especially succulents, and because the grazing capacity estimates obtained can be considered highly optimistic. Clement Cupido (pers. comm., 2010) abandoned attempts to calculate grazing capacity using the OGCA in the Klein Karoo (which also forms part of the Succulent Karoo) for the same reasons. Other researchers agree that, although working well in the summer rainfall region, the OGCA is inaccurate in the winter rainfall region (Nelmarié Saayman, pers. comm., 2010). Although it is not a published method, Bayer's method of veld condition assessment is widely used in research studies by the Western Cape Department of Agriculture (Clement Cupido & Nelmarié Saayman, pers. comm., 2010). Therefore, it was decided to make use of Bayer's method. This

method is, however, not used to make recommendations regarding stocking rates (Nelmarié Saayman, pers. comm., 2010).

In Bayer's (unpublished) method, plant species are grouped into four classes, namely highly palatable, palatable, less palatable and not palatable. Plant species were assigned to classes by Bayer and other workers in the Western Cape Department of Agriculture. The cover of each group is calculated by summing the cover of all species in the group (from data obtained using the line-intercept method). The cover of each group is then multiplied by the utilisation index value of the group (the percentage of plant mass that can be utilised) and these products are summed to obtain the realisable production. The potential production is calculated by multiplying the mean annual rainfall at the site with the mean rain-use efficiency for semi-arid and arid regions. The actual production is then calculated by multiplying the realisable production with the potential production. Grazing capacity (in ha / SSU) is calculated by dividing 650 by the actual production.

Repeated-measures ANOVAs (for sites R2, S1, S2, S3, S4 and S5 in winter 2009 and summer 2010) and one-way ANOVAs (for all sites, including R1, in summer 2010) were performed on vegetation cover, species richness and grazing capacity data, using Statistica 9.0 (Statsoft, Inc. 2009) and Fischer's LSD tests were performed to test for significant differences where appropriate. As the residuals for grazing capacity data were found not to be normally distributed, the data were transformed by inverting the original values. The residuals of the transformed data were normally distributed. Cluster analyses were performed on vegetation cover and species richness data and separately on species cover data for both sampling periods, also using Statistica 9.0.

3.3. Results

3.3.1. Vegetation Cover

The reference sites (R1 and R2) had significantly ($p < 0.05$) higher vegetation cover than all rehabilitation sites in both sampling seasons (Figure 3.1). Reference site R1 (Dwarf Shrub Strandveld) had significantly higher vegetation cover than site R2 (Tall Shrub Strandveld). These differences may be due to the respective vegetation communities having intrinsically different vegetation cover, but another factor may be that site R2 is situated on a sheep farm and has recently been grazed at a very high stocking rate, while site R1 is only very lightly grazed by wild animals.

Sites S1 (topsoil only), S2 (seeding only), S3 (topsoil + translocation) and S4 (seeding + translocation), which were experimentally rehabilitated in 2001, did not differ significantly from each other in either of the sampling seasons (Figure 3.1), which suggests that treatment does not have an effect on vegetation cover in the medium to long term (after eight and nine years). However, sites S1 and S3, which both received topsoil, had slightly higher vegetation cover than sites S2 and S4 in winter 2009, and site S1 also had slightly higher vegetetation cover in summer 2010. Site S5 (topsoil + seeding + translocation + nursery cuttings), which was rehabilitated in 2008, had significantly ($p < 0.05$) lower vegetation cover than the older experimental sites (S1 – S4) in winter 2009. It also had significantly ($p < 0.05$) lower vegetation cover than sites S1, S2 and S4 in summer 2010, but did not differ significantly from site S3. This is most likely because the vegetation at site S5 is still at an early successional stage.
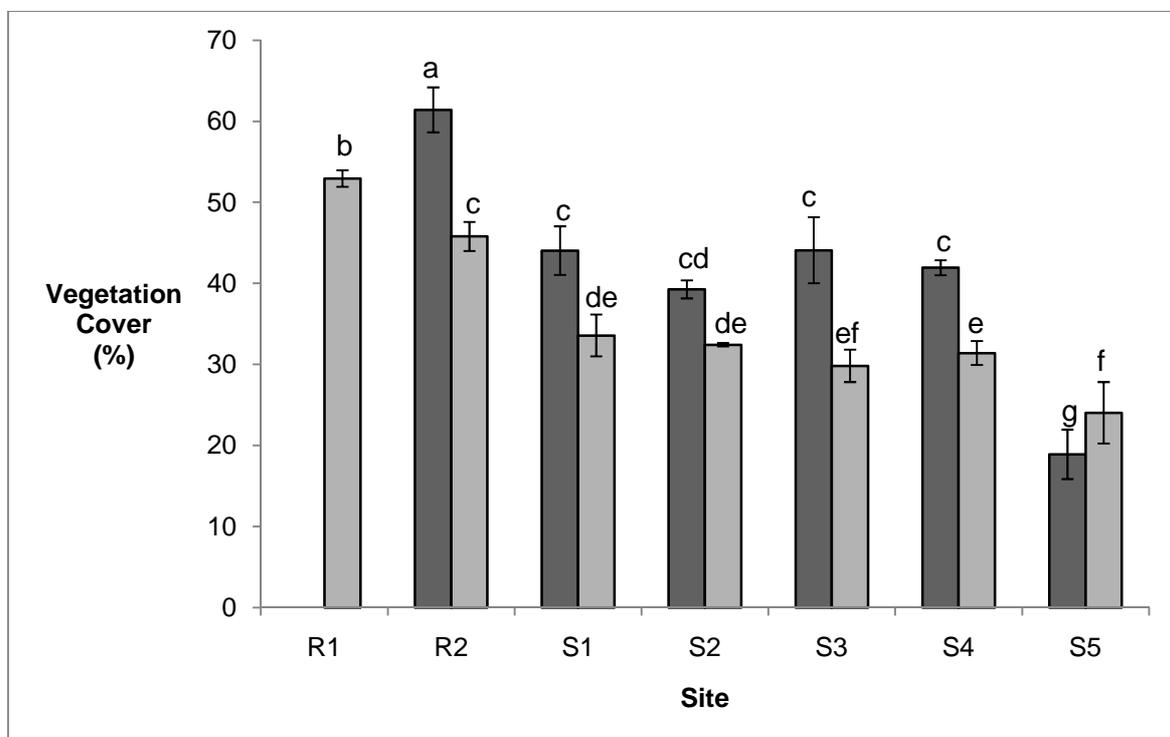
Figure 3.1: The mean (n = 4) vegetation cover (%) at all sites during winter 2009 (darker columns) and summer 2010 (lighter columns). Sites R1 and R2 are reference sites, sites S1, S2, S3 and S4 were rehabilitated in 2001, and site S5 was rehabilitated in 2008. Site R1 was not sampled in winter 2009. Vertical bars represent standard error. Different letters above bars indicate significant differences (p < 0.05).

One can expect vegetation cover to be higher in the rainy season (winter) than in the dry season (summer), due to the presence of annuals in the former. This is indeed the case at reference site R2 (Tall Shrub Strandveld) and rehabilitation sites S1 (topsoil only), S3 (topsoil + translocation)

and S4 (seeding + translocation), where the vegetation cover is significantly ($p < 0.05$) higher in winter 2009 than in summer 2010. Although the vegetation cover is also higher in winter 2009 than in summer 2010 at site S2 (seeding only), this difference is not significant. The reason for this is that sites R2, S1, S3 and S4 were strongly dominated by the annual grass *Ehrharta brevifolia* in winter 2009, while it is absent in summer 2010. Site S2 was dominated by the perennial shrub *Galenia africana*, while the perennial succulent shrub *Lampranthus godmaniae* also had relatively high cover at this site. At site S5 (topsoil + seeding + translocation + nursery cuttings), the vegetation cover was higher in summer 2010 than in winter 2009, but not significantly so. This is because site S5 has only been rehabilitated recently and the vegetation on this site is still developing. The cover of perennial species has increased between winter 2009 and summer 2010 at this site.

In winter 2009, the sites rehabilitated in 2001 (S1 – S4) all achieved the three year vegetation cover objective of having >50 % of the vegetation cover of reference site R2 (Table 3.2). Site S5, which was rehabilitated in 2008, fell short of this objective, only reaching 31 % of the vegetation cover of R2. All rehabilitation sites had more than the required 50 % of vegetation cover of R2 in summer 2010 (Table 3.2). However, none of the rehabilitated sites surpassed the five-year vegetation cover objective of 80 % of the cover of the reference site in either winter 2009 or summer 2010.

Table 3.2: The mean (n = 4) vegetation cover at each of the five rehabilitation sites (S1, S2, S3, S4 and S5) proportional to the mean (n = 4) cover of reference site R2. All sites achieved the three year vegetation cover objective of having >50 % of the vegetation cover of reference site R2 in both sampling seasons, except S5 in Winter 2009.

Site	Winter 2009	Summer 2010
S1	71.72	73.31
S2	63.93	70.83
S3	71.80	65.13
S4	68.29	68.59
S5	30.77	52.47

3.3.2. Plant Species Richness, Diversity and Evenness

The reference sites had significantly ($p < 0.05$) higher mean numbers of species than all the rehabilitation sites in both sampling seasons (Figure 3.2). Site R2 (Tall Shrub Strandveld) had the highest mean species richness of the two reference sites in summer 2010, significantly higher than

R1 (Dwarf Shrub Strandveld) ($p < 0.05$). In general, the rehabilitation sites did not differ from each other in either sampling period. Of the rehabilitated sites, S4 (seeding + translocation) had the highest mean number of species in winter 2009, but only significantly higher ($p < 0.05$) than site S3 (topsoil + translocation). Site S2 (seeding only) had the highest mean number of species in summer 2010, but did not differ significantly from the other rehabilitated sites. Surprisingly, site S5 (topsoil + seeding + translocation + nursery cuttings), which was rehabilitated in 2008, also did not differ significantly from the sites that were rehabilitated in 2001 in either of the sampling seasons. As expected, all sites contained more plant species on average in winter 2009 than in summer 2010 (Figure 3.2). The differences were significant for the reference site R2, as well as the rehabilitation sites S2, S3, S4 and S5 ($p < 0.05$).
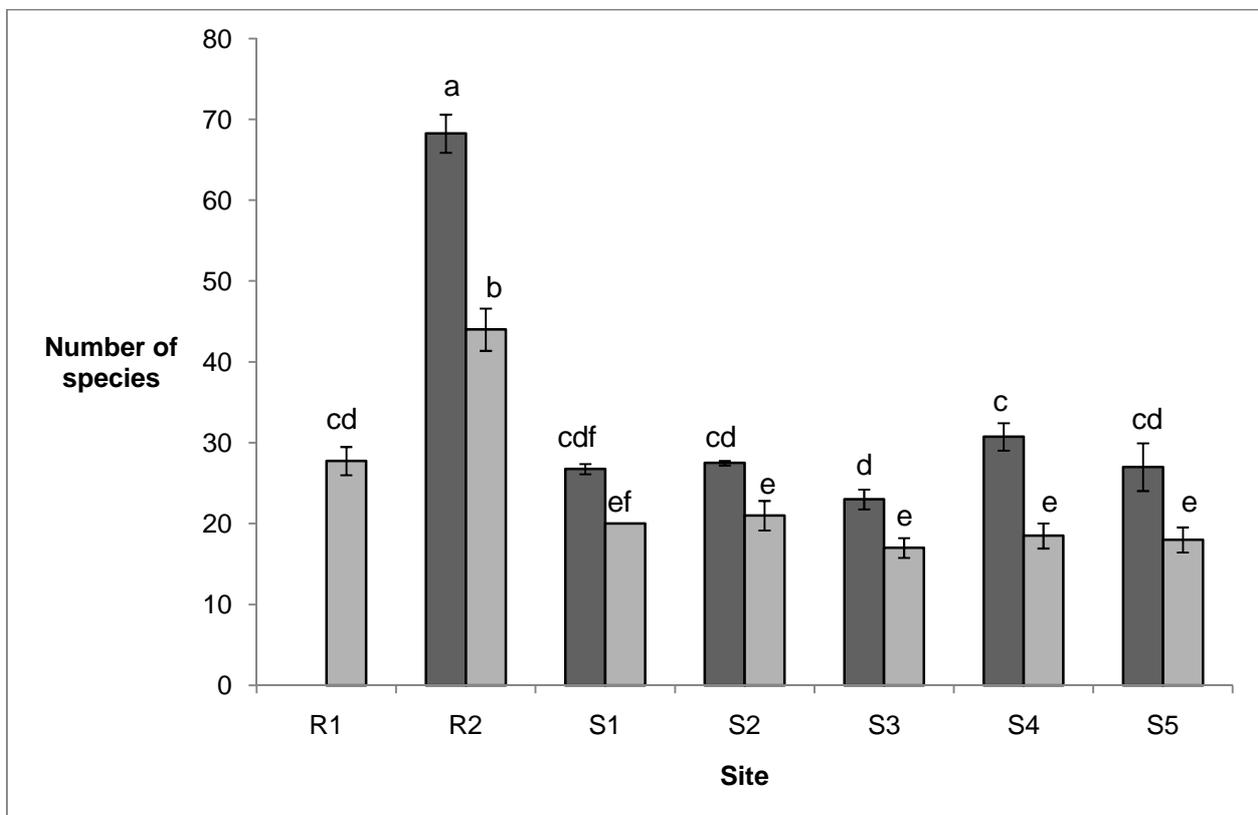
Figure 3.2: The mean number of species per plot (n = 4) at reference sites R1 and R2, and rehabilitation sites S1, S2, S3, S4 and S5 during the winter 2009 (dark columns) and summer 2010 (light columns) sampling seasons. Site R1 was not sampled in 2009. Vertical bars represent standard error. Different letters above bars indicate significant differences (p < 0.05).

The total number of species at each site (Table 3.3) followed a very similar pattern to the mean number of species (per plot) at each site (Figure 3.2). The reference sites (R1 & R2) had more species in total than all the rehabilitation sites (S1 – S5). However, where site S5 (topsoil +

seeding + translocation + nursery cuttings, rehabilitated in 2008) had the third highest mean number of species of the rehabilitated sites in winter 2009 (Figure 3.2), it had the highest total number of species of all the rehabilitated sites in this sampling season. It is also the only rehabilitation site that had more than half the total number of species of reference site R2 in winter 2009. Between the sites rehabilitated in 2001 (S1 – S4), S2 (seeding only) and S4 (seeding + translocation) had more species in total than sites S1 (topsoil only) and S3 (topsoil + translocation) in both sampling seasons. More species were encountered at each site in winter 2009 than in summer 2010.

Table 3.3: The total number of species recorded at reference sites R1 and R2, and rehabilitation sites S1, S2, S3, S4 and S5 during winter 2009 and summer 2010. Site R1 was not sampled in winter 2009.

Site	Winter 2009	Summer 2010
R1	-	49
R2	103	77
S1	40	28
S2	43	33
S3	34	25
S4	48	29
S5	55	31

All rehabilitation sites had more than the three year species richness objective of 30 % of the number of species of reference site (Table 3.4). This can be expected in sites S1 – S4, as these sites were rehabilitated in 2001, however, site S5 which was rehabilitated in 2008, reached the three-year objective within one year. None of the rehabilitation sites reached the final objective of 60 % of the number of species in reference sites.

Table 3.4: The mean number of species per plot (n = 4) at rehabilitation sites S1, S2, S3, S4 and S5 proportional to the mean number of species (n = 4) in reference site R2, in winter 2009 and summer 2010. All rehabilitation sites had more than the three year species richness objective of >30 % of the number of species of reference site R2 in both seasons.

Site	Winter 2009	Summer 2010
S1	39.19	45.45
S2	40.29	47.73
S3	33.70	38.64
S4	45.05	42.05
S5	39.56	40.91

The reference sites (R1 and R2) had significantly (p < 0.05) higher diversity and evenness than all rehabilitation sites in both sampling seasons (Table 3.5). Site R2 (Tall Shrub Strandveld) had significantly (p < 0.05) higher diversity and evenness than site R1 (Dwarf Shrub Strandveld). Sites S1 (topsoil only), S2 (seeding only) and S4 (seeding + translocation) generally performed better than sites S3 (topsoil + translocation) and S5 (topsoil + seeding + translocation + nursery cuttings) in terms of diversity and evenness. This suggests that seeding is a slightly more successful treatment at Namakwa Sands in terms of species diversity and evenness. Site S3 consistently had the lowest diversity and evenness. This is because it had the lowest number of species in both sampling seasons and was strongly dominated by few species (*Ehrharta brevifolia* and *Tetragonia fruticosa*). Site S5 had more species than site S3, but was dominated by a small number of pioneer species, such as *Ehrharta brevifolia*, *Ehrharta calycina*, *Conicosia elongata* and *Tetragonia fruticosa*. However, site S5 is still developing, and it is likely that these species will not continue to dominate this site in future, especially as this site contains more species than most other rehabilitated sites.

Table 3.5: The Shannon Diversity Index (H) and Evenness Index (J) for reference sites R1 and R2, and rehabilitation sites S1, S2, S3, S4 and S5 during the winter 2009 and summer 2010 sampling seasons. Same letters denote sites that group together (p < 0.05).

Site	Winter 2009				Summer 2010			
	H		J		H		J	
R1	-		-		2.75	a	0.53	a
R2	3.57	a	0.69	a	3.36	b	0.65	b
S1	2.70	b	0.52	b	2.49	c	0.48	c
S2	2.60	c	0.50	c	2.27	d	0.44	d
S3	2.30	d	0.45	d	1.93	e	0.37	e
S4	2.74	b	0.53	b	2.17	fd	0.42	fd
S5	2.43	d	0.47	d	2.06	f	0.40	f

3.3.3. Site Similarity

The reference sites (R1 and R2) clearly separated from the rehabilitation sites in the cluster analyses based on vegetation cover and plant species richness (Figures 3.3 and 3.4). The reference sites also conspicuously separated from each other, indicating that they are quite dissimilar in terms of vegetation cover and species richness. Site S5, which was rehabilitated in 2008, separated from the sites that were rehabilitated in 2001 (S1, S2, S3 and S4) in winter 2009 (Figure 3.3), but not in summer 2010 (Figure 3.4), indicating that it is becoming more similar to the

experimental rehabilitation sites in terms of vegetation cover and plant species richness. There were no separate groups within the experimental rehabilitated sites.
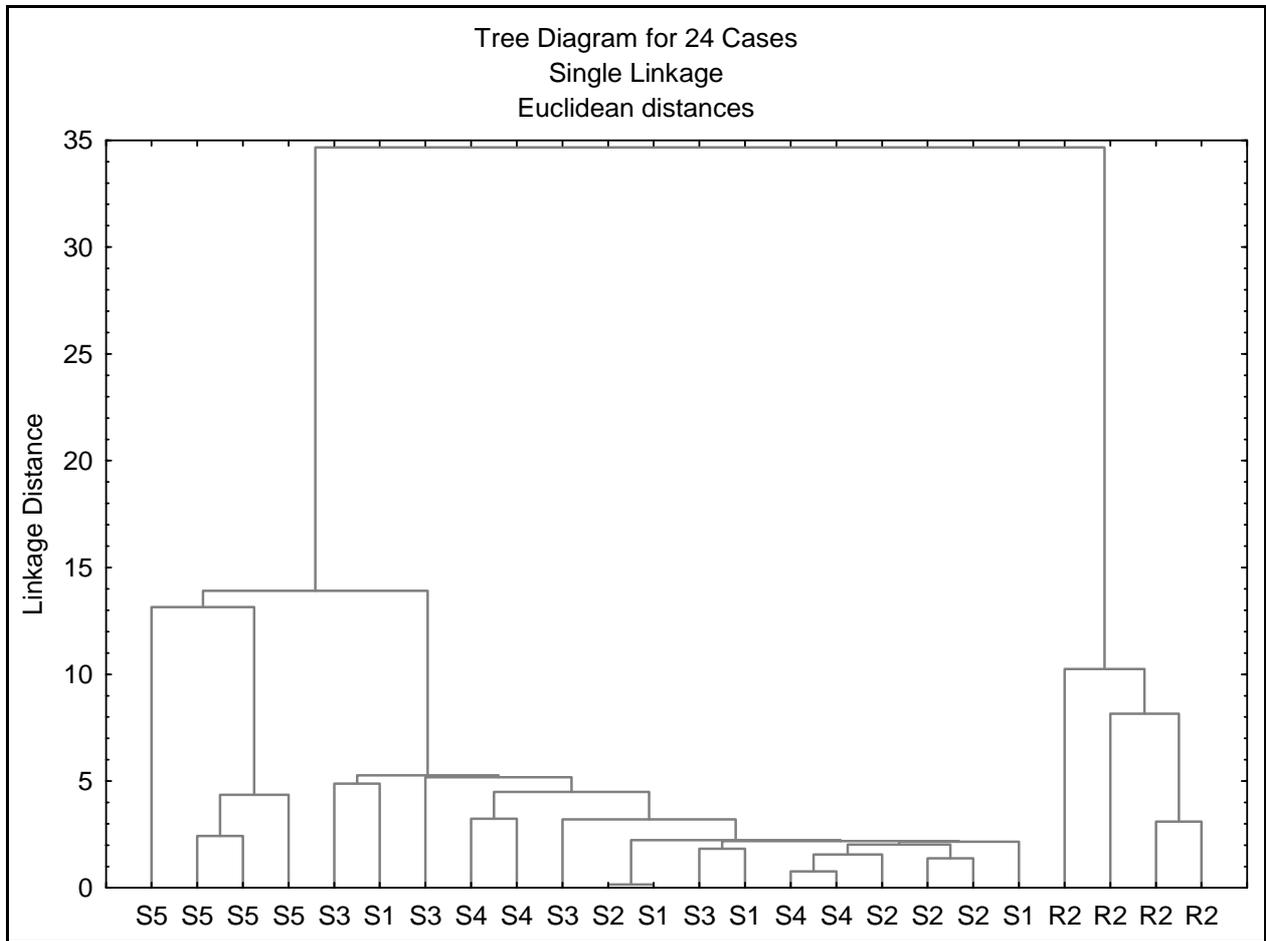
Figure 3.3: Cluster analysis (based on vegetation cover and mean species richness) of reference site R2 and rehabilitation sites S1, S2, S3, S4 and S5 (n = 4 for all sites) for winter 2009. Reference site R1 was not sampled in 2009.

46
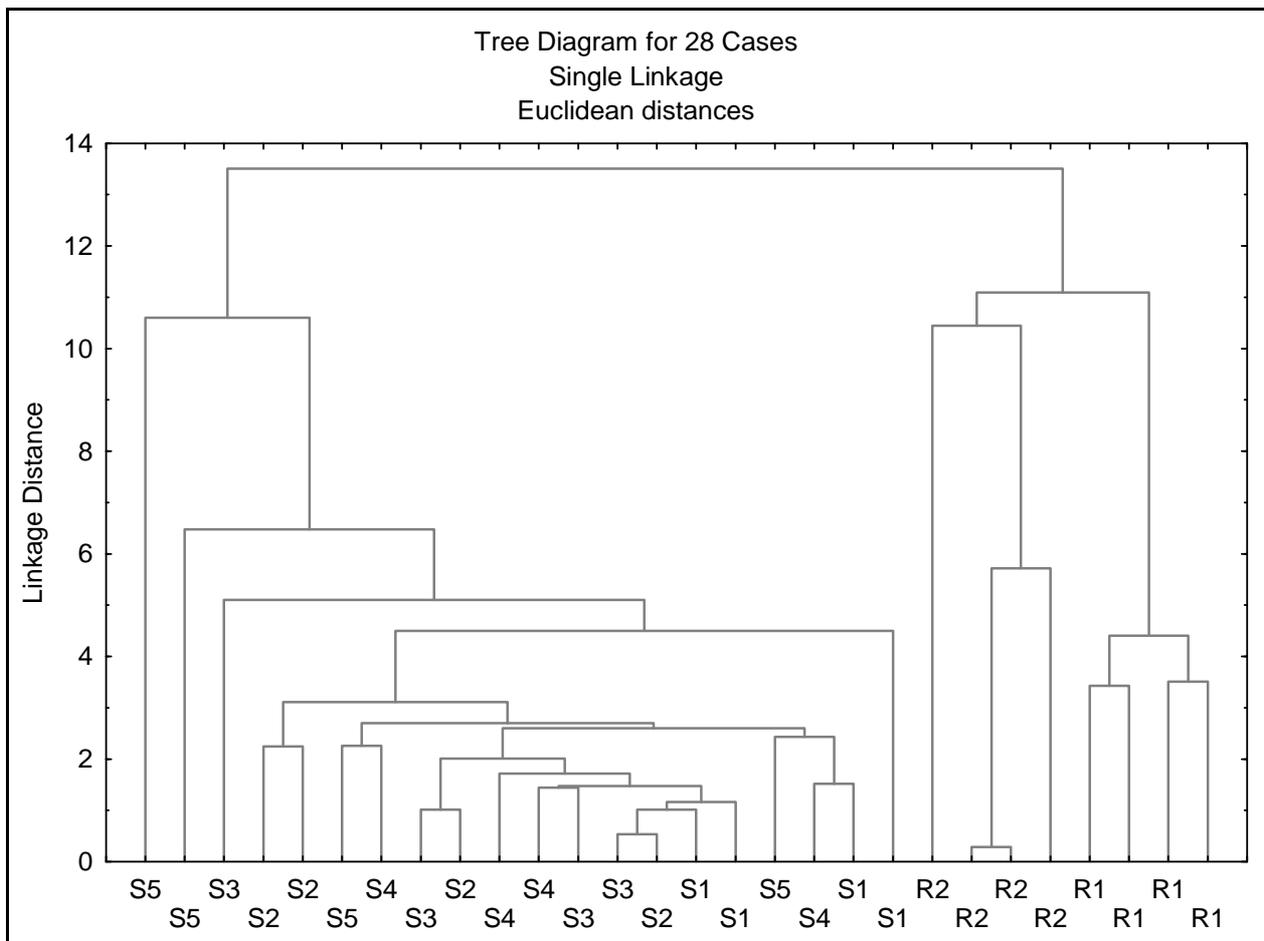
Figure 3.4: Cluster analysis (based on vegetation cover and mean species richness) of reference sites R1 and R2, and rehabilitation sites S1, S2, S3, S4 and S5 during summer 2010.

3.3.4. Species Cover

In winter 2009, all sites were dominated by the annual grass *Ehrharta brevifolia* var. *brevifolia*, except for rehabilitation site S2 (seeding only), which was dominated by the unpalatable shrub *Galenia africana* (Table 3.6). Reference site R2 (Tall Shrub Strandveld) was dominated by different species than the rehabilitation sites, having only *Ehrharta brevifolia* var. *brevifolia* in common with all and *Ehrharta calycina* in common with some of the rehabilitation sites. Rehabilitation sites S1 (topsoil only) and S3 (topsoil + translocation) were largely dominated by the same species (seven species in common in the ten with the highest cover). So too were sites S2 and S4 (seeding + translocation) (also having seven species in common). Site S2 was also dominated by similar species to sites S1 and S3, having six species of the ten most dominant ones in common with both sites. Site S5 (topsoil + seeding + translocation + nursery cuttings) had few species in common with other sites (maximum three, with rehabilitation sites S3 and S4) in the ten species with the highest cover.

47

Table 3.6: The ten plant species with the highest mean (n = 4) cover at each site in winter 2009 (R1 was not sampled). A = annual, P = perennial.

Site S1			Site S2		
Species	**Persist.**	**Cover (%)**	**Species**	**Persist.**	**Cover (%)**
Ehrharta brevifolia var. *brevifolia*	A	15.69	*Galenia africana*	P	9.30
Tetragonia fruticosa	P	4.89	*Ehrharta brevifolia* var. *brevifolia*	A	7.95
Othonna cylindrica	P	4.43	*Lampranthus godmaniae*	P	6.48
Pentastichis patula	A	4.32	*Pentastichis patula*	A	4.44
Manochlamys albicans	P	3.50	*Brassica tournefortii*	A	2.88
Lampranthus godmaniae	P	2.80	*Ehrharta calycina*	P	2.36
Brassica tournefortii	A	1.97	*Lebeckia halenbergensis*	P	1.22
Lebeckia halenbergensis	P	1.61	*Hebenstretia repens*	A	1.14
Exomis microphylla	P	1.16	*Othonna cylindrica*	P	1.11
Antimima compacta	P	0.98	*Ruschia caroli*	P	0.87
Site S3			Site S4		
Species	**Persist.**	**Cover (%)**	**Species**	**Persist.**	**Cover (%)**
Ehrharta brevifolia var. *brevifolia*	A	24.07	*Ehrharta brevifolia* var. *brevifolia*	A	10.06
Tetragonia fruticosa	P	7.42	*Ehrharta calycina*	P	7.95
Conicosia elongata	P	3.28	*Lampranthus godmaniae*	P	4.09
Brassica tournefortii	A	2.90	*Galenia africana*	P	3.87
Pentastichis patula	A	2.13	*Pentastichis patula*	A	3.19
Manochlamys albicans	P	1.41	*Hermannia trifurca*	P	3.02
Lebeckia halenbergensis	P	1.10	*Othonna cylindrica*	P	2.08
Othonna cylindrica	P	0.88	*Brassica tournefortii*	A	1.81
Lampranthus suavissimus	P	0.78	*Heliophila coronopifolia*	A	1.15
Galenia africana	P	0.70	*Atriplex lindleyi* ssp. i*nflata*	P	0.82
Site S5			Site R2		
Species	**Persist.**	**Cover (%)**	**Species**	**Persist.**	**Cover (%)**
Ehrharta brevifolia var. *brevifolia*	A	7.00	*Ehrharta brevifolia* var. *brevifolia*	A	8.84
Ehrharta calycina	P	5.32	*Ficinia argyropa*	P	6.90
Conicosia elongata	P	2.74	*Stipagrostis zeyheri* ssp. *macropus*	P	5.68
Helichrysum herniarioides	A	1.11	*Gazania krebsiana* ssp. *krebsiana*	P	4.70
Tetragonia fruticosa	P	1.06	*Ehrharta calycina*	P	4.45
Oncosiphon suffruticosum	A	1.00	*Tripteris oppositofolium*	P	4.34
Ursinia speciosa	A	0.54	*Diosma* sp. 1	P	3.92
Senecio arenarius	A	0.24	*Phyllobolus* sp. 2	P	3.83
Mesembryanthemum sp. 1	P	0.16	*Arctotis angustifolia*	P	2.72
Atriplex lindleyi ssp. *inflata*	P	0.15	*Ruschia versicolor*	P	2.67

Table 3.7: The ten plant species with the highest mean (n = 4) cover at each site in summer 2010. A = annual, P = perennial.

Site S1			Site S2		
Species	**Persist.**	**Cover (%)**	**Species**	**Persist.**	**Cover (%)**
Othonna cylindrica	P	5.85	*Galenia africana*	P	7.84
Manochlamys albicans	P	5.03	*Lampranthus godmaniae*	P	5.66
Tetragonia fruticosa	P	4.08	*Ehrharta calycina*	P	3.34
Lampranthus godmaniae	P	3.77	*Othonna cylindrica*	P	2.06
Lebeckia halenbergensis	P	2.65	*Lebeckia halenbergensis*	P	1.87
Ruschia versicolor	P	1.64	*Ruschia caroli*	P	1.32
Exomis microphylla	P	1.43	*Manochlamys albicans*	P	0.93
Conicosia elongata	P	1.28	*Hermannia trifurca*	P	0.89
Lampranthus suavissimus	P	1.24	*Antimima compacta*	P	0.64
Ruschia caroli	P	0.98	*Ruschia versicolor*	P	0.52
Site S3			Site S4		
Species	**Persist.**	**Cover (%)**	**Species**	**Persist.**	**Cover (%)**
Tetragonia fruticosa	P	6.68	*Ehrharta calycina*	P	10.34
Conicosia elongata	P	4.77	*Galenia africana*	P	4.82
Manochlamys albicans	P	2.62	*Lampranthus godmaniae*	P	3.99
Ehrharta calycina	P	1.66	*Othonna cylindrica*	P	2.71
Othonna cylindrica	P	1.36	*Hermannia trifurca*	P	2.63
Exomis microphylla	P	1.31	*Antimima compacta*	P	1.25
Galenia africana	P	1.24	*Hermannia scordifolia*	P	1.17
Lebeckia halenbergensis	P	1.22	*Ruschia caroli*	P	0.81
Lampranthus suavissimus	P	0.79	*Atriplex lindleyi* ssp. *inflata*	P	0.72
Salsola kali	A	0.66	*Lebeckia halenbergensis*	P	0.70

Site S5		
Species	**Persist.**	**Cover (%)**
Ehrharta calycina	P	5.21
Tetragonia fruticosa	P	2.65
Conicosia elongata	P	1.95
Atriplex lindleyi ssp. *inflata*	P	0.55
Exomis microphylla	P	0.47
Amellus flosculosus	P	0.38
Ehrharta brevifolia var. *brevifolia*	A	0.33
Trichogyne ambigua	P	0.21
Scirpoides dioecus	P	0.17
Lebeckia simsiana	P	0.16

Table 3.7, Continued.

Site R1			Site R2		
Species	**Persist.**	**Cover (%)**	**Species**	**Persist.**	**Cover (%)**
Cymbopogon plurinodis	P	18.44	*Tripteris oppositofolium*	P	5.10
Tripteris oppositofolium	P	7.89	*Phyllobolus* sp. 2	P	3.37
Ruschia versicolor	P	5.59	*Stipagrostis zeyheri* ssp. *macropus*	P	3.25
Zygophyllum morgsana	P	2.96	*Ruschia versicolor*	P	3.09
Phyllobolus sp. 1	P	2.93	*Diosma* sp. 1	P	2.79
Asparagus capensis	P	2.70	*Ficinia argyropa*	P	2.52
Tribolium hispidum	P	2.56	*Othonna cylindrica*	P	2.14
Eriocephalus racemosus var. *affinis*	P	2.10	*Ehrharta calycina*	P	1.92
Hermannia amoena	P	1.51	*Arctotis angustifolia*	P	1.72
Othonna cylindrica	P	1.40	*Hermannia trifurca*	P	1.64

In summer 2010, none of the sites were dominated by *Ehrharta brevifolia*, as it is an annual species and therefore not abundant in summer, although it was amongst the ten species with the highest cover at rehabilitation site S5 (Table 3.7). The only two sites that were dominated by the same species were sites S4 and S5, which were dominated by the perennial grass *Ehrharta calycina*. Each of the reference sites were dominated by different species (only three species in common in the ten with the most cover) and by different species than the rehabilitation sites. Rehabilitation site S2 had the most species in common among the ten most dominant species, with reference site R2 (four) and, jointly with site S1, having the most in common with reference site R1 (two). Rehabilitation sites S1 and S3 were again largely dominated by the same species (again having seven in common amongst the ten most dominant species), and so were sites S2 and S4 (this time having eight species in common). Site S2 was again dominated by quite similar species to site S1 (six species in common amongst the ten most dominant ones) and site S3 (five species in common). Rehabilitation site S5 again had few species in common with other sites (maximum four, with reference site S3) amongst the ten most dominant species.

In the cluster analyses based on plant species cover (Figures 3.5 and 3.6) reference site R1 (Dwarf Shrub Strandveld) again separated from the rehabilitation sites, but reference site R2 (Tall Shrub Strandveld) did not seperate as clearly from rehabilitated sites as in the analyses based on vegetation cover and species richness. This suggests that the rehabilitated sites are somewhat alike to reference site R2 in terms of the cover of different species at these sites, but differ strongly from reference site R1. This can be expected as Tall Shrub Strandveld used to be the dominant vegetation community in this section before mining. There were no separate clusters within the rehabilitation sites, indicating that they are similar in terms of species cover.
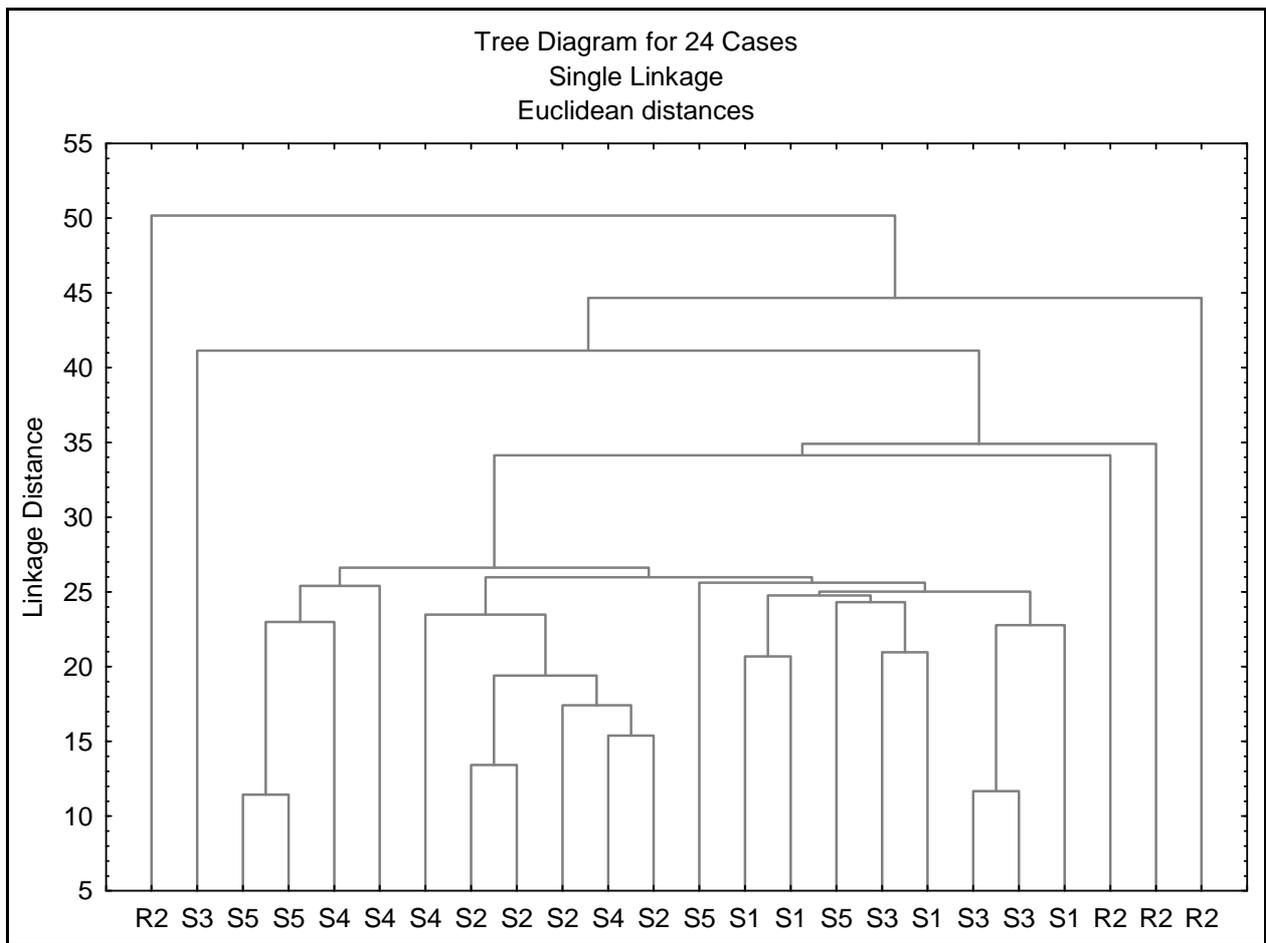
Figure 3.5: Cluster analysis (based on species cover of all species) of Reference site R2 and rehabilitation sites S1, S2, S3, S4 and S5 (n = 4 for all sites) for winter 2009. Reference site R1 was not sampled in 2009.
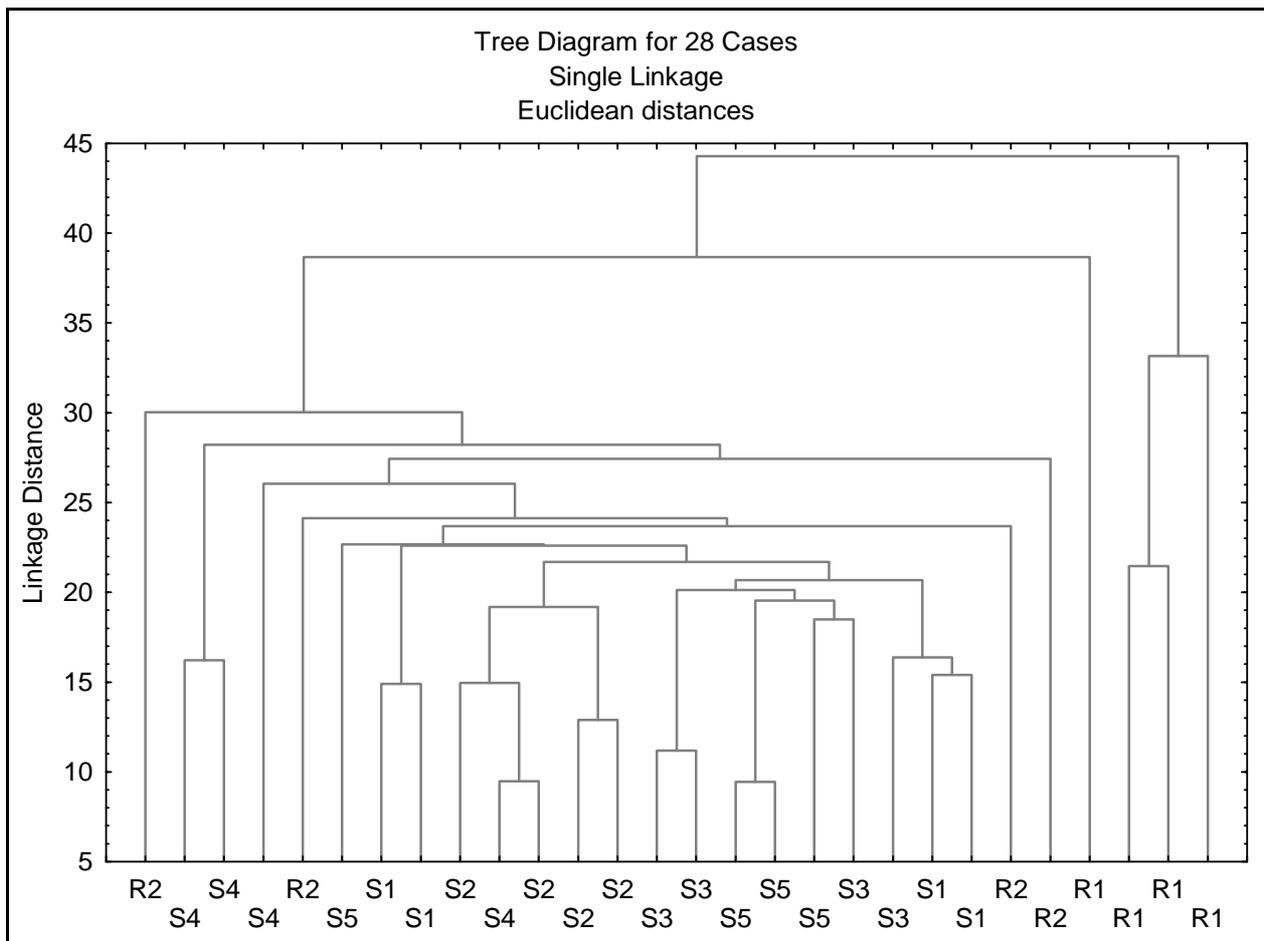
Figure 3.6: Cluster analysis (based on species cover of all species) of reference sites R1 and R2, and rehabilitation sites S1, S2, S3, S4 and S5 (n = 4 for all sites) for summer 2010.

3.3.5. Grazing Capacity

In general rehabilitated sites compared well to reference site R2 (Tall Shrub Strandveld) in terms of grazing capacity (Figure 3.7), but had significantly ($p < 0.05$) lower grazing capacities than reference site R1 (Dwarf Shrub Strandveld). This is because site R1 was dominated by the palatable perennial grass *Cymbopogon plurinodis* and the palatable shrub *Tripteris oppositofolium*, while site R2 was not as strongly dominated by palatable species, possibly due to periodic grazing by sheep at a very high stocking rate.
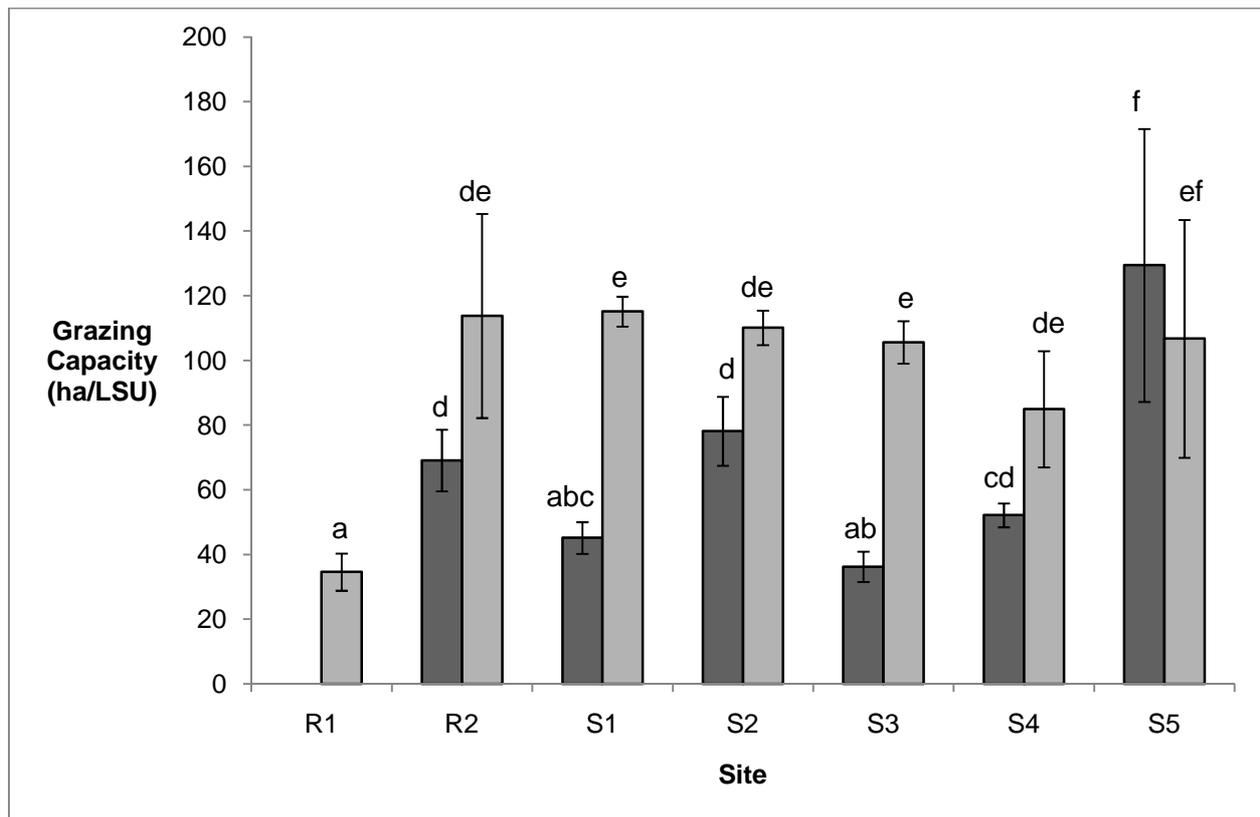
Figure 3.7: The mean (n = 4) grazing capacity at reference sites R1 and R2, and rehabilitation sites S1, S2, S3, S4 and S5 sampled in winter 2009 (dark columns) and summer 2010 (light columns). The lower the value, the higher the grazing capacity. Site R1 was not sampled in 2009. Vertical bars represent standard error. Different letters above bars indicate significant differences (p < 0.05).

Rehabilitation sites which received topsoil (S1 and S3) had significantly higher (p < 0.05) grazing capacity than most other sites during winter 2009 (Figure 3.7). This is mostly due to the high cover of the very palatable annual grass *Ehrharta brevifolia* at these sites. Site S2 (seeding only) had the lowest grazing capacity of the experimental rehabilitated sites. This site was dominated by the relatively unpalatable shrub *Galenia africana*, and had lower cover of *E. brevifolia* relative to the other rehabilitated sites. Rehabilitation site S5 (topsoil + seeding + translocation + nursery cuttings), which was rehabilitated in 2008, not surprisingly had the lowest grazing capacity. It was also dominated by *E. brevifolia*, but the cover of this species was lower at this site, as was the overall vegetation cover, due to the young age of this site. No clear pattern could be distinguished between rehabilitation treatments in summer 2010 and the differences between rehabilitation sites were small. At site S5, the vegetation cover was starting to reach similar levels to the older experimental rehabilitated sites (S1 – S4) in summer 2010. This resulted in site S5 having similar grazing capacity to those sites.

One would expect all sites to have lower grazing capacity in summer 2010 than in winter 2009, due to the lack of annuals and possibly some dieback of shrubs in the dry summer months. The grazing capacity was indeed lower at reference site R2 and rehabilitation sites S1 – S4 (which were rehabilitated in 2001). However, this difference was only significant ($p < 0.05$) at sites S1 (topsoil only) and S3 (topsoil + translocation). This can be attributed to the strong dominance of the palatable annual grass *Ehrharta brevifolia* at these sites during winter 2009. Site S5, which was rehabilitated in 2008, was the only site which had higher grazing capacity in summer 2010 than in winter 2009, due to an increase in the vegetation cover.

3.4. Discussion

Rehabilitation Success

Trends over Time

When Blood (2006) sampled the experimental rehabilitated sites (S1 – S4) in 2004 and 2005, he found that these sites had achieved the three year vegetation cover objectives and many of these sites had also achieved the five year vegetation cover objective. During this study, sites S1 – S4 did not achieve the five year vegetation cover objective, but vegetation cover remained above the three year objective at these sites. This indicates that retrogression in the vegetation cover of rehabilitated sites had occured, as Blood predicted might happen (see vegetation cover section below). During Blood's study most of the rehabilitated sites achieved the three year species richness objectives, but none achieved the five year species richness objectives. Since then, no increase in species richness was detected, as these sites did not achieve the five year species richness objective in this study, although species richness remained above the three year objective. Although Blood (2006) did not calculate grazing capacity, he did not expect the experimentally rehabilitated sites to achieve the minimum grazing capacity objective, but they were found to do so in this study.

Vegetation Cover and Plant Species Richness, Diversity and Evenness

Reference sites were found to have significantly higher vegetation cover than experimental rehabilitated sites and the recently rehabilitated site in both sampling seasons, indicating that vegetation cover at rehabilitation sites had not yet returned to reference levels. During a study on the success of rehabilitation on a phosphate mine in the western USA, Chambers *et al.* (1994) also found significantly higher vegetation cover at reference sites compared to rehabilitation sites after

54

14 years, with the exception of the most successful rehabilitation site, where topsoil, seeds and mulch were spread.

The recently rehabilitated site was the only rehabilitated site which did not achieve the three year objective of >50 % of the vegetation cover of reference site R2 in winter 2009. This is to be expected as only one year had passed since rehabilitation. However, in summer 2010, less than two years after it had been rehabilitated, the site did reach the three year objective. In both sampling seasons, all sites rehabilitated in 2001 had higher vegetation cover proportional to that of reference site R2 than the three year objective, but none of these sites surpassed the five year objective of 80 % in either of the sampling seasons, eight and nine years after they were rehabilitated. During Blood's (2006) study, sites S1 – S4 all reached the three year objective in all sampling seasons, while sites S1, S3 and S4 reached the five year objective in some sampling seasons. During his study rehabilitation sites S1 – S4 were all strongly dominated by *Tetragonia fruticosa* which he considered unstable because it could die back and reduce the vegetation cover at these sites. The cover of this species was found to be lower at sites S1, S2 and S4 during winter 2009 and summer 2010 than during Blood's study, and many dead individuals were observed during sampling – especially at sites S1 and S3. Therefore, it is likely that the decrease in the cover of *T. fruticosa* resulted in the decrease in the overall cover of rehabilitation sites S1 – S4 proportional to that of reference site R2. Drought could not have caused this drop in vegetation cover, as rainfall was above average in most years between Blood's study and this study (CSIR, 2011).

The reference sites had a significantly higher mean number of species, as well as a much higher total number of species than all rehabilitated sites. This is not surprising, as rehabilitated sites rarely have the same number of species than reference sites within a short time period (Chambers *et al.*, 1994; Blood, 2006). Chambers *et al.* (1994) also found lower species richness on rehabilitation sites than on reference sites, 14 years after rehabilitation. In contrast, Herath *et al.* (2009) found higher species richness in rehabilitated sites than in reference sites. However, during the rehabilitation in that study, seeds from a number of different vegetation communities were sown on rehabilitation sites to ensure that species richness objectives were reached.

Sites rehabilitated in 2001 surpassed the three year species richness target of 30 % of the mean number of species of the reference site in both sampling season, as did the site rehabilitated in 2008. However, none of the rehabilitated sites reached the final species richness target of 60 % of the mean number of species of the reference site. In his study, Blood (2006) found that

rehabilitation sites S1, S3 and S4 already reached the three year species richness objective. He suggested that site S2 would require adaptive management to reach this target, but this proved unnecessary. Blood (2006) also stated that it seemed unlikely that any of these rehabilitated sites would reach the final species richness target. These sites remain unlikely to reach the final target, unless measures are taken to actively increase the number of species at these sites. Carrick & Desmet (2003) suggested that it would be necessary to reseed or translocate plant species which are not represented in the soil seed bank on rehabilitation sites at Namakwa Sands, after initial rehabilitation, in order to reach the final species richness target. Norman *et al.* (2006) reached the same conclusion for jarrah forest rehabilitated after mining in Western Australia. The fact that site S5 reached the three year species richness target and had more than half the total number of species of reference site R2 in winter 2009 (one year since it was rehabilitated), suggests that this site is likely to reach the final target within the foreseeable future. It also suggests that the whole array of treatments currently applied at Namakwa Sands is required to return the desired level of species richness to rehabilitated sites.

The reference sites had higher diversity and evenness than all rehabilitation sites (S1 – S5) in both sampling seasons. Reference site R2 (Tall Shrub Strandveld) had higher diversity and evenness than site R1 (Dwarf Shrub Strandveld). Blood (2006) also found that the reference sites had higher diversity and evenness than rehabilitation sites S1 – S4 during all sampling periods, and that reference site R2 generally had higher diversity and evenness than site R1. In shrubland rehabilitated after mineral sand mining in southwestern Australia, Herath *et al.* (2009) found that rehabilitation sites had diversity equivalent to that of reference sites, but had lower evenness, mostly because of the dominance of two species. The most recently rehabilitated site in their study had the lowest diversity and evenness and was strongly dominated by one species.

Cluster analyses based on vegetation cover and species richness also showed that the rehabilitated sites (S1 – S5) are dissimilar to the reference sites (R1 and R2) in both sampling seasons. Rehabilitation sites S1 – S4 were also found to be dissimilar to reference sites R1 and R2 by Blood (2006). Initially, the recently rehabilitated site (S5) was found to be dissimilar to the older experimentally rehabilitated sites, but this was not the case during the second sampling period. This illustrates that the community at this site is still at an early successional stage.

Species Cover

The reference sites are expected to differ in terms of dominant species, as they occur in different vegetation communities. This is indeed the case, as they only have three species in common amongst the ten most dominant species at each site. The rehabilitation sites differed to a great extent from reference sites in terms of the ten species with the highest cover at each site. In a similar study conducted on rehabilitation after mineral sand mining in southwest Australia, rehabilitation sites and reference sites also largely differed in the five species with the highest cover at each site (Herath *et al.*, 2009). The fact that rehabilitation sites S1 (topsoil only) and S3 (topsoil + translocation), and sites S2 (seeding only) and S4 (seeding + translocation) had the most species in common in the ten most dominant at each site, suggests that topsoil replacement and seeding are the treatments which most affect the vegetation community that develops in terms of species cover and hence, dominance at Namakwa Sands. Although site S2 was dominated to an extent by the same species as sites S1 and S3, site S4 was not. Therefore, it can be concluded that seeding and topsoil replacement will not necessarily produce vegetation communities dominated by the same species. Site S5 (topsoil + seeding + translocation + nursery cuttings) had very few species in common with the experimental rehabilitation sites (S1 – S4) in the ten species with the highest cover. This is due to the high cover of pioneer species, such as *Tetragonia fruticosa*, *Conicosia elongata* and the alien species *Atriplex lindleyi* ssp. *inflata*.

The species composition of the sites in this study is generally similar to the composition during Blood's (2006) study, but the cover of different species have largely increased, except for *Tetragonia fruticosa*, as mentioned before. The grasses *Ehrharta brevifolia*, which had high cover during winter 2009, and *Ehrharta calycina*, which had high cover during both sampling seasons, had very low cover during Blood's study. As rehabilitated sites develop, the cover of different species is expected to change over time. This was also the case during a study conducted by Herath *et al*. (2009). Differences in the timing and quantity of rainfall also influence the cover of species in a specific year. It is very likely that these are the main factors causing the difference in species cover between the two study periods. The rainfall was below average at Brand-se-Baai during years in which Blood (2006) sampled (113.2 mm in 2004 and 113.5 mm in 2005 (CSIR, 2011)), as compared to the above average rainfall (243.7 mm in 2009 (CSIR, 2011) and 191 mm in Vredendal in 2010 (SAWS)) during this study. There were also differences in the monthly rainfall in those years (CSIR, 2011). Although the species cover differs, the same species generally have the highest cover at rehabilitation sites. This unfortunately indicates that the cover of later successional species did not increase and that of pioneer species decreases as one would expect at developing rehabilitation sites.

Species that are notably absent from rehabilitation sites include the shrubs *Tripteris oppositofolium*, *Tripteris sinuata*, *Eriocephalus racemosus*, *Asparagus capensis* and *Diosma* sp., herbs such as *Arctotis angustifolia* and *Gazania krebsiana*, and grasses such as *Cymbopogon plurinodis* and *Stipagrostis zeyheri*, to name but a few. Only a few individuals of the shrub *Zygophyllum morgsana* occur in experimental rehabilitation sites S1 – S3, while none are present at the experimental rehabilitation site S4 and the recently rehabilitateed site S5. *Tripteris oppositofolium*, *Zygophyllum morgsana* and *Eriocephalus racemosus* were present in some rehabilitation sites during Blood's (2006) study, but probably failed to establish due to the harsh conditions at the onset of rehabilitation. A factor of concern is that the perennial grass component is completely absent at site S1. Reeds, such as *Ficinia argyropa* and *Willdenowia incurvata*, which occur in reference sites R1 and R2, are also completely absent in rehabilitation sites S1 – S4, and only one species of reed occurs in site S5. A complete list of all the species that occur at each site can be found in appendix A.

Many of the species that are absent from rehabilitated sites are late successional species, which require micro-sites of favourable conditions to establish in, which would not be present at the onset of rehabilitation (Milton, 2001). Succession theory suggests that these species will naturally increase in cover over time (Clements, 1928). However, this has not happened at Namakwa Sands after nine years, nor has it happened in rehabilitated shrubland following mineral sand mining in Western Australia, after 14 years (Norman *et al.*, 2006), and jarrah forest following bauxite mining in southwestern Australia, after 24 years (Herath *et al.*, 2009). The rate of natural succession will most likely be decreased dramatically by the aridity of the area. The lack of late successional plants might be because the seeds of some of these species do not remain viable until the conditions are favourable for them to establish and because some species are absent from the seed bank. The majority of absent late successional species at Namakwa Sands are also perennial wind-dispersed species (Blood, 2006) with short-lived seeds, which Hälbich (2003) suggests are unlikely to recruit from the soil-stored seed bank. Therefore, these species, along with some other species which are also absent at the rehabilitation sites, will have to be re-introduced to these sites through seeding or transplantation, as suggested by Carrick & Desmet (2003).

The unpalatable woody shrub *Galenia africana* frequently dominates disturbed areas such as old fields and overgrazed rangeland in Namaqualand (Allsopp, 1999; Simons & Allsopp, 2007). It is considered a potential problem plant, because it produces a large number of seeds, which tend to dominate the seed bank (Esler *et al.*, 2006; Todd & Hoffman, 2009). As a result, when attempts are made to reduce the cover and abundance of *G. africana*, the seeds germinate *en masse*,

increasing the cover of this species (Esler *et al.*, 2006). Therefore, it is worrying that *G. africana* currently dominates site S2 (seeding only). Seedlings of *G. africana* are weak competitors (Todd & Hoffman, 2009) and adult plants have been proposed to act as nurse plants to other species (Simons & Allsopp, 2007). This opens up the possibility that the cover of *G. africana* will naturally decline over time. However, if this happens, it may take decades for this species to stop dominating site S2.

Another potential problem plant is *Atriplex lindleyi* ssp. *inflata*. It is an invasive alien species which can also be an ecosystem transformer (Henderson, 2001), as it commonly increases the salinity of the surrounding soil (Milton *et al.*, 1999). Just like *Galenia africana*, it produces large numbers of small seeds, which can germinate *en masse* when the soil is disturbed (Milton *et al.*, 1999; Esler *et al.*, 2006). Paradoxically, invasive alien species, such as *Atriplex lindleyi*, can also contribute to rehabilitation success (D'antonio & Meyerson, 2002). As mentioned previously, it takes up to 25 months for the salinity of soils to decrease to natural levels after rehabilitation (Prinsloo, 2005). Few species can establish in this saline soil. *Atriplex lindleyi*, being both a pioneer (le Roux & Schelpe, 1988) and salt tolerant (de Villiers *et al.*, 1992; Milton *et al.*, 1999), will most likely be one of the first plants to establish on rehabilitated sites (this seems to be the case at site S5) and may in this way help stabilize the soil, preventing the nutrient-containing topsoil and seeds from being blown away by strong winds, until the salinity has decreased to a point where more species are able to establish.

The alien species *Brassica tournefortii* and *Salsola kali* also occur at Namakwa Sands. *Brassica tournefortii* is an annual which has relatively high cover at some sites, but it is not an ecosystem transformer. Although *Salsola kali* is classified as an aggressive invasive species and a potential ecosystem transformer (Henderson, 2001), it is rare in and around the Namakwa Sands mine and has very low cover at the sites where it occurs (in both Blood's (2006) study and this study). Therefore, it is highly unlikely that these two species will have large adverse impacts on the vegetation at Namakwa Sands.

Cluster analyses based on the species cover of all plants showed that the vegetation composition at rehabilitated sites (S1 – S5) were dissimilar to the vegetation composition at reference site R1 (Dwarf Shrub Strandveld) in both sampling seasons, but were similar to reference site R2 (Tall Shrub Strandveld), especially in summer 2010. This is not surprising, as Tall Shrub Strandveld was the dominant vegetation community on this (East) section of the mine before mining. The recently rehabilitated site (S5) had similar vegetation composition to the older experimentally

rehabilitated sites (S1 – S4) in both sampling seasons. This is comparable to the results of other studies. Herath *et al.* (2009) found that sites rehabilitated between eight and 24 years prior to their study were more similar to each other than to reference sites based on vegetation composition and species cover. Norman *et al.* (2006) also found that 14 years after rehabilitation, sites were not becoming more similar to reference sites in terms of vegetation composition, but instead still strongly resembled the species mix sown initially. Similar results were observed by Chambers *et al.* (1994) 14 years after rehabilitation was carried out.

Grazing Capacity

Although Blood (2006) did not calculate grazing capacity, he was concerned by the low plant species diversity and number of palatable plants at the rehabilitation sites he sampled (S1 – S4). He stated that it is unlikely that small stock farming would be feasible at Namakwa Sands in future, unless the diversity and abundance of palatable plants increase dramatically. However, in this study, all rehabilitated sites (S1 – S5) were found to have grazing capacities higher than the rehabilitation objective.

Seasonal variation

Reference site R2 and the sites experimentally rehabilitated in 2001 (S1 – S4) generally had significantly higher vegetation cover, species richness and grazing capacity in winter 2009 than in summer 2010. This large seasonal variation emphasises the importance of conducting monitoring in the same seasons each year, as well as monitoring both the summer and winter extremes. The relatively high cover of perennial plant species at site S2 provides a potential buffer for change in vegetation cover between seasons. This is probably why the seasonal difference in vegetation cover at site S2 was not significant. The recently rehabilitated site had higher vegetation cover and grazing capacity in summer 2010 than in winter 2009, because it is still developing.

Rehabilitation Methods

Although rehabilitation methods at different mining operations are frequently described and the theory behind different treatments discussed, few studies assessing the success of rehabilitation treatments through data analysis have been published in the peer-reviewed literature. Of those that are published, most are conducted shortly after rehabilitation (Herrick *et al.*, 2006). Therefore, the contribution of different treatments to rehabilitation success in practice, and especially in the long-term, is largely unknown. Long-term studies are particularly important in semi-arid and arid

environments with low productivity, where vegetation recovery is generally slow (Dean & Milton, 1999; Rahlao *et* al., 2008).

This study did not find significant differences in vegetation cover or plant species richness between sites where topsoil was replaced and sites which were seeded in 2001 after eight to nine years. However, the vegetation community at sites where topsoil was replaced differed from the community at sites which were seeded. Grazing capacity was also higher in winter at sites which received topsoil. Translocation did not affect any of the measured parameters. It is important to note that the findings of this study may have been influenced by the fact that the topsoil which was spread at sites S1 and S3 were stockpiled for an unknown period of time (Blood, 2006). Topsoil contains organic matter, nutrients and soil fauna and flora, as well as the greatest fraction of the soil seed bank (Lubke & Avis, 1998; de Villiers, 2000; Holmes, 2001; Milton, 2001; Johnson & Tanner, 2003; Carrick & Kruger, 2007; Koch, 2007; Tanner, 2007). Many researchers agree that topsoil should be replaced as soon as possible (Lubke & Avis, 1998; Milton, 2001; Hälbich, 2003; Carrick & Kruger, 2007; Tanner, 2007; Botha *et al.*, 2008), as short lived seeds may lose their viability if stockpiled for too long or if the environmental conditions (especially temperature) in the stockpile becomes unfavourable, and nutrients may be leached out over time (Hälbich, 2003; Carrick & Kruger, 2007). Thus, the findings of this study might have been different if fresh topsoil was spread at sites S1 and S3. Spreading fresh topsoil is part of the current rehabilitation practice at Namakwa Sands.

Vegetation Cover

In contrast to the findings of this study, Chambers *et al.* (1994) found significant differences between plots with topsoil and plots without topsoil 14 years after rehabilitation.

Species Cover

There are a number of reasons why sites where topsoil have been replaced would be dominated by different species than seeded sites. Only about half the plants in the standing vegetation have been found to be represented within the soil seed bank at Namakwa Sands (de Villiers, 2000). Therefore not all species would be returned by topsoil replacement. A number of the species not present in the soil seed bank would most likely be present in the seed harvested from the standing vegetation community. Also, topsoil in good condition provide a more suitable environment for some plant species to establish in, at least in the short term (Lubke & Avis, 1998; Koch, 2007). Annuals contribute the highest number of seeds to the soil seed bank (de Villiers, 2000). This is

probably also why Blood (2006) found more "weedy" species at sites S2 and S4 than at sites S1 and S3.

The species *Lampranthus suavissimus*, *Othonna cylindrica* and *Ruschia versicolor*, which were translocated to site S3 and S4, and *Zygophyllum morgsana*, which was translocated to site S3, had higher cover in some sites where it had not been translocated than in sites where it had been translocated. This suggests that the translocation of these species does not affect its cover eight to nine years after rehabilitation took place. However, translocation might have other benefits, such as increased vegetation cover shortly after rehabilitation (Milton, 2001; Carrick & Kruger, 2007) and returning soil micro-organisms (Milton, 2001). It is clear that the translocation of *Asparagus* spp. and *Zygophyllum morgsana* to site S3 has been unsuccessful. This was already apparent during Blood's (2006) study.

Species richness

There were no significant differences in species richness between sites which received different treatments during experimental rehabilitation in 2001, which suggests that treatment does not have an effect on species richness eight to nine years after rehabilitation took place. This seems odd, as most researchers believe that topsoil replacement will return the highest number of species to a rehabilitation site in the shortest time (Johnson & Tanner, 2003). Blood (2006) also did not find a clear trend in species richness at these sites. However, some seeds may have lost their viability when the topsoil used at sites S1 and S3 were stockpiled. This might explain why sites where topsoil has been replaced did not have higher plant species richness than seeded sites. If the topsoil was replaced while still fresh, the results may have been different. However, de Villiers (2000) found that only about half the species in the standing vegetation were represented in the soil seed bank at Namakwa Sands prior to mining, and Hälbich (2003) stated that wind-dispersed, perennial species are unlikely to establish in large numbers from the topsoil seed bank. Therefore the outcome of using fresh topsoil still is uncertain. Norman *et al.* (2006) found that, in jarrah forest rehabilitated after mining in Western Australia, unseeded plots had nearly the same species richness as seeded plots after eight years, but had lower diversity and evenness, as it was dominated by a small number of annual species. Therefore, they concluded that seeding was a necessary rehabilitation treatment.

Grazing Capacity

In winter 2009 the rehabilitation sites where topsoil was replaced in 2001 (S1 and S3) were clearly more successful in terms of grazing capacity than sites which were seeded (S2 and S4), mostly due to higher cover of *Ehrharta brevifolia*, a very palatable annual grass, which is present at all sites. However, these sites did not differ significantly in summer 2010. This suggests that topsoil replacement is necessary to increase grazing capacity during the winter months.

Conclusions

The rehabilitation treatments experimented with at Namakwa Sands in the past (topsoil only, seeding only, topsoil + translocation and seeding + translocation) were not successful in returning vegetation cover and species richness to reference levels and creating a vegetation community similar to reference sites. They also did not achieve the final vegetation cover and species richness objectives. Late successional species are almost completely absent from the sites (S1 – S4), which were rehabilitated in 2001, and the perennial grass component is completely absent at site S1 (topsoil only). The grazing capacity at these sites is below the minimum requirement of 142.8 ha / LSU, which suggests that land capability has been successfully restored. Adaptive management, through seeding, translocation or planting nursery cuttings (especially of late successional species), will be required to increase the vegetation cover, species richness, diversity and evenness, and grazing capacity at these sites, and for them to become more like the reference sites. Although it is too early to judge whether the rehabilitation at site S5 (topsoil + seeding + translocation + nursery cuttings) has been successful, the signs are encouraging. This site, which was rehabilitated in 2008, has already reached the three-year objectives for vegetation cover and species richness, and even had the highest total number of species of all the rehabilitation sites in one sampling season. This site also achieved the minimum grazing capacity objective during the last sampling season. Land capability has therefore also been successfully restored at this site. The increased input by Namakwa Sands in their current rehabilitation method is clearly bearing fruit. However, this site will also need to be monitored and, if the development at this site stagnates or retrogression takes place, adaptively managed.

Recommendations

The translocation of *Zygophyllum morgsana* and *Asparagus* spp. were found to be unsuccessful, but might be more successful if better conditions for establishment are prevalent. The success of translocation of *Lampranthus suavissimus*, *Othonna cylindrica* and *Ruschia versicolor* were difficult to assess, as these species also recruited from seed in topsoil and from sown seeds. These

translocations did not seem to affect the outcome of the vegetation community development at the sites where they were carried out, but could have increased recruitment and survival of seedlings directly following initial rehabilitation, when conditions are especially adverse. Other species which are translocated on rehabilitated sites as part of current practice should be monitored to determine which can establish successfully.

Namakwa Sands should continue replacing fresh topsoil, seeding, and translocating mature plants and nursery cuttings during future rehabilitation, as this will most likely enable sites to reach the final vegetation cover and species richness objectives, as well as surpass the minimum grazing capacity objective. However, it would be best to conduct future rehabilitation in multiple stages, as suggested to Namakwa Sands by Carrick and Desmet (2003) and in general by Carrick and Kruger (2007). Topsoil replacement, seeding and translocation of mature plants should still be done directly after backfilling and contouring of tailings, but nursery cuttings should be transplanted at the beginning of the second rainy season after rehabilitation. A very high mortality rate has been observed among nursery cuttings due to sand-blasting, burial under wind-transported sand, and possibly also due to high salinity (personal observation). After the first rainy season, higher vegetation cover should prevent sand-blasting and leaching would have lowered the salinity of the soil. Furthermore, late successional species clearly fail to establish at the onset of rehabilitation due to adverse conditions. These species should be added to rehabilitation sites at a later stage, when adequate vegetation cover have developed and enough suitable micro-sites are available for them to establish in. How long after initial rehabilitation this could be done, and which species should be seeded, translocated or grown in the nursery and then planted, would have to be determined at Namakwa Sands through trial-and-error.

The proportional objectives for vegetation cover and species richness (at rehabilitation sites relative to reference sites) used at Namakwa Sands are useful in keeping perspective while assessing the vegetation cover and species richness of rehabilitation sites (especially in the light of seasonal differences and differences between years with above- or below mean rainfall). However, it is problematic to have "moving targets" such as these, as reference sites can also be subject to disturbance and degradation. For example, the usefulness of site R2 is questionable, as it is periodically subjected to grazing at a very high stocking rate. Therefore, minimum values for vegetation cover and species richness objectives should also be set, that is acceptable for the area in which Namakwa Sands occur. The pre-mining survey conducted by de Villiers *et al.* (1999) should be referred to when establishing these minimum values. The minimum grazing capacity objective, which is the benchmark for rehabilitated sites to be deemed suitable for small stock farming, is very low. Whether a small stock farm with such low grazing capacity would be

64

financially sustainable is doubtful. Therefore, Namakwa Sands should consider revising this objective.

Part of Namakwa Sands' rehabilitation goal is to "establish a self-sustaining Strandveld vegetation cover". However, the amount and predictability of rainfall in Namaqualand will decrease according to climate change models (MacKellar *et al.*, 2007). This will, amongst other impacts, lessen the moisture available to plants, which may fall below the minimum requirements of some species, leading to their local extinction. It will also result in more years in which annual plant cover is low. Overall, productivity will also be lower, which will lead to lower vegetation cover and a decrease in grazing capacity (O'Farrell *et al.*, 2010). In order to sustain the current range of plant cover and species richness, Namakwa Sands will have to maintain high perennial vegetation cover and species richness on rehabilitated sites. This will increase the resilience of the vegetation against climate change and predicted drought conditions.

3.5. References

Allsopp, N. 1999. Effects of grazing and cultivation on soil patterns and processes in the Paulshoek area of Namaqualand. Plant Ecology **142**:179–187.

Bainbridge, D.A. 2007. A guide for desert and dryland restoration. Island Press, Washington, USA.

Bayer, M.B. 1990. A proposed method of veld condition assessment for the winter rainfall region. Unpublished report. Western Cape Department of Agriculture, Elsenburg, South Africa.

Bell, L.C. 2001. Establishment of native ecosystems after mining – Australian experience across diverse biogeographic zones. Ecological Engineering **17**:179–186.

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

Blood, J.R. 2006. Monitoring rehabilitation success on Namakwa Sands heavy minerals mining operation, Namaqualand, South Africa. MSc thesis. Stellenbosch University, Stellenbosch, South Africa.

Botha, M.S., Carrick, P.J. & Allsopp, N. 2008. Capturing lessons from land-users to aid the development of ecological restoration guidelines for lowland Namaqualand. Biological Conservation **141**:885–895.

Carrick, P.J. & Desmet, P.G. 2003. Comments on Namakwa Sands Brand-se-Baai mine-site rehabilitation process. Unpublished report. Lesley Hill Institute for Plant Conservation, University of Cape Town, Cape Town, South Africa.

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.

Chamber of Mines of South Africa. 2008. Annual Report. Chamber of Mines of South Africa, Johannesburg, South Africa.

Chamber of Mines of South Africa. 2009. Annual Report. Chamber of Mines of South Africa, Johannesburg, South Africa.

Chambers, J.C., Brown, R.W. & Williams, B.D. 1994. An evaluation of reclamation success on Idaho's phosphate mines. Restoration Ecology **2**:4–16.

Clements, F.E. 1928. Plant succession and indicators. The H.W. Wilson Company, New York, USA.

Cooke, J.A. & Johnson, M.S. 2002. Ecological restoration of land with particular reference to the mining of metals and industrial minerals: A review of theory and practice. Environmental Review. **10**:41–71.

Council for Scientific and Industrial Research (CSIR). 2011. Exxaro Namakwa Sands weather monitoring programme biannual progress report: Spring 2010 and Summer 2010/2011. Unpublished report. CSIR, Stellenbosch, South Africa.

Cousins, B., Hoffman, M.T., Allsopp, N. & Rhode, R.F. A synthesis of sociological and biological perspectives on sustainable land use in Namaqualand. Journal of Arid Environments **70**:834–846.

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.

Cummings, J., Reid, N., Davies, I. & Grant, C. 2005. Adaptive management of sand-mined areas for biological conservation. Journal of Applied Ecology **42**:160–170.

Dean, W.R.J. & Milton, S.J. (eds.) 1999. The Karoo: ecological patterns and processes. Cambridge University Press, Cambridge, UK.

Department of Industry, Tourism and Resources (DITR). 2006. Leading practice sustainable development program for the mining industry – mine rehabilitation. DTIR, Canberra, Australia.

Desmet, P.G. 2007. Namaqualand – A brief overview of the physical and floristic environment. Journal of Arid Environments **70**:570–587.

Desmet, P.G. & Cowling, R.M. 1999a. Biodiversity, habitat and range-size aspects of a flora from a winter-rainfall desert in north-western Namaqualand, South Africa. Plant Ecology **142**:23–33.

Desmet, P.G. & Cowling, R.M. 1999b. The climate of the Karoo – a functional approach. Pages 3–16 in: Dean, W.R.J. & Milton, S.J. (eds.) The Karoo: Ecological patterns and processes. Cambridge University Press, Cambridge, UK.

De Villiers, A.J., van Rooyen, M.W. & Theron, G.K. 1992. Studies of the revegetation of saline mined soil at Namaqua Sands. Unpublished report. Namakwa Sands, Lutzville, South Africa.

De Villiers, A.J., Van Rooyen, M.W., Theron, G.K. & Van Rooyen, N. 1999. Vegetation diversity of the Brand-se-Baai coastal dune area, west coast, South Africa: A pre-mining benchmark survey for rehabilitation. Land Degradation & Development **10**:207–224.

De Villiers, A.J. 2000. Seed bank dynamics of the Strandveld Succulent Karoo. Ph.D. thesis, University of Pretoria, Pretoria, South Africa.

Driver, A., Desmet, P.G., Rouget, M., Cowling R.M. & Maze, K.E. 2003. Succulent Karoo Ecosystem Plan biodiversity component technical report. Cape Conservation Unit, Botanical Society of South Africa, Cape Town, South Africa.

Du Toit, P.C.V. 1995. The grazing index method of range condition assessment. African Journal of Range & Forage Science **12(2)**:61–67.

Du Toit, P.C.V. 2000. Estimating grazing index values for plants from arid regions. Journal of Range Management **53**:529–536.

D'antonio, C. & Meyerson, L.A. 2002. Exotic plant species as problems and solutions in ecological restoration: a synthesis. Restoration Ecology **10**:703–713.

Ellis, F. 1988. Die gronde van die Karoo. Ph.D. thesis, Stellenbosch University, Stellenbosch, South Africa.

Esler, K.J. & Rundel, P.W. 1999. Phenological and growth form divergence in convergent desert ecosystems: a Succelent Karoo and Mojave desert comparison. Plant Ecology **142**:97–104.

Esler, K.J., Rundel, P.W. & Cowling, R.M. 1999. The Succulent Karoo in a global context: plant structural and functional comparison with North American winter-rainfall deserts. Pages 303–313 in: Dean, W.R.J. & Milton, S.J. (eds.) The Karoo: ecological patterns and processes. Cambridge University Press, Cambridge, UK.

Francis, M.L., Fey, M.V., Prinsloo, H.P., Ellis, F., Mills, A.J. & Medinski, T.V. 2007. Soils of Namaqualand: Compensations for aridity. Journal of Arid Environments **70**:588–603.

Golder Associates. 2008. Environmental management programme for Namakwa Sands. Unpublished report nr. 10417-5659-1-E. Golder Associates, Johannesburg, South Africa.

Hälbich, T.J.F. 2003. Mine rehabilitation in the arid Succulent Karoo vegetation zone on the South African west coast, Namakwa Sands – case study. Heavy Minerals 2003. South African Institute of Mining and Metallurgy, Johannesburg, South Africa.

Henderson, L. 2001. Alien weeds and invasive plants: A complete guide to declared weeds and invaders in South Africa. Agricultural Research Council, Pretoria, South Africa.

Herath, D.N., Lamont, B.B., Enright, N.J. & Miller, B.P. 2009. Comparison of post-mine rehabilitation and natural shrubland communities in southwestern Australia. Restoration Ecology **17**:577–585.

Herrick, J.E., Schuman, G.E. & Rango, A. 2006. Monitoring ecological processes for restoration projects. Journal of Nature Conservation **14**:161–171.

Hobbs, R.J. & Harris, J.A. 2001. Restoration ecology: Restoring the earth's ecosystems in the new millennium. Restoration Ecology **9**:239–246.

Holmes, P.M. 2001. Shrubland restoration following woody alien invasion and mining: effects of topsoil depth, seed source, and fertilizer addition. Restoration Ecology **9**:71–84.

International Council for Mining and Metals (ICMM). 2006. Good practice guidance for mining and biodiversity. International Council for Mining and Metals, London, UK.

Johnson, M.S. & Tanner, P.D. 2003. Mine Site Rehabilitation and Ecosystem Reconstruction for Biodiversity Gain. IUCN/ICMM Workshop, Gland, Switzerland.

Koch, J.M. 2007. Alcoa's mining and restoration process in south western Australia. Restoration Ecology **15**:S11–S16.

Le Roux, A. & Schelpe, T. 1988. Namaqualand: South African Wildflower Guide 1. Botanical Society of South Africa, Cape Town, South Africa.

Lubke, R.A. & Avis, A.M. 1998. A review of the concepts and application of rehabilitation following heavy mineral dune mining. Marine Pollution Bulletin **37**:546–557.

MacKellar, N.C., Hewitson, B.C. & Tadross, M.A. 2007. Namaqualand's climate: Recent historical changes and future scenarios. Journal of Arid Environments **70**:604–614.

Mahood, K. 2003. Strip-mining rehabilitation by translocation in the arid coastal Namaqualand, South Africa. MSc thesis. Stellenbosch University, Stellenbosch, South Africa.

Masetlana, T.R., Dlambulo, N., Themba, L.A. & Mwape, P. (eds.) 2008. South Africa's Mineral Industry 2007/2008. Directorate: Mineral Economics, Department of Minerals & Energy, Pretoria, South Africa.

Meissner, H.H., Hofmeyer, H.S., van Rensburg, W.J.J. & Pienaar, J.P. 1983. Classification of livestock for realistic prediction of substitution values in terms of biologically defined Large Stock Unit. Technical Communication 175. Department of Agriculture, Pretoria, South Africa.

Milton, S.J., Yeaton, R.I., Dean W.R.J. & Vlok, J.H.J. 1997. Succulent Karoo. Pages 131–166. In: Cowling, R.M., Richardson, D.M. & Pierce, S.M. (eds). The vegetation of southern Africa. Cambridge University Press, Cambridge, UK.

Milton, S. J., Zimmermann, H.G. & Hoffmann, J.H. 1999. Alien plant invaders of the Karoo: attributes, impacts and control. Pages 274 – 287 in: Dean, W.R.J. & Milton, S.J. (eds.) The Karoo: ecological patterns and processes. Cambridge University Press, Cambridge, UK.

Milton, S.J. 2001. Rethinking ecological rehabilitation in arid and winter rainfall regions of southern Africa. South African Journal of Science **97**:47-48.

Mucina, L., Jürgens, N., le Roux, A., Rutherford, M.C., Schmiedel, U., Esler, K.J., Powrie, L.W., Desmet, P.G. & Milton, S.J. 2006. Succulent Karoo Biome. Pages 220 – 299 in: Mucina, L. & Rutherford, M.C. (eds.) The Vegetation of South Africa, Lesotho and Swaziland. South African National Biodiversity Institute, Pretoria, South Africa.

Namakwa Sands. 2001. Draft revised environmental management programme. Unpublished report. Namakwa Sands, Lutzville, South Africa.

Namakwa Sands. 2008. 2007 Footprint Sustainability report. Unpublished report. Namakwa Sands, Vredenburg, South Africa.

Norman, M.A., Koch, J.M., Grant, C.D., Morald, T.K. & Ward, S.C. 2006. Vegetation succession after Bauxite mining in Western Australia. Restoration Ecology **14**:278–288.

O'Farrell, P.J., Reyers, B., Le Maitre, D.C., Milton, S.J., Egoh, B., Maherry, A., Colvin, C., Atkinson, D., De Lange, W., Blignaut, J.N. & Cowling, R.M. 2010. Multi-functional landscapes in semi arid environments: implications for biodiversity and ecosystem services. Landscape Ecology **25**: 1231–1246.

Prinsloo, H.P. 2005. Alteration of the soil mantle by strip mining in the Namaqualand Strandveld. MSc thesis. Stellenbosch University, Stellenbosch, South Africa.

Rahlao, S.J., Hoffman, M.T., Todd, S.W. & McGrath, K. 2008. Long-term vegetation change in the Succulent Karoo, South Africa following 67 years of rest from grazing. Journal of Arid Environments **72**:808–819.

Rutherford, M.C., Midgley, G.F., Bond, M.J., Mucil, C.F., Powrie, L.W., Roberts, R. & Allsopp, J. 2000. Plant biodiversity: Vulnerability and adaptation assessment. Department of Environmental Affairs and Tourism, Pretoria, South Africa.

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

Singer, A., Kirsten, W. & Bühmann, C. 1995. Fibrous clay minerals in the soils of Namaqualand, South Africa: characteristics and formation. Geoderma **66**:43–70.

Sutherland, W.J. 1997. Ecological census methods. Cambridge University Press, Cambridge, UK.

Tanner, P.D. (ed.) 2007. Guidelines for the rehabilitation of mined land. Chamber of Mines of South Africa/Coaltech, Johannesburg, South Africa.

Todd, S.W. & Hoffman, M.T. 2009. A fence line in time demonstrates grazing-induced vegetation shifts and dynamics in the semi-arid Succulent Karoo. Ecological Applications **19**:1897–1908.

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

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.

Vorster, M. 1982. The development of the ecological index method for assessing veld condition in the Karoo. Procedures of the Grassland Society of South Africa **17**:84–89.

Personal Communication

Cupido, C.F. Agricultural Research Council – Animal Production Institute, Biodiversity & Conservation Biology Department, University of the Western Cape, Private Bag X17, Bellville, 7535, South Africa. Tel: +27 21 959 3373. Fax: +27 21 959 1376. E-mail: ccupido@uwc.ac.za

Saayman, N. Department of Agriculture: Western Cape, Private Bag X1, Elsenburg, 7607, South Africa. Tel: +27 21 808 5330. E-mail: nelmaries@elsenburg.com

Vlok, M. Safety, Health, Environmental & Quality Department, Exarro Namakwa Sands Ltd., P.O. Box 223, Lutzville, 8165, South Africa. Tel: +27 27 217 3330. Fax: +27 27 217 3055. E-mail: marius.vlok@exxaro.com

Chapter 4: Landscape Function Analysis as a Mining Rehabilitation Monitoring Tool in Namaqualand, South Africa

Abstract

Restoring ecosystem structure and composition has been the main goal in past rehabilitation practices. However returning ecosystem function together with structure and composition is essential to ensure rehabilitation success. At the Exxaro Namakwa Sands heavy mineral sands mine, on the west coast of South Africa, the rehabilitation goal is to "...establish a self-sustaining Strandveld vegetation cover in order to control dust generation, control wind and water erosion, as well as restore land capability". As self-sustainability requires a functional ecosystem, monitoring ecosystem functioning as a complement to traditional methods of monitoring structure is key to ensuring that this goal is achieved. Landscape Function Analysis (LFA) is a rapid monitoring method developed by researchers in Australia for rangeland and mining rehabilitation monitoring. The method provides indices of stability, water infiltration and nutrient cycling that are based on simple field indicators at the soil surface. However, before any method can be applied in a new environment, its validity must be tested against conventional scientific measurements. Therefore, LFA is tested by correlating the indices to data obtained through traditional methods. The status of landscape functioning on sites experimentally rehabilitated in 2001 and a site rehabilitated in 2008 using current practice, which received different combinations of topsoil, seeding, and mature plant- and nursery seedling translocation treatments, is compared to that on two reference sites. Another aim is to determine if two replicates of the LFA method per site are sufficient to provide statistically sound data. Results suggest that the Stability Index could be a valid indicator of soil stability at Namakwa Sands. While the Nutrient Cycling Index was found to be a valid indicator of nutrient cycling, the Water Infiltration Index was not a valid indicator of water infiltration, as assumptions in the calculation of the index are invalid for the Namaqualand environment. Two replicates per site were insufficient for most indices. It is recommended that annual monitoring of ecosystem function, using LFA is conducted at Namakwa Sands, and that the minimum number of replicates is determined experimentally. The calculation of the Water Infiltration Index should be modified for use at Namakwa Sands. The landscape functioning of sites rehabilitated in 2001 are similar to that of reference sites, but the landscape functioning at the site rehabilitated in 2008 had not yet reached reference levels.

Key words: Strip Mining; Rehabilitation Success; Monitoring; Ecosystem Function

4.1. Introduction

Mining for heavy minerals is expanding in Namaqualand (Milton, 2001) where (together with diamond mining) it is an important driver of the regional economy (Mucina *et al.*, 2006; Francis *et al.*, 2007). Unfortunately, mining is also considered the greatest threat to biodiversity (Botha *et* al., 2008) and the primary cause of degradation in the region (Carrick & Kruger, 2007; Cousins *et al.*, 2007). Strip mining, which is practiced at Namakwa Sands, is one of the most destructive methods as it involves the complete removal of topsoil and vegetation from large stretches of land (Milton *et al.*, 1997; Cooke & Johnson, 2002; Botha *et al.*, 2008) and as a result it also disrupts important soil processes (Botha *et al.*, 2008).   This is of particular concern in an environment, such as Namaqualand, where revegetation is hampered by an arid and windy climate (Lubke & Avis, 1998; Milton, 2001; Hälbich, 2003; Carrick & Kruger, 2007; Botha *et al.*, 2008), as well as saline and nutrient-poor soils (Milton, 2001; Carrick & Kruger, 2007; Botha *et al.*, 2008).

In the past rehabilitation was the exception rather than rule in the mining industry (Milton *et al.*, 1997; Johnson & Tanner, 2003; Carrick & Kruger, 2007; Botha *et al.*, 2008). Evidence of this includes mine blocks and prospecting trenches in Namaqualand that are still visible today due to the lack of vegetation (Milton *et* al., 1997; Carrick & Kruger, 2007). However, the mining industry world-wide has recently committed itself to sustainable development and responsible environmental management (ICMM, 2006). In many countries environmental legislation and their implementation has also been stepped up which has caused many mining companies to take rehabilitation more seriously. In South Africa a number of new acts have been enacted in the last decade to ensure responsible environmental management.   These include the National Environmental Management Act 107 of 1998, the National Environmental Management: Air Quality Act 29 of 2004 and the Minerals and Petroleum Resources Development Act 28 of 2002 (MPRDA).

The MPRDA requires that mined-out land "is rehabilitated, as far as is practicable, to its natural state, or to a predetermined and agreed standard or land use which conforms to the principles of sustainable development". At Exxaro Namakwa Sands, the focus of this study, the rehabilitation goal is to "rehabilitate and re-vegetate disturbed areas and establish a self-sustaining Strandveld vegetation cover in order to control dust generation, control wind and water erosion, as well as restore land capability" (Golder Associates, 2008). The land capability referred to is small stock farming, which was the land use before mining started (Hälbich, 2003).

Monitoring is an indispensable part of the restoration process (Hobbs & Harris, 2001; Cooke & Johnson, 2002) because it enables the restoration to be evaluated (Hobbs & Harris, 2001; Herrick *et al.*, 2006). Evaluation gives restoration managers an opportunity to assess and, if necessary, change their restoration objectives (Herrick *et al.*, 2006). It also allows practitioners to adapt their management strategies and improve their restoration practices (Cooke & Johnson 2002; Cummings *et al.*, 2005; Herrick *et al.*, 2006). However, in practice, the outcomes of restoration are not always monitored (Ntshotsho *et al.*, 2010). This study forms part of the monitoring and evaluation process at Namakwa Sands, as a follow-up to the work done by Blood (2006) and complements the annual vegetation monitoring conducted at the mine.

The monitoring of rehabilitation progress and success traditionally only assesses the vegetation structure and composition of a recovering ecosystem (Tongway & Hindley, 2004a). However, ecosystem function is listed by Hobbs & Norton (1996) as one of six ecosystem attributes that need to be returned through rehabilitation and is included in the Society of Ecological Restoration International's (SER) Primer for measuring the success of restoration (SER, 2004) and in Australian leading practice guidelines for the mining industry (DITR, 2007). To return only the structure and composition of an ecosystem does not comprise full restoration (Hobbs & Norton, 1996; Reay & Norton, 1999), as an ecosystem cannot sustain itself unless the functioning of the ecosystem (the processes that ensure the capture and cycling of resources such as nutrients and water, as well as the stability of the ecosystem) is also returned (Milton, 2001; Herrick *et al.*, 2006; Maestre *et al.*, 2006; Grant *et al.*, 2007). Despite recognition of the importance of ecosystem functioning, few studies on rehabilitation have included it compared with the more traditional measurements such as vegetation structure and composition. This is mostly due to a lack of understanding of ecosystem functions (Hobbs & Norton, 1996), the slower recovery of ecosystem functioning relative to structure and composition, the difficulty of monitoring it (multiple measurements are often required), and the potentially high financial and time costs of doing so (Ruiz-Jaén & Aide, 2005; Ata Rezaei *et al.*, 2006). However, methods which make use of indices of ecosystem function have been recognised to be more affordable and less time-consuming than traditional methods of assessing ecosystem function and, while being somewhat less accurate (Maestre & Cortina, 2004), do enable more efficient monitoring.

The Landscape Function Analysis (LFA) was developed by Tongway and Hindley (2004a) as a method for rapidly assessing ecosystem function of rangelands and minesites. The functional status of the landscape is assessed using indices for stability, water infiltration and nutrient cycling that are based on simple field indicators at the soil surface. These indices are strongly correlated to ecosystem processes (Holm *et al.*, 2002; Maestre & Cortina, 2004; Tongway & Hindley, 2004a).

In the model developed by Ludwig and Tongway (1997), on which the LFA is based, degradation is seen as a decrease in the ability of the ecosystem to obtain and retain essential resources, such as nutrients and water, and therefore a decrease in the suitability of that ecosystem to act as habitat for different species. Soil is the most important resource in rangelands, acting as a growing medium for the plants and as a nutrient store (Palmer *et al.*, 2001; Ata Rezaei *et al.*, 2006; Grant *et al.*, 2007). An important benefit of using LFA is that, by doing the soil surface assessment, changes in the processes related to stability, nutrient cycling and water infiltration can be detected before these are reflected in the vegetation. From this information, the ecosystem functions in need of restoration can be identified and corrective action can be taken before the vegetation is affected (Palmer, 2001; Maestre & Cortina, 2004).

LFA is considered a useful method for monitoring ecosystem functioning in many different ecosystems in different parts of the world. It has been effectively used to monitor the development of rehabilitation on mined land over time (Tongway & Hindley, 2004a). However, before any method can be used in a new environment, it is important to first test its validity against conventional scientific measurements (Maestre & Cortina, 2004; Tongway & Hindley, 2004b; Ata Rezaei *et al.*, 2006). The aim of this study is to determine whether the three LFA indices (stability, water infiltration and nutrient cycling) are accurate indicators for monitoring landscape function in Namaqualand by assessing how well the results of the LFA method correlate to that of dust collection, soil chemical analyses and water infiltration rate measurements. The dust weights, soil nutrients and water infiltration rates at rehabilitated sites are also compared to that at reference sites.

The main hypotheses being tested are therefore: That the Stability Index (SI) is an accurate predictor of soil stability, that the Nutrient Cycling Index (NCI) is an accurate predictor of nutrient status, that the Water Infiltration Index (WII) is an accurate predictor of water infiltration rate, and that two replicates of the LFA method per site are sufficient for these indices and the Landscape Organisation Index (LOI) to be accurately measured, as suggested by Tongway & Hindley (2004b). Additional hypotheses that are tested are that the dust weights, soil nutrients and water infiltration rates are similar at reference sites and experimental rehabilitated sites but differ between these sites and the recently rehabilitated site.

4.2. Methods

4.2.1. Study Area

The focus of this study is the Exxaro Namakwa Sands heavy minerals mining operation at Brand-se-Baai (31° 18' S, 17° 54' E), 92 km northwest of Vredendal, on the west coast of South Africa. The Namaqualand region, in which the mine occurs, is situated in the strongly winter rainfall part of the Succulent Karoo Biome (Milton *et al.*, 1997; Cowling *et al.*, 1999). The vegetation is dominated by succulents and in particular leaf succulent dwarf shrubs of the family Mesembryanthemaceae (Milton *et al.*, 1997; Cowling *et al.*, 1999; Desmet & Cowling, 1999a; Esler & Rundel, 1999). De Villiers *et al.* (1999) mapped six vegetation communities in the vicinity of the mine. The dominant communities were *Ruschia tumidula – Tetragonia virgata* Tall Shrub Strandveld where the East Mine is now located and *Ruschia versicolor – Odyssea paucinervis* Dwarf Shrub Strandveld where the West Mine is now located.

The mean annual rainfall at Brand-se-Baai, calculated from data collected by CSIR (2011) between 1996 and 2009, is 150 mm and, like in the rest of the Namaqualand region (Cowling *et al.*, 1999; Desmet, 2007; MacKellar, 2007), is considered very predictable. Fog occurs on approximately 100 days per year, probably contributing in excess of 120 mm to the average annual precipitation (de Villiers *et al.*, 1999). Desmet & Cowling (1999b) suggest that fog greatly increases the amount of water available to plants. This is concurrent with studies in other arid regions such as western Chile (Cereceda *et al.*, 2008) and eastern Mexico (Vogelmann, 1973). Strong south and south-easterly winds prevail from September to March and strong north to north-westerly winds from June to August (Hälbich, 2003; Mahood, 2003). Wind is the primary erosion factor and also causes mortality to seedlings and some mature plants through sand-blasting when it reaches a very high velocity. Therefore, wind is a major constraint to restoration in the region (Botha *et al.*, 2008).

Namaqualand's soils are typical of those found in arid environments (Francis *et al.*, 2007) and have certain characteristics that heavily influence hydrological processes. Soil crusts and naturally hydrophobic, sandy topsoils result in fingering rather than even water infiltration, which enables water to penetrate deeper into the soil where it cannot be lost through evapotranspiration (Francis *et al.*, 2007). Subsurface soil horizons that are cemented with silica, calcite, fibrous clays or gypsum (such as the dorbank layer at Namakwa Sands) inhibit deeper penetration of water, creating an aquifer below the plant root layer, where water can be stored temporarily (Francis *et al.*, 2007). Nocturnal distillation occurs when differences between atmospheric and soil

76

temperatures cause soil water vapour to move towards the surface. Prinsloo (2005) and Francis *et al*. (2007) suggest that this greatly influences the amount of water available to plants, especially shallow rooted species, which are dominant in this region (Esler & Rundel, 1999). Soluble salts in coastal soils slow the uptake of plant water, decreasing the rate of evapotranspiration (Francis *et al.*, 2007). Clay minerals (sepiolite and palygorskite) that are unique to arid environments and have an exceptionally high water-absorbing capacity are common in the clay fraction of Namaqualand soils (Singer *et al.*, 1995; Francis *et al.,* 2007). This causes these soils to have better water retention than expected for a given clay content (Francis e*t al.*, 2007).

The dominant soil type in the Brand-se-Baai area is red, apedal soil, while regic sands are also quite common (Ellis, 1988; Prinsloo, 2005). Only the layer of Aeolian sand is mined and excavation reaches a maximum depth of 5 m (Golder Associates, 2008). De Villiers *et al*. (1999) correlated different vegetation communities to a number of soil characteristics, which suggests that the characteristics of soils in rehabilitated sites will affect the vegetation community that develops (Blood, 2006). The handling of mined soil results in rehabilitated areas having a rather uniform distribution of soil characteristics in tailings, in contrast with the heterogeneous distribution found in undisturbed soils in the study area (Lanz, 2003) and other arid environments (Stock *et al.*, 1999). This causes the destruction of micro-habitats that might suit certain plant species (De Villiers *et al.*, 1999; Blood, 2006). The tailings generated by mining at Namakwa Sands are saline and almost completely devoid of the clay and organic matter fraction (Prinsloo, 2005). However, the salinity of the soil is expected to decrease to near-natural levels within 25 months after mining, due to natural leaching processes (Prinsloo, 2005). Topsoil hydrophobicity (which results in infiltration fingering) and a cemented dorbank layer are thought to be the key factors driving the nocturnal distillation found in the soil (Prinsloo, 2005). Therefore, losing these features (by changing the soil chemistry and mixing the soil horizons) might result in a reduction of the soil water available to plants.

Clumping of plants in multi-species patches is a common occurrence in the vegetation of Namaqualand (Eccles *et al.,* 1999; Desmet, 2007), as is often the case in semi-arid and arid environments (Ludwig & Tongway, 1995; Stock *et* al., 1999; Maestre & Cortina, 2004). These "clumps" or "patches", which have often been referred to as "fertile islands", due to increased nutrient status (Ludwig & Tongway, 1995; Stock *et* al., 1999; Burke, 2001), act as sink for water and nutrients, while the surrounding areas act as a source (Ludwig & Tongway, 1995; Aguiar & Sala, 1999; Valentin *et al.*, 1999; Maestre & Cortina, 2004; Maestre *et al.*, 2006). As a result, these patches often have different soil characteristics from surrounding areas (Stock *et al.*, 1999). Patches are thus viewed as the basic units of landscape functioning (Tongway & Hindley, 2004b). In Namaqualand, these patches are short-lived compared to other systems (Desmet, 2007). The

77

spatial and temporal distribution of patches is thought to be an important driver of cyclical succession in the vegetation (Yeaton & Esler, 1990; Desmet, 2007).

4.2.2. Study Sites

Two reference sites were located in the dominant vegetation types on the mine, as classified by De Villiers *et al.* (1999). During the development of the rehabilitation method, research was conducted on the success of different treatments. Four sites were rehabilitated in 2001 with different combinations of treatments. The lack of sites at which treatments could be replicated on a sufficient scale resulted in unavoidable pseudo-replication (Blood, 2006). These two reference sites and four rehabilitation sites were sampled by Blood (2006) and have been re-sampled in this study. In addition, a site rehabilitated in 2008, using the current rehabilitation method, was sampled.

One meter high windbreaks, consisting of polyethylene shade cloth (with a density of 40 %) and metal droppers, were placed four to five meters apart and perpendicular to the prevailing winds at all rehabilitated sites (Mahood, 2003; Blood, 2006). This was done to prevent wind erosion, loss of seeds and damage to plants due to sand-blasting (Namakwa Sands, 2001; Hälbich, 2003; Mahood, 2003; Blood, 2006). These wind breaks were removed when the vegetation cover was high enough to prevent wind erosion, except for site S5 where the vegetation cover is still relatively low (Marius Vlok, pers. comm., 2009).

The locations of the seven sites and the treatments applied on the rehabilitation sites are listed below:

1. Reference site R1 is located at 31° 15' 85.3" S, 17° 58' 41.5" E. The vegetation community at this site has been classified as *Ruschia versicolor – Odyssea paucinervis* Dwarf Shrub Strandveld by De Villiers *et al.* (1999).
2. Reference site R2 is located at 31° 16' 45.1" S, 17° 56' 18.1" E. De Villiers *et al.* (1999) classified the vegetation community at the site as *Ruschia tumidula – Tetragonia virgata* Tall Shrub Strandveld.
3. Rehabilitation site S1 is located at 31° 15' 84. 0" S, 17° 56' 14.3" E. The restoration of this site took place in June 2001. It involved only the spreading of topsoil over tailings and no seeding or transplantations.

78

4. Rehabilitation site S2 is located at 31° 15' 46. 1" S, 17° 55' 54.4" E. Sometime in 2001, a mix of indigenous species with the addition of *Eragrostis curvula* and *Sorghum sp.* was seeded over bare tailings on this site.

5. Rehabilitation site S3 is located at 31° 15' 88. 9" S, 17° 56' 00.3" E. Topsoil was spread over tailings and five indigenous species (*Ruschia versicolor*, *Lampranthus suavissimus*, *Othonna cylindrica*, *Zygophyllum morgsana* and *Asparagus sp.*) were translocated on this site in multi-species clumps. The restoration of this site took place in June 2001.

6. Rehabilitation site S4 is located at 31° 15' 26. 7" S, 17° 55' 43.3" E. A mix of indigenous species with the addition of *Ehrharta calycina* was seeded onto bare tailings on this site sometime in 2001. Three indigenous species (*Ruschia versicolor*, *Lampranthus suavissimus* and *Othonna cylindrica*) were also translocated in multi-species clumps between July and August 2002.

7. Rehabilitation site S5 has been established on an area rehabilitated in 2008. Topsoil was spread over tailings and a mix of indigenous plant species were sown in addition to transplants from natural veld. Cuttings grown in the nursery on site were also planted during the rainy season in 2008.

Reference site R2 is located on a sheep farm, and is periodically grazed at a very high stocking rate of 10 ha / SSU (Blood, 2006). In contrast, reference site R1 and rehabilitation sites S1 – S5 are only very lightly grazed by wild animals such as steenbok (*Raphicerus campestris*). Four 50 m x 50 m plots were laid out 10 m apart at each site. Starting from the given co-ordinates these plots were laid out from north to south at sites R2 and S1 – S4, from west to east at site R1, and from south to north at site S5. All data collection took place within these plots.

4.2.3. Landscape Function Analysis

The LFA method uses transects that are placed in the direction of the major erosive force. The landscape organisation (spatial distribution of patches where resources accumulate) is determined by measuring the length and width of patches and the length of interpatches along transects. These data are used to calculate the Landscape Organisation Index. During the Soil Surface Assessment that follows, eleven indicators are classified for each patch- or interpatch type. These indicators are used in different combinations to calculate the Stability-, Water Infiltration- and Nutrient Cycling indices. The LFA method is described in full in Tongway & Hindley (2004b). An LFA transect was located at each of the first two plots of each site, except site R1, where it was located at the first and third plots. This was done to better capture the variability at site R1, as the first two plots at this site were on the west side of a dune while the last two plots were on the east side. The starting point for each transect was on the 25 m mark of the northern side of the plot,

and transects were oriented in a south easterly direction because the prevailing wind directions are from the north west and south east. The LFA data were collected during May 2010.

4.2.4. Vegetation Cover

Vegetation cover was sampled in May 2010 using the Line Intercept Method (Sutherland, 1997), as this method is effective where the vegetation cover is low and patchy. Five 50 m line transects, orientated in a zig-zag pattern as described in Blood (2006), were located in each of the four plots at each site. This was done to ensure that line transects did not run parallel to lines of translocated clumps (Blood, 2006), nursery cuttings or plants that grow along the wind breaks. The species and cover of each plant intercepting the line transect was recorded.

4.2.5. Dust Collection

Buckets with a base length of 350 mm, width of 270 mm and depth of 80 mm were used to collect dust. Two buckets were placed on the ground, approximately 4 m apart, at the north western corner of each plot. The sample size was therefore two buckets per plot and eight buckets per site. The buckets were placed in the field from 10 August 2010 to 20 October 2010 (70 days). Large insects and plant material were removed using forceps and the rest of the contents of each bucket were sieved into a plastic container through a 2mm sieve. Fine particles that remained in the buckets were lightly brushed (with a paintbrush) into the container and the dust was then weighed. A large number of buckets overturned and had to be excluded from the analysis. The buckets at site S5 were removed by contractors working on the mine and therefore no data is available for that site.

4.2.6. Water Infiltration Rate

Water infiltration rates were measured during August 2010, using a single ring infiltrometer with a functional volume of 0.8 Litres (height 60 mm and diameter 130 mm). The first two plots at each site were divided in thirds across both length and width, forming a grid with nine points at which the measurements were taken (see Figure 4.1).
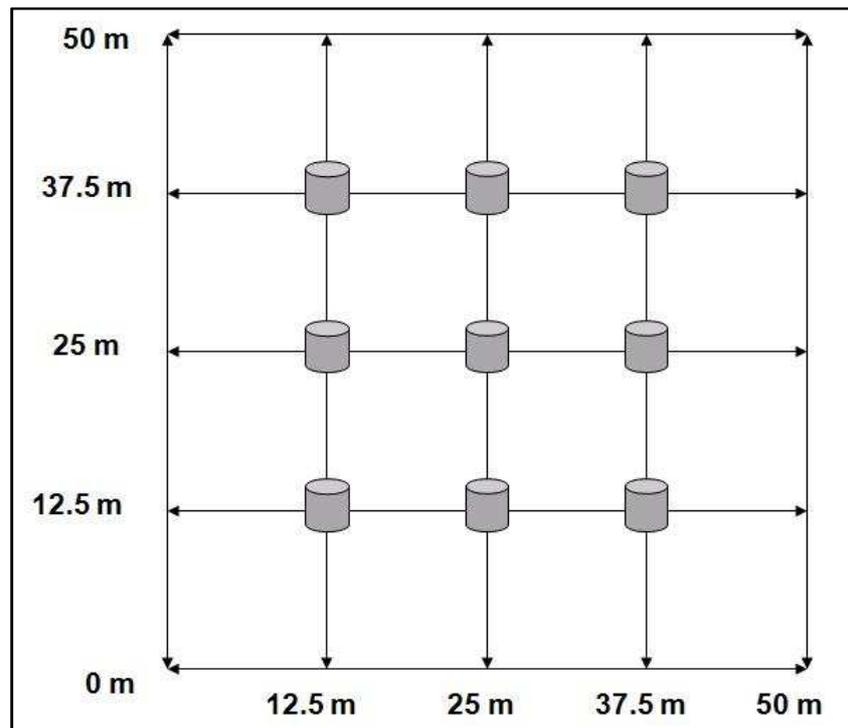
Figure 4.1: Layout of water infiltration rate measurements (represented by a grey cylinder) in each plot.

4.2.7. Soil Nutrients

Blood's (2006) soil nutrient data were used in this study. He collected 12 soil samples, each consisting of eight soil cores, along three line transects laid out in a zig-zag pattern, as illustrated in Blood (2006), at the first plot at each site. Site S5 had not been mined and rehabilitated at the time of his study, therefore soil nutrient data only exist for sites R1, R2 and S1 to S4. Soil samples were analysed by BemLab (Pty) Ltd and analyses are described in Blood (2006).

4.2.8. Data Analysis

The LFA data collected were entered into the LFA data entry workbook 3.0 (CSIRO, 2003), which calculates the Landscape Organisation Index, Stability Index, Nutrient Cycling Index and Water Infiltration Index. Kruskal-Wallis ANOVAs were conducted to test for significant differences between sites.

Kruskal-Wallis ANOVAs were also conducted on dust weights. One-way ANOVAs and Fischer LSD tests were conducted on vegetation cover data, water infiltration rate data and soil nutrient (%

organic C, Na concentration, K concentration, Ca concentration and Mg concentration) data. As the residuals for % C and Ca concentration data were found not to be normally distributed, the data were transformed by calculating the natural logarithm of the original values. The residuals of the transformed data were normally distributed.

Correlations between LFA indices and measured data were performed, and tests for significance conducted. All statistical tests were performed using Statistica 9.0 (Statsoft, Inc. 2009)

4.3. Results

4.3.1. Landscape Organisation

The Landscape Organisation Index (LOI) is the proportion of the length of a transect that consists of patches. Reference site R1 had the highest mean LOI (Figure 4.2), followed by rehabilitation sites S1 and S3. Reference site R2 and rehabilitation sites S2 and S4 all had lower mean LOI's. Rehabilitation site S5 had the lowest mean LOI. However, none of these differences were statistically significant.
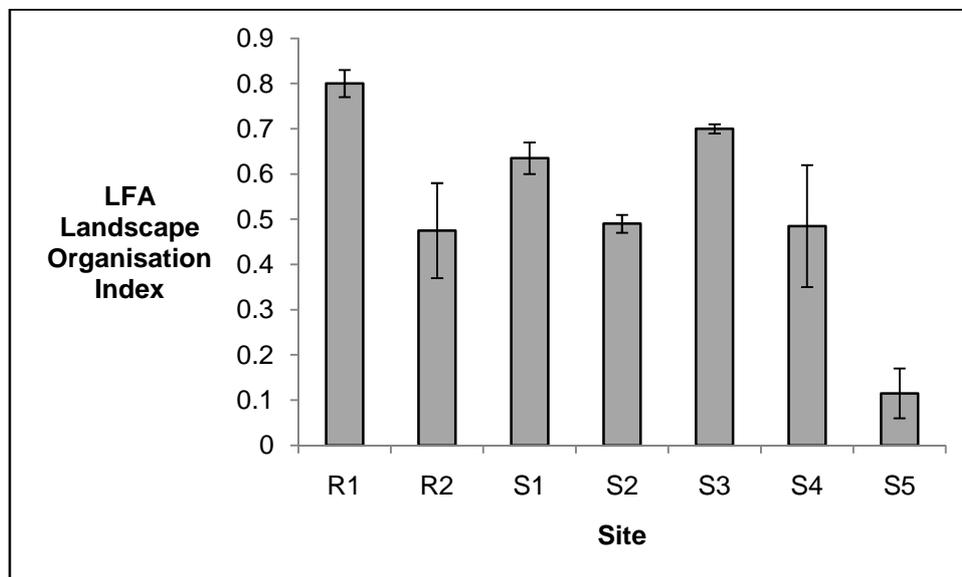

Figure 4.2: The mean (n = 2) LFA Landscape Organisation Index at all sites. Sites R1 and R2 are reference sites, sites S1, S2, S3 and S4 were rehabilitated in 2001, and site S5 was rehabilitated in 2008. Vertical bars represent standard error.

The fact that reference site R2 has a lower mean LOI than reference site R1 is a result of site R2 having fewer and smaller patches than site R1. This might be because of an inherent difference between the two different vegetation communities in which these sites occur, or due to overgrazing at site R2. However, both S1 and S3 received topsoil and had higher LOI's than sites S2 and S4 which did not. This indicates that topsoil spreading positively affects the cover of patches that capture and retain nutrients and water. Various authors have highlighted the benefits of topsoil spreading, including increased vegetation cover (Lubke & Avis, 1998; de Villiers, 2000; Holmes, 2001; Milton, 2001; Hälbich, 2003; Johnson & Tanner, 2003; Carrick & Kruger, 2007; Koch, 2007; Tanner, 2007), therefore it is not implausible that the LOI would be higher at sites where topsoil has been spread. Site S5 has the lowest LOI since it has only been rehabilitated recently and therefore the vegetation cover is low and few patches exist that can capture and retain water and nutrients.
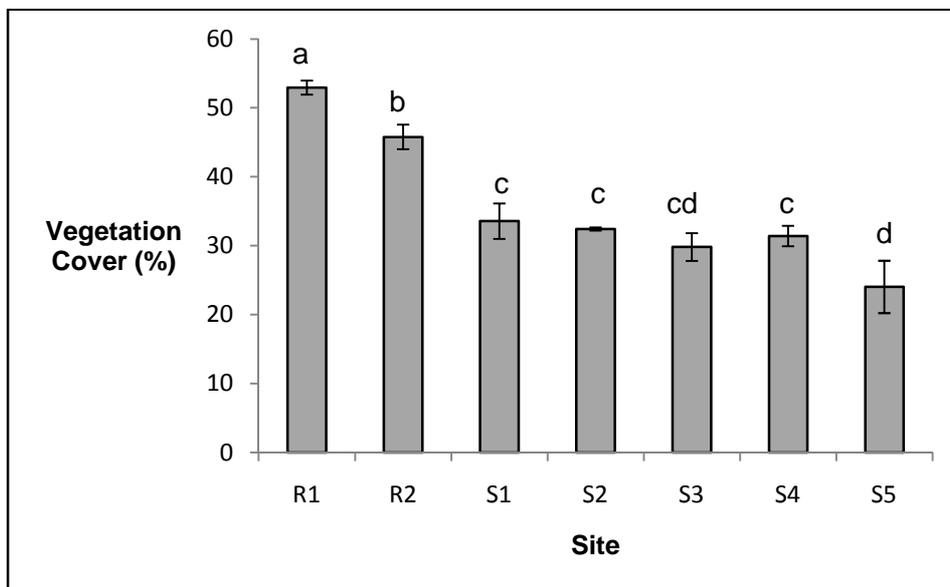
Figure 4.3: The mean vegetation cover at all sites during summer 2010 (n = 4). Sites R1 and R2 are reference sites, sites S1, S2, S3 and S4 were rehabilitated in 2001, and site S5 was rehabilitated in 2008. Vertical bars represent standard error. Different letters above bars indicate significant differences (p < 0.05).

The vegetation cover was significantly higher at reference site R1 than at reference site R2 (p < 0.05) and rehabilitated sites S1 – S5 (p < 0.01) (Figure 4.3). Reference site R2 also had significantly (p < 0.01) higher vegetation cover than rehabilitated sites S1 – S5. There were no significant differences between the experimental rehabilitated sites S1 – S4. This indicates that the topsoil addition resulted in greater LOI despite there being little difference in vegetation cover

83

between these sites. Site S5 had significantly lower vegetation cover than sites S1, S2 and S4 (p < 0.05), largely because it has had less than two years of vegetation growth.
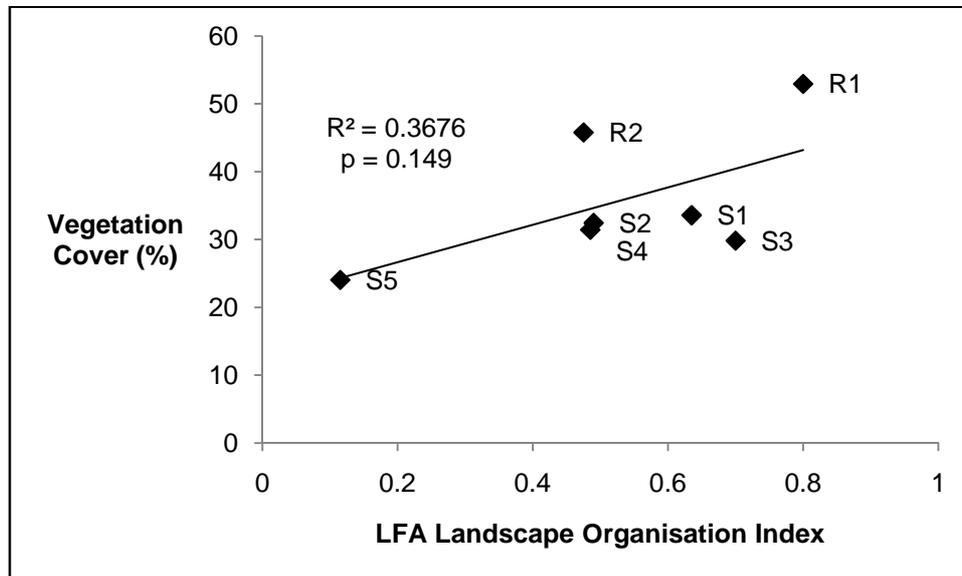
Figure 4.4: Scatter plot showing the correlation between Landscape Organisation Index and vegetation cover (n =7).

A positive trend was found between the LOI and vegetation cover (Figure 4.4), however, this was not significant. This was because a large proportion of the patches at sites S1 and S3 consisted of dead plants. Dead plants are considered to be patches where they accumulate resources, but are not included in the vegetation survey. As a result, these sites had high LOI's relative to their vegetation cover.

4.3.2. Stability

The Stability Index (SI) gives an indication of how resistant the soil is to erosion and of how capable the soil is reforming after disturbance (Tongway & Hindley, 2004b). The reference sites (R1 and R2) and sites rehabilitated in 2001 (S1 – S4) all had similar mean SI's (Figure 4.5). Site S5 (rehabilitated in 2008) had a lower mean SI, but did not differ significantly from the other sites.
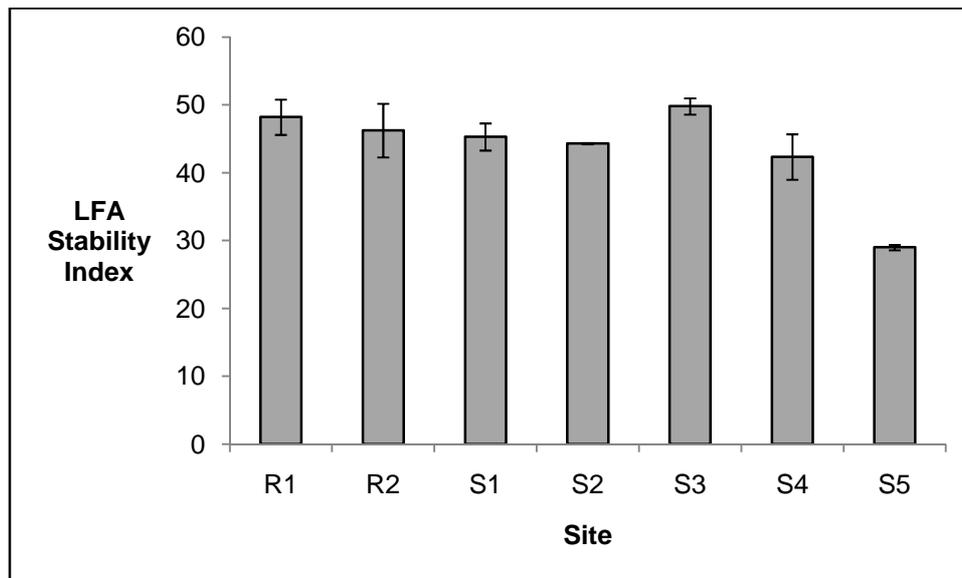
Figure 4.5: The mean (n = 2) LFA Stability Index at all sites. Sites R1 and R2 are reference sites, sites S1, S2, S3 and S4 were rehabilitated in 2001, and site S5 was rehabilitated in 2008. Vertical bars represent standard error.

The fact that sites rehabilitated in 2001 (S1 – S4) had SI's comparable to that of reference sites R1 and R2 is not unexpected, as nine years have elapsed since rehabilitation, which should be sufficient for these sites to develop sufficient vegetation and cryptogram cover to stabilise the soil. That rehabilitated sites S1 (topsoil only) and S3 (topsoil + translocation) had slightly higher SI's than sites S2 (seeding only) and S4 (seeding + translocation), with site S3 having the highest, suggests that topsoil replacement might positively affect SI, and that topsoil replacement and translocation might be the rehabilitation treatment that best stabilises the soil in the long-term. However, more replicates are necessary to determine whether this is truly the case. As expected, the site rehabilitated in 2008 (S5), which have not yet developed vegetation cover comparable to the older rehabilitated sites (S1 – S4), had a lower SI than the other sites.

The extremely high standard error of dust weight data (Figure 4.6) at sites R1, R2 and S1 reflects the large difference in the amount of dust captured by individual buckets at the same site. Each of these sites contained buckets which collected orders of magnitude more dust than the rest. In consequence, the results have probably been strongly influenced by the loss of data points (due to overturning of buckets). Therefore, this method of dust collection seems to have failed, and the data cannot be considered to be reliable.
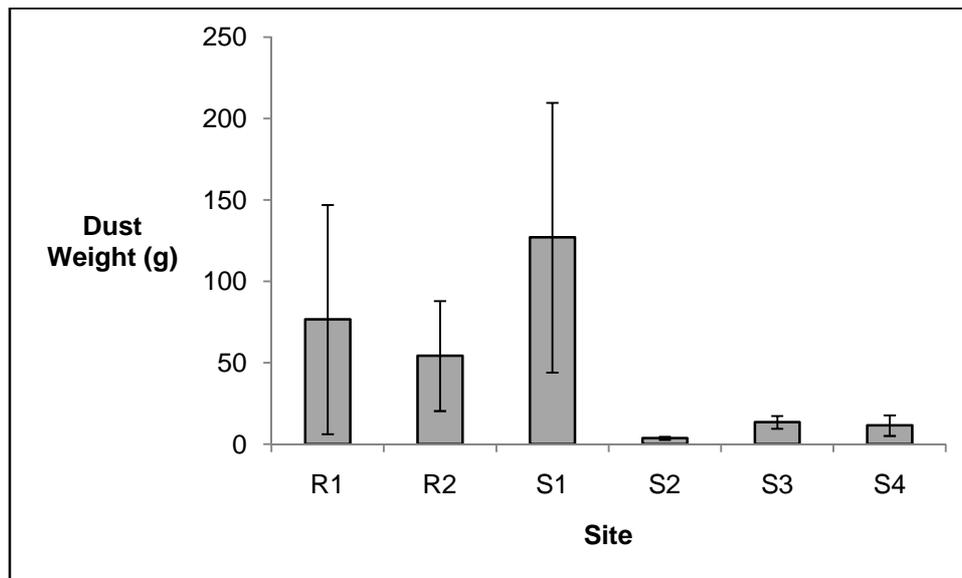
Figure 4.6: The mean weight of dust collected at all sites (due to some buckets overturning, n = 4 for R1, n = 6 for R2, n = 2 for S1, n = 3 for S2, n = 5 for S3 and n = 7 for S4). Sites R1 and R2 are reference sites and sites S1, S2, S3 and S4 were rehabilitated in 2001. Vertical bars represent standard error.

One would expect an opposite pattern in the dust collection data than in SI data, but this was not the case. The fact that more dust was captured (Figure 4.6) at reference sites R1 and R2 than at rehabilitated sites S2, S3 and S4 (although not significant) does not make sense, as the reference sites had significantly higher vegetation cover, and the soil surface at these sites are expected to be more stable.
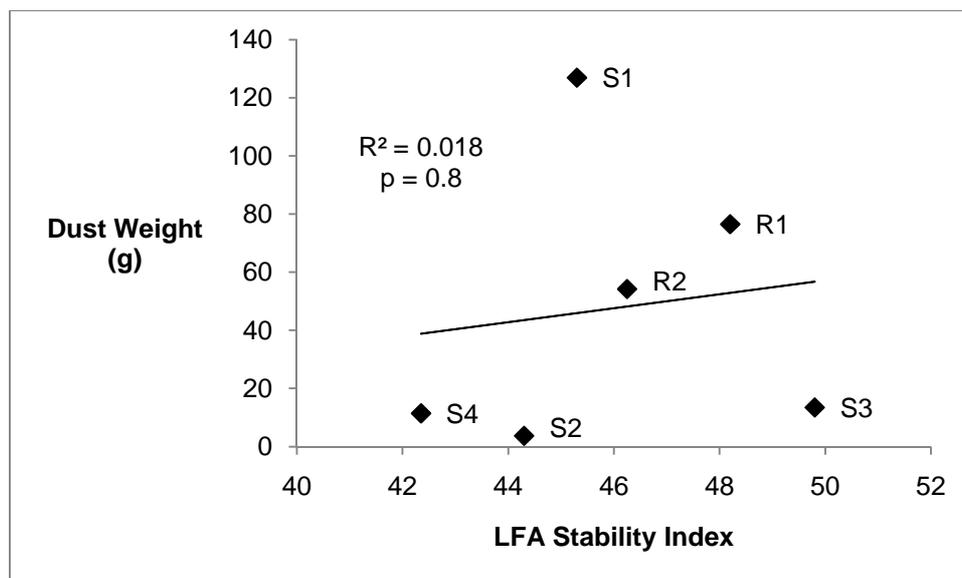
Figure 4.7: Scatter plot showing the correlation between LFA Stability Index and dust weight (n = 6).

Although there appears to be some correlation between the LFA SI and the weight of dust that collected (Figure 4.7), the results are probably not valid because of unreliable dust collection data. A negative correlation was expected between SI and dust weight.

4.3.3. Nutrient Cycling

The Nutrient Cycling Index (NCI) gives an indication of how efficiently organic matter is cycled within the system, preventing it from being lost (Tongway & Hindley, 2004b).
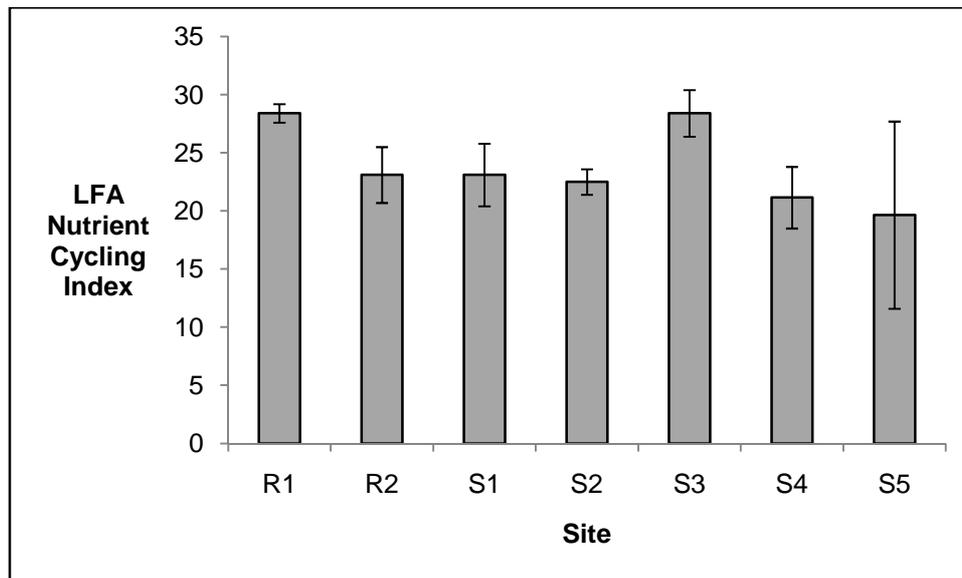
Figure 4.8: The mean (n = 2) LFA Nutrient Cycling Index at all sites. Sites R1 and R2 are reference sites, sites S1, S2, S3 and S4 were rehabilitated in 2001, and site S5 was rehabilitated in 2008. Vertical bars represent standard error.

Reference site R1 and rehabilitation site S3 had the highest mean NCI's (Figure 4.8). Reference site R2 and rehabilitation sites S1, S2, S4 and S5 had lower NCI's than the other sites and were similar to each other. There were no significant differences between sites.
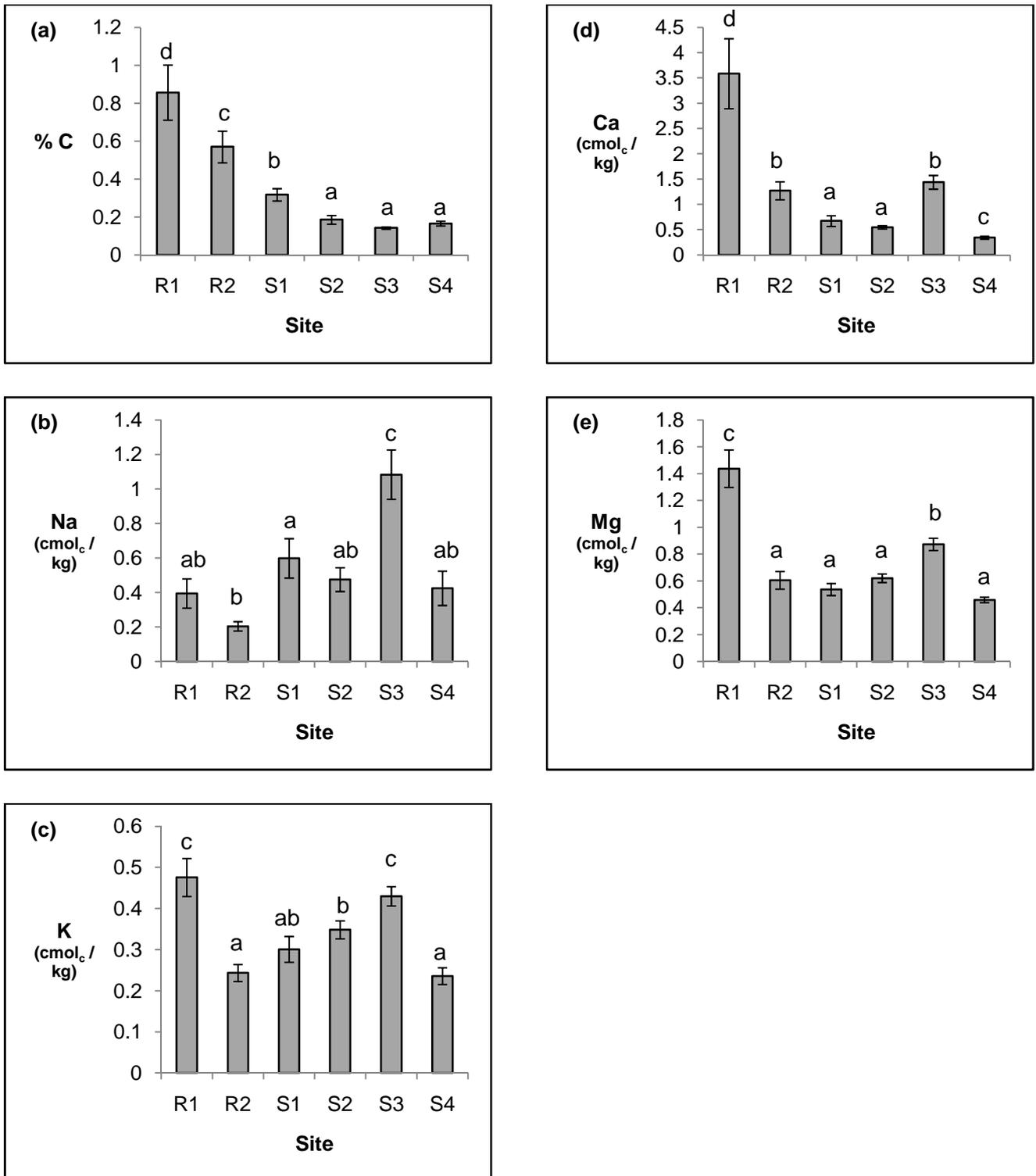
Figure 4.9: The mean (a) % organic C, (b) concentration Na, (c) concentration K, (d) concentration Ca and (e) concentration Mg at all sites. Sites R1 and R2 are reference sites and sites S1, S2, S3 and S4 were rehabilitated in 2001. Vertical bars represent standard error. Different letters above bars indicate significant differences ($p < 0.05$).

The reference sites (R1 & R2) had significantly higher mean % C (Figure 4.9a) than the rehabilitated sites S1 – S4 ($p < 0.01$). Reference site R1 also had significantly higher mean % C than site R2 ($p < 0.05$). Rehabilitation site S1 had significantly higher mean % C ($p < 0.01$) than rehabilitated sites S2 – S4, which did not differ significantly from each other.

The reference sites (R1 & R2) had lower mean Na concentrations than the rehabilitated sites (S1 – S4), but this was not significant for all sites (Figure 4.9b). Rehabilitated site S3 had a significantly higher mean Na concentration than all other sites ($p < 0.01$), while site S1 also had a significantly higher mean Na concentration than reference site R2 ($p < 0.01$). There were no significant differences between the mean Na concentrations of reference site R1 and rehabilitated sites S1, S2 and S4.

Reference site R1 had significantly higher mean Ca ($p < 0.01$) (Figure 4.9d) and Mg ($p < 0.01$) (Figure 4.9e) concentrations than all other sites. Rehabilitated site S3 had a significantly higher mean Mg concentration than reference site R2 ($p < 0.01$) and rehabilitated sites S1 ($p < 0.01$), S2 ($p < 0.05$) and S4 ($p < 0.01$) (Figure 4.9e), and also (together with reference site R2) had a significantly higher mean Ca concentration than rehabilitated sites S1, S2 and S4 ($p < 0.01$) (Figure 4.9d). Rehabilitated sites S1 and S2 also had significantly higher mean Ca concentrations than site S4 ($p < 0.01$) (Figure 4.9d), but these three rehabilitated sites and reference site R2 did not differ significantly in mean Mg concentration (figure 4.9e).

Reference site R1 had significantly higher mean K concentrations than reference site R2 and rehabilitated sites S1, S2 and S4 ($p < 0.01$) and rehabilitated site S3 also had significantly higher mean K concentrations than reference site R2 ($p < 0.01$) and rehabilitated sites S1 ($p < 0.01$), S2 ($p < 0.05$) and S4 ($p < 0.01$) (Figure 4.9c). Rehabilitated site S2 had the next highest mean K concentration, followed by S1 and then R2 and S4. However, rehabilitated site S2 only had a significantly higher mean K concentration than reference site R2 and rehabilitated site S4 ($p < 0.05$).
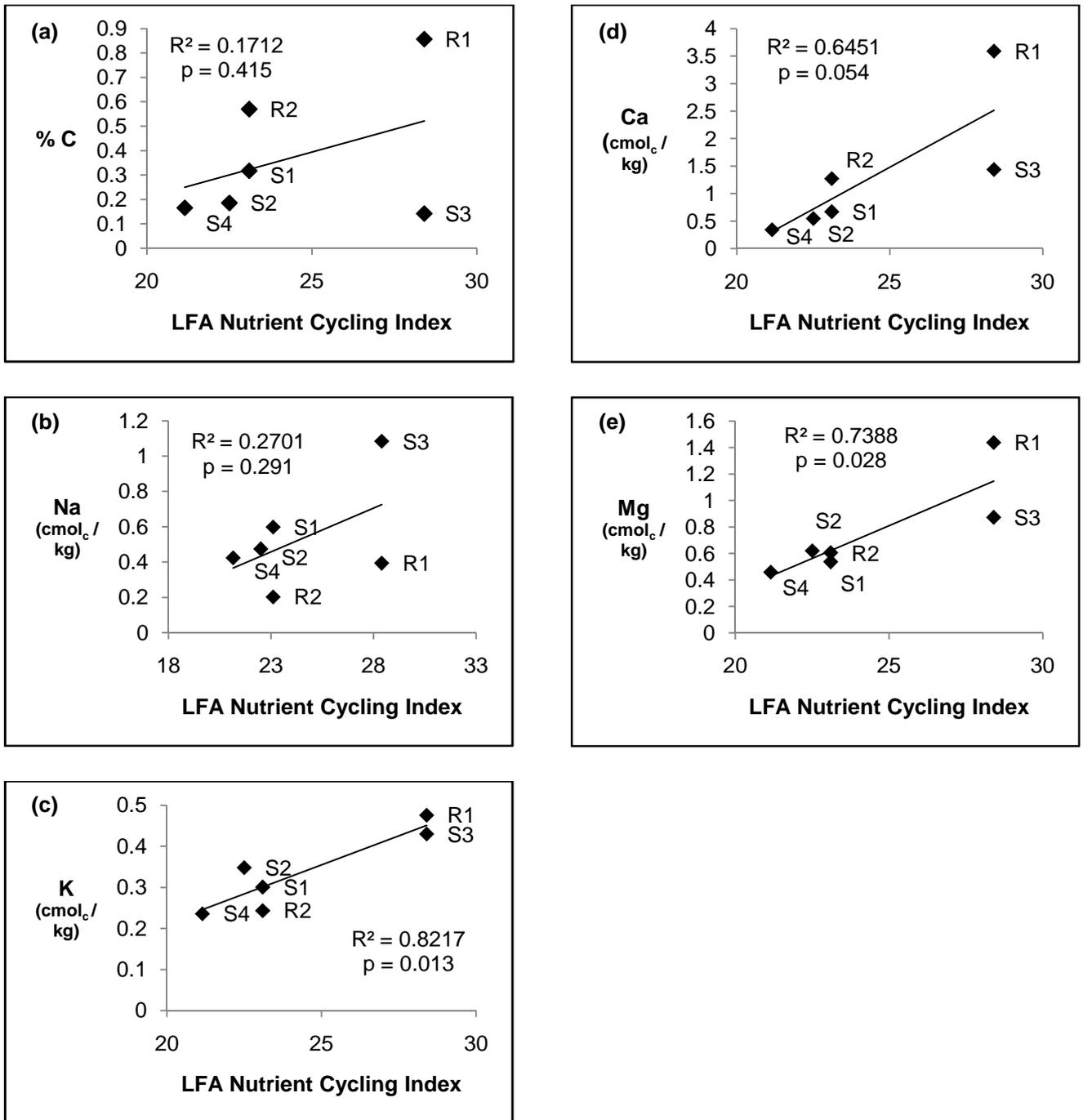
Figure 4.10: Scatter plots showing the correlation between LFA Nutrient Cycling Index and (a) % organic C, (b) concentration Na, (c) concentration K, (d) concentration Ca and (e) concentration Mg (n = 6 for all plots).

Moderately strong positive correlations were found between LFA NCI and mean % organic C (Figure 4.10a) and between NCI and mean Na concentration (figure 4.10b), but these were not significant. Strong positive correlations were found between NCI and mean K concentration (Figure 4.10c), between NCI and mean Ca concentration (Figure 4.10d) and between NCI and mean Mg concentration (Figure 4.10e). The correlations between NCI and K and NCI and Mg were significant ($p < 0.05$), but the correlation between NCI and Ca was not significant ($p = 0.054$).

4.3.4. Water Infiltration

The Water Infiltration Index (WII) gives an indication of how easily water infiltrates the soil, preventing it from being lost to the system through runoff (Tongway & Hindley, 2004b).
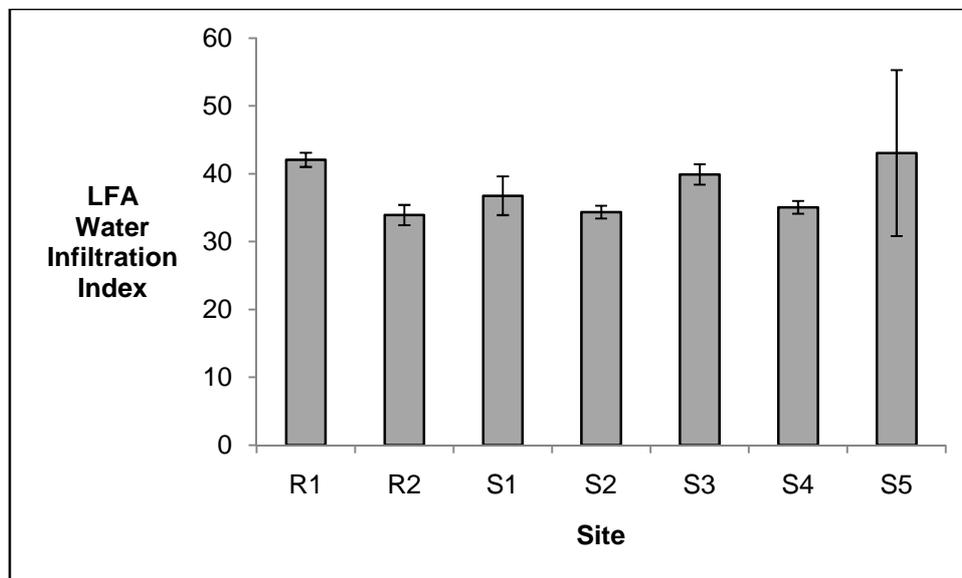
Figure 4.11: The mean (n = 2) LFA Water Infiltration Index at all sites. Sites R1 and R2 are reference sites, sites S1, S2, S3 and S4 were rehabilitated in 2001, and site S5 was rehabilitated in 2008. Vertical bars represent standard error.

Site S5 (rehabilitated in 2008) had the highest mean WII, followed by reference site R1 (Figure 4.11). Sites S1 and S3 (rehabilitated in 2001) had slightly lower WII's, while sites S2 and S4 (also rehabilitated in 2001) had still lower WII's and reference site R2 the lowest. None of these differences were statistically significant.
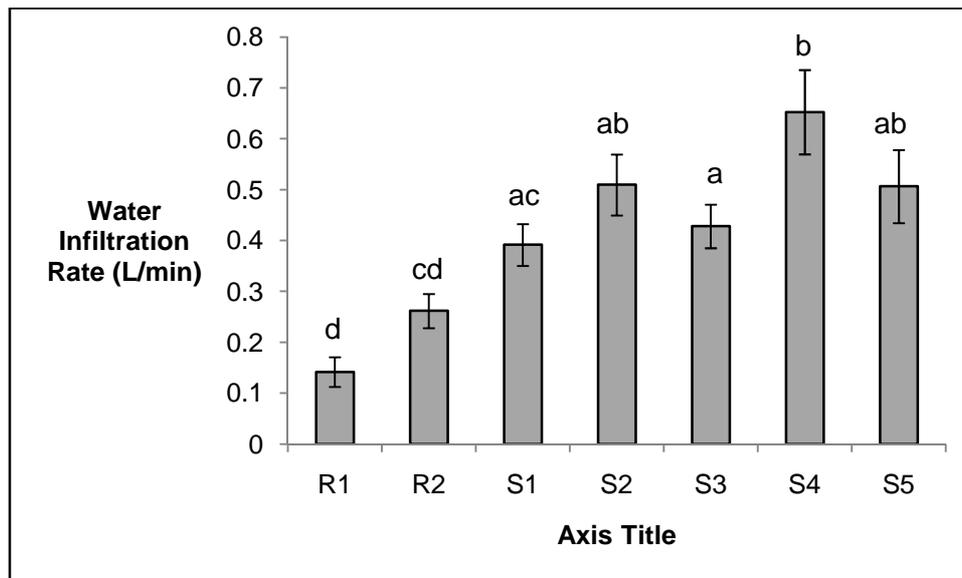
Figure 4.12: The mean (n = 18) measured water infiltration rate at all sites. Sites R1 and R2 are reference sites, sites S1, S2, S3 and S4 were rehabilitated in 2001, and site S5 was rehabilitated in 2008. Vertical bars represent standard error. Different letters above bars indicate significant differences (p < 0.05).

The mean measured water infiltration rate did not differ significantly between reference sites R1 and R2 (Figure 4.12). The reference sites had significantly lower mean infiltration rates than rehabilitation sites S1 – S5 (p < 0.05), except for site R2, which did not differ significantly from site S1. Site S4 had the highest mean infiltration rate, but only significantly higher than rehabilitation sites S1 and S3 (p < 0.01). Sites S2 and S5 also had higher mean infiltration rates than sites S1 and S3, but these differences were not significant. These results indicate that topsoil replacement causes a decline in water infiltration rate with age since rehabilitation as hydrophobicity builds up.
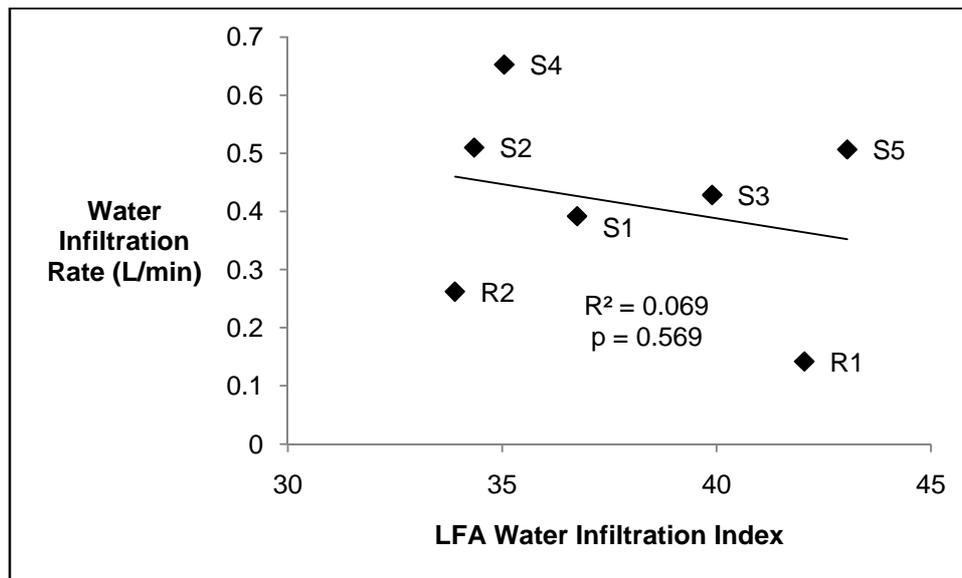
Figure 4.13: Scatter plot showing the correlation between LFA Water Infiltration Index and measured water infiltration rate (n = 7).

A weak, non-significant, negative correlation was found between the LFA WII and measured water infiltration rate (figure 4.13).

4.4. Discussion

The applicability of the original version of the LFA method (Tongway & Hindley, 1995) in Namaqualand was evaluated by Petersen *et al.* (2004) and it was concluded that the LFA method is unsuitable in this environment. However, LFA results were only compared with, and not correlated with, results of conventional scientific methods. This study is the first attempt to test the current version of the LFA method (Tongway & Hindley, 2004b) in Namaqualand. The results suggest that it can be used to rapidly assess soil stability and nutrient cycling, but not water infiltration at the Namakwa Sands mine. This highlights the importance of testing this method before it is used in a new environment.

Landscape Organisation Index

The purpose of the LOI is to give an indication of the cover (the number and size) of nutrient- and water capturing patches in the landscape and, by implication, also vegetation cover (Tongway & Hindley, 2004b). Theoretically, it is expected that the LOI would exhibit a sigmoidal growth curve when a rehabilitated site is monitored over time, and that it will become more similar to the LOI of

reference sites (Tongway & Hindley, 2004b). A decrease in LOI implies a decrease in the ability of the system to capture and retain nutrients and water (Tongway & Hindley, 2004b). Therefore, it should be coupled to a decrease in SI, NCI or WII that would explain this decrease in LOI. Although this method is useful in being more rapid than traditional vegetation sampling methods, Tongway & Hindley (2004b) cautions that the LFA should be used as complement to- and not replacement for those traditional methods.

As expected, a positive correlation was found between LOI and vegetation cover, however, this was not significant. As patches are not limited to vegetation, and vegetation does not necessarily constitute a patch, LOI will theoretically not correlate fully with vegetation cover. For example, patches can consist of rocks or plant debris on soil with a rough surface, where nutrients and water accumulate (Tongway & Hindley, 2004b). In contrast, annuals often grow between vegetation patches, in areas where nutrients and water are leaked (personal observation). However, it is still expected that LOI should show a significant positive correlation with vegetation cover. This suggests that more replicates of the LFA method are necessary to accurately estimate the cover of patches at a site.

Stability Index

The purpose of the Stability Index is to give indication of ability of soil to resist erosion. A low SI indicates vulnerability to erosion, and therefore loss of favourable substrate on which plants can grow. The SI at rehabilitated sites is also expected to exhibit sigmoidal growth as rehabilitated sites become more similar to reference sites (Tongway & Hindley, 2004b). When monitored over time, a decrease in- or consistently low SI would signify a need to determine the specific causes of this at the site, and active intervention to ameliorate these causes.

While testing the validity of the LFA method, Tongway & Hindley (2004b) found a significant positive correlation between SI and aggregate stability on minesites. When correlating SI with dust collection measurements a negative correlation is expected, as higher mobility of soil particles would be the result of lower resistance to erosion. When SI was correlated with dust collection measurements to test its efficacy at Namakwa Sands, a slight, non-significant, positive correlation was found. Whether this is due to issues with the dust collection method or the LFA method, or because of a lack of replication in either cannot be established, but it is believed to be due to the lost data points in the dust collection data, as no pattern was observed in the data. The outcome of this test is therefore inconclusive. However, based on the fact that the reference sites and

94

experimental sites rehabilitated in 2001 had similar SI's, while the SI of the site rehabilitated in 2008 was lower (although not significantly so), as predicted by theory, it is believed that the SI will be an accurate predictor of soil stability provided that enough replicates of the LFA method are conducted. Two replicates per site are not sufficient to accurately estimate soil stability, but more replicates probably would have resulted in significant differences in SI between site S5 and all other sites.

Nutrient Cycling Index

The Nutrient Cycling Index gives an indication of how efficiently organic matter is cycled within the system, preventing it from being lost. A low NCI indicates that little organic matter is being cycled back into the soil. When monitored over time, one can expect an increasing trend in NCI as a rehabilitated site develops, as more patches, which can intercept and retain nutrients that come from interpatches and external sources such as fog (Ludwig & Tongway, 1995; Aguiar & Sala, 1999; Valentin *et al.*, 1999; Maestre & Cortina, 2004; Maestre *et al.*, 2006; Grant *et al.*, 2007), develop and existing patches increase in size. Over time these nutrients accumulate, leading to higher concentrations in the soil (Ludwig & Tongway, 1995; Stock *et* al., 1999; Burke, 2001). The NCI is also expected to exhibit sigmoidal growth as rehabilitated sites become more similar to reference sites (Tongway & Hindley, 2004b). A consistently low NCI or decreasing trend in NCI would trigger an investigation into the possible causes thereof, so that the necessary corrective action can be taken.

Tongway & Hindley (2004b) found significant positive correlations between NCI and total and organic % C as well as NCI and total and mineralisable % N. In this study positive correlations were found between NCI and all measured nutrients. These correlations were not significant between NCI and mean % organic C and between NCI and mean Na concentration, but were significant between NCI and mean K concentration and NCI and mean Mg concentration, while marginally non-significant between NCI and mean Ca concentration. The lack of significance in the correlations between NCI and mean % organic C and between NCI and mean Na concentration, as well as between NCI and mean Ca concentration can possibly be attributed to the low number of replications (two) of the LFA method. However, contrary to the findings of Prinsloo (2005), the Na concentration at rehabilitated sites, which is increased by treatment of ore with sea water, have not yet reduced to near-natural levels at the time of sampling (between four and five years after rehabilitation). This could explain the lack of significance in the correlation between NCI and mean Na concentration. Due to the fact that the NCI correlates well with mean K, Mg and to a lesser extent Ca concentrations, it is believed that the NCI would be an accurate

indicator of nutrient cycling at Namakwa Sands, provided that more than two replications are performed at each site.

Water Infiltration Index

The Water Infiltration Index gives an indication of the proportion of water that can infiltrate the soil as opposed to water that is lost through runoff. Water infiltration is often low after mining and subsequent rehabilitation, due to compaction, loss of soil structure and other factors (Loch & Orange, 1997; Holmes, 2001; Grant, 2006; Koch, 2007). The WII is expected to show sigmoidal growth when rehabilitated sites are monitored over time and the WII at rehabilitated sites are expected to become more similar to that of reference sites (Tongway & Hindley, 2004b). Again, a consistently low- or decreasing WII would necessitate further investigation into the cause of this, and some sort of soil amelioration to improve water infiltration and reduce runoff.

When the WII was correlated with measured water infiltration rate to test its validity at Namakwa Sands, a weak, non-significant, negative correlation was found. This is unexpected, as Tongway & Hindley found a significant positive correlation between WII and measured water infiltration. This is thought to be due to assumptions made in developing the LFA method, which do not hold true for this particular (Namaqualand) environment. The first assumption is that higher vegetation cover causes higher water infiltration rate. In a study of the soils at Namakwa Sands, Prinsloo (2005) found that vegetation clumps made the soil hydrophobic. This is thought to be related to the increased organic matter underneath the plant canopy (Prinsloo, 2005). Hydrophobicity is caused by a range of organic materials contained in particulate organic matter. These materials can diffuse out and coat sand grains, making the soil hydrophobic (Franco *et al.*, 1995). The second assumption is that cryptogram cover does not affect water infiltration rate. In reality, it conspicuously decreases the water infiltration rate at Namakwa Sands (own observation). This has also been observed by other researchers in different study areas (Eldridge, 2000; Maestre *et al.*, 2002; Belnap, 2006; Malam Issa, 2009). However, cryptogram cover can also increase water infiltration, or have no effect (Belnap, 2006; Malam Issa, 2009), depending on the methods used, biological composition and structure of the crust, soil characteristics and rainfall characteristics (Belnap, 2006; Malam Issa, 2009). Therefore, this assumption is only valid in certain circumstances. Also, crust brokenness is not taken into account in the LFA WII calculations, although it would affect water infiltration rate where a crust is present. As the WII was found to be inappropriate for use at Namakwa Sands, it was not possible to determine whether two replicates per site are sufficient. However, this is thought to be unlikely. If it was sufficient, the negative correlation between WII and measured water infiltration rate would probably have been significant.

96

Site similarity

Dust Weight

Due to the unreliable dust collection data the results of the analysis of site differences could not be accepted to be accurate and therefore it is not discussed further.

Soil Nutrients

The fact that reference site R2 had significantly lower mean % organic C and mean concentrations of K, Ca and Mg than site R1, might be attributed to the fact that it had significantly lower vegetation cover than site R1 and very little litter cover compared to all other sites. This is most likely due to occasional heavy grazing by sheep, as the site is located on a sheep farm. The concentration of K, Na and Mg is marine-influenced (Lanz, 2003; Francis, 2008), therefore the lower concentration of nutrients at site R2 may also be due to increased distance from the ocean compared to reference site R1 and rehabilitated sites S1 – S4.

The low mean % organic C in rehabilitated sites (S1 – S4) compared to reference sites (R1 & R2) is not surprising, as soil amelioration after rehabilitation is expected to be slow (Chambers *et* al., 1994; Lubke *et al.*, 1996; Ruiz-Jaén & Aide, 2005), and carbon recovery would be especially slow in an environment such as Namaqualand, where revegetation is hampered by an arid and windy climate, as well as saline and nutrient-poor soils (Lubke & Avis, 1998; Milton, 2001; Hälbich, 2003; Carrick & Kruger, 2007; Botha *et al.*, 2008). Studies on rehabilitation of abandoned agricultural fields also found limited accumulation of organic matter and total carbon in the soil (Baer *et al.*, 2002; Foster *et al.*, 2007), indicating that it would take decades to return to natural levels (Foster *et al.*, 2007). Blood (2006) also found fewer annuals, a source of organic carbon, in rehabilitated sites than reference sites. During a study on the soil at Namakwa Sands, Prinsloo (2005) also found significantly lower organic carbon in rehabilitated sites compared to reference sites.

It is clear that, when Blood (2006) took soil samples in 2004 (three years after rehabilitation), there were still higher than normal Na levels in the soil at rehabilitated sites. This is because tailings are treated with saline sea water during the separation process and possibly also because stockpiling increases the salinity of topsoil (Mahood, 2003). The Na in rehabilitated sites is expected to leach out to near-natural concentrations within 25 months after rehabilitation (Prinsloo, 2005), so it is surprising that rehabilitated sites (S1 – S4) still had higher Na concentrations than reference sites (R1 & R2) three years after rehabilitation, although this difference was only significant for site S3.

As silt and clay particles are removed during the mineral separation process, soils in rehabilitated areas have lower nutrient status and cation exchange capacity (Prinsloo, 2005). Topsoil contains a large portion of the nutrients in the soil, therefore topsoil replacement contributes to the nutrient status of rehabilitated sites (Lubke & Avis, 1998; Milton, 2001; Prinsloo, 2005; Carrick & Kruger, 2007; Grant *et al.*, 2007; Koch, 2007). This is also evident in this study – in general rehabilitated sites S1 (topsoil only) and S3 (topsoil + translocation) had higher nutrient concentrations than S2 (seeding only) and S4 (seeding + translocation). Site S3 had significantly higher concentrations of Na, K, Ca and Mg than rehabilitated sites S1, S2 and S4, which suggests that topsoil replacement and translocation is the rehabilitation treatment that best returns nutrients to rehabilitated sites. While the concentrations of K and Mg returned to near-natural levels at all rehabilitated sites, the concentration of Ca at rehabilitated sites S1, S2 and S4 was still significantly lower than at both reference sites (R1 & R2). The concentration of Ca and other nutrients have been inferred to affect the outcome of competition between different species of plants in the eastern part of the Succulent Karoo (Yeaton & Esler, 1990). This makes sense, as the ability of plants to extract water from the soil can be negatively affected by a high concentration of Na and Mg, relative to Ca, so that plant species which have better developed mechanisms to deal with this obstacle will outcompete plants with weaker developed or no mechanisms to do so (Hagenmeyer, 1997; Prinsloo, 2005). Therefore, the low concentration of Ca in rehabilitated sites might affect the vegetation community that develops. This has important implications for aspects such as landscape-scale diversity and grazing capacity.

Water Infiltration Rate

Water infiltration is affected by soil texture, structure, salinity, crust, vegetation cover and root mass, and soil hydrophobicity (Ellis, 1988; Van den Berg & Kellner, 2005; Prinsloo, 2005; Medinski *et al.*, 2009). The main reasons why rehabilitated sites had higher water infiltration rates than reference sites are probably related to the lack of clay and silt particles and lower vegetation cover (and therefore root mass) at rehabilitated sites. The clay and silt fractions, which are removed during processing (Prinsloo, 2005), cannot be expected to return in the near future. The water infiltration rate on rehabilitated sites is therefore unlikely to become similar to that at reference sites at Namakwa Sands. It is important to keep in mind that an infiltration rate that is similar to that of reference sites does not imply similar water holding capacity (Ata Rezaei *et al.*, 2006a). The loss of clay particles at rehabilitated sites and the destruction of the dorbank layer will result in lower water holding capacity in the soil and therefore less water available to plants (Prinsloo, 2005). This will surely affect vegetation recovery on rehabilitated sites.

Site S4 had significantly higher water infiltration rate than S1 and S3, while site S2 also had a slightly higher water infiltration rate than these sites. This suggests that topsoil replacement might cause rehabilitated sites to have water infiltration rates more similar to that of reference sites than sites which did not receive topsoil. This is supported by the findings of Prinsloo (2005) that topsoil replacement returns hydrophobic properties to rehabilitated sites. Also, silt and clay particles, which lower infiltration rate, are still present in the topsoil. Mahood (2003) also found that stored topsoil, as was placed on site S1 and S3, had higher salinity. This could result in the formation of a chemical crust, which would reduce water infiltration (Ellis, 1988). This would also explain why site S5 had similar water infiltration to site S2, despite the fact that the former was only rehabilitated in 2008, while the latter was rehabilitated in 2001.

Conclusions & Recommendations

The test for efficacy and accuracy of the SI was inconclusive, due to problems with dust collection which reduced sample size and led to total loss of data at one site. However, based on the differences in SI between sites which are consistent with predictions, it is believed that the results of the SI will be accurate if enough replications are performed at each site. The Nutrient Cycling Index showed positive correlations with mean % organic C and mean concentrations of Na, Ca, K and Mg, although this was only significant for correlations with K and Mg and marginally non-significant for Ca. This indicates that the NCI is an accurate index for nutrient cycling at Namakwa Sands, but that more than two replicates are needed to make the results more accurate. The WII showed a non-significant, negative correlation with measured water infiltration rate data. Inappropriate assumptions in the WII calculations were identified and may explain the lack of a positive correlation. However, as discussed above, the water infiltration rates at rehabilitated sites are unlikely to become similar to those at the reference sites in the near future, and a more relevant attribute to investigate would be the water holding capacity of the soil. Therefore, it is recommended that the WII results are disregarded if the LFA method is applied at Namakwa Sands. Two replicates per site were also found to be insufficient to deliver accurate results for the LOI.

It is recommended that annual monitoring of landscape functioning is conducted, using the LFA method, as it can supply very useful information on the status and development of ecosystem functioning in rehabilitated sites over time. It would complement vegetation monitoring well, as it can act as an early detection mechanism for degradation or retrogression, and provide possible explanations for lack of development. The number of replicates needed to supply statistically rigorous data should be determined through experimentation.

4.5. References

Aguiar, M.R. & Sala, O.E. 1999. Patch structure, dynamics and implications for the functioning of arid ecosystems. Trends in Ecology & Evolution **14**:273–277.

Ata Rezaei, S., Arzani, H. & Tongway, D.J. 2006. Assessing rangeland capability in Iran using landscape function indices based on soil surface attributes. Journal of Arid Environments 65:460–473.

Baer, S.G., Kitchen, D.J., Blair, J.M. & Rice, C.W. 2002. Changes in ecosystem structure and function along a chronosequence of restored grasslands. Ecological Applications **12**:1688–1701.

Belnap, J. 2006. The potential roles of biological soil crusts in dryland hydrological cycles. Hydrological Processes **20**:3159–3178.

Botha, M.S., Carrick, P.J. & Allsopp, N. 2008. Capturing lessons from land-users to aid the development of ecological restoration guidelines for lowland Namaqualand. Biological Conservation **141**:885–895.

Blood, J.R. 2006. Monitoring rehabilitation success on Namakwa Sands heavy minerals mining operation, Namaqualand, South Africa. MSc thesis. Stellenbosch University, Stellenbosch, South Africa.

Burke, A. 2001. Determining landscape function and ecosystem dynamics: contribution to ecological restoration in the southern Namib Desert. Ambio **30**:29–36.

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.

Cereceda, P., Larrain, H., Osses, P., Farìas, M. & Egaña, I. 2008. The spatial and temporal variability in fog and its relation to fog oases in the Atacama Desert, Chile. Atmospheric Research **87**:312–323.

Chambers, J.C., Brown, R.W. & Williams, B.D. 1994. An evaluation of reclamation success on Idaho's phosphate mines. Restoration Ecology **2**:4–16.

Cooke, J.A. & Johnson, M.S. 2002. Ecological restoration of land with particular reference to the mining of metals and industrial minerals: A review of theory and practice. Environmental Review. **10**:41–71.

Council for Scientific and Industrial Research (CSIR). 2011. Exxaro Namakwa Sands weather monitoring programme biannual progress report: Spring 2010 and Summer 2010/2011. Unpublished report. CSIR, Stellenbosch, South Africa.

Cousins, B., Hoffman, M.T., Allsopp, N. & Rhode, R.F. A synthesis of sociological and biological perspectives on sustainable land use in Namaqualand. Journal of Arid Environments **70**:834–846.

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.

Cummings, J., Reid, N., Davies, I. & Grant, C. 2005. Adaptive management of sand-mined areas for biological conservation. Journal of Applied Ecology **42**:160–170.

Department of Industry, Tourism and Resources (DITR). 2007. Leading practice sustainable development program for the mining industry – biodiversity management. DTIR, Canberra, Australia.

Desmet, P.G. & Cowling, R.M. 1999a. Biodiversity, habitat and range-size aspects of a flora from a winter-rainfall desert in north-western Namaqualand, South Africa. Plant Ecology **142**:23–33.

Desmet, P.G. & Cowling, R.M. 1999b. The climate of the Karoo – a functional approach. Pages 3–16 in: Dean, W.R.J. & Milton, S.J. (eds.) The Karoo: Ecological patterns and processes. Cambridge University Press, Cambridge, UK.

Desmet, P.G. 2007. Namaqualand – A brief overview of the physical and floristic environment. Journal of Arid Environments **70**:570–587.

De Villiers, A.J., Van Rooyen, M.W., Theron, G.K. & Van Rooyen, N. 1999. Vegetation diversity of the Brand-se-Baai coastal dune area, west coast, South Africa: A pre-mining benchmark survey for rehabilitation. Land Degradation & Development **10**:207–224.

De Villiers, A.J. 2000. Seed bank dynamics of the Strandveld Succulent Karoo. Ph.D. thesis, University of Pretoria, Pretoria.

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.

Eldridge, D.J., Zaady, E. & Shachak, M. 2000. Infiltration through three contrasting biological soil crusts in patterned landscapes in the Negev, Israel. Catena **40**:323–336.

Ellis, F. 1988. Die gronde van die Karoo. Ph.D. thesis, Stellenbosch University, Stellenbosch, South Africa.

Esler, K.J. & Rundel, P.W. 1999. Phenological and growth form divergence in convergent desert ecosystems: a Succelent Karoo and Mojave desert comparison. Plant Ecology **142**:97–104.

Foster, B.L., Murphy, C.A., Keller, K.R., Aschenbach, T.A., Questad, E.J. & Kindscher, K. 2007. Restoration of Prairy community structure and ecosystem function in an abandoned hayfield: a sowing experiment. Restoration Ecology **15**:652–661.

Francis, M.L., Fey, M.V., Prinsloo, H.P., Ellis, F., Mills, A.J. & Medinski, T.V. 2007. Soils of Namaqualand: Compensations for aridity. Journal of Arid Environments **70**:588–603.

Francis, M.L. 2008. Soil formation on the Namaqualand coastal plain. Ph.D. thesis, Stellenbosch University, Stellenbosch, South Africa.

Franco, C.M.M., Tate, M.E. & Oades, J.M. 1995. Studies on non-wetting sands I. The role of intrinsic particular organic matter in the development of water-repellency in non-wetting sands. Australian Journal of Soil Research **33**:253–263.

Golder Associates. 2008. Environmental management programme for Namakwa Sands. Unpublished report nr. 10417-5659-1-E. Golder Associates, Johannesburg, South Africa.

Grant, C.D. 2006. State-and-transition successional model for bauxite mining rehabilitation in the Jarrah forest of Western Australia. Restoration Ecology **14**:28–37.

Grant, C.D., Ward, S.C. & Morley, S.C. 2007. Return of ecosystem function to restored Bauxite mines in Western Australia. Restoration Ecology **15**:S94–S103.

Hagenmeyer, J. 1997. Salt. Pages 173 – 206. In: Prasad, M.N.V. (ed.) Plant Ecophysiology. John Wiley & Sons, New York, USA.

Hälbich, T.J.F. 2003. Mine rehabilitation in the arid Succulent Karoo vegetation zone on the South African west coast, Namakwa Sands – case study. Heavy Minerals 2003. South African Institute of Mining and Metallurgy, Johannesburg, South Africa.

Herrick, J.E., Schuman, G.E. & Rango, A. 2006. Monitoring ecological processes for restoration projects. Journal of Nature Conservation **14**:161–171.

Hobbs, R.J. & Norton, D.A. 1996. Towards a conceptual framework for restoration ecology. Restoration Ecology **4**:93–110.

Hobbs, R.J. & Harris, J.A. 2001. Restoration ecology: Restoring the earth's ecosystems in the new millennium. Restoration Ecology **9**:239–246.

Holm, A.McR., Loneragan, W.A. & Adams, M.A. 2002. Do variations on a model of landscape function assist in interpreting the growth response of vegetation to rainfall in arid environments? Journal of Arid Environments **50**:23–52.

Holmes, P.M. 2001. Shrubland restoration following woody alien invasion and mining: effects of topsoil depth, seed source, and fertilizer addition. Restoration Ecology **9**:71–84.

International Council for Mining and Metals (ICMM). 2006. Good practice guidance for mining and biodiversity. International Council for Mining and Metals, London, UK.

Johnson, M.S. & Tanner, P.D. 2003. Mine Site Rehabilitation and Ecosystem Reconstruction for Biodiversity Gain. IUCN/ICMM Workshop, Gland.

Koch, J.M. 2007. Alcoa's mining and restoration process in south western Australia. Restoration Ecology **15**:S11–S16.

Lanz, J. 2003. Specialist study on the impact of the Namakwa Sands mining operation on soil conditions with emphasis on the effect on re-vegetation. Unpublished Report. Crowther Campbell, Cape Town.

Loch, R.J. & Orange, D.N. 1997. Changes in some properties of topsoil at Tarong Coal-Meandu Mine coalmine with time since rehabilitation. Astralian Journal of Soil Research **35**:777–784.

Lubke, R.A. & Avis, A.M. 1998. A review of the concepts and application of rehabilitation following heavy mineral dune mining. Marine Pollution Bulletin **37**:546–557.

Lubke, R.A., Avis, A.M. & Moll, J.B. 1996. Post-mining rehabilitation of coastal sand dunes in Zululand, South Africa. Landscape and Urban Planning **34**:335–345.

Ludwig, J.A. & Tongway, D.J. 1995. Spatial organisation of landscapes and its function in semi-arid woodlands, Australia. Landscape Ecology **10**:51–63.

Ludwig, J.A. & Tongway, D.J. 1997. The conservation of water and nutrients within landscapes. In: Ludwig, J.A., Tongway, D.J., Freudenberger, D., Noble, J. & Hodgkinson, K. (eds.) Landscape ecology: Function and management. CSIRO, Collingwood, Australia.

MacKellar, N.C., Hewitson, B.C. & Tadross, M.A. 2007. Namaqualand's climate: Recent historical changes and future scenarios. Journal of Arid Environments **70**:604–614.

Maestre, F.T., Huesca, M., Zaady, E., Bautista, S. & Cortina, J. 2002. Infiltration, penetration resistance, and microphytic crust composition in contrasted microsites within a Mediterranean semi-arid steppe. Soil Biology & Biochemistry **34**:895–898.

Maestre, F.T. & Cortina, J. 2004. Insights into ecosystem composition and function in a sequence of degraded semiarid Steppes. Restoration Ecology **12**:494–502.

Maestre, F.T., Cortina, J. & Vallejo, R. 2006. Are ecosystem function, structure and functional status related to restoration success? A test from semiarid Mediterranean Steppes. Restoration Ecology **14**:258–266.

Mahood, K. 2003. Strip-mining rehabilitation by translocation in the arid coastal Namaqualand, South Africa. MSc thesis. Stellenbosch University, Stellenbosch, South Africa.

Mallam Issa, O., Défarge, C., Trichet, J., Valentin, C. & Rajot, J-L. 2009. Microbiotic soil crusts in the Sahel of western Niger and their influences on soil porosity and water dynamics. Catena **77**:48–55.

Medinski, T.V., Mills, A.J. & Fey, M.V. 2009. Infiltrability in sois from south-western Africa: effects of texture, electrical conductivity and exchangeable sodium percentage. South African Journal of Plant and Soil **26**:157–163.

Milton, S.J., Yeaton, R.I., Dean W.R.J. & Vlok, J.H.J. 1997. Succulent Karoo. Pages 131–166. In: Cowling, R.M., Richardson, D.M. & Pierce, S.M. (eds). The vegetation of southern Africa. Cambridge University Press, Cambridge, UK.

Milton, S.J. 2001. Rethinking ecological rehabilitation in arid and winter rainfall regions of southern Africa. South African Journal of Science **97**:47-48.

Mucina, L., Jürgens, N., le Roux, A., Rutherford, M.C., Schmiedel, U., Esler, K.J., Powrie, L.W., Desmet, P.G. & Milton, S.J. 2006. Succulent Karoo Biome. Pages 220 – 299 in: Mucina, L. & Rutherford, M.C. (eds.) The Vegetation of South Africa, Lesotho and Swaziland. South African National Biodiversity Institute, Pretoria, South Africa.

Namakwa Sands. 2001. Draft revised environmental management programme. Unpublished report. Namakwa Sands, Lutzville, South Africa.

Ntshotsho, P., Reyers, B. & Esler, K.J. 2010. Assessing the evidence base for restoration in South Africa. Restoration Ecology (available early online, doi: 10.1111/j.1526-100X.2010.00753.x).

Palmer, A.R., Killer, F.J., Avis, A.M. & Tongway, D.J. 2001. Defining function in rangelands of the Peddie district, Eastern Cape, using Landscape Function Analysis. African Journal of Range & Forage Science **18**:53–58.

Petersen, A., Young, E.M., Hoffman, T.M. & Mucil, C.F. 2004. The impact of livestock grazing on landscape biophysical attributes in privately and communaly managed rangelands in Namaqualand. South African Journal of Botany **70**:777–783.

Prinsloo, H.P. 2005. Alteration of the soil mantle by strip mining in the Namaqualand Strandveld. MSc thesis. Stellenbosch University, Stellenbosch, South Africa.

Reay, S.D. & Norton, D.A. 1999. Assessing the success of restoration plantings in a temperate New Zealand forest. Restoration Ecology **7**:298–308.

Ruiz-Jaén, M.C. & Aide, T.M. 2005. Restoration success: how is it being measured? Restoration Ecology **13**:569–577.

SER. 2004. The SER International primer on ecological restoration. Society for Ecological Restoration International, Tucson, USA.

Singer, A., Kirsten, W. & Bühmann, C. 1995. Fibrous clay minerals in the soils of Namaqualand, South Africa: characteristics and formation. Geoderma **66**:43–70.

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.

Tanner, P.D. (ed.) 2007. Guidelines for the rehabilitation of mined land. Chamber of Mines of South Africa/Coaltech, Johannesburg, South Africa.

Tongway, D.J. & Hindley, N.L. 1995. Manual for soil condition assessment of tropical grasslands. CSIRO, Canberra, Australia.

Tongway, D.J. & Hindley, N.L. 2004a. Landscape Function Analysis: a system for monitoring rangeland function. African Journal of Range & Forage Science **21**: 109–113.

Tongway, D.J. & Hindley, N.L. 2004b. Landscape Function Analysis: procedures for monitoring and assessing landscapes. CSIRO, Canberra, Australia.

Valentin, C., d'Herbes, J.M. & Poesen, J. 1999. Soil and water components of banded vegetation patterns. Catena **37**:1–24.

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

Vogelmann, H.W. 1973. Fog precipitation in the cloud forests of eastern Mexico. BioScience **23**:96–100.

Yeaton, R.I. & Esler, K.J. 1990. The dynamics of a succulent karoo vegetation: a study of species association and recruitment. Vegetatio **88**:103–113.

Personal Communication

Vlok, M. Safety, Health, Environmental & Quality Department, Exarro Namakwa Sands Ltd., P.O. Box 223, Lutzville, 8165, South Africa. Tel: +27 27 217 3330. Fax: +27 27 217 3055. E-mail: marius.vlok@exxaro.com

Chapter 5: Conclusions and Recommendations on Rehabilitation Objectives, Methods, Management and Monitoring

5.1. Introduction

Strip mining has taken place at the Namakwa Sands mine since 1992 (Golder Associates, 2008). It is a very destructive mining method which disrupts natural ecosystems on a large scale, as the vegetation is destroyed and the topsoil is removed (Milton *et al.*, 1997; Cooke & Johnson, 2002; Hälbich, 2003; Prinsloo, 2005; Botha *et al.*, 2008). This severe, large-scale disturbance creates a particularly difficult task for rehabilitation practitioners in an environment, such as Namaqualand, where revegetation is hampered by an arid and windy climate, as well as saline and nutrient-poor soils (Lubke & Avis, 1998; Milton, 2001; Hälbich, 2003; Carrick & Kruger, 2007; Botha *et al.*, 2008). A site-specific rehabilitation method, which addresses these constraints, needed to be developed. For this reason, Namakwa Sands experimented with different rehabilitation treatments in 2001. Four sites each received a different combination of treatments, those being: topsoil only, seeding only, topsoil and translocation, and seeding and translocation. The success of these treatments was assessed by Blood (2006) in 2004 and 2005. Another site was rehabilitated in 2008 using the current rehabilitation method, which combines topsoil replacement, seeding, translocation and planting nursery cuttings. All these sites are located on the East Mine, where the layer of Aeolian sand and the underlying dorbank layer are mined to a depth of five metres. The success of rehabilitation on the experimental rehabilitated sites and the recently rehabilitated site were assessed in chapter 3 of this study, while the Landscape Function Analysis as a monitoring tool was tested in chapter 4. This chapter provides a summary of the conclusions from chapters 3 and 4, and recommends improvements on the rehabilitation objectives, rehabilitation methods, management of rehabilitated sites and monitoring at Namakwa Sands.

5.2. Rehabilitation Objectives

Exxaro Namakwa Sands' rehabilitation goal is to "rehabilitate and re-vegetate disturbed areas and establish a self-sustaining Strandveld vegetation cover in order to control dust generation, control wind and water erosion, as well as restore land capability. In general, vegetation will be rehabilitated to a minimum grazing standard capable of supporting small stock (sheep) grazing." The minimum grazing standard set in the Environmental Management Programme is 20 ha per small stock unit (Golder Associates, 2008). The vegetation cover and plant species richness objectives used in this study were developed by the Environmental Evaluation Unit, who conducted the environmental impact report for the Namakwa Sands mine in 1990 (Blood, 2006). The

107

vegetation cover objectives were that rehabilitated sites should have 50 % of the cover at reference sites after three years and 80 % after five years, respectively. The objectives for species richness were that rehabilitated sites should have 30 % of the average number of species at reference sites after three years, and 60 % at the end of rehabilitation (Blood, 2006). However, these vegetation cover and species richness objectives have been found to be inappropriate by Namakwa Sands and were not included in their updated EMP (Golder Associates, 2008). This is because a single set of objectives cannot be applied to sites which differ in environmental conditions such as slope and depth of mining. Namakwa Sands is currently developing objectives that are specific to different sets of environmental conditions.

Although reference sites provide context to the assessment of rehabilitation success, only using proportional values for objectives, as in the vegetation cover and plant species richness objectives above, are problematic. Reference sites may be degraded, for example by being overgrazed, or rehabilitated sites may cross critical thresholds without it being detected. Therefore it is recommended that Namakwa Sands include minimum values for vegetation cover and species richness in their new objectives. The minimum grazing capacity objective is very low and it is doubtful whether small stock farming would be sustainable at such low stocking rates, especially in view of Namaqualand's vulnerability to climate change (see MacKellar *et al.*, 2007; O'Farrell *et al.*, 2010). A grazing capacity which would enable sustainable small stock farming should be determined and this should become the minimum objective for land use.

5.3. Rehabilitation Methods

Topsoil replacement, seeding of indigenous plants, translocation of mature plants and planting nursery cuttings all have theoretical benefits. This study found that, between the experimental rehabilitated sites, those that were seeded had slightly higher species richness and diversity than sites where topsoil had been replaced, while sites which received topsoil had slightly higher annual cover in winter. Sites which received topsoil also contained higher concentrations of nutrients and had water infiltration rates closer to that of reference sites. Translocation of mature plants did not affect vegetation cover or plant species richness and diversity, however, the site which received topsoil and translocation of mature plants generally had the highest concentrations of nutrients. The topsoil used in the experimental rehabilitation treatments was stored for an unknown period of time, and had it been fresh, the results may have been somewhat different.

The site rehabilitated recently, using a combination of all four treatments, seems to be doing very well in terms of vegetation cover, plant species richness and grazing capacity. Namakwa Sands should therefore continue to apply this combination of treatments. However, it is recommended that rehabilitation should be conducted in multiple stages in future. The first stage should consist of topsoil replacement, seeding and translocation. Nursery cuttings should be planted in the next stage (a year after the first stage) to allow some vegetation cover to develop that will reduce wind speed and therefore seedling mortality due to sand-blasting. Late successional species are almost completely absent from all rehabilitated sites. They are unable to establish in the harsh conditions at the onset of rehabilitation, and their seeds do not last long enough in the seed bank for them to establish when the conditions are favourable. Therefore, it is recommended that late successional species should be re-introduced in a third stage (two years after the first, or later if this proves unsuccessful) through seeding or translocation or by growing and planting nursery cuttings. Seeding has been suggested to be an effective way of returning late successional species (Carrick & Desmet, 2003; Norman *et al.*, 2006). It is possible that some of these species will only successfully establish in wet years. It might be necessary to conduct trials to establish which treatment is most successful in returning which species, and whether it is cost-effective to apply these treatments in years of low- or average rainfall.

5.4. Management of Rehabilitated Sites

The recovery of vegetation on experimental rehabilitated sites has stagnated and some of these sites have even showed retrogression in terms of vegetation cover since it was sampled by Blood (2006). As mentioned before, late successional species are almost completely absent from these sites. Perennial grasses are completely absent from the site which only received topsoil, while reeds are absent from all the experimental rehabilitated sites. Namakwa Sands should return the absent groups to these sites through seeding or translocation or by growing and planting nursery cuttings. It might be necessary to conduct trials to determine which treatment would best return which species or groups. The recently rehabilitated site is doing well, having reached the three-year objectives for vegetation cover and plant species richness, as well as the grazing capacity objective. However, should monitoring reveal that this site is stagnating, adaptive management should also be applied to this site.

5.5. Monitoring Rehabilitation Success

Rehabilitation monitoring at Namakwa Sands currently consists of annual vegetation monitoring using the line-point method. This method is not suited for vegetation surveys in semi-arid or arid

shrublands such as the Succulent Karoo, as the vegetation is too sparse. As a result, this method cannot provide accurate vegetation cover, species cover or species richness data. Instead, the line-intercept method should be used during monitoring. However, this will require more time for field work per sampling period. Namakwa Sands should therefore consider doing vegetation surveys at longer intervals, such as biennially.

Ecosystem functioning should also be monitored at Namakwa Sands, as the self-sustainability of the vegetation on rehabilitated sites relies on the ability of these sites to resist erosion and to retain water and nutrients (Milton, 2001; Herrick *et al.*, 2006; Maestre *et al.*, 2006; Grant *et al.*, 2007). The Landscape Function Analysis (LFA) which was developed by Tongway and Hindley (2004a; 2004b) is a transect-based method that rapidly assesses ecosystem function of rangelands that should be considered for this purpose. The functional status of the landscape is monitored using indices for stability, water infiltration and nutrient cycling that are based on simple field indicators at the soil surface. Another index which is derived from the LFA data is the landscape organisation index, which represents the proportion of the length of a transect that consists of patches where resources accumulate. LFA is well suited to track the development of rehabilitated sites over time, and changes in the processes related to stability, nutrient cycling and water infiltration can be detected before these are reflected in the vegetation. From this information, the ecosystem functions in need of restoration can be identified and corrective action can be taken before the vegetation is affected (Palmer, 2001; Maestre & Cortina, 2004).

The results of this study re-affirm the importance of testing any method against conventional scientific measurements before it can be used in a new environment, as suggested by Maestre and Cortina (2004), Tongway and Hindley (2004b), and Ata Rezaei *et al.* (2006). This study found that the nutrient cycling index can accurately predict nutrient cycling at Namakwa Sands, but that the water infiltration index is not an accurate predictor of water infiltration at Namakwa Sands, due to some underlying assumptions that are not true for this environment. However, the water infiltration rate at rehabilitated sites are unlikely to become similar to that of reference sites in the near future, due to the loss of clay and silt fractions from the soil. Therefore, results of the water infiltration index should be disregarded at Namakwa Sands. The test for accuracy of the stability index was inconclusive. However, based on the differences in the stability index between sites which are consistent with predictions, it is believed that the results of the stability index will be accurate, provided that enough replications are performed. Two replicates per site of the LFA were found to be insufficient to provide accurate stability, nutrient cycling and landscape organisation indices. The required number of replicates should be determined experimentally. It is recommended that ecosystem functioning should be monitored annually using LFA.

110

5.6. References

Ata Rezaei, S., Arzani, H. & Tongway, D.J. 2006. Assessing rangeland capability in Iran using landscape function indices based on soil surface attributes. Journal of Arid Environments 65:460–473.

Blood, J.R. 2006. Monitoring rehabilitation success on Namakwa Sands heavy minerals mining operation, Namaqualand, South Africa. MSc thesis. Stellenbosch University, Stellenbosch.

Botha, M.S., Carrick, P.J. & Allsopp, N. 2008. Capturing lessons from land-users to aid the development of ecological restoration guidelines for lowland Namaqualand. Biological Conservation **141**:885–895.

Carrick, P.J. & Desmet, P.G. 2003. Comments on Namakwa Sands Brand-se-Baai mine-site rehabilitation process. Unpublished report. Lesley Hill Institute for Plant Conservation, University of Cape Town, Cape Town, South Africa.

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.

Cooke, J.A. & Johnson, M.S. 2002. Ecological restoration of land with particular reference to the mining of metals and industrial minerals: A review of theory and practice. Environmental Review. **10**:41–71.

Golder Associates. 2008. Environmental management programme for Namakwa Sands. Unpublished report nr. 10417-5659-1-E. Golder Associates, Johannesburg.

Grant, C.D., Ward, S.C. & Morley, S.C. 2007. Return of ecosystem function to restored Bauxite mines in Western Australia. Restoration Ecology **15**:S94–S103.

Hälbich, T.J.F. 2003. Mine rehabilitation in the arid Succulent Karoo vegetation zone on the South African west coast, Namakwa Sands – case study. Heavy Minerals 2003. South African Institute of Mining and Metallurgy, Johannesburg.

Herrick, J.E., Schuman, G.E. & Rango, A. 2006. Monitoring ecological processes for restoration projects. Journal of Nature Conservation **14**:161–171.

Lubke, R.A. & Avis, A.M. 1998. A review of the concepts and application of rehabilitation following heavy mineral dune mining. Marine Pollution Bulletin **37**:546–557.

MacKellar, N.C., Hewitson, B.C. & Tadross, M.A. 2007. Namaqualand's climate: recent historical changes and future scenarios. Journal of Arid Environments **70**:604–614.

Maestre, F.T. & Cortina, J. 2004. Insights into ecosystem composition and function in a sequence of degraded semiarid Steppes. Restoration Ecology **12**:494–502.

Maestre, F.T., Cortina, J. & Vallejo, R. 2006. Are ecosystem function, structure and functional status related to restoration success? A test from semiarid Mediterranean Steppes. Restoration Ecology **14**:258–266.

Milton, S.J., Yeaton, R.I., Dean W.R.J. & Vlok, J.H.J. 1997. Succulent Karoo. Pages 131–166. In: Cowling, R.M., Richardson, D.M. & Pierce, S.M. (eds). The vegetation of southern Africa. Cambridge University Press, Cambridge.

Norman, M.A., Koch, J.M., Grant, C.D., Morald, T.K. & Ward, S.C. 2006. Vegetation succession after Bauxite mining in Western Australia. Restoration Ecology **14**:278–288.

O'Farrell, P.J., Reyers, B., Le Maitre, D.C., Milton, S.J., Egoh, B., Maherry, A., Colvin, C., Atkinson, D., De Lange, W., Blignaut, J.N. & Cowling, R.M. 2010. Multi-functional landscapes in semi arid environments: implications for biodiversity and ecosystem services. Landscape Ecology **25**: 1231–1246.

Palmer, A.R., Killer, F.J., Avis, A.M. & Tongway, D.J. 2001. Defining function in rangelands of the Peddie district, Eastern Cape, using Landscape Function Analysis. African Journal of Range & Forage Science **18**:53–58.

Prinsloo, H.P. 2005. Alteration of the soil mantle by strip mining in the Namaqualand Strandveld. MSc thesis. Stellenbosch University, Stellenbosch.

Tongway, D.J. & Hindley, N.L. 2004a. Landscape Function Analysis: a system for monitoring rangeland function. African Journal of Range & Forage Science **21**: 109–113.

Tongway, D.J. & Hindley, N.L. 2004b. Landscape Function Analysis: procedures for monitoring and assessing landscapes. CSIRO, Canberra, Australia.

Appendix A: Plant Species List

Family	Species	Persistance
Aizoaceae	*Carpobrotus quadrifidus* L.Bolus	perennial
	Galenia africana L.	perennial
	Galenia c.f. *sarcophylla* Fenzl	perennial
	Galenia sp. 1	
	Prenia pallens (Aiton) N.E.Br. ssp. *namaquensis* Gerbaulet	perennial
	Tetragonia fruticosa L.	perennial
Amarynthaceae	*Atriplex bolusii* C.H.Wright	perennial
	Atriplex nummularia Lindl.	perennial
	Atriplex lindleyi Moq. ssp. *inflata* (F.Muell.) P.G.Wilson	perennial
	Atriplex semibaccata R.Br.	perennial
	Exomis microphylla (Thunb.) Aellen	perennial
	Manochlamys albicans (Aiton) Aellen	perennial
	Salsola kali L.	annual
Anacardiaceae	*Rhus glauca* Thunb.	perennial
	Rhus undulata Jacq.	perennial
Apocynaceae	*Microloma sagittatum* (L.) R.Br.	perennial
Asparagaceae	*Asparagus aethiopicus* L.	perennial
	Asparagus capensis L.	perennial
	Asparagus retrofractus L.	perennial
Asphodelaceae	*Bulbine* sp. 1	
	Bulbine sp. 2	
	Trachyandra bulbinifolia (Dinter) Oberm.	perennial
	Trachyandra falcata (L.f) Kunth.	perennial
	Trachyandra sp. 1	
Asteraceae	*Amellus flosculosus* DC.	perennial
	Arctotis angustifolia L.	perennial
	Arctotis auriculata Jacq.	perennial
	Arctotis venusta Norl.	annual
	Berkheya fruticosa L. Ehrh.	perennial
	Chrysanthemoides incana (Burm.f.) Norl.	perennial
	Chrysocoma ciliata L.	perennial
	Cotula pedicellata Compton	annual
	Didelta carnosa (L.f.) Aiton	perennial
	Eriocephalus africanus L.	perennial
	Eriocephalus racemosus L. var. *affinis* (DC.) Harv.	perennial
	Euryops sp. 1	
	Felicia sp. 1	
	Gazania krebsiana Less. ssp. *krebsiana*	perennial
	Gymnodiscus capillaris (L.f.) DC.	annual
	Helichrysum herniarioides DC.	annual
	Helichrysum stellatum (L.) Less.	perennial
	Metalasia densa (Lam.) Karis	perennial
	Oncosiphon suffruticosum (L.) Kallersjö	annual
	Othonna cylindrica (Lam.) DC.	perennial
	Pteronia onobromoides DC.	perennial

	Pteronia paniculata Thunb.	perennial
	Pteronia sp. 1	
	Senecio aloides DC.	perennial
	Senecio arenarius Thunb.	annual
	Senecio sp. 1	
	Senecio sp. 2	
	Stoebe nervigera (DC.) Sch.Bip.	perennial
	Trichogyne ambigua (L.) Druce	perennial
	Tripteris clandestina Less.	annual
	Tripteris hyseroides DC.	annual
	Tripteris oppositofolia (Aiton) B.Nord.	perennial
	Tripteris sinuata DC.	perennial
	Ursinia speciosa DC.	annual
Brassicaceae	*Brassica tournefortii* Gouan	annual
	Heliophila coronopifolia L.	annual
Campanulaceae	*Cyphia* sp. 1	
	Wahlenbergia sp. 1	
	Wahlenbergia sp. 2	
Caryophyllaceae	*Silene* sp. 1	
Celastraceae	*Gloveria integrifolia* (L.f) M.Jordaan	perennial
Crassulaceae	*Crassula expansa* Dryand.	perennial
	Crassula muscosa L.	perennial
Cyperaceae	*Ficinia argyropa* Nees	perennial
	Scirpoides dioecus (Kunth.) J.Browning	perennial
Ebenaceae	*Diospyros austro-africana* De Winter var. *austro-africana*	perennial
	Euclea racemosa Murray	perennial
Euphorbiaceae	*Euphorbia mauritanica* L. var. *mauritanica*	perennial
	Euphorbia tuberculata Jacq.	perennial
Fabaceae	*Acacia* sp. 1	
	Aspalathus sp. 1	
	Aspalathus sp. 2	
	Aspalathus sp. 3	
	Aspalathus sp. 4	
	Crotalaria excisa (Thunb.) Baker f.	perennial
	Lebeckia halenbergensis Merxm. & A.Schreib	perennial
	Lebeckia simsiana Eckl. & Zeyh.	perennial
	Lebeckia sp. 1	
	Lebeckia sp. 2	
	Lessertia sp. 1	
	Lotononis sp. 1	
	Lotononis sp. 2	
Gereniaceae	*Monsonia spinosa* L'Hér.	perennial
	Pelargonium seneciodes L'Hér.	annual
	Pelargonium triste (L.) L'Hér.	perennial
	Pelargonium sp. 1	
	Pelargonium sp. 2	
	Pelargonium sp. 3	
Hyacinthaceae	*Albuca* sp. 1	

	Lachenalia sp. 1	
Iridaceae	*Babiana* sp. 1	
	IRIDACEAE sp. 1	
	IRIDACEAE sp. 2	
	Lapeirousia arenicola Schltr.	perennial
	Lapeirousia sp. 1	
	Moraea fugax (D.Delaroche) Jacq.	perennial
Lamiaceae	*Salvia lanceolota* Lam.	perennial
Malvalaceae	*Hermannia amoena* Dinter ex Friedr.-Holzth.	perennial
	Hermannia cuneifolia Jacq.	perennial
	Hermannia heterophylla (Cav.) Thunb.	perennial
	Hermannia scordifolia Jacq.	perennial
	Hermannia trifurca L.	perennial
	Hermannia sp. 1	
Menispermaceae	*Cissampelos capensis* L.f.	perennial
Mesembryanthemaceae	*Antimima compacta* (L.Bolus) H.E.K.Hartmann	perennial
	Dorotheanthus rourkei L.Bolus	annual
	Drosanthemum hispidum (L.) Schwantes	perennial
	Conicosia elongata (Haw.) N.E.Br.	perennial
	Lampranthus godmaniae (L.Bolus) L.Bolus	perennial
	Lampranthus suavissimus (L.Bolus) L.Bolus	perennial
	Mesembryanthemum guerichianum Pax	annual / biennual
	Mesembryanthemum sp. 1	
	Phyllobolus trichotomus (Thunb.) Gerbaulet	perennial
	Phyllobolus sp. 1	
	Phyllobolus sp. 2	
	Psilocaulon foliosum L.Bolus	perennial
	Ruschia bolusiae Schwantes	perennial
	Ruschia brevicyma L.Bolus	perennial
	Ruschia caroli (L.Bolus) Schwantes	perennial
	Ruschia stricta L.Bolus	perennial
	Ruschia tumidula (Haw.) Schwantes	perennial
	Ruschia versicolor L.Bolus	perennial
	Ruschia sp. 1	
Molluginaceae	*Pharnaceum incanum* L.	perennial
Neuradaceae	*Grielum humifisum* Thunb.	annual
Oxalidaceae	*Oxalis flava* L.	perennial
	Oxalis pes-caprae L.	perennial
	Oxalis sp. 1	
	Oxalis sp. 2	
Poaceae	*Chaetobromus dregeanus* Nees	perennial
	Cymbopogon plurinodis (Stapf) Stapf ex Burtt Davy	perennial
	Ehrharta brevifolia Schrad. var. *brevifolia*	annual
	Ehrharta calycina J.E.Sm.	perennial
	Eragrostis curvula (Schrad.) Nees	perennial
	Odyssea paucinervis (Nees) Stapf	perennial
	Pentaschistis patula (Nees) Stapf	annual
	Stipagrostis zeyheri (Nees) De Winter ssp. *macropus* (Nees) De Winter	perennial

	Tribolium hispidum (Thunb.)	perennial
Polygalaceae	*Muraltia obovata* DC.	perennial
	Muraltia sp. 1	
Polygonaceae	*Emex australis* Steinh.	annual
Restionaceae	*Ischyrolepis gaudichaudianus* (Kunth.) H.P.Linder	perennial
	Ischyrolepis sp. 1	
	Willdenowia incurvata (Thunb.) H.P.Linder	perennial
Rutaceae	*Diosma* sp. 1	
Santalaceae	*Thesium spinosum* L.f.	perennial
Scrophulariaceae	*Hebenstretia dendata* L.	annual
	Hebenstretia repens Jaroscz.	annual
	Lyperia tristis (L.f.) Benth.	annual
	Manulea altissima L.f. ssp. *glabricaulis* (Hiern) Hilliard	perennial
	Manulea benthamiana Hiern	perennial
	Manulea sp. 1	
	Nemesia versicolor E.Mey ex Benth.	annual
	Phyllopodium sp. 1	
	Zaluzianskya affinis Hilliard	annual
Solanaceae	*Lycium ferocissimum* Miers	perennial
Zygophyllaceae	*Zygophyllum morgsana* L.	perennial

116