STRIP MINING REHABILITATION BY TRANSLOCATION IN ARID COASTAL NAMAQUALAND, SOUTH AFRICA

BY

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I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

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Date:

ABSTRACT

This study investigates the use of top-soiling, irrigation and translocating indigenous plants to facilitate the cost-effective return of a mined landscape to its former land-use (small stock farming) in an arid winter rainfall Succulent Karoo shrubland biome on the West Coast of South Africa.

Effects of topsoil stockpiling and subsoil mineral concentration on soil fertility and chemistry were investigated, as soils are likely to determine rates of vegetation recovery on post-mined areas. Results of a radish bioassay show that stockpiling topsoil and mineral concentration sub-soil decreased soil fertility. Mineral concentration decreased phosphorus, potassium, calcium, magnesium, carbon and nitrogen levels significantly relative to other soil treatments. Sodium in freshly deposited tailings was at potentially toxic levels and significantly higher than for all other soil treatments. Spreading of stockpiled topsoil over tailings may ameliorate harsh conditions created by mineral separation.

Translocation of plants from pre-mined to post-mined areas was carried out on a trial basis in an effort to facilitate the return of natural vegetation and processes to strip-mined landscapes. Five local indigenous plant species: *Asparagus* spp., *Ruschia versicolor*, *Othonna cylindrica*, *Lampranthus suavissimus* and *Zygophyllum morgsana* were planted into multi-species clumps in a replicated experiment. Variables examined in the translocation trial included the effects of plant origin, soil treatment and/or irrigation on plant survival and establishment. The proportion of *O. cylindrica* transplants surviving for 15 months was greater than for other species. Whole plants survived better than salvaged plants, and *Asparagus* spp., *R. versicolor*, *L. suavissimus* and *Z. morgsana* survived better on stockpiled topsoil spread over tailings than on tailings alone. Irrigation had no consistent effect across species and treatment replicates. Salvaged-plant clumps were significantly larger than whole-plant clumps at planting, however, this effect was not observed after 12 months, indicating that whole-plant clumps grew faster than salvaged-plant clumps. The evergreen, leaf succulent shrubs *O. cylindrica*, *L. suavissimus* and *R. versicolor* appeared to be most suitable for large-scale translocation at Namakwa Sands.

The return of biodiversity and changes in soil quality 15 months after translocation trials began were compared for combinations of top-soiling, irrigation, plant translocation and unmodified tailings. Irrigation may reduce biodiversity and seedling densities. Over a 15-month period

following back filling and topsoil spreading, sodium, potassium and calcium appeared to return to levels observed for undisturbed soils. Magnesium remains at levels lower than in pre-mined soil conditions. Soil conditions may be more conducive to plant establishment and rehabilitation after back-filling of tailings and topsoil spreading. Electrical resistance increased over time indicating a reduction of free salts and salinity on rehabilitation sites. Phosphorus did not return to pre-disturbance levels, and carbon remained below pre-mining levels for at least 15 months after rehabilitation began, remaining a potential limiting factor in rehabilitation.

Each rehabilitation technique that a mine employs has costs and benefits, and it is increasingly important that insights from ecology and economics are coupled if restoration efforts are going to succeed. A review of valuation systems indicates that Discounted Cash Flow Techniques (DCF) are suitable for valuation of rehabilitation operations.

OPSOMMING

Hierdie studie ondersoek die gebruik van bogrond, besproeiing en die oorplanting van inheemse plante om die koste-effektiewe rehabilitasie van 'n stroopmynlandskap in die droë, winter reënval streek, Vetplant Karoo aan die Weskus van Suid-Afrika, wat vroeër gebruik is vir kleinvee boerdery, te bespoedig

Die uitwerking van bogrondopberging en minerale konsentrasie op vrugbaarheid en chemise komposisie van grond is ondersoek, aangesien dié gronde gewoonlik die herstelspoed van plantegroei op 'n ou myn terein bepaal. Uitslae van radys proewe toon dat berging van bogrond en minerale konsentrasie van die onderliggende grond vrugbaarheid van grond laat afneem. Mynaktiwiteite en die minerale konsentrasie lei tot 'n betekenisvolle verlies aan fosfaat, kalium, kalsium, magnesium, koolstof en stikstof as die geval met ander bedrywighede. Die vlak van natrium in oorgeblywende sand na die minerale ekstraksie is hoogs giftig en is veel hoër as na ander bedrywighede. Die toediening van bogrond oor die oorblywende sand verbeter die toestand wat deur die skeiding van minerale veroorsaak is.

Oorplasing van plante vanaf ongemynde na rehabilitasie gebiede is op proefbasis uitgevoer in 'n poging om die terugkeer van natuurlike plantegroei by die strookmyn te bespoedig. Vyf plaaslike inheemse plantspesies: *Asparagus* spp., *Ruschia versicolor, Othonna cylindrical, Lampranthus suavissimus* en *Zygophyllum morgsana* is in multi-spesie groepe geplant. Veranderlikes getoets tydens hierdie proef sluit in plantoorsprong, grond behandeling, en/of besproeiing, op die oorlewing en vestiging van plante. 'n Groter proporsie *O. cylindrical* as enige ander spesie het na 15 maande oorleef. Heel plante het beter oorleef as beskadigde plante. *Asparagus* spp., *R. versicolor, L. suavissimus* en *Z. morgsana* het beter oorleef op gebergde bogrond oor oorblywende sand as op oorblywende sand self. Besproeiing het nie 'n volgehoue uitwerking gehad op spesies of op herhaalde replisering nie. Beskadigde plantgroepe was groter as heelplant groepe toe hulle geplant is maar na 12 maande is opgemerk dat die heel-plante vinniger gegroei het. Die immergroen vetplante, *O. cylindrical, L. suavissimus* en *R. versicolor* blyk die mees geskik vir grootskaalse oorplanting by Namakwa Sands.

Herstel van biodiversiteit en veranderings in grondeienskappe 15 maande na proewe begin het, is vergelyk m.b.t. die toediening van bogrond, besproeiing, oorplanting en onbehandelde oorblywende sand. Besproeiing kan biodiversiteit en digtheid van saailinge verminder. Vyvtien

maande na opvulling en die toediening van bogrond, het kalium, natrium en kalsium teruggekeer na vlakke in onversteurde grond. Magnesium vlakke was nog altyd laer as dié voordat mynaktiwiteite aangevang is. Terugplasing van sand en toediening van bogrond mag die vestiging en rehabilitasie van plante bespoedig. Weerstand vermeerder met tyd wat 'n verlaaging in vry soute en soutagtigheid in die grond wat gebruik is vir rehabilitasie aantoon. Fosfor het nie teruggekeer tot vlakke van voorheen nie en vlakke van koolstof het na 15 maande verlaag gebly, en kan die potential tot rehabilitasie belemmer.

Elke rehabilitasie tegniek wat die myn gebruik bring kostes sowel as voordele mee. Om restorasie pogings te laat slaag moet insigte vanaf ekologie en ekonomie saam ingespan word. 'n Oorsig van waardasie sisteme toon dat Afslag Kontant Vloei Tegnieke geskik is vir die evaluasie van rehabilitasie programme.

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CHAPTER 1

INTRODUCTION: MINING AND THE NAMAQUALAND KAROO

INTRODUCTION

Over the last century mining has formed the core around which the South African economy has developed (Reichardt 2001). Modern man's dependence on mineral derived artefacts is unlikely to decrease in the future and mining companies are entrusted with the task of satisfying these needs (Wells *et al.* 1999). The far-reaching effects of mining are well documented and relate to environment, economic and social impacts (Cave 1978; Bradshaw 1997; Milton *et al.* 1997; Wells *et al.* 1999). This thesis deals specifically with the mitigation of the environmental impacts of surface or strip-mining in respect of the remedying of the adverse effects of mining. This form of mining results in the destruction of natural vegetation (Wells *et al.* 1999; Ashton *et al.* 2001) and damage to stockpiled soils (Hunter and Currie 1956; Stahl *et al.* 2002) so that repair involves high mine site rehabilitation and closure costs (Reichardt 2001). Wells *et al.* (1999) propose that the mitigation of environmental impacts of mining by moving a mine to a more environmentally suitable site cannot be considered, as mining can only take place where minerals occur. Mining is often a temporary land use and apart from retrenchment costs, the largest expense associated with mine closure (at present) arises from legal rehabilitation requirements (Reichardt 2001). Since 1991 mining companies have been obliged to set aside funds during the life of the mine, which by the end of the economic life of the mine should cover the closure costs. Effective and continual environmental management systems on strip-mines should help to curtail the environmental costs associated with mine closure (Reichardt 2001).

Under South African law, mining companies are compelled to rehabilitate mined areas (Mining Rights Act No. 20 of 1967, Minerals Act 50 of 1991 and National Environmental Management Act 1998). The rehabilitation programme that is referred to in the Minerals Act 50 of 1991 is the programme that is required from the mining company by the Regional Director of the Department of Minerals and Energy Affairs (DME) in the application for a mining authorisation (Swanepoel 1998).

The mining company should complete an Environmental Impact Assessment[1] for the mining operation, on which the mining company reports. The EIA and the EIA report should then form the basis of and Environmental Management Programme (EMP), which once accepted by the DME becomes legally binding on the mining company and is referred to as the Environmental Management Programme Report (EMPR) (T. Hälbich 2001, personal communication). The EMPR contains conceptual management recommendations based on the principle of "best available technology not entailing excessive costs" (Read 1998).

Currently there is much debate as to the definition of the word "rehabilitation". The Society for Ecological Restoration (van Diggelen *et al.* 2001) suggests: *"ecological restoration is the process of assisting the recovery and management of ecological integrity. Ecological integrity includes a critical range of variability in biodiversity, ecological processes and structures, regional and historical context and sustainable cultural practice"*. In the context of this project, restoration is carried out to restore a highly degraded, but localised site, ensuring the return of natural vegetation cover (Hobbs and Norton 1996).

Heavy minerals in particular occur in economically extractable quantities in the coastal areas of South Africa. It is this location that causes controversy over mineral recovery (Wells *et al.* 1999). In the past strip-mines have earned a bad reputation, mostly because of problems that relate to poor or no land reclamation (Seltzpatrash 1980; Gerard 2000) and a consequent reduction of biodiversity, as well as of the economic and cultural values and livelihood options of the land. Strip-mining is generally carried out when deposits are found within 60-m of the earth's surface (Wells *et al.* 1999). The heavy mineral sand strip-mining process involves the removal of all vegetation and topsoil from mined areas, resulting in a total loss of vegetation from the site. Topsoil is stored in stockpiles for later use in rehabilitation. The subsoil to be mined is then removed and processed. Once the processing of mined soil is complete, processed soil (known as tailings) is returned to the area from which it was removed, a process known as back filling. Tailings are landscaped to blend with the natural topography of the area once back filling is completed. Stockpiled topsoil is spread over the tailings. The mined surface is then revegetated in accordance with current legislation. The mining operations move gradually over the area being mined in parallel strips, hence the name "strip-mines". The replacement of tailings into the back-fill areas is regarded as the start of mine rehabilitation

[1] Environmental Impact Assessment = EIA

processes (Wells *et al.* 1999). Strip-mines have an advantage over underground mines in that rehabilitation can begin on areas that are back-filled many years before mine closure. According to Baxter *et al.* (1998) the EMPR for any South African mine should encompass mine closure. The objectives of rehabilitation programmes early in the life of the mine for areas that are strip-mined should be to facilitate eventual mine closure. Rehabilitation problems facing strip-mined surfaces, especially in arid regions, arise from a lack of information on the requirements for indigenous plant establishment and changes in the salinity of strip-mined surfaces (Milton *et al.* 1997; Lubke and Avis 1998). It is on areas that are back-filled in the early stages of the life of the mine that rehabilitation techniques can be tested and the best methods for future rehabilitation can be determined.

Namakwa Sands Pty (Ltd) owns 14 892 hectares of coastal, arid Strandveld in Namaqualand and has received authorisation to strip-mine an area of 9 400 ha for heavy mineral concentrate (ilminite, rutile and zircon minerals) (Figure 1.1). Much of the mine area is uncultivated land that was previously used for small stock grazing. The mine site has been divided into two sectors, Farm Hartebeeste Kom 156 – East (approximately 3370 ha) and Farm Hartebeeste Kom 156 – West (approximately 1400 ha). Due to the different mining techniques being employed, this study is restricted to Farm Hartebeeste Kom 156 – East. The mining process at the Hartebeeste Kom 156 – East involves the strip-mining of coastal alluvial sandplains for heavy minerals. This process involves the stripping, by bulldozer, of all natural vegetation, organic material and a minimum of 50-mm of topsoil from areas to be mined. This topsoil is stockpiled for approximately three months, to be used later in rehabilitation (Environmental Evaluation Unit 1990). According to legislation the top 500-mm of topsoil should be kept for rehabilitation. Namakwa Sands received an exemption from the DME in the amount of topsoil that has to be stored during mining operations, as the top layer of soil holds high concentrations of the minerals being mined (T. Hälbich 2001, personal communication; G.A. Agenbag 2002, personal communication). Once topsoil is removed; hydraulic excavators mine the remaining sand to a depth of between one and six meters; continually moving forward from mined to un-mined ground. Mined soil is transported to a mineral concentration plant via conveyer belt where seawater is used to wash all mined soil during mineral concentration. Once minerals have been removed from the soil, the by-products produced (tailings) are returned to the mine pit for back-filling. During the environmental impact assessment carried out for Namakwa Sands it was determined that a major negative impact of the mine would be a sustained loss of

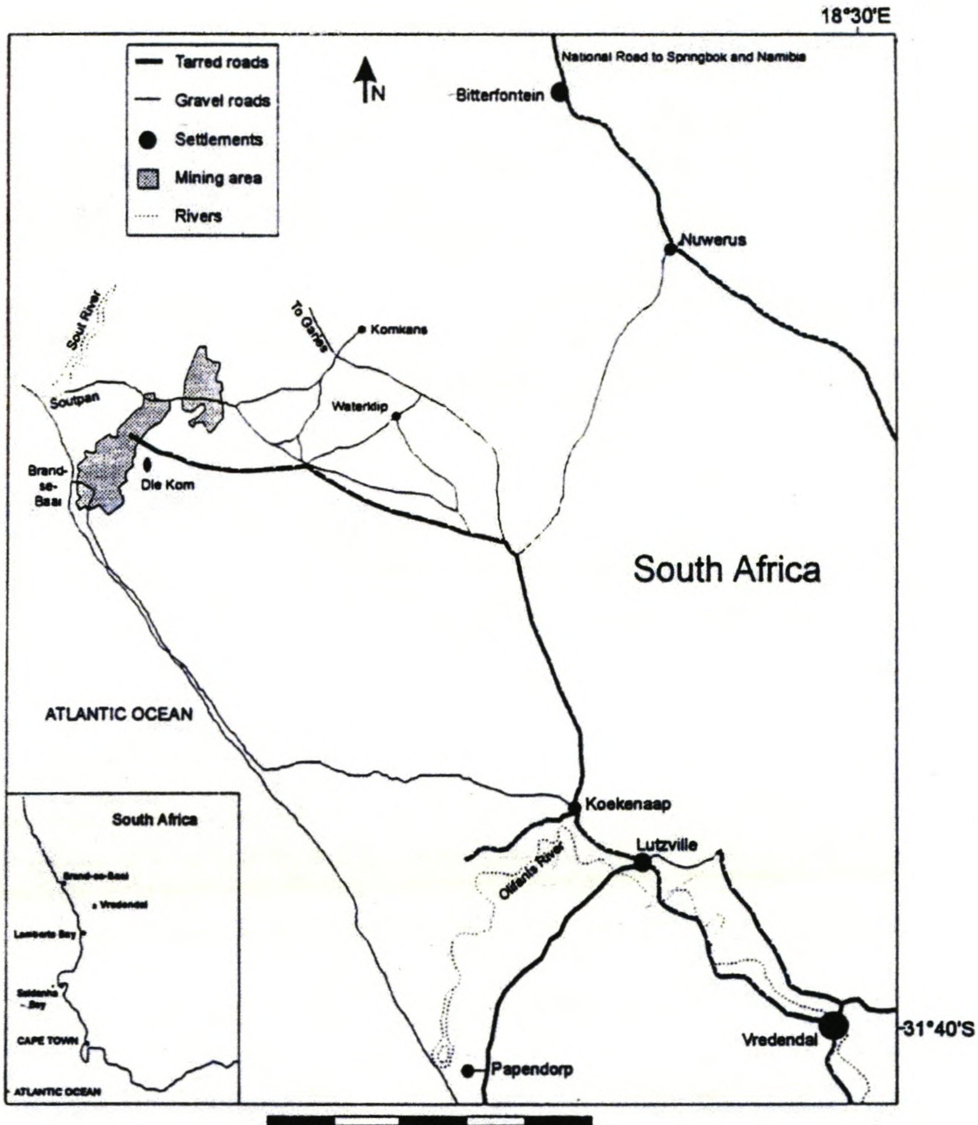

Figure 1.1: Map showing the location of Namakwa Sands Mine (de Villiers 2000).

vegetation and its associated fauna on the mine site (Environmental Evaluation Unit 1990). A rehabilitation goal set by Namakwa Sands was to return the vegetation cover and biodiversity of post-mined areas to a state equivalent to pre-mining conditions (Namakwa Sands Limited 1992).

NAMAQUALAND IN A GLOBAL CONTEXT

The Succulent Karoo

In the past mines have been accused that although they revegetate post-mined areas, they do not restore the natural communities on coastal dune systems (Mentis and Ellery 1994). At present there are limited guidelines for the re-establishment of self-sustaining natural vegetation in damaged arid coastal environments. Lubke and van Eeden (1994) state that rehabilitation with local indigenous species in the arid West Coast areas of South Africa is not easy and that a variety of innovative techniques should be used to accomplish this task. Lubke and Avis (1998) reviewed the concepts and applications of rehabilitation that followed after heavy mineral dune mining. In Australia, with the extension in mineral sand mining, rehabilitation technologies have been advanced to a level whereby native ecosystems can be re-established. In Africa, for the last twenty years much research has been carried out at Richards Bay, in KwaZulu-Natal, on rehabilitation techniques. These and other rehabilitation studies provide baseline information for any proposed dune mining rehabilitation project.

To understand the full environmental impact of the strip-mining process and the consequent loss of natural vegetation at Namakwa Sands, it is important to place the ecological system (arid winter rainfall) in which the mine occurs into a global context. Warm desert ecosystems occupy approximately 47 percent of the Earth's surface. These desert ecosystems, especially in South Africa, are coming under increasing pressure from human population growth, habitat destruction and other components of global change (Cowling *et al.* 1999). The Succulent Karoo Biome of southern Africa (Figure 1.2) which forms part of the greater Cape Flora (Jürgens 1991; Cowling and Hilton-Taylor 1999), has a recorded area of 100 251-km². This biome has the highest species richness recorded (over 5000 species) for semi-arid vegetation. More than 50 percent of the species are endemic to this biome (Milton *et al.* 1997). Approximately 30 percent of the world's succulent species are located in the relatively small area of the Succulent Karoo Biome. These features make the Succulent Karoo a unique biome of global importance (Esler *et al.* 1999). In addition to long-lived succulents, the Succulent Karoo has a remarkable dominance and unique diversity of short to medium-lived leaf succulent shrubs as well as a rich geophyte flora. Plant species diversity (at a local and regional level) is considered to be the highest recorded for any arid region in the world (Cowling and Hilton-Taylor 1999; Esler *et al.* 1999). In the late 1980s "biodiversity hotspots" were identified as geographical regions of conservation priority using the criteria that these regions contained exceptional numbers of endemic species within relatively small areas that were facing significant threats of habitat loss (Myers 1988; Myers 1990; Reid 1998; Myers *et al.* 2000). The Succulent Karoo has been recognised as one of the twenty-five biodiversity hotspots (Myers 1990; Shaw 2000).

The Namaqualand Region

Namaqualand is regarded as the strongly winter-rainfall region of southern Africa's Succulent Karoo Biome (Milton *et al.* 1997; Cowling *et al.* 1999). This region is now recognised as the Namaqualand-Namib Domain of the Succulent Karoo floristic region (Jürgens 1991; Cowling *et al.* 1999) (Figure 1.2). The Namaqualand-Namib Domain is described as the area extending from the Olifants River and Bokkeveld Mountains in the south and south-west, including the area from the Atlantic coast to a line that runs from the vicinity of Loeriesfontein, along the inland margin of the escarpment, to the Orange River, east of the border post at Vioolsdrift, to the mouth of the Orange River at Alexander Bay. The Namaqualand-Namib Domain has an approximate area of 50 000 km^2 (Cowling *et al.* 1999) and at least 2 750 vascular plant species, of which approximately half are endemic (Cowling *et al.* 1999; Eccles 2000). Climatically the Namaqualand-Namib Domain is unusual in that it has relatively predictable winter rainfall and moderate temperatures through the year. In comparison to other arid or desert systems this climate could be thought of as mild, with the consequence of creating a unique selective regime, which is responsible for the unique plant ecological features of Namaqualand (Cowling *et al.* 1999; Esler *et al.* 1999). The dominance of dwarf communities (less than 0.5 m) indicates that the region's structural-functional types as being

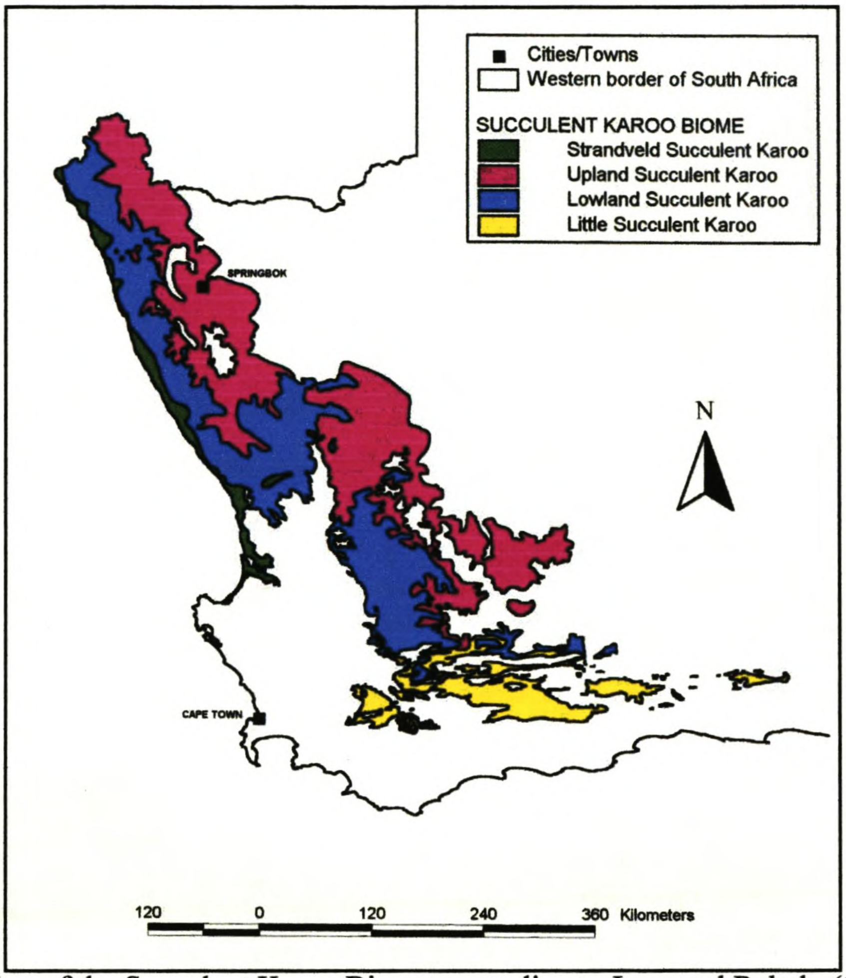

Figure 1.2: Location of the Succulent Karoo Biome, according to Low and Rebelo (1996), indicating each vegetation type for this biome.

unique amongst the world's desert ecosystems. Most of the leaf succulents occurring in the Namaqualand region are shallow rooted (0.1 – 0.2 m), even when growing in deeper soils, resulting in members of this growth form being vulnerable to drought-induced mortality after rare episodes of lower-than-average rainfall. Many of these species also have limited water storage capacity, adding to a low drought tolerance. These factors may lead to many of Namaqualand's leaf succulents being relatively short lived (5 – 10 years) (Cowling *et al.* 1999; Esler *et al.* 1999).

The high compositional turnover of perennials along habitat and geographical gradients is also considered a unique feature of this domain (Cowling *et al.* 1999) and may be caused by the low drought tolerance of the shallow-rooted leaf succulents. Plants die and are replaced continuously, with little evidence for either inter- or intra-specific competition between succulent shrubs in these communities (de Villiers *et al.* 2001) resulting in the age structure within these communities being uneven. In some communities, including those at Namakwa Sands, there is a marked occurrence of clumping or spatial aggregation across a wide range of spatial scales (Cowling *et al.* 1999; van Rooyen 2001). The reliable winter rainfall and mild winter temperatures select for a winter growth phenology. Both perennial and annual species begin vegetation development with autumn rains and continue active growth to reproductive maturity during the winter months, resulting in regular and spectacular spring flower displays. When all the above mentioned factors are considered, Namaqualand can truly be regarded as a unique desert ecosystem, which is worthy of sound environmental management.

The Strandveld vegetation in which Namakwa Sands Mine is found (de Villiers *et al.* 1999; de Villiers 2000) forms the western coastal margin of the Namaqualand system. Although the Strandveld is similar to the rest of the Namaqualand region in terms of its diversity of plant life, this diversity exists in a very homogeneous abiotic context (Eccles 2000). The Strandveld covers an area of approximately 3 817 km^2 and comprises the vegetation of the sandy coastal plains on the West Coast of South Africa. The vegetation of the Strandveld is dominated by scattered low shrubs (such as *Salvia lanceolata* and *Nylandtia spinosa*) and small trees, with succulent shrubs (such as *Zygophyllum morgsana* and *Euphorbia burmannii*). Geophytes and annuals become more dominant where Strandveld vegetation is associated with Sand Plain Fynbos (Low and Rebelo 1996). Eccles (2000) noted that perennial plants assembled into cosmopolitan vegetation clumps. Van Rooyen (2001) confirmed the clumping effect for perennial plants on Namakwa Sands. Boucher and Le

Roux (1989) describe the communities in the coastal strip from the Olifants River in the south to the Spoeg River in the north, an area that includes the location of Namakwa Sands. They defined five main vegetation sub-types: 1) Strand Communities; 2) Strandveld Communities; 3) Succulent Karoo; 4) Sand Plain Fynbos; and 5) Rivers and Estuarine Vegetation. Within the Strandveld sub-type three broad "communities" based largely on vegetation height were recognised. The Short Strandveld community, with an average shrub height of between 10 and 35 cm and vegetation cover of perennial species less than 50 percent. The Medium Strandveld, which is characterised by a greater dominance of larger shrubs (> 50 cm), with a suggested vegetation cover of between 50 and 60 percent. The third community was Tall Strandveld, which was found on the deeper calcareous sands, dominated by shrubs of 1 – 2 m tall with a canopy cover of 60 to 70 percent.

Currently less than 0,5 per cent of the Succulent Karoo Biome is under formal conservation. The Strandveld Succulent Karoo (in which Namakwa Sands Mine is found) is the least well conserved of the Succulent Karoo types (Low and Rebelo 1996). The major threats identified for the Strandveld Succulent Karoo were strip-mining and resort development (Hilton-Taylor and Le Roux 1989; Low and Rebelo 1996). Apart form the unquantified impact of mining on the succulent plant community in Namaqualand, past mining has left large heaps of unvegetated spoil within sight of major tourist routes (Milton *et al.* 1997). It is vital that the impacts of mining on this unique vegetation type be mitigated.

Namakwa Sands Mine was one of the first mines in South Africa to undergo a full environmental impact assessment before permission was granted for mining to commence (Environmental Evaluation Unit 1990; T. Hälbich 2001, personal communication). Mining at Namakwa Sands began in 1992; the expected life of the mine is 30 years (Namakwa Sands Limited 1992). Requirements related to the rehabilitation of mined areas were given in the EIA (Environmental Evaluation Unit 1990; de Villiers *et al.* 1999). The environmental impact assessment gave specific recommendations together with aims and goals for rehabilitation of mined areas. The broad aims of the rehabilitation process for Namakwa Sands (from the EIA report) are four-fold:

1. To minimise the non-rehabilitated exposed areas of the mine and stockpiles.
2. To aim for a reasonable canopy cover of a variety of species which should preferably be indigenous to the area.

3. To aim for a return to natural, self-sustaining, indigenous vegetation cover and a species complement equivalent to that recorded prior to disturbance.
4. To aim for the recreation of habitats that will attract a fauna composition (including invertebrates) similar to that recorded prior to disturbance (Environmental Evaluation Unit 1990; de Villiers *et al.* 1999).

Boucher and Le Roux (1981) first raised concerns regarding the high sensitivity to disturbance of the vegetation on the Namaqualand coast, on which the mine now occurs. This high sensitivity is due to the vegetation's subjection to heavy winds, salt spray and drift sands. Concerns relating to the rehabilitation of the mine were initially raised due to the lack of available information and lack of research done on the study area. De Villiers *et al.* (1999) carried out a survey of the pre-mining vegetation of the mine area to serve as an inventory of the representative plant communities. The ecosystem in which Namakwa Sands occurs could be considered as fragile, with a low resilience, and a high susceptibility to disturbance and destruction (Boucher and Le Roux 1981; Boucher and Le Roux 1989). There are other concerns relating to the rehabilitation of the Namakwa Sands mine. The mine site is known to have one of the strongest wind regimes in the world (Environmental Evaluation Unit 1990; de Villiers *et al.* 1999).

Healthy ecosystems have built-in repair mechanisms, but extensive damage can exceed their capacity for self-repair. After crossing the threshold where self-repair is no longer possible natural systems cannot repair unassisted (Whisenant 1999). It is in this degraded state that we find strip-mined areas. Recovery now requires modifications of the physical environment and the physical limitations of the site need to be addressed (Milton *et al.* 1994; Whisenant 1999). In the past, agronomic approaches have been used in strip-mine rehabilitation in southern Africa. However, these approaches have failed in southern Africa's arid areas. Often the use of exotic species gives the initial impression of successful rehabilitation; the use of exotic species does not lead to a self-sustaining vegetation cover (Milton 2001). According to Whisenant (1999) it is possible to initiate natural, plant-driven (autogenic) recovery processes that do not require continued management. Milton (2001) suggests that the resilience that will ensure self-sustaining vegetation cover on a rehabilitated site can only be achieved if diverse and self-perpetuating plant and animal communities are established. General principles for the rehabilitation of arid winter rainfall areas have emerged from studies carried out in Fynbos, Karoo and Kalahari vegetation types. These principles now need testing in the west-coast

Strandveld, Namaqualand and Namibia. Translocation of plants, although costly, has been recommended for the re-establishment of vegetation structure (Lubke and van Eeden 1994; Milton 2001). Large plants attract various faunal elements that assist in pollination and seed dispersal. These plants may also shed seeds and other organic matter directly into the ecosystem undergoing rehabilitation. It has been suggested that transplanted plants contributed to the rehabilitation process even if they died, as the soil brought to the site on transplanted plants roots included microbes and fungi that re-establish decomposition and symbiotic processes (Milton 2001). It has been suggested that indigenous plants of the arid west coast germinate in sub-canopy micro-sites that are protected from sun and wind and are usually well supplied with mycorrhizal symbionts as many indigenous plants of the arid, winter rainfall regions have internal fungal symbionts (Milton 2001). Conditions on mine-spoil that require rehabilitation are very different to undisturbed soils, being exposed to sun and wind and often the mycorrhizal activities of soil and soil structure are affected by the mining process (Hunter and Currie 1956; Rivers *et al.* 1980). According to Swanepoel (1998) the needs of modern society necessitate that disturbed areas be returned to some type of stable ecosystem as rapidly as possible. The slowness of the natural reclamation process is not acceptable to rehabilitate derelict lands produced by mining activities when considering the demands placed on land today.

THE STUDY

Following from the above principles regarding rehabilitation in arid winter rainfall areas, Namakwa Sands instituted a research project to determine whether translocation of indigenous plants could facilitate the rehabilitation of areas affected by the mining process.

The overall objective of this research was to investigate the effectiveness of top-soiling, irrigation and translocations of indigenous plants, for facilitating the cost-effective return of the mined landscape to its former land-use.

With this aim in mind the remaining chapters of the thesis build a background to the rehabilitation process at Namakwa Sands Mine and the effects rehabilitation processes may have on the degree of success of rehabilitation. Chapter two gives a more detailed account of the study area. Specific site location, site vegetation, climate and geology are described. Climate is especially important in the potential success or failure of rehabilitation due to the extreme weather conditions on the site (Environmental Evaluation Unit 1990).

Chapter three reviews the current literature relating to facilitation and competition effects within arid areas and the role these interactions may play in the rehabilitation of the mine site. Competition and facilitation are well documented for arid areas, with strong emphasis placed on the nurse-plant effect (Pyke and Archer 1991; De Villiers *et al.* 2001; Eccles *et al.* 2001 and others). Vegetation patterns in arid areas, which are well documented (Milton 1995; Aguiar and Sala 1999; Ludwig *et al.* 1999) are also discussed as these patterns may also play a role in potential rehabilitation success.

Chapter four of this thesis investigates whether soil fertility and soil chemical properties are affected by soil treatment. During the mining process approximately the top five centimetres of topsoil are stockpiled for up to three months while the subsoil is mined (T. Hälbich 2001, personal communication). Numerous studies have shown that when topsoil is stockpiled (or mined) soil fertility, structure, pH and salinity can be affected (Visser *et al.* 1984; Stahl *et al.* 2002; Stromayer 2002). If soil fertility and soil chemical composition are negatively affected by soil treatment this may have implications for the success of rehabilitation efforts. Chapter five describes the full translocation field trials. The chapter includes details on experimental design, data collection statistical analyses used and gives the results and discussion of the translocation trials. Chapter six investigates whether different rehabilitation techniques influence the return of biodiversity and soil chemical properties in the experimental plots on the mine site.

Chapter seven discusses the economics of the rehabilitation techniques used for strip-mining operations in general and with particular reference to the techniques investigated in the translocation trials. In large scale rehabilitation for any corporate organisation, the costs and benefits of rehabilitation should be weighed up carefully. Due to the nature of the study it was important for the mine to determine which of the rehabilitation treatments used in the trials were most cost-effective, relative to their success. Chapter eight gives a general discussion of the findings from all work done during the study and summarises findings within the context of the thesis. Recommendations specific to Namakwa Sands, based on these findings, are also given in Chapter eight.

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CHAPTER 2

THE STUDY SITE, MINING METHOD AND ENVIRONMENTAL MANAGEMENT POLICY

ABSTRACT

Chapter two gives information on the study site location and description, paying attention to climatic conditions, pre-mining vegetation and faunal components on the mine site. The chapter also gives a full description of the mining process at Namakwa Sands and regulations that govern mining operations in South Africa. The climatic conditions of the site and the mining operations are important factors in determining the techniques that can be applied for mine site rehabilitation.

LOCATION

The rehabilitation study area is situated on the Namakwa Sands Mine, in the vicinity of Brand-se-Baai on the Namaqualand Coast (31°18'S, 17°54'E) approximately 350 km north of Cape Town and about 80 km north west of Vredendal, the nearest major town (De Villiers *et al.* 1999). The total mine area is 14 892 hectares[1]. However, only a portion of this area is to be mined, the extent of which will be determined by market conditions. At present Namakwa Sands expects to mine an area of approximately 4 700 ha (Environmental Evaluation Unit 1990; T. Hälbich 2001, personal communication). The borders of the area to be mined extend from approximately 300 m inland from the coast to about 18 km inland. Land surrounding the mine is generally used for small stock grazing and dry land crops, with diamond mining identified as the major economic activity in the area (Environmental Evaluation Unit 1990).

[1] Hectares = ha

CLIMATE

The study area lies, climatically, in a transitional zone between the Namib Desert, to the north, and the Cape Mediterranean-type climate to the south. The area has hot, dry summers (November – January) and rain during the cooler, moist winter months (May – August). Rainfall increases from north to south, with an average of 160 mm per annum occurring on the study area. Rainfall is augmented by heavy dew falls and sea fogs characteristic of the Namaqualand coastal climate. There are approximately 100 sea fog days per annum on the study site. Sea fog, heavy dew fall and rainfall leads to a cumulative average annual precipitation of 282 mm per annum measured over four years (Environmental Evaluation Unit 1990; de Villiers 2000).

The average annual temperature is 15.8°C. There is little seasonal temperature fluctuation due to the marine influence on the study site. The maximum average monthly temperature is 24.1°C in summer (January) and the minimum monthly average temperature is 7.5°C in winter (July) (Environmental Evaluation Unit 1990).

The Namaqualand coast has one of the strongest wind regimes in the world. Winds blow with the highest frequencies from the south and south south east during spring and summer (September to March) (Figure 2.1).

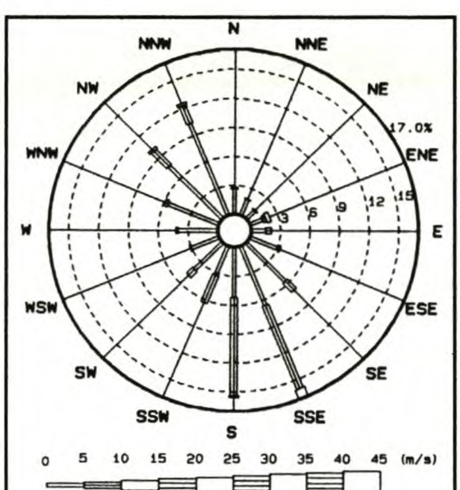

Figure 2.1: Wind rose for summer 2001/2002 (1923 records) (CSIR 2002a). The isolines (concentric circles labelled 3,6,9 etc) in the wind rose represents the percentage of observed records for the record period.

Less frequent but stronger winds blow from the north and north north east during winter (June to August) (Figure 2.2). Easterly berg winds blow from the interior, bringing hot, dry conditions to the coast. The main agent of erosion on the study site is wind. During summer afternoons the wind is strong enough to mobilise vast quantities of surface sand from ground level. Wind speeds reach a peak velocity between 16h00 and sunset and are at a minimum at 06h00 in summer and 10h00 in winter. Mining aggravates this erosion process by removing the stabilising effect of the natural vegetation (Washington 1990).

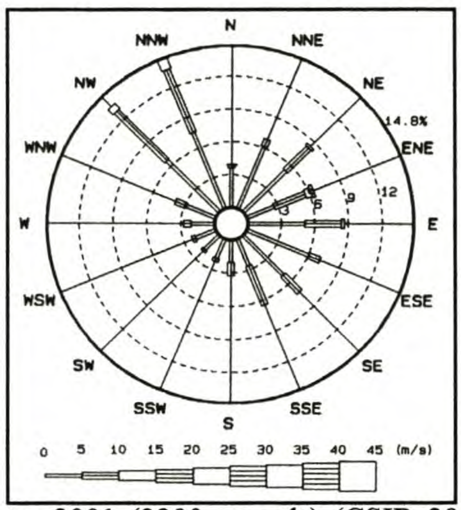

Figure 2.2: Wind rose for winter 2001 (2200 records) (CSIR 2001). The isolines (concentric circles labelled 3,6,9 etc) in the wind rose represents the percentage of observed records for the record period.

This extreme wind regime has implications for any rehabilitation program that the mine may implement. One of the first steps in rehabilitation would be to reduce wind speed on exposed surface areas and prevent wind erosion from occurring.

PHYSICAL ENVIRONMENT

A retrograding coastline, which tends north north west, bounds the study area, exposing the coastal land to strong southerly winds. The coast features wave-cut rocky platforms separated by a number of small, isolated beaches and a large primary dune belt known as the Graauwduinen, which is approximately five kilometres long and 500 m wide. In most places the terrain rises steeply from the coast to the coastal plain. The inland area is undulating and covered with vegetated sand dunes, which are roughly aligned parallel to the prevailing wind direction, which is north-south. The area is included in a geomorphological subdivision of the Namib Desert, and is referred to as the Namaqualand Metamorphic Complex (Environmental Evaluation Unit 1990; Watkeys 1999). Grey regic sands bordering the ocean are recent aeolian deposits that show little evidence of pedogenesis. At the southern end of the west coast region, in which the mine is found, these sands are associated with the remnants of the Post-African surface. Inland of these the soils are derived from the underlying Proterozoic rocks with variable amounts of aeolian contribution, decreasing towards the escarpment. Yellow, high-base soils occur nearest the coast, consisting of moderately deep uniform coarse-textured sand, usually underlain by a more clayey neocutanic horizon. A transition zone of yellow-red soils separates these from the most common soil of the West Coast, a red, high base status soil, which is weakly structured, freely drained with a medium to course texture and variable thickness (Watkeys 1999).

At Namakwa Sands mine the dunes along the coast are generally light grey coloured becoming progressively more red further away from the coast. The red terrestrial deposits are derived from orange feldspathic sands. A thick overburden of marine and aeolian sediments overlies older basement rocks of the Namaqualand granite-gneiss suite and metamorphosed Vanrynsdorp Group rocks (Environmental Evaluation Unit 1990). It is these terrestrial deposits which often display heavy mineral enrichment. Heavy minerals currently being mined at Namakwa Sands include ilmenite, rutile, leucoxene, zircon and monazite. Soils tend to be saline and alkaline with a pH between seven and eight (Ellis 1988; Environmental Evaluation Unit 1990; de Villiers 2000). The topography of the study site can be broadly described as undulating flats with a low relief (Ellis 1988). The rehabilitation study site is relatively flat in the south, becoming slightly steeper in the north. There is a drainage line within the study area running from south west to north east (Namakwa Sands 2002).

The area is extremely dry with no visible surface water supply. The catchments of the Goerap River and Salt River, which flow episodically, are the only drainage systems near the study area (Environmental Evaluation Unit 1990).

VEGETATION

Acocks (1988) first described the vegetation of the study area as Strandveld Proper (Veld type 34b, a Strandveld variant), with the Namaqualand Coastal Belt Succulent Karoo (Veld type 31a, a Succulent Karoo form) in the north eastern part of the study area (de Villiers *et al.* 1999).

According to Acocks (1988), Strandveld Proper (34b) is a more open and rather clumpy scrub veld type. There are a variety of smaller bushes, annuals and grasses in the spaces between the larger shrub clumps. Namaqualand Coastal Belt Succulent Karoo (31a) is an open, semi-succulent scrub, forming an intermediate between the Coastal Fynbos and the Succulent Karoo. There is a range of *Mesembryanthemum*, succulent, semi-succulent and non-succulent species occurring in this vegetation type.

Subsequently Boucher and Le Roux (1981) identified the littoral vegetation of the study area as Southern Namaqualand Strandveld Communities. These communities are described as being sensitive to disturbance because of their subjection to heavy winds, salt spray and drift sands. Low and Rebelo (1996) classified the vegetation of the study area as consisting of Strandveld Succulent Karoo and Lowland Succulent Karoo, both classified under the Succulent Karoo Biome. The Strandveld Succulent Karoo vegetation is confined to the sandy coastal plains and contains many drought deciduous and succulent species and is associated with areas of calcareous sand. The smaller patches of Lowland Succulent Karoo occurring within the study area are characterised by a sparse cover of dwarf succulent-leaved shrub vegetation that does not recover from disturbance easily (Low and Rebelo 1996).

Boucher and Le Roux (1989) classified Strandveld vegetation of the mine site and surrounding region into three variants according to vegetation height, with taller vegetation generally developing on deeper soils. Short Strandveld varies in average shrub height from 10 to 35 cm. Soils are shallow, with very little ground storage of moisture, reflected in the considerable succulent element within the short Strandveld. The projected vegetation canopy cover of perennial species is usually less than 50%. The medium Strandveld is characterised by shrubs in the region of 50 cm tall and a greater grass component (*Odyssea paucinervis* is a dominant understory grass where stable sand occurs) compared to the short Strandveld. The projected vegetation canopy cover of perennial species is usually between 50 – 60%. Tall Strandveld occurs on fairly deep calcareous sands, with a fairly dense projected canopy cover of 60 – 75%, under a light grazing regime. Shrub height ranges from 1 to 2-m. Tall Strandveld vegetation is the tallest vegetation in the area and takes many years to develop to its full potential (Boucher and Le Roux 1989).

A detailed survey of the mine area was carried out to identify plant communities in the pre-mined vegetation of the site (de Villiers *et al.* 1999). The study divided the mine area into six major vegetation units, some including several variants (Figure 2.3). The most prominent species which occur in almost all of the communities are the shrubs *Tetragonia virgata, Zygophyllum morgsana, Othonna floribunda*, and *Lebeckia multiflora*, the grass *Ehrharta calycina* and the ephemerals *Senecio arenarium* and *Tripteris clandestina*. In general perennials constituted the highest number of taxa, while grasses constituted the lowest number of taxa recorded for each vegetation unit. All vegetation units had a shrub and a herbaceous stratum. Shrub strata were dominated by perennial vegetation and herbaceous strata were dominated by ephemeral and grass species. Average canopy cover and total number of plant species recorded for the six vegetation units identified by de Villiers (2000) is summarised in Table 2.1.

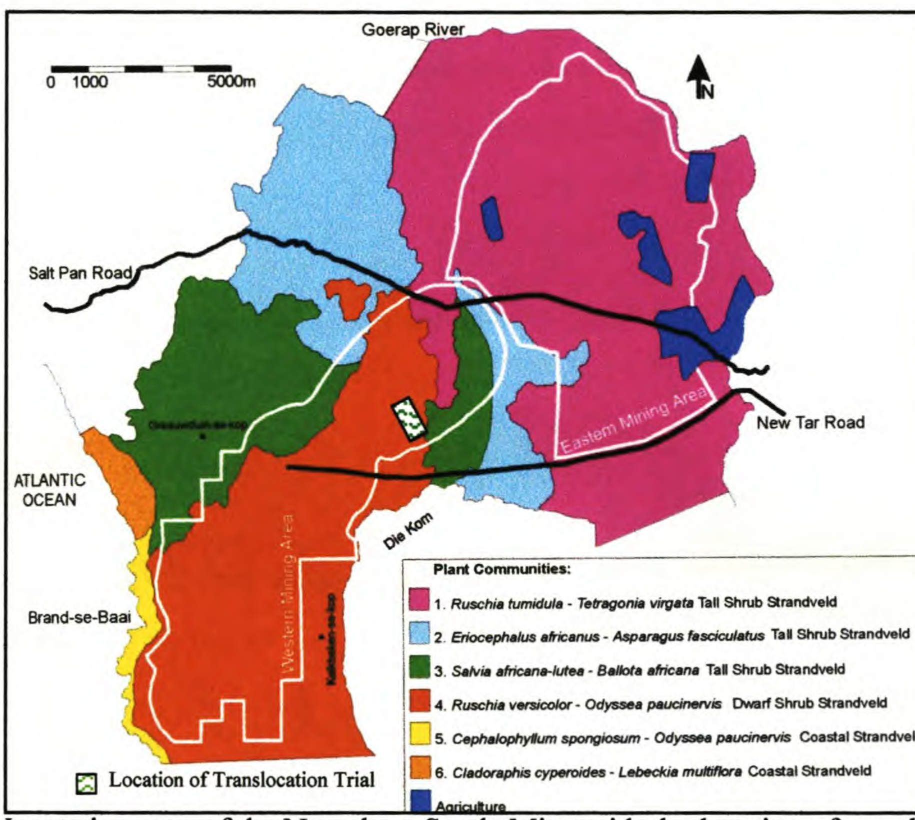

Figure 2.3: Vegetation map of the Namakwa Sands Mine with the location of translocation trials marked on it (de Villiers 2000).

Translocation trials were carried out on vegetation unit four (*Ruschia versicolor - Odyssea paucinervis* - Dwarf Shrub Strandveld) and vegetation unit three (*Salvia africana-lutea - Ballota africana* - Tall Shrub Strandveld).

Table 2.1: Average canopy cover and total number of plant species recorded for six vegetation units identified on Namakwa Sands (de Villiers 2000).

Vegetation Unit	Canopy Cover (%)		Total number of Plant Species Recorded
	Shrub Stratum	Herbaceous Stratum	
1. *Ruschia tumidula - Tetragonia virgata* Tall Shrub Strandveld	22.2	8.0	132.0
2. *Ericephalus africanus - Asparagus fasciculatus* Tall Shrub Strandveld	14.7	4.9	109.0
3. *Salvia africana-lutea - Ballota africana* Tall Shrub Strandveld	26.0	6.0	140.0
4. *Ruschia versicolor - Odyssea paucinervis* Dwarf Shrub Strandveld	16.8	15.5	171.0
5. *Cephalophyllum spongiosum - Odyssea paucinervis* Coastal Strandveld	13.0	26.0	83.0
6. *Cladoraphis cyperoides - Lebeckia multiflora* Coastal Strandveld	4.0	4.3	23.0

Dwarf Shrub Strandveld is found in the southern part of the vegetation survey area and covers the largest part of the western areas to be mined (Figure 2.3). Soils vary from compact, dark red in the west to loose yellowish sand in the east. This community receives more sea spray and fog compared to vegetation units 1, 2 and 3, but less sea spray and fog than vegetation units 5 and 6 (Figure 2.4). Shrubs and dwarf shrubs including *Ruschia caroli* and *Asparagus capensis* dominate the shrub stratum. Ephemeral species and *Odyssea paucinervis*, a perennial creeping grass dominate the herbaceous stratum. The highest number of different plant species within one vegetation unit was recorded within this community (Table 2.1). Dwarf Shrub Strandveld has more succulents belonging to the family Aizoaceae compared to other vegetation units (de Villiers 2000).

Tall Shrub Strandveld is associated with loose, yellow sand and due to the deep soil on which it occurs is taller than that of the surrounding communities. Although this community is closer to the sea than vegetation unit one it still received relatively little salt spray and fog (Figure 2.4). Abundant and conspicuous species in this community include the shrubs *Salvia africana-lutea, Eriocephalus africanus* and *Helichrysum hebelepis*; the dwarf shrub *Conicosia pugioniformis* and the ephemerals *Dimorphotheca pluvialis* and *Nemesi bicornis* (de Villiers 2000).

Vegetation unit 1 (*Ruschia tumidula - Tetragonia virgata* – Tall Shrub Strandveld) is situated farthest inland, and consequently received the least amount of fog and salt spray and is the driest of the communities in the study area. The area consists mainly of small dune systems. The community occurs on a range of soil depths, but is restricted to the more yellow sands (Figure 2.4). A large part of this community will be destroyed by the mining activities. Diagnostic species are *Ruschia tumidula*, *Galenia africana*, *Leysera gnaphalodes*, *Pharnaceum lanatum, Oncosiphon suffruticosum* and several *Pteronia* species (de Villiers 2000).

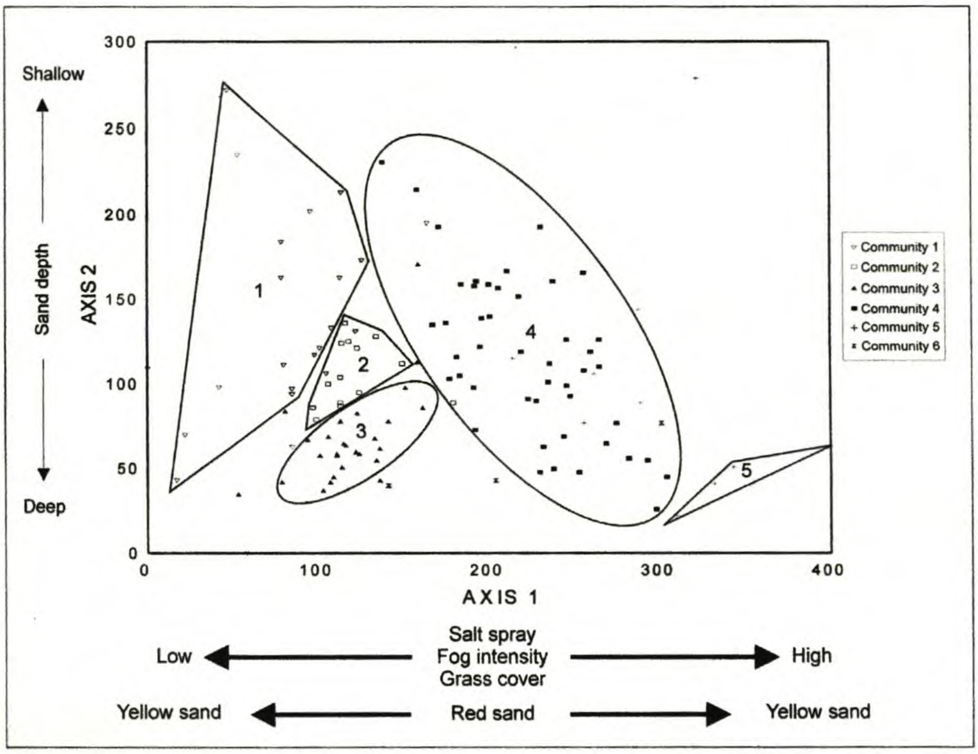

Figure 2.4: The relative position of the plant communities along the first and second axes of a floristic ordination by means of DECORANA (Eigenvalues: Axis 1 = 0.466, Axis 2 = 0.306) (numbers refer to vegetation units in text) (de Villiers 2000).

Vegetation unit 2 (*Eriocephalus africanus* - *Asparagus fasciculatus* – Tall Shrub Strandveld) represents a transition between communities one and three. Sea fog and salt spray intensity are less than that of the communities closer to the coast (Figure 2.4). Only a small part of this community is included in the area to be mined. Conspicuous shrubs within this community include *Asparagus aethiopicus*, *Nestlera biennis, Eriocephalus africanus*, *Asparagus capensis* and *Pharnaceum aurantium*. Abundant species included in the herbaceous stratum are *Manulea altissima* and *Oxalis* species (de Villiers 2000).

Vegetation unit 5 (*Cephalophyllum spongiosum – Odyssea paucinervis* – Coastal Strandveld) and vegetation unit 6 (*Cladoraphis cyperoides – Lebeckia multiflora* - Coastal Strandveld) are found in a narrow strip along the coast and are not scheduled for inclusion in mining activities. Vegetation unit 5 is found on yellowish sand to the south and vegetation consists mainly of dwarf succulent species including *Drosanthemum calycinum, Helichrysum incarnatum* and *Hypertelis salsoloides*. Conspicuous dwarf shrubs in vegetation unit 5 include *Galenia sarcophylla, Arctotis scullyi, Vanzijlia annulata, Pharnaceum aurantium* and *Cladoraphis cyperoides*. The ephemerals *Didelta carnosa,* and *Mesembryanthemum crystallinum* and the perennial grass *Odyssea paucinervis* are conspicuous species in the herbaceous stratum, which has the highest value for average canopy cover (26.0%) for all communities identified (de Villiers 2000). Vegetation unit 6 is found predominantly on white sand dunes on the northern coast of the study area. *Leipoldtia jacobeniana* (a Mesembryanthemaceae) is the only diagnostic species for this community (de Villiers 2000).

An additional feature of the study site is the clumped nature of the vegetation. Van Rooyen (2001) found that clumping was an unchanging feature of the vegetation on the study site. However the amount of clumping, height, area, composition and percentage cover of the clumps fluctuated. Percentage vegetation cover (55%) and vegetation composition stayed relatively constant. Van Rooyen (2001) also found that generally succulent and non-succulent species tended to clump together in this vegetation type. Species carrying fleshy fruits were normally associated with species that rely on wind as a seed dispersal mechanism. Clumps were found to be on average 9.59-m^2 in area and 0.78-m in height (average) with some fluctuation. There was an average interval of 2.82 m between clumps.

FAUNA

Specialist studies were carried out during the Environmental Impact Assessment for Namakwa Sands to determine the impacts mining would have on the faunal component affected by mining operations.

Insect fauna play an important role in the functioning of the West Coast ecosystem and may be of great importance in plant pollination due to the mass, but brief flowering period, when insect pollination is at a premium. Soil movement involved in the mining process may destroy the larval stages of many insects on the mine site. Due to the limited area to be mine, emigration of adult insects of the same species from surrounding areas into rehabilitation areas would not be restricted. Watts and Gibbs (2002) found that as habitat or vegetation heterogeneity increases at a site, beetle diversity and abundance also increased. It could be concluded that revegetation was successfully facilitating the establishment and recolonisation of the beetle fauna. Of more concern at the mine site is the destruction of the large and well-established termitaria of the region, which could be a major disturbance to the ecological cycle of the area. Termites (*Microhodotermes viator*), which form "heuweltjies", play a role in increasing soil fertility though the collection and breakdown of litter. These activities would be impeded by mining operations, and could take hundreds of years to be re-established and develop to their present size. This could have a considerable impact on subsequent plant life in the area (Picker 1989).

One amphibian and 38 reptiles are expected to occur on the mine site. This list includes two tortoise species (*Chersina angulata* (angular tortoise) and *Psammobates tentorius trimeni* (Namaqua tent tortoise)). One species (*Bitis schneideri* (Namaqua dwarf adder)) listed as vulnerable in the South African Red Data Book – Reptiles and Amphibians (Branch 1988) is confirmed as occurring on the mine site (de Villiers 1990). *Gerrhosaurus typicus* (Namaqua plated lizard) is classified as rare by the South African Red Data Book – Reptiles and Amphibians (Branch 1988) and is expected to occur on the mine site. The importance of various amphibian and reptile species in the ecological functioning of the west coast ecosystem is difficult to ascertain due to lack of studies in this region, however, many of these species play a role in controlling insect and rodent numbers (de Villiers 1990).

Eighty-three bird species (four were incidental vagrants) are confirmed as occurring at the mine site, an additional 66 species could confidently be expected to occur on the study site. A high proportion of these species are endemic to southern Africa (57 species), with only one Red Data species (*Neotis ludwigii* (Ludwig's Bustard)) observed and confirmed breeding on the site. Four additional Red Data species can confidently be expected as non-breeding visitors to the site (i.e., *Polemaetus bellicosus* (Martial Eagle), *Hydroprogne caspia* (Caspian Tern), *Sterna vittata* (Antarctic Tern) and *S. balaenarum* (Damara Tern)). Karoo and coastal species, with the occasional pelagic species identified on the study site dominate avifauna of the study site. A small proportion of identified avifauna is known to occur in ploughed fields. Inland avifauna of the site are not unique in any significant sense and most species present could, theoretically, relocate to the larger adjacent areas of the same habitat. However, territorial species may find this relocation more difficult. Viewed within the region as a whole, the magnitude and significance of the mining operation on the region's avifauna should be relatively minor (Allen and Jenkins 1990). Coastal areas are not affected by mining and consequently coastal birds occurring in the region are unlikely to be affected by mining operations.

Nineteen mammals have been confirmed as occurring at Namakwa Sands (Table 2.2), with an additional sixteen mammal species which could confidently be assumed to occur on the mine site (Table 2.3). The African wild cat (*Felis lybica*) is listed as vulnerable and Grant's golden mole (*Erimitalpa granti*) is listed as rare on the Red Data List. In general the study area can be described as having exceptionally low mammal species diversity, which is seen as a natural zoological phenomenon.

Table 2.2: Mammal species confirmed as occurring on Namakwa Sands Mine (Rautenbach 1990).

Order	INSECTIVORA	
	Suncus varilla	Lesser dwarf shrew
	Chrysochloris asiatica	Cape golden mole
	Erimitalpa granti	Grant's golden mole
Order	CARNIVORA	
	Otocyon megalotis	Bat-eared fox
	Vulpes chama	Cape fox
	Canis mesomelas	Black-backed jackal
	Suricata suricata	Suricate
	Cynictis penicillata	Yellow mongoose
	Galerella pulverulenta	Small grey mongoose
Order	HYRACOIDEA	
	Procavia capensis	Rock dassie
Order	ARTIODACTYLA	
	Sylvicapra grimmia	Common duiker
	Raphicerus campestris	Steenbok
Order	RODENTIA	
	Bathyergus suillus	Cape dune mole
	Hysterix africaeaustralis	Porcupine
	Gerbillurus paeba	Hairy-footed gerbil
	Tatera afra	Cape gerbil
	Rhabdomys pumilio	Striped mouse
Order	LAGOMORPHA	
	Lepus capensis	Cape hare
	Lepus saxatilis	Scrub hare

Table 2.3: Mammal species that could confidently be assumed to occur on the mine site (Rautenbach 1990).

Order	INSECTIVORA	
	Myosorex varius	Forest shrew
	Crocidura cyanea	Reddish-grey musk shrew
Order	CHIROPTERA	
	Eptesicus hottentotus	Long-tailed serotine bat
	Eptesicus capensis	Cape serotine bat
	Eptesicus pumila	Little free-tailed bat
	Tadarida aegyptiaca	Egyptian free-tailed bat
Order	CARNIVORA	
	Ictonyx striatus	Striped polecat
	Genetta genetta	Small-spotted genet
	Genetta tigrina	Large-spotted genet
	Felis lybica	African wild cat
Order	RODENTIA	
	Otomys unisulcatus	Bush karoo rat
	Malacothrix typica	Large-eared mouse
	Dendromus melanotis	Grey climbing mouse
	Steatomys krebsii	Kreb's fat mouse
	Mus minutoides	Pygmy mouse
Order	MACROSCELIDEA	
	Macroscelides proboscideus	Round-eared elephant-shrew

The return of fauna to rehabilitation areas is a vital part of the rehabilitation process. The diggings of animals such as bat-eared fox and other insectivores will create microhabitats suitable for seed trapping and germination. Faecal matter deposited by various faunal species traversing rehabilitation areas will also add nutrients to rehabilitation areas and may bring seeds from undisturbed areas into rehabilitation areas. Insect fauna's importance in the functioning of the ecosystem has been identified in terms of pollination agents. The speedy return of insect fauna to the rehabilitation areas will facilitate the rehabilitation process on post-mined areas.

PREVIOUS LAND-USE

Virtually nothing is known about the history of human settlement along the Namaqualand coast. Archaeological sites that have been found in the vicinity of the mine site range in age from very recent (probably only a few hundred years old) to sites 100 000 years old and include stone quarries, rock shelters, temporary camps in dune deflation hollows and shell middens. Settlement appears to have been episodic, possibly restricted to periods of reasonable climate or abundant resources (Environmental Evaluation Unit 1990).

Most of the proposed mining area is uncultivated and is used for small stock grazing. There are a few isolated cultivated lands occurring in the north eastern sector of the mine area. Stocking rates are generally low, varying from 10 to 20 hectares per small stock unit, the carrying capacity of the vegetation is limited. De Beers own 30% of the proposed mining site, with the remainder being owned privately (Environmental Evaluation Unit 1990). During the approximately 30 year life of the mine the areas that were used for small stock grazing and cultivation will be completely devastated due to the operations involved in strip-mining. The aim of the overall rehabilitation programme for Namakwa Sands is to return the area to a vegetation cover and productivity that is equivalent to the pre-mining condition. This implies that the vegetation that is re-established on the post-mined areas should have a carrying capacity of between 10 and 20 hectares per small stock unit.

THE MINING PROCESS

The Namakwa Sands Mine has been divided into two sectors, Graauwduinen East (approximately 3370 ha) and Graauwduinen West (approximately 1400 ha). The depth to which sand is excavated varies for the two sites. At Graauwduinen West excavation will be to depths of between 2 and 45 meters. Not all areas in this sector can be accessed easily. A hard layer of pedocrete (cemented silica, iron oxide and calcium carbonate), known as the dorbank layer lies between 1 and 5-m below the surface. This hard layer will be excavated to gain access to lower lying mineral deposits. At Graauwduinen East excavation will be between 1 and 5 meters, however this section of the mine will cover a greater area than that at Graauwduinen West (Environmental Evaluation Unit 1990). Due to the diversity of the vegetation on the mine site and the different mining processes employed, the contents of this study have been confined to Graauwduinen East and further descriptions of mine operations are confined to this sector.

The mining process begins with the removal (by bulldozer) of the top layer of sand (approximately 50 mm) together with vegetation from a strip to be mined. In the Western Cape Province the Department of Minerals and Energy suggest that approximately 300 mm of topsoil trials carried out at Kleinzee (T. Hälbich 2002, personal communication). Windbreaks also act as seed and fog traps on rehabilitation areas.

Figure 2.5: Newly erected windbreaks at Namakwa Sands.

The process described to this point could be considered as standard rehabilitation for Namakwa Sands. However, to date the mine has seen a retarded return of natural vegetation in terms of cover and species diversity to rehabilitation areas. The mine determined to initiate trials to test whether translocation of selected perennial species would facilitate the rehabilitation of post-mined areas. It is at this point in the rehabilitation program that this study departs. It was important to determine the impacts of the mining process on rehabilitation and to test techniques that can be implemented to facilitate rehabilitation on previously mined sites. It was suggested that the washing of mined soil with seawater increases salinity of the tailings to be used in rehabilitation (de Villiers 2000). The activities of washing soil being mined, separating tailings into sand and clay fractions and the stockpiling of topsoil may be causing a delayed return of vegetation cover and diversity to the post-mined areas.

MINE REHABILITATION AND LEGISLATION

Mining in South Africa is governed by several acts including the Mining Rights Act No. 20 of 1967, Minerals Act 50 of 1991, the Environment Conservation Act of 1989 and National Environmental Management Act of 1998. The procedure followed to commence mining operations in South Africa is that an organisation or individual will apply to the Department of should be stored to serve as the growth medium in rehabilitation (G.A. Agenbag 2002, personal communication). However, each mine operation has the opportunity to be considered individually. In this regard Namakwa Sands received an exemption from the Department of Minerals and Energy whereby a layer of at least 50 mm of soil must be kept for rehabilitation (T. Hälbich 2001, personal communication; G.A. Agenbag 2002, personal communication). Topsoil together with plant remains and organic debris are stored in stockpile for approximately three months while hydraulic excavators mine the subsoil, which is transported to a mineral separation plant via conveyer belt. Mining is a continuous process of forward movement from mined to un-mined areas. Seawater is used to wash all the mined soil during mineral extraction. The residue left after mineral extraction is known as tailings and has two components, the sand portion (tailings) and the slimes (clay) portion. The clay proportion is separated from the sand proportion and stored in slimes dams (Environmental Evaluation Unit 1990).

LANDSCAPE AND VEGETATION REHABILITATION

The sand tailings are deposited (back-filled) into the mined out area (Environmental Evaluation Unit 1990). Deposited sand tailings are shaped to fit the contours of the surrounding landscape. The reshaping and grading of a site are essential aspects of rehabilitation. Unless slopes are stabilised the effectiveness of subsequent topsoil spreading and revegetation can be greatly reduced through the processes of erosion and surface soil movement. The final land-form should be hydrologically and if possible, visually compatible with the surrounding area (Australian Mining Industry Council 1990). Stockpiled topsoil is spread over the contoured tailings. It has been shown in numerous studies that one of the most effective ways to encourage the revegetation of disturbed areas is through the use of topsoil spreading (Rethman *et al.* 1999; Sharma and Gough 1999; de Villiers 2000). Wind has been identified as the major form of potential erosion on the Namakwa Sands Mine (Washington 1990). Eccles *et al.* (2001) found that wind played a role in causing damage to isolated plants. To reduce wind speed windbreaks are erected on rehabilitated areas that have had topsoil spread over tailings, thus reducing potential damage to plants. Windbreaks consist of polyethylene shade net (40% shade) with a height of approximately 1 m, with vertical pockets sown into it to hold metal droppers. These droppers are then hammered into the sand to keep the net upright. Windbreak nets are placed at 4 to 5 m intervals perpendicular to the dominant wind directions (Figure 2.5). The best spacing and height of the windbreak net with the aim to reduce wind speed and sand erosion was tested in

Minerals and Energy (DME) for mining right to an area. Applicants complete an Environmental Impact Assessment Checklist after which the DME either rejects or accepts the application. If the application is accepted the applicant should complete an independent Environmental Impact Assessment (EIA) on which the mine reports via the Environmental Impact Report (EIR) and develop an Environmental Management Plan (EMP) for the proposed operations. The EIA should contain information on all possible impacts the mine may have (social, economic and environmental) as well as measures to mitigate[2] adverse effects of mining activity as described in Principle 4(a) of the National Environmental Management Act No. 107 of 1998 which states that sustainable development requires the consideration of all relevant factors (S. Olckers 2002, personal communication). The EIA and the EMP are sent to various government bodies including the Department of Environmental Affairs and Tourism (DEAT) and the DME for authorisation. Once authorisation is granted the EMP becomes legally binding and mining operations can commence (T. Hälbich 2002, personal communication).

The EMP is an important tool that bridges the gap between the completion of the EIA and the implementation of the project, particularly with regard to implementing the mitigation measures recommended in the EIR and the monitoring, auditing and taking of corrective actions during their implementation. An EMP is typically drawn up after an EIA and is implemented from the construction phase, throughout the project lifecycle up to and including decommissioning. An EMP allocates responsibility, resources and deadlines to each of the actions. An EMP must detail actions to ensure compliance with regulatory bodies and that environmental performance is verified through information on impacts as they occur (CSIR 2002b). EMP implementation is a cyclical process that converts mitigation measures into actions and through cyclical monitoring, auditing, review and corrective action, ensures conformance with stated EMP aims and objectives. An EMP must respond to unforeseen events and changes in project implementation that were not considered in the EIA. Through monitoring and auditing, feedback for continual improvement in environmental performance must be provided and corrective action taken to ensure that the EMP remains effective.

The objectives of an EMP should include (Hill 2000):

- ensuring compliance with regulatory authority stipulations which may be local, national and/or international;

[2] Mitigation = Measures designed to avoid, reduce or remedy adverse impacts (Department of Environmental Affairs and Tourism 1998).

- ensuring that there is sufficient allocation of resources so that the scale of EIA follow-up activities is consistent with the significance of project impacts;
- verifying environmental performance through information on impacts as they occur;
- responding to changes in project implementation not considered in the EIA;
- responding to unforeseen events; and
- providing feedback for continual improvement in environmental performance.

The EMP should also contain details on the rehabilitation programme that the mine aims to implement. The term "rehabilitation" has many definitions. The Society for Ecological Restoration (van Diggelen *et al.* 2001) suggests *"ecological restoration is the process of assisting the recovery and management of ecological integrity. Ecological integrity includes a critical range of variability in biodiversity, ecological processes and structures, regional and historical context and sustainable cultural practice"*.

There is also much debate as to the use of terms such as rehabilitation and restoration and the difference between these terms. According to the "Guidelines for standardised EMP", the definition of rehabilitation is given as: "*repairing or enhancing affected resources, such as natural habitats or water sources, particularly when previous development has resulted in significant resource degradation*". The term restoration is defined as: "*restoring affected resources to an earlier (and possibly more stable and productive) state, typically a 'pristine' condition*" by the same guidelines document (CSIR 2002b). In the context of this project restoration is carried out to restore a highly degraded, but localised site, ensuring the return of natural vegetation cover (Hobbs and Norton 1996).

The rehabilitation programme that is referred to in the Minerals Act No. 50 of 1991 definition is the programme that is required by the Regional Director of the DME in the application for a mining authorisation in terms of the Minerals Act 50 of 1991 (Swanepoel 1998). Once an EMP for a mine has been passed for implementation it is referred to as the Environmental Management Programme Report (EMPR), which contains conceptual management plans based on the principles of "best available technology not entailing excessive costs" (Read 1998). The EMPR is a legally binding document within the confines of which the mine is to operate (T. Hälbich 2002, personal communication). According to the Minerals Act 50 of 1991, the holder of the prospecting permit or mining authorisation shall carry out the rehabilitation of the surface of land concerned in any mining:

- In accordance with the EMPR that has been approved by the Regional Director (DME);
- As an integral part of the prospecting or mining operations concerned;
- Simultaneously with such operations, unless determined otherwise in writing by the Regional Director (DME); and
- To the satisfaction of the Regional Director (DME) concerned (Swanepoel 1998).

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CHAPTER 3

STRANDVELD VEGETATION STRUCTURE AND ECOLOGY AS A BASIS FOR REHABILITATION

ABSTRACT

Strip-mining results in large tracts of natural vegetation being destroyed to gain access to the ore body being mined. To rehabilitate these areas to self-sustaining vegetation systems, it is essential to re-establish patterns and processes that occurred on the site prior to mining. Recent ecological studies in West Coast Strandveld of South Africa have shown that this is a strongly patterned vegetation in which shrubs occur in clumps interspersed with herbaceous plants. The clump formation appears to be the result of dispersal. Clumps may ameliorate harsh environmental conditions, facilitating establishment of the longer-lived elements of the vegetation. I suggest that re-establishment of pattern and process on rehabilitation sites is likely to lead to a self-sustaining plant community.

INTRODUCTION

The strip-mining process results in large tracts of natural vegetation being destroyed to gain access to the ore body, which is mined. Rehabilitation of mined areas is compulsory for commercial mines in South Africa. During the rehabilitation processes the aim is often to restore the mined area to a vegetation type and cover equivalent to the pre-mining capabilities of the site, which was generally used for stock grazing. Mines on the arid West Coast of South Africa (Namaqualand) have to date shown a slow increase in the occurrence of natural vegetation on post-mined areas (T. Hälbich 2001, personal communication). Mentis and Ellery (1994) suggest that mine rehabilitation may revegetate, but does not restore natural communities and processes on coastal dunes subject to strip-mining.

For any rehabilitation efforts to be successful, self-sustaining processes such as plant-plant and plant-animal interactions should be re-established, as these processes in turn control successional processes that will determine the eventual vegetation pattern and composition of the area being rehabilitated and ensure that self-sustaining natural vegetation is perpetuated (Whisenant 1999). An understanding of biotic interactions and successional processes is central to revegetation, as strategies for rehabilitation typically centre around augmenting, enhancing or accelerating changes in species composition. In the context of rehabilitation, early intraspecific competition may minimise establishment and seed production of undesirable species. Early competition will also slow the growth of desirable plants and if individuals must achieve a minimum size to survive unfavourable conditions, competition may contribute to mortality (Pyke and Archer 1991). In the Succulent Karoo Biome of southern Africa (in which Namakwa Sands is found) there are generally two harsh environmental conditions with which plants have to deal, namely heat and water stress (Milton 1995; Eccles *et al.* 1999). Any rehabilitation efforts that are considered for Namakwa Sands should not introduce unnecessary competition into an already harsh environment, but should rather facilitate germination and survival. Namakwa Sands is testing the translocation of indigenous species from un-mined areas to rehabilitation areas to create a facilitative environment for the establishment of seedlings on the rehabilitation areas.

This chapter reviews current literature on the patterns and interactions of plants within arid ecosystems, giving a background to processes that need to be established in rehabilitation areas, looking in particular at the arid West Coast of South Africa.

VEGETATION PATTERNING

The concept of patterns in arid ecosystems is not new and has been described by Aguiar and Sala (1999) and Ludwig *et al.* (1999) in some detail. Patterns in the distribution of biotic components are a function of the interactions between the biota and environmental conditions. A recent review of the structure of arid ecosystems throughout the world supports the idea that vegetation is commonly arranged in a two-phase mosaic composed of patches with high plant cover interspersed in a low-cover matrix. Vegetation patterns in arid ecosystems are characterised by the size, shape and spatial distribution of high plant-cover patches. In some arid ecosystems dense patches form bands or stripes and communities presenting this pattern are generically named as banded or "tiger" vegetation. High cover patches or spots ("leopard") have irregular circular shapes (Aguiar and Sala 1999). Ludwig *et al.* (1999) described the leopard patterning as "stippled".

Eccles *et al.* (1999) found that in the short and medium Strandveld communities of the Succulent Karoo Biome of Namaqualand on the West Coast of South Africa, in which Namakwa Sands is found, there was a significant pattern of multi-species clumps (leopard pattern) of perennial plants for both communities investigated. Van Rooyen (2001) suggested that multi-species clumping was an unchanged feature of the veld type in which the mine occurs, however the amount, height, area, composition and percentage cover of the clumps fluctuated. Bare soil between clumps is covered by annual species in the winter rainfall season. The most popular interpretation of these patterns has been the "maturation thinning" model which is nested in competition theory. This model involves a combination of seed dispersal processes that produce aggregated patterns in juveniles and competition that will convert these patterns into random and ultimately into regular patterns. The overall clumped pattern is attributed to the fact that there tends to be greater numbers of juveniles in populations. Several authors have begun to question whether competition, on its own, is a suitable framework within which to interpret clumped patterns. A more tangible framework for interpreting clumped patterns is the balance between positive and negative interactions. According to this framework, plants will have a preference for clumping if there is some net benefit associated with occurring in clumps (Eccles *et al.* 2001).

The strictly winter rainfall Namaqualand West Coast is not characterised by as great a structural and functional diversity as the Southern Karoo Domain (Succulent Karoo Biome). In addition, evidence for the competitive interactions, which are considered crucial to the succession model in the Southern Karoo Domain, are not a common feature of the Namaqualand Coast. It would appear that there is an additional dimension to plant interactions, which is important in the dynamics of these Namaqualand plant communities (Eccles *et al.* 1999).

The two-phase mosaic affects ecosystem processes ranging from water dynamics and nutrient cycling to biotic interactions (Aguiar and Sala 1999), but little attention has been paid to the function that patchiness plays in arid and semi-arid environments. One hypothesis is that patchiness functions to optimise the capture and storage of limited water and nutrients within these ecosystems tending to maximise plant production within the system. This hypothesis is based on the theory that many arid lands are source-sink or runoff-run-on systems, predicting that in environments with limited rainfall, plant productivity will be higher if rainwater is intercepted and concentrated into patches rather than being uniformly dispersed over the landscape (Ludwig *et al.* 1999). Subsequently low-cover patches become drier and poorer in nutrient status, whereas vegetated patches become wetter and richer in nutrient status. This redistribution of resources between sources and sinks results in an increase in total productivity, with overall production being greater in heterogeneous systems compared with homogeneous systems. The same is considered for nutrient distribution in a heterogeneous system, where "islands of fertility" found underneath the vegetation patches are sinks for nutrients exported from the low-cover matrix through wind and sheet water flow (Aguiar and Sala 1999).

Ludwig *et al.* (1999) showed that the loss of landscape patchiness could result in a dramatic reduction in available water resource due to decreased infiltration and can reduce plant production by 40 percent. This loss of landscape patchiness would also impact on soil fertility, where areas with intact patches had significantly higher concentrations of soil nitrogen and organic carbon, water infiltration rates and plant production compared to landscapes with degraded patches. Once a landscape had lost its patchiness, it also lost its ability to capture, store and recycle any new materials that were washed or blown into the system. These systems have become "leaky", where rainwater and nutrients are no longer efficiently captured and stored within the landscape, resulting in lowered or no plant production, levels of available water and nutrients remain below critical thresholds and plants fail to respond to rainfall because of loss of patches. Dysfunctional landscapes become poor in nutrients, lose water infiltration potential and have significant declines in plant production. When considered in the context of rehabilitation on Namakwa Sands these findings indicate why it is essential to re-establish a patchy vegetation structure similar to that in the pre-mined vegetation of the mine site. Once a vegetation structure similar to pre-mining conditions is re-established functions such as water infiltration, nutrient accumulation and vegetation function can be re-established, which would eventually lead to a higher plant production and a functionally restored vegetation cover. Patchiness has an additional benefit where spatial heterogeneity resulting from vegetation patterns enhances α and β diversity. The contrasting environmental conditions of vegetated patches and the low-cover matrix selects for different characteristics for species and ecotypes (Aguiar and Sala 1999).

PLANT INTERACTIONS

Within any habitat, individual organisms are more likely to interact with neighbouring organisms than with more distant ones. Studies suggest that sessile organisms often have strong interactions within neighbourhoods, but that neighbourhoods can differ in composition because of colonisation limitations such as recruitment or dispersal limitations. These limitations have been cited as an important factor determining successional dynamics, community diversity and competition (Tilman 1994), which play a role in vegetation functioning. Plant-plant interactions are well documented for arid areas (Pyke and Archer 1991; Aguiar and Sala 1999; Tewksbury and Lloyd 2001). Interactions range from antagonistic to mutualistic and the full range of these interactions needs to be considered to ensure successful revegetation (Pyke and Archer 1991; Holmgren *et al.* 1997). The occurrence of clumped vegetation on areas unaffected by mining at Namakwa Sands indicates some form of plant-plant interactions within the vegetation of the mine site. There is still much debate as to whether these interactions are positive (Eccles *et al.* 2001) or negative (de Villiers *et al.* 2001).

Most evidence for positive interactions come from ecosystems where plants are exposed to stress, for instance as a result of heat and desiccating conditions. In such cases the establishment of new plants is often restricted to shady places under the canopy of other plants (Holmgren *et al.* 1997). Positive interactions are important in structuring communities and promoting biological diversity, and have been recognised as an important driving force in primary and secondary succession (Holmgren *et al.* 1997). Bertness and Callaway (1994) put forward the hypothesis that competition increases in importance towards the productive part of the environmental gradient, whereas facilitation is more important under harsher conditions. Namakwa Sands is considered to be a harsh environment due to sea salt spray, low winter rainfall and extreme wind conditions (Boucher and Le Roux 1989; Washington 1990) and vegetation at the site is considered to be extremely sensitive to disturbance (Boucher and Le Roux 1981). Following from the above hypothesis one would expect to find facilitative interactions in vegetation on Namakwa Sands. Benefactor species can influence recruitment, growth and spatial associations of beneficiary species, either directly or indirectly (Tewksbury and Lloyd 2001). Competition occurs for limited resources such as water and nutrients (Wilson and Tilman 1993; Yeaton *et al.* 1993). Facilitative and competitive effects can lead to a complex interaction within plant communities, especially when considering that interactions do not occur in isolation (Callaway and Walker 1997). The balance of facilitation and competition appears to vary with the life stages and physiology of the interacting species, indirect interactions with other neighbours and the intensity of abiotic stresses experienced by the interacting species. To understand the net effect of interactions it is necessary to know the combined responses of interacting species to multiple environmental factors (Pyke and Archer 1991; Holmgren *et al.* 1997).

Plants may facilitate other plants directly by ameliorating harsh environmental conditions, altering substrate characteristics or increasing the availability of resources. Facilitation may also be indirect, by eliminating potential competition, introducing other beneficial organisms such as soil microbes, mycorrhizae or pollinators or providing protections from herbivores or other mechanical damage (Callaway 1995). Competition occurs when two or more plants require a shared limited resource, such as water or nutrients. When facilitative or competitive effects are considered it is difficult to isolate individual effects. For example when considering the effects of a facilitative plant, it is often not a single factor that is altered by the plant but rather the whole microenvironment around the facilitative plant. Plants, including facilitator plants, may also compete for the same resources, such as water or nutrients.

It is essential to consider all possible plant-plant interactions in any rehabilitation process, as these interactions could either facilitate or retard rehabilitation. It is also important to determine which interactions occur when, in terms of life form and life history strategies for various species. Is the interaction between perennial species or between annual species or between annuals and perennials? Is the interaction between an adult plant and a seedling, between seedlings or between adult plants? Is competition or facilitation between two plants of the same species (intra-specific) or between two plants of different species (inter-specific)? All these potential interactions have to be considered. Studies of *Lupinus lepidus* and its effects on the survival of other herbs was negative in the first year, positive in the second year and appeared to be even more positive after the death of the *L. lepidus* plant (Callaway and Walker 1997).

Nurse-Plant Effect

The nurse plant effect is where one plant, the nurse plant, facilitates the establishment and/or survival of another plant, the beneficiary, by providing an environment conducive to germination and/or growth. The nurse plant may or may not be the same species as the beneficiary species. Facilitation by nurse plants is a common phenomenon in arid and semi-arid ecosystems. The most commonly reported mechanisms of facilitation include cooler temperatures and increased soil nutrient availability beneath the nurse plant canopy, which favour the establishment of other plant species (Franco-Pizaña *et al.* 1996). Beukman (1991) showed that certain shrubs in the Karoo facilitate other species by the provision of a suitable growth environment beneath their canopies, showing that certain shrubs are more effective as nurse plants than others and that beneficiary plants could be nurse specific. It was found that, in time, the relationship between nurse and beneficiary plant changed to become more competitive. Nurse vigour declined, as beneficiary plants grew larger. The beneficiary plant ultimately replaced the nurse plant. Franco-Pizaña *et al.* (1996) found similar results when studying the relationship between *Prosopis glandulosa* and *Celtis pallida*. *C. pallida* germination was facilitated by *P. glandulosa*, however, *C. pallida* growth was not facilitated by its position under *P. glandulosa*. Growth patterns might change as the shrubs become established and different results could have been obtained with older, established plants. In many cases, seedlings of beneficiary species are found spatially associated with nurse plants, whereas adults are not, implying that the balance of competition and facilitation shifts among the various life-stages of the beneficiary and the nurse plant (Callaway and Walker 1997).

For the Succulent Karoo seedlings with large cotyledons tend to be more vulnerable to herbivory and/or water stress. The establishment of these species below canopies of other plants possibly provides these species with added advantages against these threats (Esler 1999). The provision of suitable germination sites for a range of species is essential to facilitate the increase in biodiversity and the return of species onto rehabilitation areas.

De Villiers *et al.* (2001) tested the nurse-plant hypothesis in Strandveld Succulent Karoo dominated by different shrub species. Seedling emergence and survival were investigated at three localities dominated by annual species. Species richness and seedling densities were significantly higher in open areas than underneath shrubs, while seedling survival percentages were not different between microsites of either between or under perennial plants, concluding that seedling recruitment and survival were not facilitated by the presence of shrub species. It was stated, however, that perennial shrubs could have other interaction affects that may be advantageous when restoring post-mined areas in the Strandveld Succulent Karoo.

Nurse-plants can also enhance air humidity and prevent extreme temperature fluctuations, improve soil quality through the accumulation of nutrients and organic matter, and reduce the risk of damage through plant herbivory or mechanical damage. Positive and negative interactions will occur simultaneously, where nurse plants that improve some environmental factors will tend to negative effect other factors (Holmgren *et al.* 1997).

Light and Temperature

Callaway (1995) suggests that temperature should be considered as a resource. Temperature and light are functions of total irradiation and both are often incorporated in studies of the effects of shading. Shade provided by the canopies of larger nurse plants may protect seedlings and smaller plants from temperature extremes, reduce water loss and reduce photo-inhibition during stomatal closure, but is does so at the cost of reduced energy for photosynthesis. According to Milton *et al.* (1999) the succulent species of the arid zone of southern Africa can be separated broadly into two guilds, namely the shade-loving and sun-loving guilds. The shade-loving guild is restricted, either during establishment or throughout their life span, to patches of deep shade beneath shrubs or amongst rocks. This group includes all leaf- and stem-succulent plant families of southern Africa except the Mesembryanthema and Zygophyllaceae. The latter two leaf-succulent families are able to colonise open, unshaded sites and are therefore important in determining pattern in some types of karoo vegetation. From the description of the two guilds occurring in karoo vegetation it can be said that shade and light play important roles in the establishment and succession of a wide range of plants within the karoo biome. This fact is of significance when considering rehabilitation at Namakwa Sands, as the sites to be rehabilitated are completely barren, with no shade. If translocation of indigenous plants were to be used as a technique in facilitating rehabilitation, it would be important to select species that could survive in direct sunlight.

Soil Moisture and Nutrients

The two-phase mosaic of patchy vegetation affects water dynamics and nutrient cycling processes within plant interactions (Aguiar and Sala 1999). These effects of especially perennial canopies (as they are longer lived than annuals) can alter the physical and chemical characteristics of the substrate (Callaway 1995), which can either lead to facilitation or competition for associated species.

Available moisture is a major limiting factor at Namakwa Sands, with a total average annual precipitation of 282-mm per annum (combined rain, fog and dew fall) (de Villiers 2000). Soil moisture can be affected in two ways when nurse plants are considered. The hypothesis that patchiness functions to optimise the capture and storage of limited water and nutrient supplies within arid ecosystems, as described earlier, is similar to the effect nurse plants may have in increasing water infiltration (Aguiar and Sala 1999; von Hardenberg *et al.* 2001). In leopard vegetation water infiltration is higher and soil evaporation lower in densely vegetated patches compared with that in the bare-soil dominated matrix. In the tiger ecosystems, inter-banded areas represent areas of catchment and transport of rainfall water down-slope, whereas vegetation bands are sinks for the transported water (Aguiar and Sala 1999). The second way in which soil moisture can be affected by nurse plants is indirectly by altering the area under the nurse plant. Studies have shown that under the canopy of plants, soil and air temperatures and wind velocity are lowered and the air humidity is higher than in the open. These microclimatic changes result in transpiration demands being lower in the shade and evaporation from the superficial soil layer being lower. In summary the microsite for a seedling under a nurse plant has its own microclimate, which is usually characterised by more favourable moisture conditions but less light than in the nearby open areas (Holmgren *et al.* 1997; von Hardenberg *et al.* 2001).

Studies were carried out on the interactions between a short-lived perennial species and an annual species in the Strandveld of the West Coast, South Africa. Where moisture stress through the year was expected to be the greatest (on slopes due to slope run-off and reduced infiltration) annuals were denser and larger than those at the base of the slope were. Results appeared to be due to reduced competition rather than from expected allelopathy from the perennials, individuals of which were found to be more sparsely distributed on the slope. Results assumed that the base of the slope would be relatively wetter over the year than the side of the slope (Yeaton and Esler 1993). In studies carried out on plants growing in clumps in the strongly winter rainfall areas of West Coast Namaqualand, the hypothesis that plants should receive benefit in regard to water relations by living in clumps was rejected (Eccles *et al.* 2001). Beukman (1991) found that competition between nurse and beneficiary plants was not for water resources, as the nurse and beneficiary plants' rooting systems were vertically and horizontally separated in space, implying some degree of resource partitioning within the system.

Soil nutrient availability is known to vary regionally and may be highly variable at small scales, with many researchers measuring higher nutrient levels in soil directly beneath the canopies of perennials than in the surrounding open spaces without perennial cover (Callaway 1995). Banded and spotted vegetation displays a pattern of higher soil organic matter and mineral nutrients in the vegetation patches compared with the low-cover matrix. This has lead to what is known as the "fertile island effect", which is the consequence of accumulation processes driven by abiotic and biotic processes. Abiotic processes, driven mainly by wind and water, include the redistribution of fine soil particles, associated mineral nutrients and litter that is concentrated under vegetated patches (Pugnaire *et al.* 1996; Aguiar and Sala 1999; Cowling and Hilton-Taylor 1999; Ludwig *et al.* 1999). Biotically driven accumulation results from the root actions ("nutrient pumping"), which absorb nutrients from the soil under the densely vegetated patches and from the soil of the bare-soil matrix, yet above-ground litter falls mostly in the vegetated patches, increasing mineral nutrients within the vegetated patch (Aguiar and Sala 1999). Nutrient enrichment may also occur indirectly through nitrogen fixation (Callaway 1995).

Wilson and Tilman (1993) found that when nitrogen was limited, below ground competition was a dominant interaction, whereas both below and above ground competition controlled plant growth when fertiliser was applied. Below ground competition was most intense in plots with the lowest nitrogen availability and decreased significantly with increasing nitrogen availability.

Root architecture may also contribute to plant interactions for moisture and nutrients. Root architecture refers to the spatial configuration of a plant's root system. Although relatively little is known about the root architecture of karoo growth forms, early studies indicate a range of root systems. Two non-succulents investigated revealed extensive, deep root systems, two *Euphorbia* species investigated revealed shallow root systems and a leaf succulent revealed a root system comprising a concentration of shallow roots and a few roots penetrating to four metres or more (Midgley and van der Heyden 1999). Beukman (1991) described vertical separation of the roots of nurse and beneficiary plants; suggesting a reduced competition between these closely spaced individuals. It has also been shown that benefactor species may retrieve up to 50 percent more soil water than exposed individuals due to the reduction in soil surface evaporation in the shade of the nurse plant (Scott and Van Breda 1937; Scott and Van Breda 1939; Midgley and van der Heyden 1999). Yeaton *et al.* (1977) found that the sparsely distributed root systems of perennial species in arid zones enabled individuals of annual species to fit their root systems into the interstices.

Few conclusions can be reached regarding root architecture in karoo plant growth forms based on current information. It does appear that vertical root separation in the soil profile may facilitate the coexistence of non-succulent and succulent shrubs and may encourage the nurse-plant effect (Midgley and van der Heyden 1999). This form of structural separation is sometime known as resource partitioning, which is differential use by organisms of resources such as food and space, allowing coexistence of species that would otherwise have competed for a common resource

(Begon *et al.* 1990). The effects resource partitioning could have in rehabilitation should also be considered. For example if seeding is to be used to facilitate rehabilitation, seed mixtures used should contain species with contrasting above- and below-ground forms, enhancing resource partitioning and potentially decreasing potential competition and enhancing diversity on the site (Pyke and Archer 1991).

Root Grafts, Mycorrhizae and Soil Microbes

There is evidence for root grafting between plants of the same species (intra-specific) as well as for between plants of different species (inter-specific) in which water, nutrients and photosynthate are passed between different individuals. Mycorrhyzal fungi appear to form below ground connections between plants. It is through these below ground connections that nutrients and carbon are exchanged. Plants may also alter soil microflora in ways that enhance the growth of other plant species (Callaway 1995).

There is currently no definite evidence of mycorrhyzal fungi at Namakwa Sands, however, Allsopp (2002, personal communication) suggests that mycorrhizae are highly likely to occur on Namakwa Sands due to its location within the Strandveld vegetation. Further research is needed to determine if mycorrhizae do occur at Namakwa Sands and if so, what role mycorrhizae may have in rehabilitation.

Protection from Physical Damage

Some documented examples of inter-plant (plants of different species) facilitation are indirect and mediated through herbivores (Callaway 1995). Todd (2000) found that in the succulent Karoo of Namaqualand refuge plants were important in providing protected recruitment sites for *Tetragonia fruticosa*, where *Tripteris sinuatum* used refuge plants to provide safe recruitment sites as well as sites for increased seed production. Results indicate that unpalatable and thorny species such as *Lycium ferocissimtum* play an important role in providing refuge sites for palatable species that might otherwise become lost from overgrazing.

From a rehabilitation viewpoint it becomes important to establish a variety of species on post-mined area, with plants not necessarily providing forage for animals but possibly providing protected sites for palatable species to survive and produce seed, ensuring a sustained post-mined land use.

Eccles *et al.* (2001) found that when plants were isolated they were significantly more at risk of damage than when occurring in clumps. It was found that damage to *Eriocephalus*, *Salvia*, *Pteronia* and *Othonna* isolated plants appeared to be due either to sheep trampling or wind damage. At present there are no sheep grazing on the rehabilitation areas of Namakwa Sands. The effect of physical damage on rehabilitation areas due either to grazing or trampling can be excluded at this stage. When grazing is initiated on rehabilitation areas the trampling effect must be considered when determining the stocking rate. The wind regime occurring on Namakwa Sands has been described as one of the most severe in the world (Washington 1990). This fact, together with the fact that wind plays a role in damaging isolated plants (Eccles *et al.* 2001), must be considered when developing a rehabilitation strategy for Namakwa Sands. Protection from wind on rehabilitation areas at Namakwa Sands may be vital for rehabilitation success. At Namakwa Sands windbreak nets give initial protection from wind (as described earlier). At some point in the rehabilitation process nets will be removed and it will be essential that protection be offered to emerging and emerged seedlings. If translocation of plants from areas to be mined to areas that have been mined is used to facilitate rehabilitation, these translocated plants may provide protection for seedlings from wind and sand blasting.

Concentration of Propagules

The mechanism considered is that of the aboveground plant parts in trapping and concentrating propagules of other and like species, either by wind or sheet water flow (Silvertown and Wilson 1994). The overall facilitative effect of this mechanism is questionable, as according to Callaway (1995), if propagules are prevented from being lost to the system or destroyed altogether, then propagule filters are facilitative. If aboveground architecture acts to alter the spatial patterns of distribution without providing sites more suitable for germination than open sites, the process may actually have a competitive effect by suppressing germination of potential future competitors, for example nurse-plants could impede seedling emergence by litter accumulation (Holmgren *et al.* 1997).

Seed morphology can direct seeds to microsites where seeds are more likely to germinate and survive. In the succulent Karoo, tumble seeds (large winged or bristly propagules, which tumble over the soil surface by the wind and move considerable distances in open vegetation) are generally trapped in mat-like succulents, which provide shelter and soils that are likely to be more fertile than bare soil (Milton 1995).

Pollination

In the winter rainfall areas of the succulent karoo, flowering occurs mostly in showy, multi-species displays in spring, followed by seed ripening in late spring and early summer. Annuals are usually the first to flower followed by many geophytes and succulent species towards the end of spring. This mass flowering may cause these plants to compete for pollinators if pollinator populations are under supplied (Esler 1999). Despite the synchrony of flowering in the succulent karoo some species, which have storage organs, flower outside of the main season by uncoupling flowering and growth. The production of flowers at times when the surrounding vegetation is dormant is presumed to enhance pollination for the flowering species (Esler 1999).

INTERACTIONS BETWEEN FACILITATION AND COMPETITION

As described earlier, there may be a shift in competitive and facilitative effects over time. Various facilitative mechanisms may also act simultaneously with resource competition or allelopathy and the overall effect of one species on another may be the cumulative effect of multiple, complex interactions. The balance of facilitation and competition may be affected by the life-stages of the interacting plants. Patterns of nurse-plant mortality observed in several systems indicates that species that begin their lives as the beneficiaries of nurse plants often become significant competitors with their former benefactors as they mature. In some cases a particular benefactor species has been found to have facilitative effects on some species but competitive effects on other, apparently similar species (Callaway 1995).

The balance between facilitation and competition often appears to be affected by the harshness of the physical conditions. Bertness and Callaway (1994) put forward the hypothesis of a shift in importance of facilitation in plant communities, where facilitation increases in importance with increased abiotic stress and the importance of competition would increase when physical stresses were relatively low. Wilson and Tilman (1993) also showed this process, where competition decreased with increased resource availability. Simultaneous interactions suggest that current conceptual models of inter-plant interactions based on resource competition alone are limited in their potential for accurately depicting processes in natural plant communities.

Holmgren *et al.* (1997) suggest that the interplay of facilitation and competition can be understood from the two components of growth and survival of plants in relation to water and light availability and the effect of plant canopies on microsite light and moisture. Under low light conditions, plants invest proportionally more biomass in leaves and aboveground parts; increasing the transpiration surface relative to the amount of roots and, consequently, increasing susceptibility to dry conditions. The reverse is also true, where under drier conditions; plants allocated relatively more biomass to roots than to aboveground structures. As a consequence the ratio of respiring biomass to photosynthetic material would increase and the amount of light needed to keep a positive carbon balance should be higher (Holmgren *et al.* 1997). This is based on the hypothesis that plants cannot adapt to shade and drought tolerance simultaneously (Callaway and Walker 1997).

CONSEQUENCES FOR COMMUNITY STRUCTURE

Plant interactions may determine community spatial patterns, permit coexistence, enhance diversity and productively and drive community dynamics. Plant communities are profoundly affected by facilitative and competitive interactions. Facilitation is considered by some as an essential, albeit controversial, component of the traditional concept of plant succession, often providing regeneration niches. The establishment and maturation of beneficiary plants in the same space as the benefactor plant suggests that the beneficiary may ultimately replace the benefactor, or at least that intense competition may eventually develop. Facilitative interactions may drive dynamic changes in the absence of large-scale disturbances and studies have built a large body of evidence for the importance of facilitation during primary and secondary succession. Due to the exceptionally harsh initial physical conditions common during primary succession, facilitation may be of greater importance here than in secondary succession. Nurse plant relationships also appear to be more common during early stages of succession than during later stages (Callaway 1995). Milton (2002, personal communication), however, suggests that pioneers are often short-lived annuals and succulents that die during dry conditions, appearing to require no facilitation as they are in the form of seeds when harsh conditions occur. As the succulent communities mature from early to late succession, community complexity increases largely to shade succulents and climbers, both of which require facilitators, however, there is still much debate around these ideas and further research is needed.

In a qualitative theoretical model proposed by Hacker and Gaines (1997) it is predicted that direct positive interactions increase species diversity by facilitating species that might not normally survive under very high physical disturbance, stress or predation. The model also suggests that, under intermediate physical disturbance, stress or predation, facilitator species that might normally be competitively excluded are released from competition, suggesting that facilitator species might create new interaction webs that would not be possible in their absence.

According to Cowling and Hilton-Taylor (1999), it appears that community membership in the Namaqualand-Namib Domain of the Succulent Karoo is determined by a lottery process whereby functionally equivalent shrubs coexist in highly dynamic communities. A predictable winter rainfall and fog-ameliorated summers provide conditions for continuous recruitment, with occasional droughts rearrange emerging competitive hierarchies through the mass death of shallow-rooted and drought intolerant succulent shrubs.

In higher rainfall areas of the karoo, perennial plants appear to control the abundance of ephemerals through competition for water. This results in spatial and temporal heterogeneity in the density and performance of ephemerals within a landscape. Improved survival, growth and seed production of ephemerals occurs when and where large or small disturbances, such as drought, grazing, vegetation clearing and soil excavation, kill or reduce perennial grasses or shrubs (Milton *et al.* 1999).

In studies on the dynamics of Succulent Karoo vegetation it was found that the open areas in the interstices of the existing vegetation are colonised by mound building species of Mesembryanthemaceae. Mounds are built by the capture of wind and water transported sands and organic material at their bases. Later these species serve as sites of establishment for seedlings of several species of woody shrubs. Eventually the woody shrubs through interspecific competition replace the mound-building mesembs (change from facilitation to competition). Woody shrubs then persist in the community until they reach senescence and die or are removed by other means. Superimposed on this dynamic pattern is a further temporal pattern involving a combination of disturbance by burrowing vertebrates or termites, and subsequent soil changes (Yeaton and Esler 1993). Termites (*Microhodotermes viator*), form "heuweltjies" (Mima-like mounds causing heterogeneity in soil fertility (Milton and Dean 1990)), which play a role in increasing soil fertility through the collection and breakdown of litter. Heuweltjies are a rich source of titanium deposits (part of the ore body mined at Namakwa Sands) and are mined more deeply than the surrounding soil. Mining operations would destroy heuweltjie processes, and could take hundreds of years to be re-established. This could have a considerable impact on subsequent plant life and vegetation patterns in the area (Picker 1989).

Spatial analysis of two Namaqualand Strandveld plant communities (Eccles *et al.* 1999) revealed a definite spatial pattern. The interpretation that best suited the clumping pattern found was that the dominant form of interaction between individuals is direct facultative mutualism. Wind and the seed trapping effect of existing vegetation play a key role in the dispersal and maintenance of the clumped vegetation structure of many species. Where seed dispersal is limited, seeds may simply fall below the parent plant where they germinate and grow, also promoting the formation of a clumped vegetation structure. It was felt that the models of maturation thinning, cyclical succession and the nurse plant effect (as described earlier) did not explain the pattern observed, and that the interactions between plants in the communities investigated were dominated by direct facultative mutualisms (Eccles *et al.* 1999).

Eccles *et al.* (1999) suggests the mechanisms at work within Strandveld communities may fall within the ecosystem engineer concept. Ecosystem engineers are organisms that physically modify, maintain and create habitats. This could be through the processes of soil enrichment, seed trapping and increased water infiltration. In terms of community processes, it is important to establish that these interactions can be stable. Recent work has suggested that the juxtaposition of positive and negative interactions is important in constraining these mutualisms, and in this way stabilising them. The concept of net interactions again becomes important and the balance between positive and negative interactions will dictate stability, and will play a central role in determining the spatial patterns that will emerge in the communities. The authors conclude that the clumped vegetation pattern observed in the Strandveld communities investigated is the product of a positive feedback between substantial physical benefits associated with mutual shading and microhabitat modifications (ecosystem engineering) and the dominant seed dispersal strategies of the plant community.

CONCLUSION

Species interactions are potential driving forces for successional change. Three models of succession based on species interactions: facilitation, tolerance, and inhibition have been put forward by Connell and Slatyer (1977). In the facilitation model, the entry of new species into a habitat is made possible by other species altering conditions or resource availability. This is particularly true for seed germination and for early seedling survival and is exemplified by the nurse plant phenomenon, whereby established plants protect seedlings of other species from stresses such as grazing, trampling, high temperatures, freezing and desiccation. The tolerance model suggests that a predictable sequence of species is produced in a habitat because different species have different strategies for exploiting resources. Species that appear later in succession can tolerate lower resource levels and can grow and reproduce in the presence of earlier species, eventually out competing them. Inhibition occurs when a species prevents establishment of other species. Late species gradually accumulate by replacing individuals of pioneer species when they die (Pyke and Archer 1991; Whisenant 1999).

When the harsh conditions occurring on post-mined areas of Namakwa Sands are considered in the context of facilitation and competition, one would assume that any plants occurring on the site would have a facilitative effect for rehabilitation. If one were to transplant plants from areas to be mined to post-mined areas these transplants should provide some form of facilitation. This facilitation could be in the form of creating a microclimate conducive to seed germination due to decreased temperatures and evapo-transpiration. Transplants would also increase water infiltration and could accumulate nutrients. These plants would also act as seed traps and reduce wind speed.

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CHAPTER 4

DOES SOIL TREATMENT AFFECT THE SOIL FERTILITY AND SOIL CHEMICAL PROPERTIES OF STRIP-MINED AREAS?

ABSTRACT

The effects of soil treatment during a strip-mining operation on soil fertility and soil chemical properties in the arid, winter rainfall West Coast of South Africa are examined. It is thought that soil treatment may influence soil fertility and soil chemical properties within stockpiled topsoil and tailings (mined soil) of post-mined areas, leading to a delayed recovery of natural vegetation on these areas. A fertility bioassay showed radishes in undisturbed soil grew significantly better compared to those grown in disturbed (stockpiled topsoil and tailings) soil. Soil chemical analysis showed that there were significant changes in soil chemistry when soils were either stockpiled, mined or when mineral concentration took place. Mining and mineral concentration decreased phosphorus, potassium, calcium, magnesium, and carbon and nitrogen levels significantly relative to other soil treatments. Sodium in undisturbed subsoil increased significantly to toxic levels after mineral concentration. Decreased electrical resistance in tailings indicated a high proportion of free salts and a consequent high salinity in tailings. I conclude that soil treatment does affect soil fertility and soil chemistry, however the chemical composition of stockpiled topsoil remains more similar to undisturbed topsoil and subsoil compared to tailings. Spreading of stockpiled topsoil over tailings may ameliorate harsh conditions created by mineral concentration.

Key Words: fertility bioassay, soil analyses, strip mines, arid areas, restoration ecology.

INTRODUCTION

The process of topsoil stockpiling during strip-mining operations is known to alter soil properties such as pH, fertility (C/N ratio), salinity, nutrient cycling and soil aggregation (Abdul-Kareem and McRae 1984; Visser *et al.* 1984a; Visser *et al.* 1984b; Galajda 1999; Strohmayer 2002). These changes may affect germination and survival of seedlings, causing an overall change in the biodiversity of revegetation and influencing the establishment of a self sustaining vegetation cover on post-mined areas. However, it has been stated that the use of stockpiled topsoil in rehabilitation is vital to achieving a suitable plant cover on post-mined areas (Rethman *et al.* 1999; Rokich *et al.* 2000). Maximising the value of stockpiled topsoil as an amendment is necessary and while topsoil is in stockpile no significant changes in chemical, physical and biological properties should take place (Visser *et al.* 1984a). It is known that soil is an ecosystem composed of physical, chemical and biological components and the disturbance of the topsoil ecosystem affects all three components (Rivers *et al.* 1980). The full effects of storing topsoil are not known. Testing and inventorying of stockpiled topsoil and tailings (mined soil) to anticipate potential rehabilitation problems is recommended (Sharma and Gough 1999).

Namakwa Sands Pty (Ltd) is currently strip-mining large tracts of the arid, winter rainfall area of coastal Namaqualand for heavy mineral concentrate (ilminite, rutile and zircon minerals). During the mining process large areas of natural vegetation are destroyed. According to the Mining Rights Act No. 20 of 1967, the Environment Conservation Act of 1988 and the Minerals Act No. 50 of 1991, rehabilitation of mined areas is compulsory for commercial mines. During the processes of rehabilitation at Namakwa Sands the mine aims to restore the area to a vegetation type and productivity equivalent to the pre-mining capabilities of the site, as described by de Villiers *et al.* (1999), which was originally used for small stock farming (Environmental Evaluation Unit 1990). However, to date the mine has had a slow increase in the occurrence of natural vegetation on post-mined areas (T. Hälbich 2001, personal communication). In this regard it has become important to determine why the revegetation process on the mine has been slow. A possible reasons for the slow emergence of natural vegetation on post-mined sites is that soil fertility and chemical composition may be negatively affected by the treatment of either stockpiling or mining

In this study I will compare the fertility of undisturbed topsoil, stockpiled topsoil and tailings and I will test the assumption that the fertility of undisturbed topsoil is greater than stockpiled topsoil, but that stockpiled topsoil is more fertile than mine tailings. I will also test the assumption that the chemical composition of stockpiled topsoil is more similar to the chemical composition of undisturbed topsoil and subsoil compared to tailings.

METHODS

Study Site

The study site is located at Namakwa Sands Mine, in the vicinity of Brand-se-Baai (31°18'S, 17°54'E) on the Namaqualand coast, approximately 70-km west of the nearest town, Lutzville. The area has hot, dry summers (November – January) and rain during the cooler, moist winter months (May – August) with a rainfall average of 160-mm per annum. Rainfall is augmented by heavy dew falls and sea fogs leading to a cumulative average annual precipitation of 282 mm per annum measured over four years. The study site is considered to be extremely arid (Environmental Evaluation Unit 1990; de Villiers 2000). The average annual temperature is 15.8°C with little seasonal temperature fluctuation due to the marine influence on the study site. The maximum average monthly temperature is 24.1°C in summer (January) and the minimum monthly average temperature is 7.5°C in winter (July) (Environmental Evaluation Unit 1990).

Winds blow with the highest frequencies from the south and south south east during spring and summer (September to March). Less frequent but stronger winds blow from the north and north north east during winter (June to August). Easterly berg winds blow from the interior, bringing hot, dry conditions to the coast. The main agent of erosion on the study site is regarded as being wind with summer afternoon winds being strong enough to mobilise vast quantities of surface sand from ground level. Wind speeds reach a peak velocity between 16h00 and sunset and are at a minimum at 06h00 in summer and 10h00 in winter. Mining aggravates this erosion process by removing the stabilising effect of the natural vegetation (Washington 1990).

The inland area on which the mine occurs is undulating and covered with vegetated sand dunes, which are aligned roughly parallel to the prevailing wind direction, which is north-south (Environmental Evaluation Unit 1990; Watkeys 1999). Grey regic sands bordering the ocean are recent aeolian deposits that show little evidence of pedogenesis (soil formation). Inland of these the soils are derived from the underlying Proterozoic rocks with variable amounts of aeolian contribution, decreasing towards the escarpment. Yellow, high-base soils occur nearest the coast, consisting of moderately deep uniform coarse-textured sand, usually underlain by a more clayey neocutanic horizon. A transition zone of yellow-red soils separates these from the most common soil of the West Coast, a red, high base status soil, which is weakly structured, freely drained with a medium to course texture and variable thickness (Watkeys 1999).

At Namakwa Sands mine the dunes along the coast are generally light grey coloured becoming progressively more red further away from the coast. The red terrestrial deposits are derived from orange feldspathic sands. A thick overburden of marine and aeolian sediments overlies older basement rocks of the Namaqualand granite-gneiss suite and metamorphosed Vanrynsdorp Group rocks (Environmental Evaluation Unit 1990). It is these terrestrial deposits which often display heavy mineral enrichment. Soils tend to be saline and alkaline with a pH between six and seven (Ellis 1988; Environmental Evaluation Unit 1990; de Villiers 2000). The topography of the study site can be broadly described as undulating flats with a low relief (Ellis 1988). The rehabilitation study site is relatively flat in the south, becoming slightly steeper in the north. There is a slight drainage line within the translocation study area running from south west to north east. Heuweltjies (Mima-like mounds) are a feature of the mine site (Picker 1989), playing a role in increasing soil fertility though the collection and breakdown of litter resulting in heterogeneity in soil fertility (Milton and Dean 1990).

For this study undisturbed soil at Namakwa Sands has been divided into two portions: that portion (the top 5 cm) that is removed and stored as stockpiled topsoil, which I will call topsoil; and the remainder of the soil profile which is mined, which I will call subsoil.

The mining process at Namakwa Sands influences the potential changes occurring in soils and begins with the removal, by bulldozer, of the top layer of sand (approximately 50-mm) together with vegetation from a strip to be mined. Topsoil together with plant remains and organic debris are stored in stockpiles, usually for a period of three months. Hydraulic excavators mine the subsoil, continually moving forward from mined to un-mined ground. Subsoil is transported to a mineral concentration plant via conveyer belt, and seawater is used to wash all the mined soil during mineral concentration. The residue left after mineral concentration has two components, the sand portion (tailings) and the slimes (clay) portion. The clay proportion is separated from the sand proportion and stored in slimes dams. The sand tailings are deposited into the mined out area (Environmental Evaluation Unit 1990). Deposited sand tailings are shaped to fit the contours of the surrounding land and stockpiled topsoil is spread over the contoured tailings. It has been shown in numerous studies that one of the most effective ways to encourage the revegetation of disturbed areas is through the spreading of topsoil (Australian Mining Industry Council 1990; Rethman *et al.* 1999; de Villiers 2000). Wind has been identified as having major erosion potential on Namakwa Sands (Washington 1990). To reduce wind speed and potential damage to plants on rehabilitation areas, windbreaks are erected on stockpiled topsoil spread over tailings. Windbreaks consist of polyethylene shade net (40% shade) approximately 1-m high, with vertical pockets sown into them to hold metal droppers. These metal droppers are then hammered into the sand to keep the nets upright. Windbreak nets are placed at 4 to 5-m intervals perpendicular to the dominant wind directions (T. Hälbich 2002, personal communication).

Fertility Bioassay

All soil was collected over a two-day period (23 and 24 April 2001) using a hand spade. Three treatment sites; undisturbed soil (a site in front of the mine face, not yet mined); stockpiled topsoil (recently spread over the tailings) and tailings were selected. Ten samples (1 kg each) were collected from each site. Each sample comprised 10 sub-samples of 50-mm deep spaced 7 m apart. Soil samples were marked and transported to the University of Stellenbosch Department Conservation Ecology Nursery. Each soil sample was placed into a single plastic seedling pocket. Radishes (*Raphanus sativus*) were selected for use as an indicator of soil fertility in the bioassay, as they are fast growing and the effects of nutrient imbalances on their morphology are well documented (Skinner and Purvis 1949). Three radish seeds were planted into each bag. Seedling pockets were randomly placed on a single nursery bench and watered (using an automated watering system) to stimulate germination. Seedling pockets were randomly shifted on the nursery bench on a weekly basis to ensure that variations in watering, light and airflow did not influence germination and growth. Once seedlings had germinated, seedlings were randomly thinned to one seedling per pocket. Radish seedlings were grown for a period of approximately six weeks, at which stage most plants had formed swollen roots. At six weeks all radish plants were harvested and washed in water keeping as many fine roots intact as possible. Roots (including the bulb) were severed from the leaves. Roots and leaves were oven dried at 70°C for 24 hours and weighed, separately.

Soil Chemical Analysis

Soil was collected from four treatment sites (undisturbed topsoil and undisturbed subsoil at sites still to be mined, stockpiled topsoil heaps and tailings heaps) over a two-day period (8^{th} and 9^{th} September 2002). Undisturbed topsoil collection was restricted to the top 50-mm of soil. Subsoil was collected at a depth of between 50 and 80-mm below the soil surface. Stockpiled topsoil and tailings were sampled from at least 80-mm below the surface of the soil heap. A total of 8 soil cores (50-mm deep, 47-mm in diameter) was collected for each of seven samples per treatment.

Samples were marked and sent for analysis at BemLab (Pty) Ltd[1]. Analyses were carried out for soil pH, electrical resistance, exchangeable cations, available phosphorus, total nitrogen and organic carbon.

STATISTICAL ANALYSIS

Fertility Bioassay

Data obtained for dry leaf and dry root weights were tested for homogeneity of variance and a normal distribution using Levene's Test and the Kolmogorov-Smirnov Test, respectively. Data for dry leaf weight and dry root weights were not homogenous or normally distributed and underwent a Box-Cox Transformation (Krebs 1989). Once data were transformed the assumptions of homogeneity of variance and a normal distribution were satisfied enabling parametric statistics to be used on the data (Zar 1999). An ANOVA (analysis of variance) was used to compare transformed radish dry leaf weight data and radish dry root weight data. Post-hoc comparisons were carried out used the Scheffe Test. The ANOVA and post-hoc comparisons were executed within the STATISTICA Program (StatSoft Incorporated 2002).

Soil Samples: Chemical Analysis

Data obtained for soil pH, resistance, exchangeable cations (%), phosphorus (mg/kg), nitrogen (%) and organic carbon (%) were tested for normality and homogeneity of variance (Levene's Test and the Kolmogorov-Smirnov Test, respectively). Due to all data sets, except C%, not adhering to these assumptions, resampling statistics were used on soil nutrient data. Resampling statistical tests were carried out on data for pH, resistance, sodium (Na), calcium (Ca), magnesium (Mg) and percentage nitrogen (N%) (Microsoft Corporation 1998). The Bonferroni adjustment was applied to the 5% confidence level, which was then reset at 1.25% (or the 98.75% confidence level; p significant at 0.013). Resampling methods do not rely on assumptions about how data are distributed (parametric vs. non-parametric data). Permutation methods for significance testing have the added advantage that they produce p-values that can be used for comparison purposes (Microsoft Corporation 1998). All graphic results are presented as untransformed box and whiskers plots for comparisons.

[1] BemLab (Pty) Ltd. 2002. AECI Building W21, De Beers Road, Somerset West, Western Cape.

RESULTS

Fertility Bioassay

Radishes grown in undisturbed topsoil grew significantly larger (dry root weight and dry leaf weight) than in stockpiled topsoil and tailings (significance at $p < 0.05$). However, there was no difference in dry root weight and dry leaf weight between the stockpiled topsoil and the tailings (Figure 4.1 and Figure 4.2, respectively).

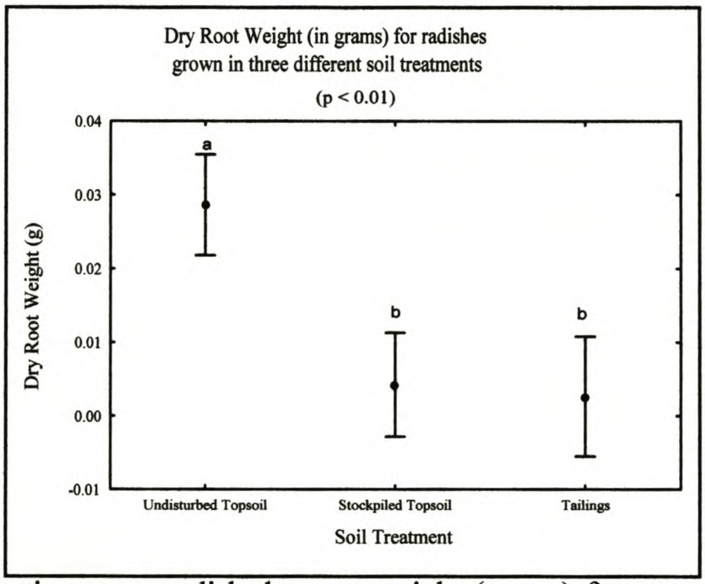

Figure 4.1: Plot indicating mean radish dry root weight (grams) for treatments of undisturbed topsoil, stockpiled topsoil and tailings. Vertical bars indicate 95% confidence intervals. Treatments with the same letter are not significantly different. (Values below 0.0-g are a statistical anomaly due to working with means and 95% confidence limits.)

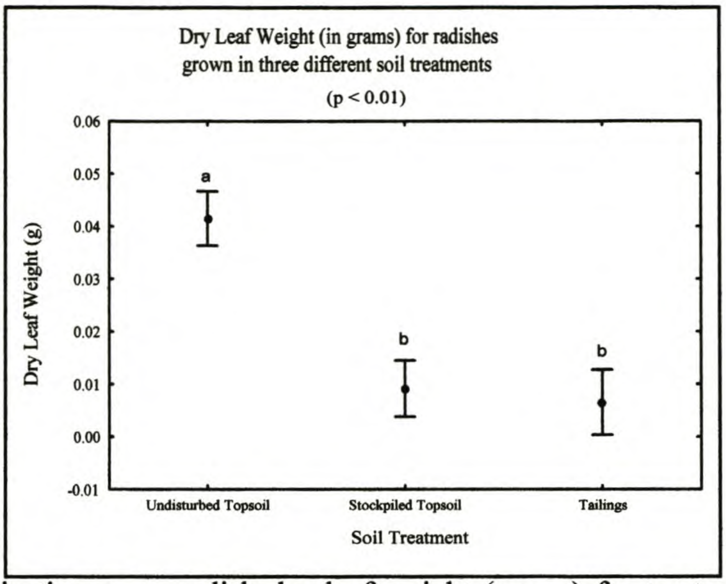

Figure 4.2: Plot indicating mean radish dry leaf weight (grams) for treatments of undisturbed topsoil, stockpiled topsoil and tailings. Vertical bars indicate 95% confidence intervals. Treatments with the same letter are not significantly different. (Values below 0.0-g are due to a statistical anomaly caused by working with means and 95% confidence limits.)

Soil Samples: Chemical Analysis

A full list of soil chemical analysis results, as supplied by BemLab (Pty) Ltd, is given in Appendix 4.1.

pH

Undisturbed topsoil had a significantly lower pH than stockpiled topsoil and tailings. Subsoil from undisturbed sites had a significantly lower pH than stockpiled topsoil and tailings. Stockpiled topsoil had significantly higher pH than tailings. pH levels in topsoil and subsoil from undisturbed sites did not differ at the 5% confidence level (Figure 4.3).

Electrical Resistance

Tailings had significantly lower electrical resistance than all other soil treatments. Stockpiled topsoil had significantly lower electrical resistance than topsoil from undisturbed sites, but was not significantly different from subsoil from undisturbed sites. Electrical resistance in topsoil from undisturbed sites was not significantly different from subsoil from undisturbed sites (Figure 4.4).

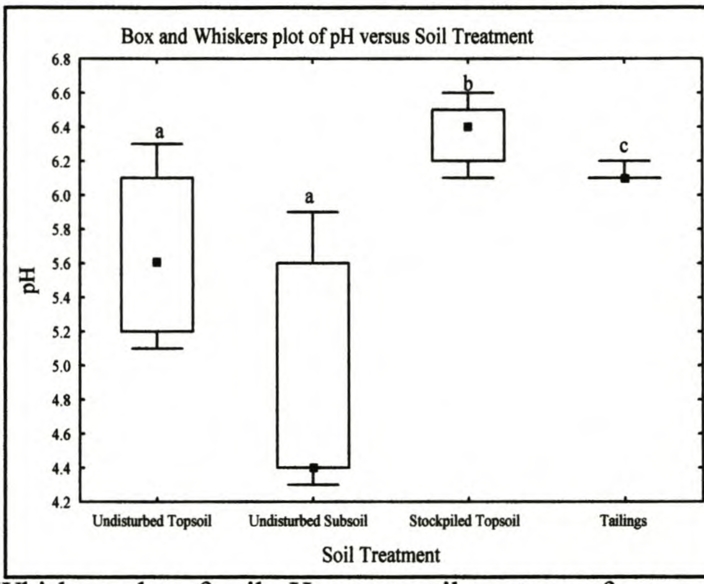

Figure 4.3: Box and Whiskers plot of soil pH versus soil treatment for topsoil and subsoil from undisturbed sites, stockpiled topsoil and tailings. Whiskers indicate minimum and maximum values. Rectangular boxes indicate the 25% to 75% quartiles, and the small solid box indicates the median value. Treatments with the same letter are not significantly different.

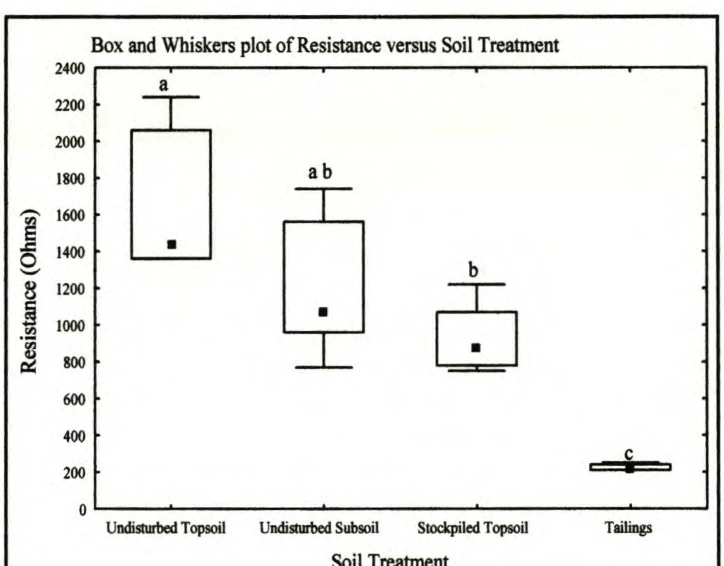

Figure 4.4: Box and whiskers plot of electrical resistance versus soil treatment for topsoil and subsoil from undisturbed sites, stockpiled topsoil and tailings. Whiskers indicate minimum and maximum values. Rectangular boxes indicate the 25% to 75% quartiles, and the small solid box indicates the median value. Treatments with the same letter are not significantly different.

Available Phosphorus (P)

Results showed available phosphorus levels in tailings to be significantly lower than for all other soil treatments. Topsoil from undisturbed sites had significantly higher phosphorus levels than subsoil from undisturbed sites and stockpiled topsoil. Subsoil from undisturbed sites and stockpiled topsoil were not significantly different (Figure 4.5).

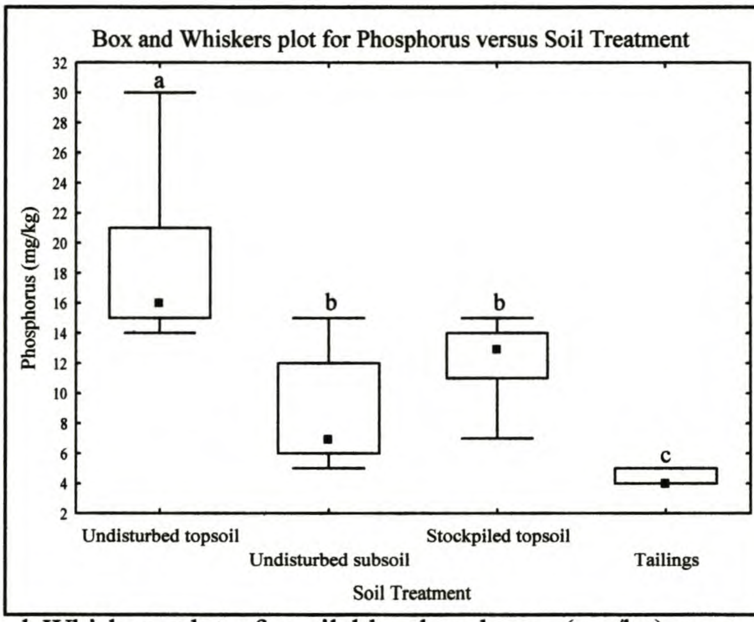

Figure 4.5: Box and Whiskers plot of available phosphorus (mg/kg) versus soil treatment for topsoil and subsoil from undisturbed sites, stockpiled topsoil and tailings. Whiskers indicate minimum and maximum values. Rectangular boxes indicate the 25% to 75% quartiles, and the small solid box indicates the median value. Treatments with the same letter are not significantly different.

Sodium (Na)

Sodium levels in topsoil from undisturbed sites were significantly lower than for all other soil treatments. Subsoil from undisturbed sites and stockpiled topsoil had significantly lower sodium levels compared to tailings. Sodium levels were not significantly different for stockpiled topsoil and subsoil from undisturbed sites (Figure 4.6). Results are given in exchangeable sodium percentage (ESP), which is the percentage cation exchange capacity of the soil occupied by sodium (van der Watt and van Rooyen 1995).

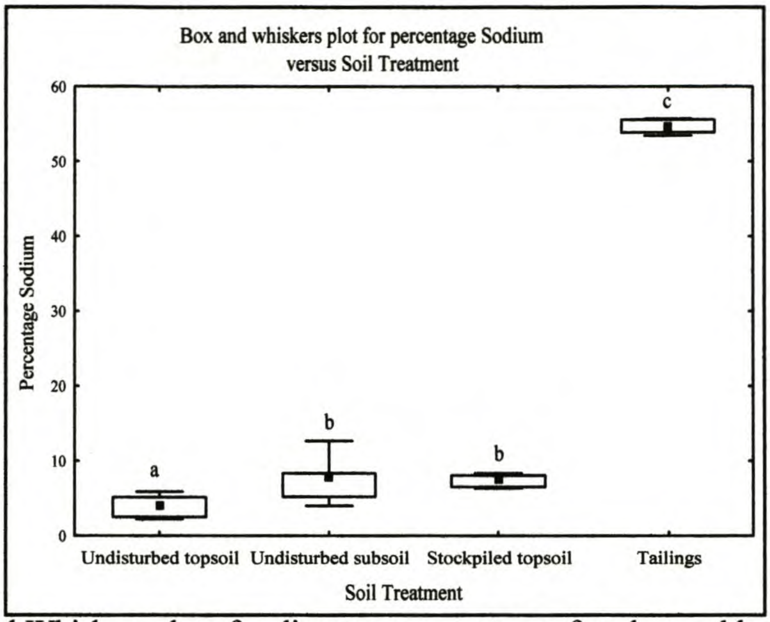

Figure 4.6: Box and Whiskers plot of sodium as a percentage of exchangeable cations versus soil treatment for topsoil and subsoil from undisturbed sites, stockpiled topsoil and tailings. Whiskers indicate minimum and maximum values. Rectangular boxes indicate the 25% to 75% quartiles, and the small solid box indicates the median value. Treatments with the same letter are not significantly different.

Potassium (K)

Tailings had significantly lower levels of potassium compared to all other soil treatments. Potassium levels in topsoil from undisturbed sites were not significantly different from levels in either subsoil from undisturbed sites or stockpiled topsoil. Stockpiled topsoil had significantly higher levels of potassium compared to subsoil from undisturbed sites (Figure 4.7). Results are given as a percentage of the extractable base cations occupied by potassium.

Calcium (Ca)

Results found that tailings had significantly lower calcium levels compared to all other soil treatments. Topsoil and subsoil from undisturbed sites and stockpiled topsoil were not significantly different at the 5% confidence limit. Subsoil from undisturbed sites was not significantly different from stockpiled topsoil (Figure 4.8). Results are given as a percentage of the extractable base cations occupied by calcium.

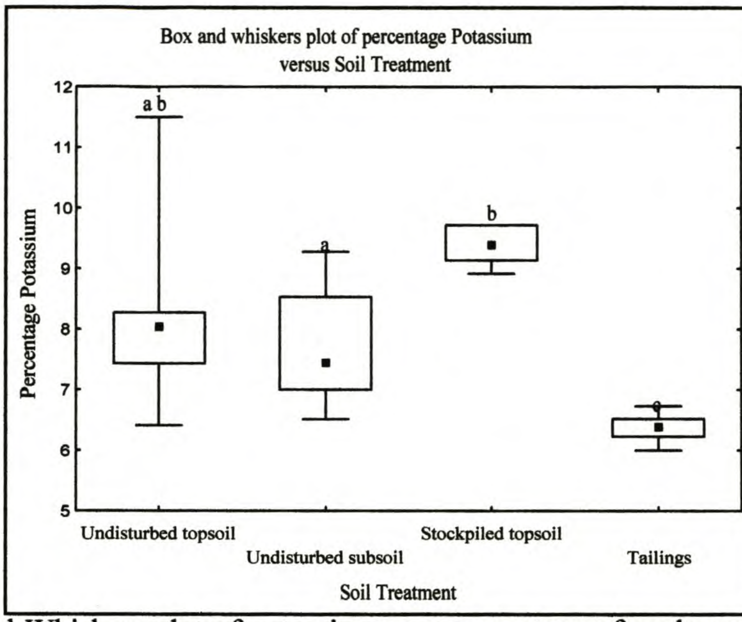

Figure 4.7: Box and Whiskers plot of potassium as a percentage of exchangeable cations versus soil treatment for topsoil and subsoil from undisturbed sites, stockpiled topsoil and tailings. Whiskers indicate minimum and maximum values. Rectangular boxes indicate the 25% to 75% quartiles, and the small solid box indicates the median value. Treatments with the same letter are not significantly different.

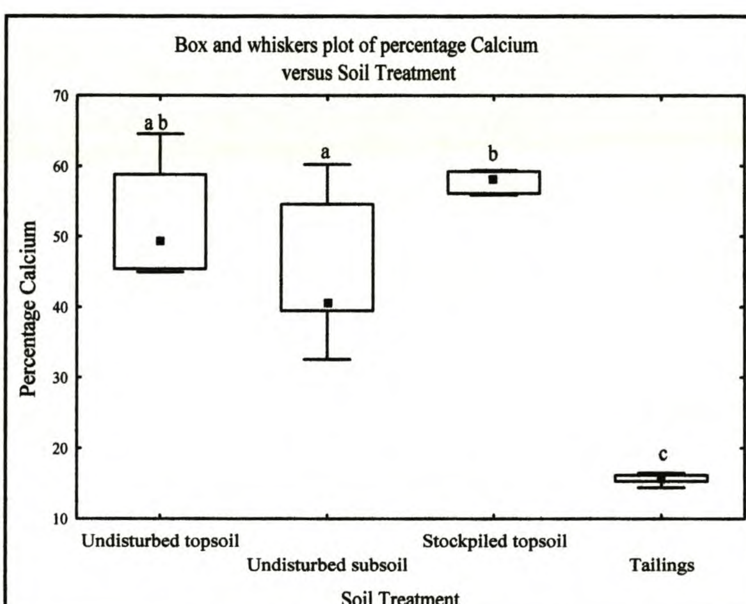

Figure 4.8: Box and Whiskers plot of calcium as a percentage of exchangeable cations versus soil treatment for topsoil and subsoil from undisturbed sites, stockpiled topsoil and tailings. Whiskers indicate minimum and maximum values. Rectangular boxes indicate the 25% to 75% quartiles, and the small solid box indicates the median value. Treatments with the same letter are not significantly different.

Magnesium (Mg)

Magnesium levels in topsoil and subsoil from undisturbed sites were not significantly different. Both topsoil and subsoil from undisturbed sites had significantly higher magnesium levels compared to tailings and significantly lower magnesium levels compared to stockpiled topsoil. Stockpiled topsoil had significantly higher magnesium levels than tailings (Figure 4.9). Results are given as a percentage of the extractable base cations occupied by magnesium.

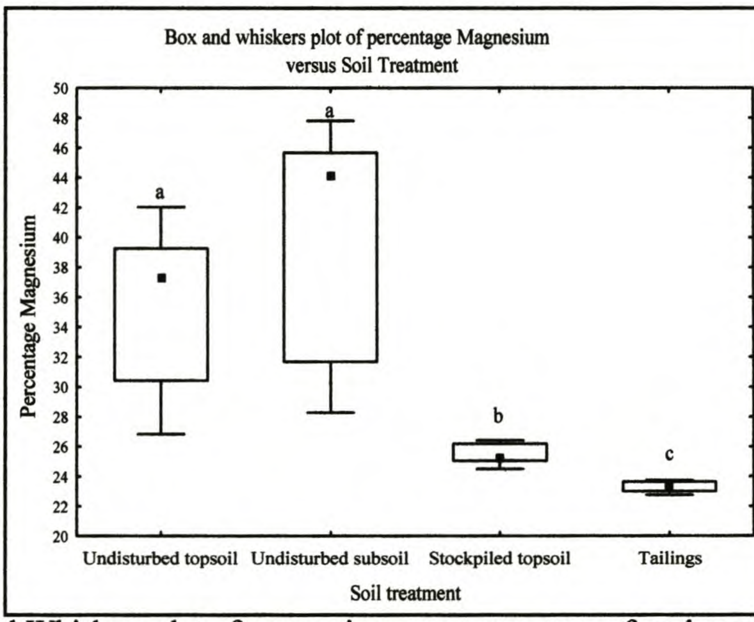

Figure 4.9: Box and Whiskers plot of magnesium as a percentage of exchangeable cations versus soil treatment for topsoil and subsoil from undisturbed sites, stockpiled topsoil and tailings. Whiskers indicate minimum and maximum values. Rectangular boxes indicate the 25% to 75% quartiles, and the small solid box indicates the median value. Treatments with the same letter are not significantly different.

Percentage Nitrogen (N%)

Nitrogen levels in tailings were significantly lower than for all other soil treatments (topsoil and subsoil from undisturbed sites and stockpiled topsoil). There was no significant difference in the nitrogen between the treatments of topsoil and subsoil from undisturbed sites and stockpiled topsoil (Figure 4.10).

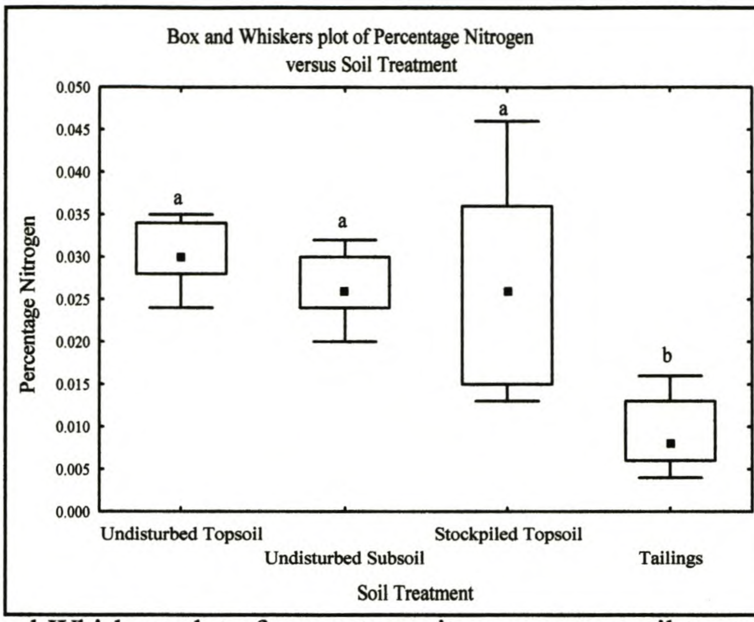

Figure 4.10: Box and Whiskers plot of percentage nitrogen versus soil treatment for topsoil and subsoil from undisturbed sites, stockpiled topsoil and tailings. Whiskers indicate minimum and maximum values. Rectangular boxes indicate the 25% to 75% quartiles, and the small solid box indicates the median value. Treatments with the same letter are not significantly different.

Percentage Carbon (%C)

Percentage carbon in tailings was found to be significantly lower than the percentage carbon in any of the other soil treatments (topsoil and subsoil from undisturbed sites and stockpiled topsoil). The percentage of carbon in all other treatments (topsoil and subsoil from undisturbed sites and stockpiled topsoil) were not significantly different (Figure 4.11).

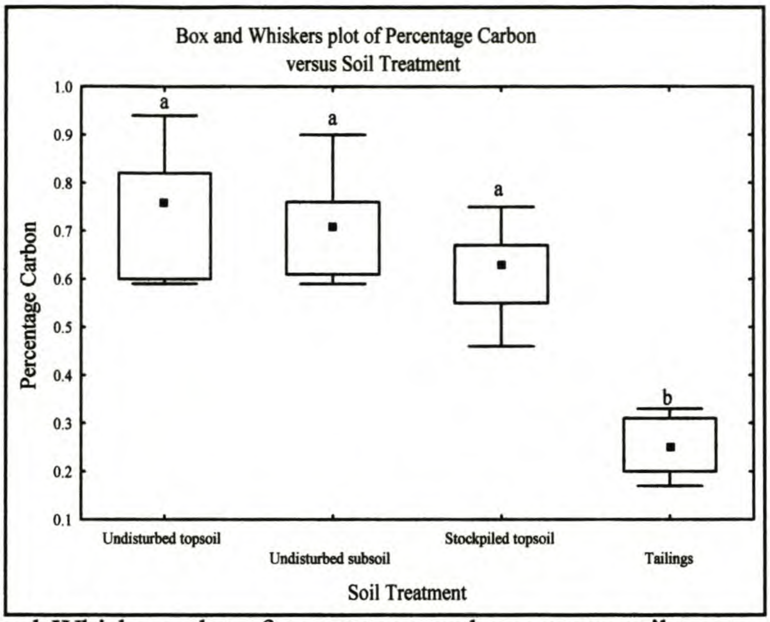

Figure 4.11: Box and Whiskers plot of percentage carbon versus soil treatment for topsoil and subsoil from undisturbed sites, stockpiled topsoil and tailings. Whiskers indicate minimum and maximum values. Rectangular boxes indicate the 25% to 75% quartiles, and the small solid box indicates the median value. Treatments with the same letter are not significantly different.

DISCUSSION

Nutrient related processes in natural vegetation are vital to plant functioning and degraded landscapes are often found to be deficient in the major nutrients. The nutrient limitations of any degraded landscape should be addressed through the restoration of organisms that recycle nutrients from litter to the soil. Rather than focusing on the amounts of nutrients it may be more meaningful to focus on the restoration of the functioning of nutrient processes. Soil that originally occurred on the site that has been damaged or is in need of repair ought to be considered. The mine should attempt to develop healthy soils, which are comparable to soils that occurred on the mine site prior to mining, as local plant species are adapted to those particular soil conditions (Whisenant 1999).

Topsoil is regarded as a highly effective amendment for improving the chemical and physical properties of tailings or mine spoil, with the potential to greatly enhance primary productivity and the rate of revegetation (Visser *et al.* 1984a). When soil nutrients are compared between treatments for Namakwa Sands it is important to note that undisturbed topsoil should be compared to stockpiled topsoil, as it is important to determine if the undisturbed topsoil is affected by stockpiling or disturbance. Results from stockpiled topsoil and undisturbed subsoil should be compared to tailings, as the mining of subsoil creates tailings and it is also important to determine if stockpiled topsoil is of a better quality than tailings. If the re-spreading of stockpiled topsoil is to be effective it is important that stockpile soil quality is as close as possible to that of undisturbed topsoil, whereas the tailings should be of a quality similar to that of undisturbed subsoil.

Mining Effects on Soil Fertility and Chemistry

Studies of the effect of mining on soils have shown that soil form and structure are affected by mining techniques. Most studies have concentrated on changes in stockpiled topsoil, not on post-mined soils (tailings) (Abdul-Kareem and McRae 1984; Visser *et al.* 1984a; Visser *et al.* 1984b; Galajda 1999; Strohmayer 2002). Sharma and Gough (1999) showed that mine spoil was extremely low in organic carbon. Harris *et al.* (1993) found that total nitrogen in stockpiled topsoil at depths of 1.8-m and lower did decrease significantly. The fertility bioassay carried out in this study showed that the soil treatments of stockpiled topsoil and tailings did lower soil fertility, which is in agreement with the finding of Schmidt (2002), which indicated that soil fertility decreased when soils were removed and stockpiled. Plants grown in undisturbed soil showed better growth than plants grown in samples of stockpiled soil or tailings.

Most plants obtain optimal growth at a neutral pH, with acidic soils inhibiting plant growth by limiting nutrient availability (Australian Mining Industry Council 1990). Soil pH affects the solubility of plant nutrients and can affect plant growth indirectly by suppressing bacterial growth at pH extremes (Weier *et al.* 1982). In analyses carried out it was determined that the topsoil and subsoil from undisturbed sites tended to have a medium acidity, which became significantly more alkaline when in stockpile and after mining. A more alkaline pH of between 6 and 8 has been shown to make the nutrients nitrogen, phosphorus, potassium, calcium and magnesium more available for plants (Figure 4.12) (Australian Mining Industry Council 1990). The fact that seeds and plants occurring on Namakwa Sands are naturally adapted to the pH of undisturbed topsoil and subsoil must be considered. Although the change in pH is significant, it is a small change, and is unlikely to have a significant effect the plant growth on rehabilitation areas.

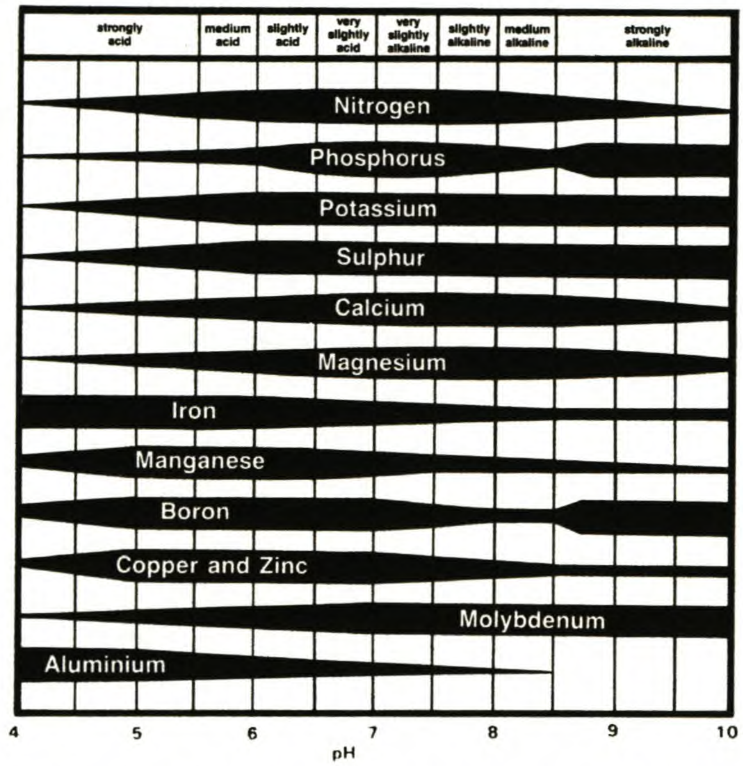

Figure 4.12: Effect of pH on soil nutrient availability (Australian Mining Industry Council 1990).

The decreased resistance in tailings compared to all other soil treatments indicates an increase in soluble salts (free salts) in tailings, which is most likely due to the subsoil being washed with sea water during heavy mineral concentration (see results and discussion for sodium). This indicates saline conditions, with a resultant potential osmotic effect and the possibility of Na and/or Cl toxicity, which could have a negative effect on plant growth.

Phosphorus plays a role in plant energy transformation and biosynthetic reactions (Weier *et al.* 1982). The mining of soil did lower phosphorus levels in tailings significantly from levels found in undisturbed subsoil. Phosphorus levels observed in undisturbed topsoil decreased when in stockpile. The effect of stockpiling topsoil on phosphorus levels has been shown before (Abdul-Kareem and McRae 1984). Stockpiled topsoil phosphorus levels remained significantly higher than those measured in tailings, indicating that the spreading of stockpiled topsoil over tailings might ameliorate reduced phosphorus levels in the tailings, providing conditions more conducive to seedling germination and survival.

High levels of salt in the soil (known as soil salinity) coupled with low levels of available water are known to restrict plant growth. The two main factors affecting plant growth under these conditions are a high osmotic concentration resulting in low water potential and the presence of potentially toxic levels of sodium and other ions. Salinity is generally measured in ESP (exchangeable sodium percentage). Ellis (2002, personal communication) suggests that an ESP higher than 10 could be considered as toxic for the Namaqualand region. Reasons for the increased sodium levels in stockpiled topsoil compared to undisturbed topsoil are unclear. However, sodium levels in stockpiled topsoil are not at a toxic level and may not have a negative effect on rehabilitation success. However, further investigation into the change in sodium levels in stockpiled topsoil is needed. Sodium levels in tailings (ESP = 54.68±0.82) were significantly higher than for all other soil treatments (undisturbed topsoil, undisturbed subsoil and stockpiled topsoil). The spreading of stockpiled topsoil over tailings may ameliorate saline conditions to some degree, creating conditions more conducive to rehabilitation. However, further measures may be necessary to ameliorate saline conditions in tailings, as the soil nutrient status of post-mined subsoil becomes more important in later rehabilitation (Australian Mining Industry Council 1990).

Some plants are halophytic (plants that can survive at high salt levels) and may be tolerant to salt spray or soil salinity. High soil salinity is known to inhibit uptake of several nutrients such as nitrate, potassium, and calcium. It has also been found that under saline stress a large portion of a plant's nitrogen capital was invested in compatible osmotic solutions such as proline and glycine betaine (Weier *et al.* 1982; de Villiers *et al.* 1997). De Villiers *et al.* (1997) found that for Namaqualand pioneer species perennials generally tolerate saline soil conditions better than ephemeral and a bi-annual species. Plant size was reduced (except *Mesembryanthemum barklyi*, a halophytic species) and biomass allocation changed towards leaves with increasing salinity. The main factor affecting growth in saline soils was sodium chloride (NaCl). De Villiers *et al.* (1997) suggest that magnesium chloride (in significant amounts in sea water) may also be toxic and could prevent colonisation of sites with soils affected by sea water, such as Namakwa Sands, unless genetically based tolerances to high salt levels occurred within colonising species. Soil analysis for Namakwa Sands however, showed decreased Mg levels in tailings compared to undisturbed subsoil (Figure 4.13). This indicates that seawater Mg is unlikely to play a role in changed soil conditions on the mine site. It must be remembered, however, that during mineral concentration the tailings are split into a clay and sand fraction and much of the magnesium may be retained in the clay fraction.

The irrigation of post mined areas with fresh water may have the benefit of leaching soil, creating a less saline environment. However, the implementation of irrigating large areas of post-mined sites may be highly impractical due to the isolated location and lack of fresh water at Namakwa Sands.

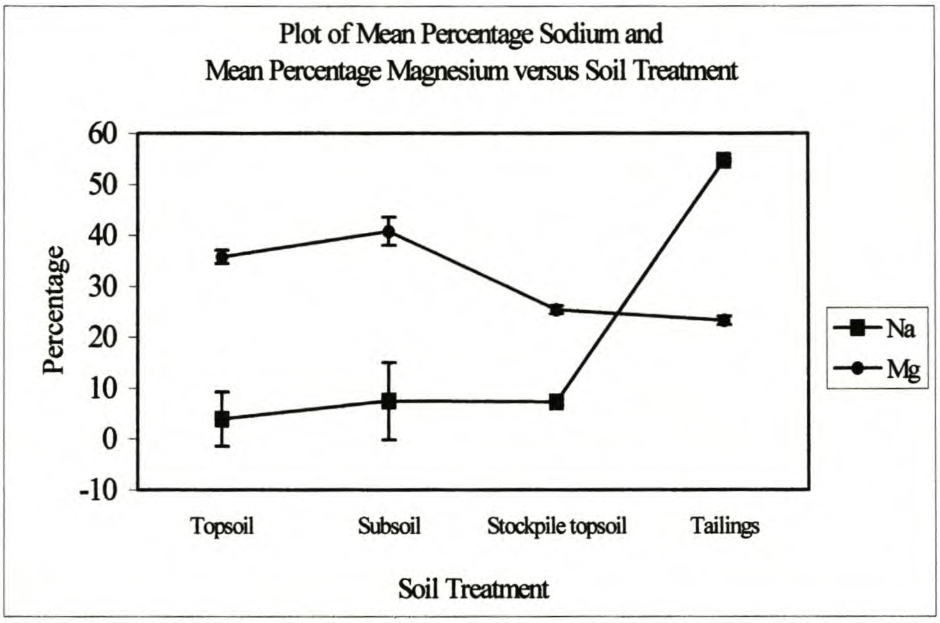

Figure 4.13: Graph depicting mean sodium as a percentage of exchangeable cations and mean magnesium as a percentage of exchangeable cations versus soil treatment. Vertical bars indicate 95% confidence intervals. Values below 0.0% are due to a statistical anomaly caused by working with means and 95% confidence limits.

The primary role of potassium in plants is that of an enzyme activator (required for maximal enzyme activity) (Weier *et al.* 1982). Symptoms of potassium deficiency are characterised by a yellowing and eventual death of the leaf margin, commonly known as *necrosis* (Foth 1990). The decrease in potassium levels in tailings compared to undisturbed topsoil and stockpiled topsoil, may be a limiting factor in revegetation efforts. Lowered potassium levels in the tailings is likely to be caused by the mineral concentration process. Spreading of stockpiled topsoil, with a potassium level not significantly different from undisturbed topsoil, but significantly higher than tailings may have an ameliorating effect on rehabilitation in post mined areas. The reason for the lack of significance between potassium levels in undisturbed topsoil and stockpiled topsoil may be due to high variability in the data obtained for undisturbed topsoil.

All green plants require calcium as it forms part of the plant cell wall. Calcium deficiency is frequently characterised by a death of the growing points of a plant (Weier *et al.* 1982). A reduced level of calcium in the tailings is likely to be caused by the processes involved in mineral concentration. This reduced calcium level in tailings may have a negative impact on rehabilitation of post-mined areas. Stockpiled topsoil has significantly higher calcium levels compared to tailings and the spreading of stockpiled topsoil over tailings may ameliorate reduced calcium levels in rehabilitation areas at Namakwa Sands.

Magnesium is a constituent of chlorophyll, where it occupies a central position in the molecule. Many enzyme reactions, particularly those involved in a transfer of phosphate, are activated by magnesium ions. Magnesium deficiency affects many aspects of plant metabolism (Weier *et al.* 1982).

Slight decreases in magnesium levels in stockpile topsoil have been noted before (Abdul-Kareem and McRae 1984). However, the decrease observed in stockpiled topsoil at Namakwa Sands should be investigated further, as this is a significant decrease from magnesium levels observed in undisturbed topsoil. It is expected that the mineral concentration process (using seawater) caused decreased magnesium levels in tailings. Low magnesium levels in the tailings may have a negative effect on rehabilitation of post-mined areas. Stockpiled topsoil has significantly higher level of magnesium than tailings, although this level was significantly lower than undisturbed topsoil and undisturbed subsoil. The spreading of stockpiled topsoil over tailings may have an ameliorating effect for revegetation on Namakwa Sands rehabilitation areas.

The rate of growth of plants is largely influenced by available nitrogen, which is very mobile in plants and can be translocated from mature to immature regions in the plant. Early symptom of nitrogen deficiency is a yellowing of the leaves, particularly the older leaves, followed by stunted growth in all plant parts. Excess nitrogen results in vigorous vegetative growth and a suppression of food storage and fruit and seed development (Weier *et al.* 1982). Nitrogen availability is maximised between pH 6 and 8, as this is the most favourable range for soil microbes that mineralise nitrogen in organic matter and those organisms that fix nitrogen symbiotically (Foth 1990).

The significant decrease in nitrogen levels in the tailings compared to all other treatments indicates that nitrogen levels in tailings may be a limiting factor in rehabilitation efforts. The washing of subsoil during the mineral concentration process possibly causes these losses in nitrogen. The loss of nitrogen may also be due to the separation of mine tailings into a clay and sand fraction, where the clay fraction contains most of the humus and therefore much of the nitrogen.

Although not observed in stockpiled topsoil at Namakwa Sands (possibly due to short stockpile time (Visser *et al.* 1984a)) studies have shown that soil nitrogen is lost while soils are in stockpile. The form in which nitrogen occurs in the stockpiled topsoil is also changed (Abdul-Kareem and McRae 1984; Davies *et al.* 1995). Davies *et al.* (1995) showed that anaerobic conditions developed below about 1-m depth in stockpiled topsoil, which could lead to an accumulation of ammonium, which corresponds with an increase in pH (Abdul-Kareem and McRae 1984). It has also been shown that nitrogen deficiencies are a common problem during reclamation of mined soils (Li and Daniels 1994). The spreading of stockpiled topsoil over tailings could help to alleviate the reduced nitrogen levels in tailings and facilitate rehabilitation of post-mined areas on Namakwa Sands. However, nitrogen in the stockpiled topsoil may be in a volatile state, that when spreading takes place nitrogen may be lost from the soil to the atmosphere (Davies *et al.* 1995). This potential negative effect of spreading stockpiled topsoil should be investigated further for Namakwa Sands.

Percentage organic carbon is an indirect measure of the amount of organic material present in soil and includes both living and dead material (Soil Classification Working Group 1991; Lambrechts *et al.* 1995). Significantly lower organic carbon level in tailings compared to all other soil treatments indicates that the mining process does negatively affect carbon levels in the tailings. This effect is possibly due to the washing of soils during mineral concentration and the subsequent separation of tailings into a sand and clay fraction, where most of the organic carbon would be concentrated in the slimes section, which is not used in rehabilitation. Although not noted in analyses for Namakwa Sand, carbon levels have been shown to decrease in stockpiled topsoil (Abdul-Kareem and McRae 1984; Visser *et al.* 1984a) and become a limiting factor in stimulating microbial metabolic activity (Galajda 1999). Decreases in carbon levels are noted as being an immediate effect of stockpiling, which may be an artefact of stockpile creation due to mixing of soil layers, rather than by biological oxidation or leaching of organic carbon (Visser *et al.* 1984a). The similar carbon levels in undisturbed topsoil and stockpiled topsoil at Namakwa Sands may be because only the top 50-mm of topsoil is pushed into stockpile and the dilution effect of mixing surface soil and subsoil may not occur. The spreading of stockpiled topsoil over tailings on post-mined areas may alleviate potential rehabilitation problems caused by reduced carbon levels in tailings.

A possible reason for the reduced phosphorus, nitrogen and carbon levels in tailings may be due to the fact that after mineral concentration, mine residue (or tailings) is separated into a slimes (clay) fraction and a sand (fines) fraction. Currently only the sand fraction is used in rehabilitation. The slimes fraction, which is stored in slimes dams, contains much of the clay and humus content of the mined soils. The slimes fraction's mineral and inorganic component was not investigated in this study and it may be that if slimes are used in rehabilitation, post-mined soils may be of a better quality for rehabilitation than if only the sand fraction is used. It is important to investigate the potential of using the slimes in rehabilitation.

MITIGATION OF MINING-RELATED SOIL CHANGES

Soil fertility is decreased by the treatment mineral concentration and this is confirmed by changes observed in carbon and nitrogen levels in the soil chemical analyses for this soil treatment. Although the problem of reduced nutrient levels can be addressed by the addition of soil fertilisers; this is an intermediate solution with short-lived results indicating that it may be unsustainable and could become extremely expensive.

Sodium in tailings is at toxic levels due to seawater washing in the mineral concentration process. This effect was reflected in the decreased resistance in tailings. Toxic levels of sodium in tailings should be ameliorated, as high sodium levels are likely to retard the revegetation process on post-mined areas. Resistance should increase as sodium levels decrease. Irrigation of rehabilitation areas with high quality water may alleviate high sodium levels in tailings. However, care must be taken to ensure that if irrigation is applied that salts that are more soluble than sodium, such as potassium are not leached out, creating further limits in rehabilitation. Watering of large tracts of land in an arid area may be highly impractical and should only be considered in extreme cases. If watering is to be considered by Namakwa Sands, it is suggested that cost-benefit studies be carried out to determine all potential scenarios.

Phosphorus, potassium, calcium and magnesium levels decreased significantly after subsoil washing. These lowered levels should be ameliorated for effective rehabilitation. Levels of these nutrients in stockpiled topsoil were significantly higher than for tailings. This indicates that the spreading of stockpiled topsoil over tailings may be an efficient means of ameliorating the lowered nutrients levels in tailings. Topsoil generally contains more of the nutrients and micro-organisms that are essential for plant growth and if lost the system will generally take longer to re-establish. Although revegetation has been achieved on various substrates, the Australian Mining Industry Council (1990) regards the use of stockpiled topsoil as an essential factor in successful rehabilitation programmes, especially during the period of initial plant growth. It is recommended that stockpiled topsoil be used in rehabilitation operations at Namakwa Sands. Subsoil condition (and thus tailings) becomes of more importance in the longer term. Studies are needed into the long-term changes that occur in tailings after they have been back-filled into post-mined areas.

Keeping the upper 50-mm of topsoil is considered not to be enough topsoil for rehabilitation. However, the stripping and storing of the upper layer of undisturbed topsoil reduces the extent to which topsoil is mixed with the subsoil that is to be mined. Mixing of topsoil and subsoil has been known to dilute the mineral concentrations in the topsoil, making it less effective in rehabilitation efforts (Rokich *et al.* 2000; Strohmayer 2002). It is also recommended that methods used in the stripping and spreading of topsoil be refined to reduce the negative effects of stockpiling topsoil. Removing the topsoil from an area to be mined and placing it directly onto contoured tailings will reduce the need for topsoil stockpiling. In this way chemical properties of topsoil may not be as adversely affected as at present. Investigation should be carried out regarding the effect that season (wet and dry) may have on the stockpiling and spreading of topsoil on rehabilitation efforts.

CONCLUSION

In this study the aspects of soil fertility and soil nutrients were examined, showing that the process of mining and mineral concentration through washing has negative effects on soil fertility and soil nutrient status. Previous studies on the effects of mining on soil nutrient status have concentrated on carbon, nitrogen and pH levels. Further investigation into the effects of mining operations on soil mineral, organic and inorganic components is also necessary to determine the full effects of mining on soil quality. Investigation into the separation of mine residue into a slimes and sand fraction is needed. Further investigations should also include site specific studies of the effects of stockpiling and mineral concentration on soil form and structure. Studies are also needed to determine how soil seed banks are affected by soil stockpiling and mineral concentration.

ACKNOWLEDGEMENTS

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APPENDIX 4.1

COMPLETE SOIL ANALYSIS RESULTS OBTAINED FROM BEMLAB (Pty)Ltd.

AECI Building W21
De Beers Road
Somerset West

P O Box 12457
Die Boord, Stellenbosch 7613

BemLab (Pty) Ltd

Reg. Nr. 2002/017933/07

Tel. (021) 851 6401
Fax (021) 851 4379
Sel. 082 804 7499
E-Mail akotze@adept.co.za

VAT Reg. No. 4160185577

Dear Kirsten Mahood

The results of your soil analyses are as follows:

Date received: 12/09/2002

Orchard No.	Lab. No.	Depth (cm)	Soil	pH (KCl)	Resist. (Ohm)	P Bray II mg/kg	K	Exchangeable cations (cmol(+)/kg) Na	K	Ca	Mg	N %	C %
Tailings 1	11640	0	Sand	6.1	230	5	53	1.17	0.14	0.35	0.52	0.006	0.17
Tailings 2	11641	0	Sand	6.1	210	5	61	1.34	0.16	0.35	0.56	0.007	0.31
Tailings 3	11642	0	Sand	6.1	220	4	63	1.49	0.16	0.42	0.61	0.016	0.20
Tailings 4	11643	0	Sand	6.1	240	4	56	1.17	0.14	0.33	0.49	0.012	0.25
Tailings 5	11644	0	Sand	6.1	210	4	49	1.10	0.13	0.33	0.47	0.013	0.29
Tailings 6	11645	0	Sand	6.2	220	4	51	1.08	0.13	0.31	0.46	0.004	0.23
Tailings 7	11646	0	Sand	6.1	250	4	49	1.04	0.12	0.32	0.46	0.008	0.33
Undisturbed Topsoil 1	11647	0	Sand	5.1	2020	15	87	0.11	0.22	0.88	0.72	0.030	0.78
Undisturbed Topsoil 2	11648	0	Sand	5.6	2060	15	83	0.10	0.21	1.28	1.01	0.035	0.61
Undisturbed Topsoil 3	11649	0	Sand	5.4	1360	16	70	0.09	0.18	1.09	0.88	0.030	0.82
Undisturbed Topsoil 4	11650	0	Sand	5.2	1360	17	64	0.09	0.16	1.16	0.78	0.024	0.60
Undisturbed Topsoil 5	11651	0	Sand	6.1	1390	21	77	0.06	0.20	1.40	0.72	0.028	0.76
Undisturbed Topsoil 6	11652	0	Sand	6.3	2240	30	131	0.12	0.34	3.38	1.40	0.034	0.94
Undisturbed Topsoil 7	11653	0	Sand	5.6	1440	14	79	0.13	0.20	1.15	1.08	0.028	0.59
Undisturbed Subsoil 1	11654	0	Sand	5.6	1140	12	69	0.11	0.18	1.13	0.66	0.026	0.59
Undisturbed Subsoil 2	11655	0	Sand	4.4	1740	8	42	0.12	0.11	0.63	0.66	0.020	0.90
Undisturbed Subsoil 3	11656	0	Sand	5.9	1070	15	100	0.14	0.25	2.05	0.96	0.030	0.76
Undisturbed Subsoil 4	11657	0	Sand	4.4	1560	5	45	0.15	0.12	0.70	0.81	0.024	0.76
Undisturbed Subsoil 5	11658	0	Sand	4.3	960	6	51	0.23	0.13	0.60	0.88	0.029	0.66
Undisturbed Subsoil 6	11659	0	Sand	4.4	770	6	51	0.14	0.13	0.71	0.78	0.026	0.71
Undisturbed Subsoil 7	11660	0	Sand	4.8	1010	7	68	0.12	0.17	0.76	0.83	0.032	0.61
Stockpiled Topsoil 1	11661	0	Sand	6.2	1220	13	88	0.19	0.23	1.48	0.64	0.036	0.62

Orchard No.	Lab. No.	Depth (cm)	Soil	pH (KCl)	Resist. (Ohm)	P Bray II mg/kg	K mg/kg	Exchangeable cations (cmol(+)/kg) Na	K	Ca	Mg	N %	C %
Stockpiled Topsoil 2	11662	0	Sand	6.4	910	15	94	0.17	0.24	1.44	0.62	0.026	0.63
Stockpiled Topsoil 3	11663	0	Sand	6.4	790	11	106	0.22	0.27	1.72	0.75	0.024	0.67
Stockpiled Topsoil 4	11664	0	Sand	6.1	880	7	69	0.15	0.18	1.06	0.50	0.046	0.46
Stockpiled Topsoil 5	11665	0	Sand	6.5	1070	14	147	0.26	0.37	2.42	1.02	0.015	0.75
Stockpiled Topsoil 6	11666	0	Sand	6.3	750	13	121	0.27	0.31	1.82	0.85	0.013	0.65
Stockpiled Topsoil 7	11667	0	Sand	6.6	780	12	143	0.24	0.36	2.23	0.92	0.029	0.55

If the pH > 7.0 the Olsen method is used to determine P.

Base Saturation

Orchard No.	Lab. No.	Na %	K %	Ca %	Mg %	T-Value cmol/kg
Tailings 1	11640	53.89	6.27	16.10	23.74	2.17
Tailings 2	11641	55.69	6.49	14.39	23.44	2.40
Tailings 3	11642	55.59	6.00	15.65	22.76	2.68
Tailings 4	11643	54.96	6.73	15.31	23.00	2.13
Tailings 5	11644	54.45	6.23	16.16	23.16	2.02
Tailings 6	11645	54.71	6.52	15.41	23.35	1.98
Tailings 7	11646	53.49	6.40	16.45	23.65	1.94
Undisturbed Topsoil 1	11647	5.88	11.50	45.39	37.24	1.93
Undisturbed Topsoil 2	11648	3.69	8.14	49.37	38.80	2.59
Undisturbed Topsoil 3	11649	4.03	8.03	48.68	39.26	2.23
Undisturbed Topsoil 4	11650	3.98	7.43	53.06	35.53	2.19
Undisturbed Topsoil 5	11651	2.51	8.27	58.80	30.42	2.38
Undisturbed Topsoil 6	11652	2.21	6.41	64.54	26.84	5.23
Undisturbed Topsoil 7	11653	5.14	7.87	44.96	42.03	2.56
Undisturbed Subsoil 1	11654	5.20	8.53	54.58	31.69	2.07
Undisturbed Subsoil 2	11655	7.79	7.17	41.40	43.64	1.52
Undisturbed Subsoil 3	11656	3.99	7.47	60.25	28.29	3.41
Undisturbed Subsoil 4	11657	8.32	6.51	39.50	45.67	1.78
Undisturbed Subsoil 5	11658	12.64	7.00	32.55	47.81	1.85
Undisturbed Subsoil 6	11659	7.82	7.45	40.45	44.28	1.77
Undisturbed Subsoil 7	11660	6.22	9.28	40.42	44.08	1.88
Stockpiled Topsoil 1	11661	7.39	8.92	58.45	25.24	2.53
Stockpiled Topsoil 2	11662	6.84	9.72	58.22	25.21	2.47
Stockpiled Topsoil 3	11663	7.57	9.14	58.10	25.19	2.96
Stockpiled Topsoil 4	11664	8.03	9.40	56.14	26.42	1.89

CHAPTER 5

TRANSLOCATION OF INDIGENOUS PLANT SPECIES TO FACILITATE REHABILITATION ON ARID COASTAL STRIP MINED AREAS IN NAMAQUALAND, SOUTH AFRICA

ABSTRACT

Strip-mining results in the destruction of vast areas of natural vegetation. Rehabilitation of strip-mined areas is compulsory for commercial mines in South Africa. To facilitate the return of natural vegetation and processes to strip-mined landscapes in an arid winter rainfall Succulent Karoo shrubland biome on the West Coast of South Africa the technique of translocating plants from areas to be mined to areas that have been mined was tested. In this study I investigate whether plant origin, soil treatment and/or irrigation has an effect on the success of translocating five plant species: *Asparagus* spp., *Ruschia versicolor*, *Othonna cylindrica*, *Lampranthus suavissimus* and *Zygophyllum morgsana* planted into multi-species clumps (each clumps consisting of one of each of the species). The proportion of *O. cylindrica* transplants surviving for fifteen months was greater than for the other species. Whole plants survived better than salvaged plants, while *Asparagus* spp., *R. versicolor*, *L. suavissimus* and *Zygophyllum morgsana* survived better on stockpiled topsoil spread over tailings than on tailings alone. Irrigation had no consistent effect across species and treatment replicates. Irrigated topsoil over tailings showed an improvement in growth for all blocks, however to varying degrees. Clump size was affected by plant origin, where at planting salvaged-plant clumps were significantly larger than whole-plant clumps. This significant effect was no longer present at July 2002. When considered in conjunction with the fact that whole plants tended to grow significantly more than salvaged plants it can be assumed that whole clumps grew more than salvaged clumps. The leaf succulent shrubs *O. cylindrica*, *L. suavissimus* and *R. versicolor* appeared to be most successful for translocation to facilitate rehabilitation areas at Namakwa Sands.

Key Words: restoration ecology, indigenous plant translocation, soil treatment, irrigation, strip mines, arid areas.

INTRODUCTION

Strip-mining results in the destruction of vast areas of natural vegetation (Bradshaw 1997; Wells *et al.* 1999). Rehabilitation of these strip-mined areas is generally carried out to ensure the return of natural vegetation cover (Hobbs and Norton 1996). Strategies for rehabilitation and restoration are typically centred around augmenting, enhancing or accelerating changes in species composition and therefore in successional processes (Pyke and Archer 1991). The translocation of indigenous plants from pre- mined areas to post-mined areas may facilitate or accelerate the successional processes needed to create a self-sustaining vegetation. In the past exotic species have been purposefully introduced for rehabilitation purposes, however over the past 15 years the use of indigenous plant species in rehabilitation efforts has gained momentum.

The use of indigenous plants has ecological implications relating to ease of establishment, competitive interactions and the ability to facilitate succession and sustainability (Redente and Keammerer 1999). Indigenous plant species may have a greater potential to reproduce and disperse in an unmanaged habitat, ensuring long-term persistence and population spread (Handel *et al.* 1994). Revegetation with indigenous species leads to the establishment of more diverse plant communities than would be achieved by using exotic species. Greater indigenous plant diversity contributes to greater ecosystem stability (Tilman 1996) and enables the plant communities to more effectively meet the demands of future multiple land uses. Diverse communities have also been shown to resist invasion by exotic species (Kennedy *et al.* 2002).

The creation of indigenous plant communities on mined land allows grazing management strategies to be consistent with surrounding indigenous plant communities by allowing a biological mesh with surrounding natural communities (Handel *et al.* 1994). This is rarely the case when exotic species are used in rehabilitation, as plant communities dominated by exotic species require more intensive management and markedly different management strategies to maintain a productive system and high forage quality (Redente and

Keammerer 1999). As the aim of the Namakwa Sands rehabilitation programme is to return the post-mined areas to a system of small stock grazing, the use of indigenous plants becomes critical.

In such areas as the arid, windy Namaqualand coast, where conditions are regarded as harsh, adaptations to environmental conditions should also be considered in the selection of plant species for restoration. The use of the term indigenous, or native, within the context of restoration ecology has stimulated debate. Studies found that in both plants and animals, populations can be locally adapted (Montalvo *et al.* 1997). The term indigenous could refer to plants that naturally occur within a broad geographical region, such as southern Africa. A more narrow view may restrict natural occurrence within a defined ecosystem or plant community type (such as a biome) within a specific geographical region (Redente and Keammerer 1999).

Some ecologists feel that the use of a wide range of genotypic variation from local areas in natural plant populations could be advantageous for rehabilitation, ensuring that genotypes used are best adapted to local conditions and have a greater probability of survival than arbitrarily chosen material (Handel *et al.* 1994). Studies indicate that local adaptations promote higher fitness under the specific ecological conditions of a site under rehabilitation. The introduction of non-local species that dominate a population initially, but cannot withstand extreme selective events (such as drought) over the long term, represents a non-sustainable restoration strategy (Montalvo *et al.* 1997).

Short-lived plants include all those that complete their entire life cycle within one year and whose shoot and root systems die after seed production. To contrast these species with perennials (long-lived plants), the term annual is used, although most annual species complete their life cycles within a much shorter period (van Rooyen 1999). Undisturbed West Coast shrubland (Strandveld) is dominated by perennial shrubs and grasses, however an indigenous annual flora dominates openings and natural disturbance areas in this vegetation type (van Rooyen 1999). Degraded sites, with reduced vegetation cover, such as strip-mined areas suffer high erosion rates due to wind and water action and the first stage of restoration could depend on plants that have the ability to spread quickly over bare sites to conserve soil (Handel *et al.* 1994). Annual species with a mat-forming growth form might be more suitable for use in the initial phases of rehabilitation at Namakwa Sands, and do naturally return to rehabilitation areas on this site (T. Hälbich 2001, personal communication). A second stage of rehabilitation could include plants that would have the traits appropriate for long-term plant persistence, such as perennial species (Handel *et al.* 1994).

Perennial, locally indigenous plant species were therefore selected for translocation trials. The replanting of disturbed areas with indigenous species has been considered for rehabilitation at the Skorpion Zink Mine in southern Namibia. This site had comparable physical limiting constraints as those on Namakwa Sands, such as strong winds and aridity, making conventional methods of rehabilitation such as seeding pastures and afforestation impractical (Burke and Dauth 2000). Burke and Dauth (2000) found that *Dracophilus dealbatus* (dwarf succulent), *Ebracteola derenbergiana* (leaf-succulent shrub) and *Euphorbia melanohydrata* (dwarf stem succulent) were suited to *in situ* relocation. However, these species were not found on the Namakwa Sands area when the pre-mining benchmark vegetation study was carried out (de Villiers *et al.* 1999), and other common, local plants were selected for the trials.

Namakwa Sands is currently strip-mining large areas of arid coastal Namaqualand for heavy minerals. Through the rehabilitation processes the company aims to restore the mined areas to a vegetation type and productivity equivalent to the pre-mining capabilities of the pre-mined site, which supported small stock farming (Environmental Evaluation Unit 1990). Lubke and van Eeden (1994) suggests that rehabilitation with local indigenous plant species in harsh environments require the use of innovative techniques. The use of indigenous plant species in strip-mine rehabilitation is considered to result in the development of plant communities that are self-sustaining over the long-term.

Currently there is a lack of knowledge regarding the translocation of indigenous plants in Strandveld vegetation of the succulent karoo biome of southern Africa. In this study I investigate whether the success of translocating indigenous plant species is influenced by plant origin (whole or salvaged plants), soil type (stockpiled topsoil or tailings) or the application of irrigation, as well as the interactions amongst species and treatments.

METHODS

Study Site

Namakwa Sands is situated in the vicinity of Brand-se-Baai on the Namaqualand Coast (31°18'S, 17°54'E) approximately 350 km north of Cape Town. The area is extremely arid, with an average winter rainfall (cumulative rainfall, fog and dew falls) of 282 mm per annum. The average annual temperature is 15,8°C, with little seasonal temperature fluctuation due to the marine influence. The maximum average monthly temperature is 24,1°C in summer (January) and the minimum monthly average temperature is 7,5°C in winter (July) (Environmental Evaluation Unit 1990). The Namaqualand coast has one of the strongest wind regimes in the world. Winds blow with the highest frequencies from the south and south south east during spring and summer (September to March). Less frequent but stronger winds blow from the north and north north east during winter (June to August). Occasional easterly berg winds blow from the interior, bringing hot, dry conditions to the coast. The main agent of erosion on the study site is wind and during summer afternoons the wind is strong enough to mobilise vast quantities of surface sand from ground level. Wind speeds reach a peak velocity between 16h00 and sunset and are at a minimum at 06h00 in summer and 10h00 in winter. Mining aggravates this erosion process by removing the stabilising effect of the natural vegetation (Washington 1990).

In a pre-mining vegetation study by de Villiers *et al.* (1999) the vegetation of Namakwa Sands was described and divided into six vegetation units, some of which included several variants. All vegetation units had a shrub stratum, dominated by perennial species and a herbaceous stratum dominated by ephemeral and grass species.

The translocation trial was situated in what was originally Dwarf Shrub Strandveld (*Ruschia versicolor* - *Odyssea paucinervis*) vegetation and a portion of what was Tall Shrub Strandveld (*Salvia africana-lutea* - *Ballota africana)* vegetation adjoining the Dwarf Shrub Strandveld (Figure 2.3, Chapter 2). The Dwarf Shrub Strandveld had a shrub stratum canopy cover of between 16 and 20% and a herbaceous stratum canopy cover of between 15 and 20%. Ephemeral species and *Odyssea paucinervis*, a perennial creeping grass dominated the herbaceous stratum. This vegetation unit has more succulents belonging to the family Aizoaceae compared to the other vegetation units. Dwarf Shrub Strandveld covers the largest part of the western area to be mined. The soil varies from compact, dark red in the west to loose yellowish sand in the east. This community receives an intermediate to high amount of sea spray and fog relative to other communities on the mine. Common shrubs within this community include *Ruschia caroli* and *Asparagus capensis*. *Odyssea paucinervis* is the most common grass species in the herbaceous stratum of this community (de Villiers 2000).

Tall Shrub Strandveld has a shrub canopy cover of 26% and a herbaceous canopy cover of 6%. Tall Shrub Strandveld is associated with loose, yellow sand and due to the deep soil on which it occurs is taller than that of the surrounding communities. This community receives relatively little salt spray and fog (Figure 2.4, Chapter 2). Abundant species in this community include the shrubs *Salvia africana-lutea, Eriocephalus africanus* and *Helichrysum hebelepis*, the dwarf shrub *Conicosia pugioniformis* and the ephemerals *Dimorphotheca pluvialis* and *Nemesia bicornis* (de Villiers 2000).

Eccles *et al.* (1999) found that there was a definite pattern of clumping within perennial species in the Strandveld Succulent Karoo in which Namakwa Sands is found. Van Rooyen (2001) found that on Namakwa Sands clumps usually consisted of a mixture of species, including *Atriplex vestita, Cephalophyllum namaquanum, Eriocephalus ericoides, Zygophyllum morgsana, Lampranthus suavissimus* and *Chrysocoma ciliata*. Most clumps contained at least one of the following species: *Z. morgsana, C. namaquanum, E. ericoides, C. ciliata, A. vestita, L. suavissimus, Othonna cylindrica, Senecio spp.*, or *Lebeckia multiflora*. Certain species occurred together more frequently than by chance. For example *Salvia lanceolata* showed an affinity to *E. ericoides* and *O. cylindrica* to *Z. morgsana*.

During the mining process (described fully in Chapter 2) stockpiled topsoil, consisting of approximately the top 5-cm of topsoil, organic material and plant debris, is stored for up to three months to be used in rehabilitation. Once topsoil has been removed; hydraulic excavators mine the remaining sand to a depth of between one and six meters; continually moving forward from mined to un-mined ground (Environmental Evaluation Unit 1990).

Tailings (the sand portion remaining after mineral extraction) are deposited into the mined out area (Environmental Evaluation Unit 1990). Deposited sand tailings are shaped to fit the contours of the surrounding land. Slopes of deposited sand tailings should be stable to ensure the effectiveness of subsequent top-soiling and revegetation are not reduced due to erosion and movement of surface soil (Australian Mining Industry Council 1990). The pattern and shape of the back-filled tailings influences all rehabilitation processes and the final structure of the plant communities that develop on rehabilitation areas. To achieve a vegetation type and pattern similar to the pre-mining conditions it is essential that the contours of the rehabilitation areas are similar to those before mining began. The stockpiled topsoil is then spread over the contoured tailings. It has been shown in numerous studies that one of the most effective ways to encourage the revegetation of disturbed areas is through the use of topsoil spreading (Australian Mining Industry Council 1990; Rethman *et al.* 1999). Wind has been identified as the major form of potential erosion on Namakwa Sands (Washington 1990). To reduce wind speed and associated soil erosion on rehabilitation areas windbreaks are erected on spread stockpiled topsoil; reducing potential wind and sandblasting damage to plants. (Windbreaks are described fully in Chapter 2.)

Experimental Design

Translocated plants were subjected to three factors (irrigation, soil treatment and plant origin), with two treatment levels each. Irrigation was either applied or not applied. Irrigation took place in the winter season only as a supplement to long term monthly averages. Irrigation was not applied in summer as this could cause plants to rot (S.J. Milton 2001, personal communication). Soils consisted of either stockpiled topsoil spread over tailings or tailings only. Plant origin was from areas that were still to be mined (whole plants) or plants collected from fresh (two to three days old) topsoil stockpiles (salvaged plants). Whole plants were collected as intact as possible, with as many roots, branches, stems and leaves as possible. The plants collected from stockpiled topsoil had varying degrees of damage, caused through the process of stockpile creation. Damage included the shearing off of roots and the loss of branches and/or leaves. A total of eight treatments were tested.

The study site consisted of six plots, each 50x50-m. Each 50x50-m plot received the treatment of either irrigation or no irrigation, with a 50-m interval between each plot to prevent subterranean water flow from influencing non-irrigated blocks. Adjacent irrigated and non-irrigated blocks were grouped, so that the two most northern blocks were together

(Block 1), the two central blocks were together (Block 2) and the two most southern blocks were together (Block 3) (Figure 5.1). Each 50x50-m block was divided east-west into two 50x25-m sub-plots. The northern sub-plots received the treatment of tailings and the southern sub-plots received the treatment of stockpiled topsoil spread over tailings (Figure 5.1).

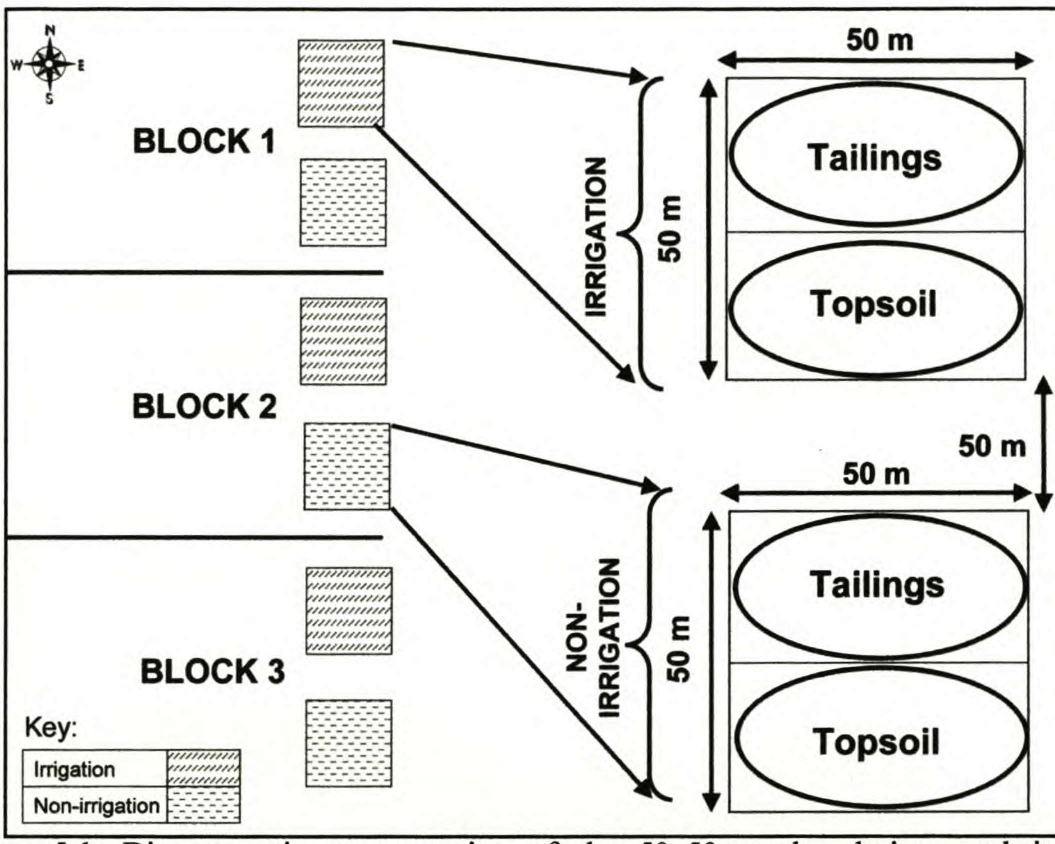

Figure 5.1: Diagrammatic representation of the 50x50-m plot design used in the translocation trials at Namakwa Sands showing irrigation treatment and soil treatment levels.

Plants vary in their ability to survive during stressful events. A succulent plant stores water and nutrients for later use (Midgley and van der Heyden 1999) as a means to cope with water stress. Currently there is not much information on the direct translocations of succulent species for rehabilitation (Burke and Dauth 2000). Five commonly occurring perennial plant species at Namakwa Sands (de Villiers *et al.* 1999) were selected for the translocation study. All species selected for trials had above or belowground storage organs, as such reserves were likely to improve survival (Midgley and van der Heyden 1999). One species with root storage organs, two leaf succulent species and two stem succulent species were selected for the translocation trials. The leaf succulent species are

Ruschia versicolor (L.Bolus) and *Lampranthus suavissimus* (L.Bolus). The drought-deciduous stem succulent *Zygophyllum morgsana* (L.) and *Othonna cylindrica* (Lam) (includes *O. floribunda* Schltr.) a stem succulent with drought-deciduous leaves were used. The species selected with a root storage organ were various *Asparagus* species found on the mine site. Due to the variety of *Asparagus* spp. species found on the site and the difficulty experienced finding the same species for use in translocation, various *Asparagus* spp. species were used in the translocation trials. Perennial plants were selected for use in these trials, as short-lived annuals would not contribute to a maintained rehabilitation status during the dry windy summer months.

Each 50x25-m plot (Figure 5.1 and Figure 5.2) was subdivided north-south into two 25x25-m blocks. Each 25x25-m block received the treatment of either whole plants (NW and SE corner blocks) or salvaged plants (NE and SW corner blocks). Each 25x25-m block (as described above) was subdivided into twenty-five 5x5-m sub-blocks. Each 5x5-m sub-block had one of each of the five species being used planted in a clump (Figure 5.2). In each 25x25-m block ten out of the twenty-five 5x5-m sub-blocks were randomly selected for measurement and analysis. Each species within the clump was measured.

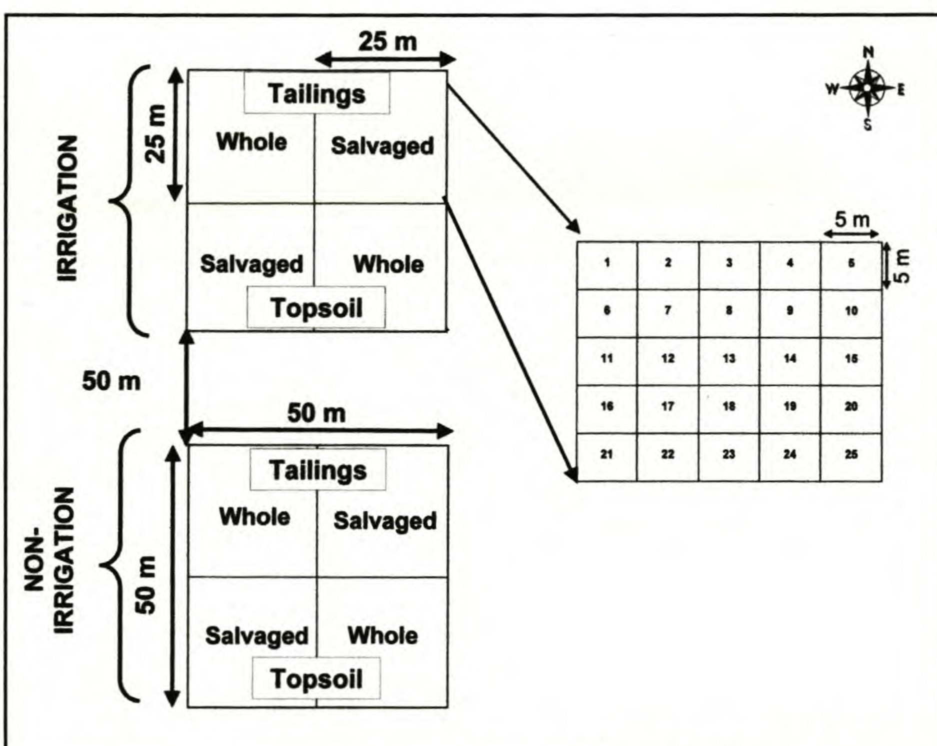

Figure 5.2: Diagrammatic representation of the 50x50-m, 25x50-m, 25x25-m and 5x5-m plot designs used in the translocation trials at Namakwa Sands showing irrigation treatment, soil treatment and plant origin treatment levels.

The entire experiment was set out in June 2001. Six hundred plants of each species (300 salvaged and 300 whole plants of each species, totalling 3 000 plants) were collected and transplanted. There were a total of eight treatments with three replicates per treatment, resulting in a nested split-plot design (also known as a split-split plot design). A total of 30 plants per species per treatment were measured (a total of 1200 plants (240 per species) were measured).

Data Collection

Data collection for the experiment took place in June 2001 (base line data), September 2001, December 2001, April 2002 and July 2002. All data were collected from individuals marked in the initial experiment set out in June 2001. Three data sets were collected for each data collection period. These were for presence and survival, growth and cover.

Presence and Survival

During the September 2001 data collection period it was noticed that some plants of various species that had been transplanted had either been blown out of the ground or had been covered by mobile sand. For this reason, the presence or absence and status (live\dormant\dead) of all plants within the clumps were noted. Plants with any green leaves were regarded as being alive.

Growth

Two branches on each species within the 5x5-m sub-blocks selected for measurement (as described above) were randomly selected. One branch was marked with white paint and the other with black paint, and branch lengths were measured in June 2001. Incremental growth was measured for each of the two branches for each of the subsequent data collection periods. Mean incremental growth above the paint-mark and including lengths of all side shoots, was then used as an indication of plant growth. A third branch was randomly selected in April 2002, marked with blue paint and re-measured in July 2002.

Cover (Clump size)

Cover was measured as the ground surface area covered by the five species within a clump within the 5x5-m sub-blocks randomly selected for measurement. Cover is given as average clump size. Clump size was measured as two perpendicular clump diameter readings per clump, with the average of these two diameter readings being used to determine clump surface area, measured in square meters (m^2).

$$\text{Average diameter } (d) = (d_1 + d_d)/2 \qquad (1)$$

Where:

d_1 = first diameter measure

d_2 = second diameter measure

$$\text{Surface area} = \pi\left(r^2\right), \text{ where } r = (d/2) \qquad (2)$$

Where:

r = radius

Remaining symbols are as for equation (1)

STATISTICAL ANALYSIS

Presence and Survival

Data collected for presence and survival were categorical. In the "present" category a plant could either be "present" or "absent". In the "survival" category plants could either be "alive", "dead/dormant" or "missing". The missing category was used when plants were absent. Due to the nature of data collected, use was made of classification tree analyses to determine differences in presence and survival for the irrigation, soil treatment and plant origin factors being tested. Classification trees can be used to derive predictor rules for a categorical target variable based on a set of predictor variables (for further information on the methodology of classification tree techniques see Appendix 5.1). Regression tree analysis divides the data into subsets based on a target variable and a set of predictor variables. Subsets are divided in such a way as to minimise the variance of the target variable within each subset. The result is a set of rules, based on the predictor variables, that characterises each of the subsets (for information on the applications of regression tree methodology see Appendix 5.2). The flexibility of classification trees makes them an attractive analysis option (StatSoft Incorporated 2002). Classification tree rules for the "presence-absence" and the "alive-dormant/dead-missing" data were constructed within the CART® Program (Snedecor and Cochran 1989, Steinberg and Phillip 1998). Categorical predictors for both data sets were irrigation, soil treatment and plant origin. Rules created were exported to Excel (Microsoft Corporation 1998) where graphs of results were created. Classification tree analyses were carried out per species for the data collection period of July 2002.

Growth Analysis

It is sometimes necessary and convenient to test one factor on a large experimental unit and to test a second (and/or third as in this case) factor on a smaller experimental unit embedded in the larger unit (Snedecor and Cochran 1989). These types of designs are known as split-plot designs, which falls within the category of nested designs. The design used here is that of a split-split-plot. In this experiment the main treatment was irrigation. The six 50x50-m plots were grouped into three main-blocks (first irrigated and non-irrigated plots together; second irrigated and non-irrigated plots together; and third irrigated and non-irrigated plots together). Therefore, each main-block had the treatment of either irrigated or not irrigated. The first split was for the soil treatment factor of either tailings or stockpiled topsoil. The second split was for the plant origin factor of either whole or salvaged plants (Figure 5.1 and Figure 5.2). The split-split plot design limited the analyses that could be applied to the data to detect significant differences in factors being tested and to show which factors possibly had more influence on growth than others did. For this reason a general linear model was used for analysis of growth within these trials. The general linear model is a generalisation of the linear regression model. The general linear model was applied to an ANOVA (Analysis of Variance) design with categorical predictor variables. Factors were assigned either a random or fixed effect for all analyses. Table 5.1 indicates which factors were fixed or random. If a significant ANOVA test was obtained, a univariate F-test was carried out for each variable to determine which single or interaction effects were significant (StatSoft Incorporated 2002). A result was regarded as significant at 95% confidence ($p \leq 0.05$). Although some results did not show significance at the 95% level, these results may have been significant between the 95% and 90% level. These non-significant results are given to indicate patterns found in data that may contribute to the better understanding the effects various factors may have had on species growth performance. The general linear model ANOVA and the Univariate F-tests were carried out for each species for each data collection period, excluding June 2001, as plants were only planted in this month and as such new growth had not taken place. All analyses were carried out within the STATISTICA program (StatSoft Incorporated 2002).

Table 5.1: Assignment of fixed and random effects for treatment factors applied in the general linear model experimental design.

Effect	Fixed or Random
Block	Random
Irrigation	Fixed
Block * Irrigation	Random
Soil Treatment	Fixed
Irrigation * Soil Treatment	Fixed
Block * Irrigation * Soil Treatment	Random
Plant Origin	Fixed
Irrigation * Plant Origin	Fixed
Soil Treatment * Plant Origin	Fixed
Irrigation * Soil Treatment * Plant Origin	Fixed

Clump Size Analysis

Clump size data were obtained from the same experimental design as for growth data. Data collected for cover were analysed by use of a general linear model on an ANOVA. If a significant ANOVA test was obtained, a univariate F-test was carried out for each factor to determine which individual or interaction effects were significant (StatSoft Incorporated 2002). A result was regarded as significant at 95% confidence ($p \leq 0.05$). Although some results did not show significance at the 95% level, these results may have been significant between the 95% and 90% level. These non-significant results are given to indicate patterns found in data that may contribute to better understanding the effects various factors had on cover performance. The general linear model ANOVA and the Univariate F-tests were carried out for each species for each data collection period, excluding June 2001, as plants were only planted in this month and as such new growth had not taken place. All analyses were carried out within the STATISTICA program (StatSoft Incorporated 2002).

A regression tree analysis was used to show general trends in the data relating to which factors played more important roles in differences in cover obtained in the statistical analysis. Where classification trees are characterised by categorical target variables (with discrete levels such as 0, 1, 2, ... or 1, 2, 3...), regression trees have a continuous target variable, in this case the continuous target variable is cover, given in square meters.
Time series graphs were developed for average clump size data obtained from pivot tables for the three factors being tested. These graphs give an indication of how cover changed between data collection periods. Graphs were created in Excel (Microsoft Corporation 1998).

RESULTS

Presence and Survival: July 2002

For *Asparagus* spp., *R. versicolor* and *L. suavissimus* a greater percentage of salvaged plants than whole plants were present for July 2002. Presence was not influenced by irrigation or soil treatment (Figure 5.3).

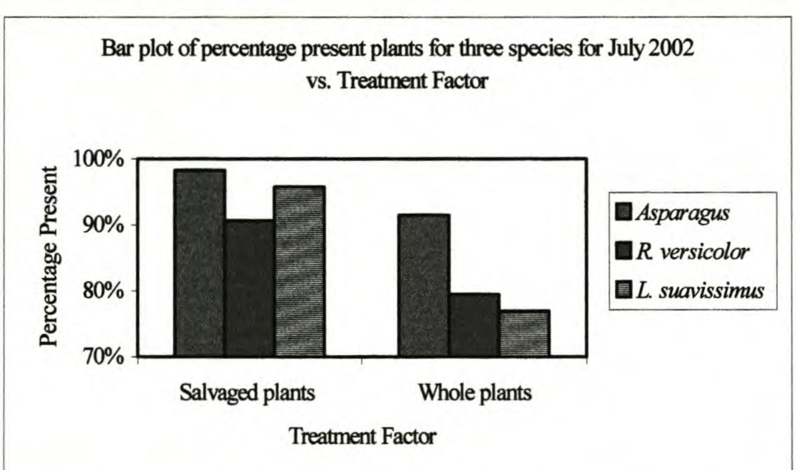

Figure 5.3: Percentage of *Asparagus* spp., *R. versicolor* and *L. suavissimus* present in July 2002 for the treatments of salvaged plants and whole plants. (The y-axis has 70% as its minimum value.)

For *O. cylindrica* 100% of all non-irrigated plants and 100% of salvaged plants that were irrigated were present. Whole plants that were irrigated had a 95% presence. For *Z. morgsana* 100% of salvaged plants and 97% of whole plants that were planted on tailings were present. Eighty-eight percent of the whole plants planted on stockpiled topsoil spread over tailings were present in July 2002.

Results for survival indicated that *Asparagus* spp.; *R. versicolor*, *L. suavissimus* and *Z. morgsana* had the same classification tree rules for the predictor of "alive" and are represented in Table 5.2. The factor of irrigation did not influence the classification tree developed for *Ruschia versicolor* for July 2002. *L. suavissimus* showed a survival rate of 56%, 35% and 16% for the treatment combinations of whole plants transplanted onto stockpiled topsoil, whole plants transplanted on tailings and salvaged plants, respectively for the data collection period of July 2002.

Table 5.2: Classification tree rules indicating the percentage of living plants per treatment factor or combination of treatment factors for *Asparagus* spp., *R. versicolor*, *L. suavissimus* and *Z. morgsana* for the data collection period July 2002.

	Species			
Treatment Factor	*Asparagus* spp.	*Ruschia versicolor*	*Lampranthus suavissimus*	*Z. morgsana*
Stockpiled topsoil and whole plants	5%	41%	56%	9%
Tailings and Whole plants	2%	32%	35%	10%
Salvaged plants	0%	23%	16%	3%

O. cylindrica had different classification tree rules for survival compared to the other four species. Whole *O. cylindrica* had a 77% survival rate, regardless of irrigation treatment. Salvaged *O. cylindrica* had a survival rate of 49% regardless of irrigation or soil treatment (Figure 5.4). Results for *O. cylindrica* are given for the data collection period of July 2002.

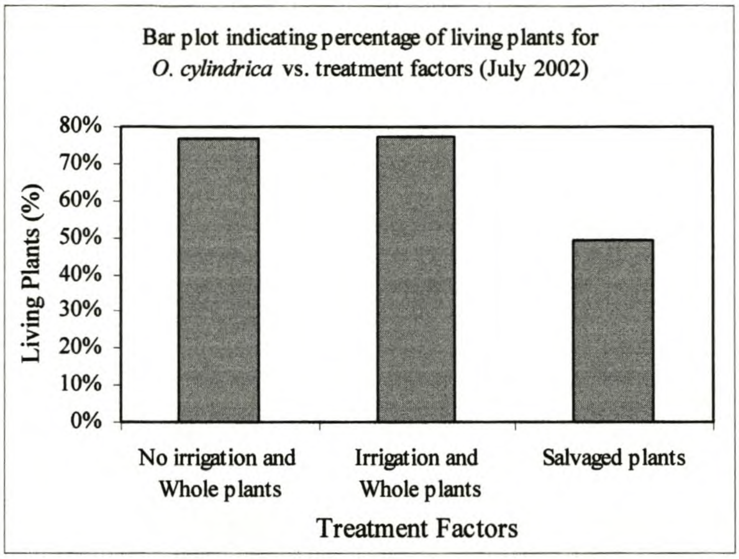

Figure 5.4: A bar chart presenting the classification tree rules of survival percentages for *O. cylindrica* for July 2002. Classification rules represent three classes: Whole plants that were not irrigated, whole plants that were irrigated and salvaged plants.

Growth Results

Significant differences were found in the block factor. However, block was not of interest, as block represents replicates within the experimental design and not a factor being tested. It was later determined that irrigation was not applied evenly to all replicates, with blocks 1 and 2 receiving more irrigation than block 3 (Table 5.3). This difference in irrigation together with other unknown factors may have caused the significant differences observed in results for the Block effect. For these reasons, limited results will be given for block effects.

Table 5.3: Quantities of irrigation applied for the 2001 winter and spring seasons at Namakwa Sands (T. Hälbich 2002, personal communication).

Date	Block	Quantity	Comment
August 13, 2001	1	25mm	
August 13, 2001	3	25mm	
August 16, 2001	2	25mm	
September 19, 2001	1	25mm	
September 25, 2001	2	25mm	
October 24, 2001	2	50mm	
October 25, 2001	1	50mm	Block 3 not irrigated due to lack of water
November 26, 2001	1	50mm	
November 28, 2001	2	50mm	Block 3 not irrigated due to lack of water

Asparagus spp.

There were no significant differences in growth data obtained for *Asparagus* spp. for data collection periods: September 2001 and December 2001. For April 2002 and July 2002 not enough growth had taken place to carry out analyses for *Asparagus* spp. plants. For this reason no results pertaining to growth analysis for *Asparagus* spp. are given.

Ruschia versicolor

Data for *R. versicolor* for April 2002 was incomplete due to lack of growth by plants for this species consequently analyses could not be carried out for this data collection period. The only effect found that for *R. versicolor* was for July 2002, where irrigated plants grew better than non-irrigated plants (Figure 5.5). Although not significant at the 95% level, this finding should be considered within the context of growth results obtained for other species within the translocation trials.

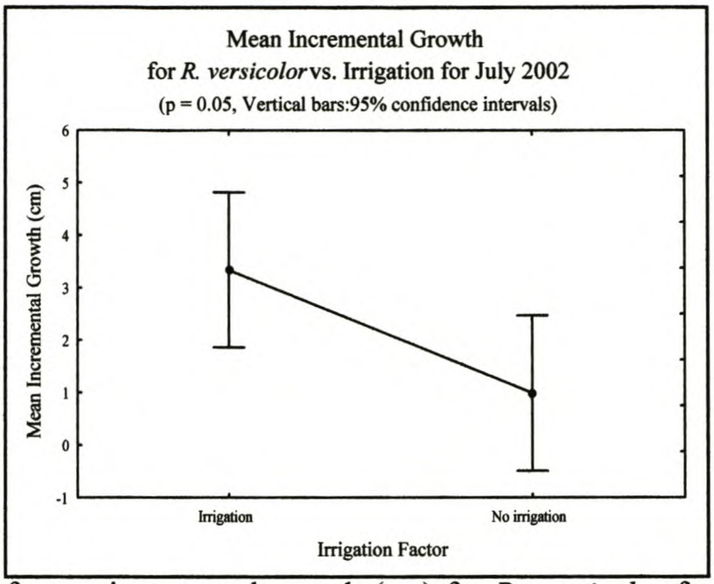

Figure 5.5: Plot of mean incremental growth (cm) for *R. versicolor* for the treatment of irrigation in July 2002. (Vertical bars below 0-cm Mean Incremental Growth is a statistical anomaly due to working with a low mean value.)

Othonna cylindrica

Data obtained for September 2001 showed no significant effects for any single or interaction effects. For December 2001 whole plants grew significantly better than salvaged plants (Figure 5.6). Growth data collected for *O. cylindrica* for April 2002 indicated that too few plants had shown growth since the previous data collection period (December 2001) consequently analyses could not be carried out for April 2002.

For July 2002 whole plants had a significantly higher mean incremental growth than salvaged plants plant (Figure 5.7). There were no interaction effects for *O. cylindrica* for July 2002.

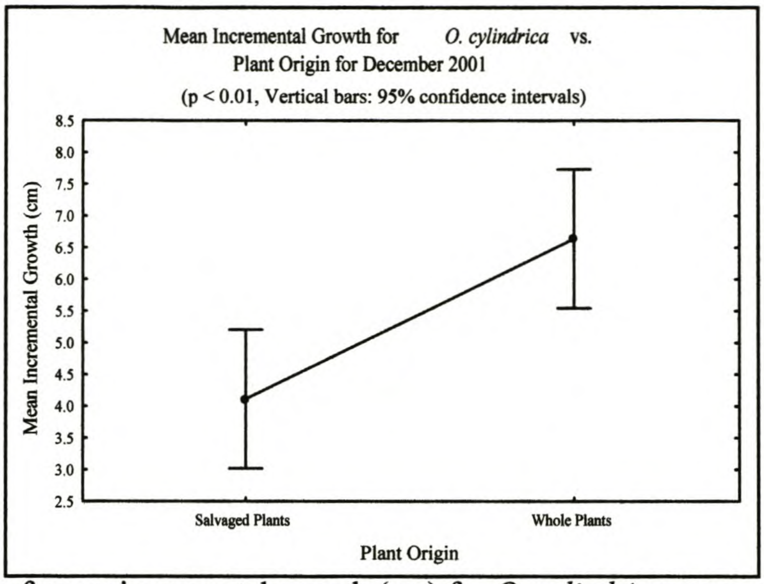

Figure 5.6: Plot of mean incremental growth (cm) for *O. cylindrica* versus plant origin for December 2001.

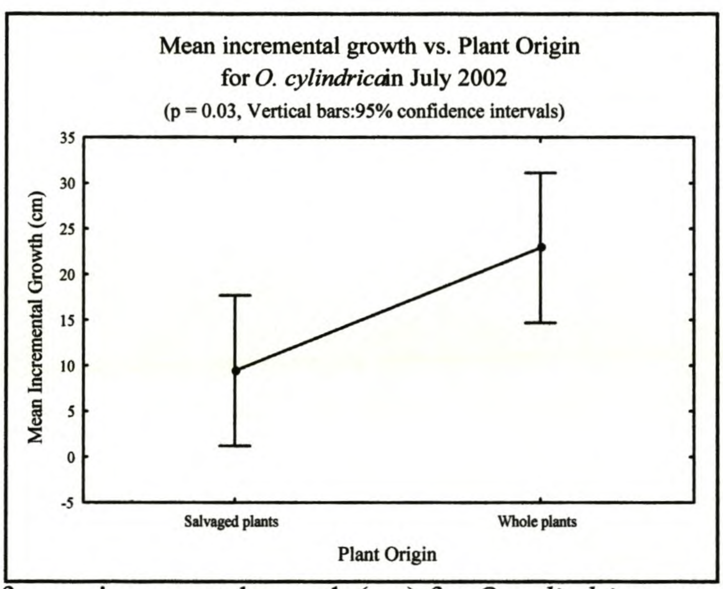

Figure 5.7: Plot of mean incremental growth (cm) for *O. cylindrica* versus plant origin for July 2002.

Lampranthus suavissimus

Results for *L. suavissimus* for September 2001 showed no significant effects for any single or interaction effects. For December 2001 whole plants had a significantly higher mean incremental growth than salvaged plants (Figure 5.8). Growth data for April 2002 indicated that too few plants had shown growth since the previous data collection period, consequently analyses could not be carried out for April 2002. Results for July 2002 did not show any significant differences at the 95% confidence level. However, data obtained showed a degree of significance for the plant origin factor (Figure 5.9), and should be considered within the context of significant results obtained for growth for this species in December 2001.

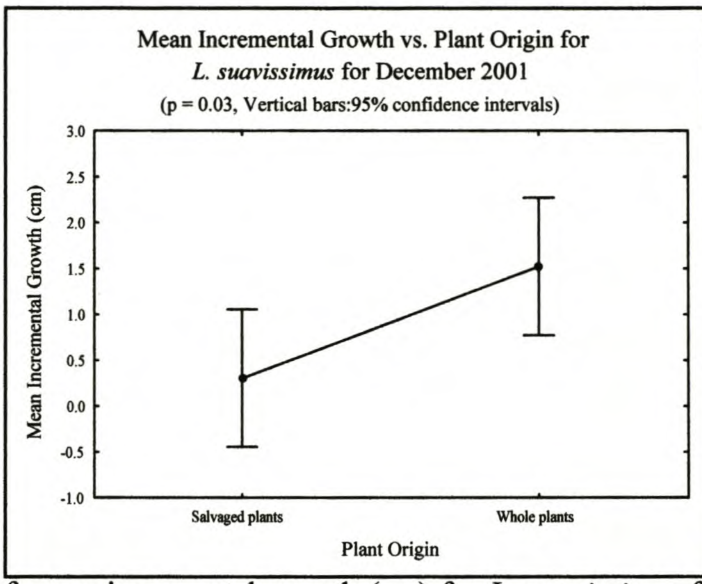

Figure 5.8: Plot of mean incremental growth (cm) for *L. suavissimus* for plant origin for December 2001. (Vertical bars below 0-cm mean incremental growth is a statistical anomaly due to working with a low mean value.)

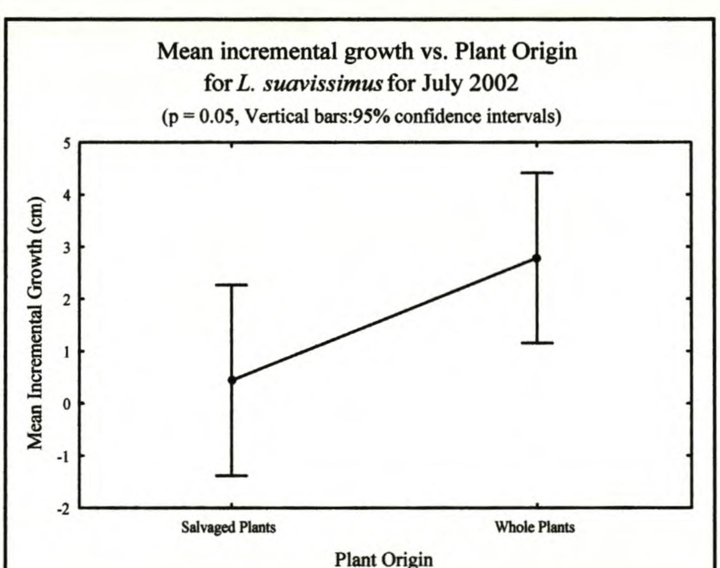

Figure 5.9: Plot of mean incremental growth (cm) for *L. suavissimus* for plant origin in July 2002. (Vertical bars below 0-cm mean incremental growth is a statistical anomaly due to working with a low mean value.)

Zygophyllum morgsana

Results obtained for September 2001 showed whole plants grew significantly better than salvaged plants (Figure 5.10). *Z. morgsana* showed an interaction effect for September 2001 where whole plants that were irrigated grew significantly better than whole plants that were not irrigated. Salvaged plants did not grow better if irrigation was or was not applied (Figure 5.11). For December 2001 whole plants had significantly better growth than salvaged plants (Figure 5.12).

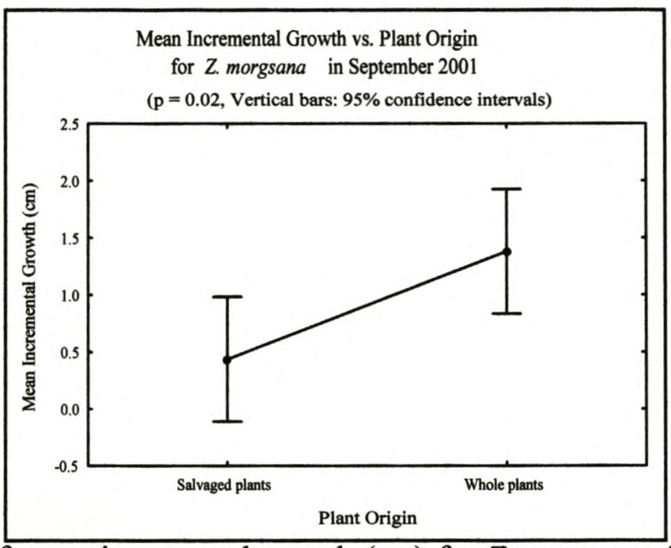

Figure 5.10: Plot of mean incremental growth (cm) for *Z. morgsana* for plant origin for September 2001. (Vertical bars below 0-cm mean incremental growth is a statistical anomaly due to working with a low mean value.)

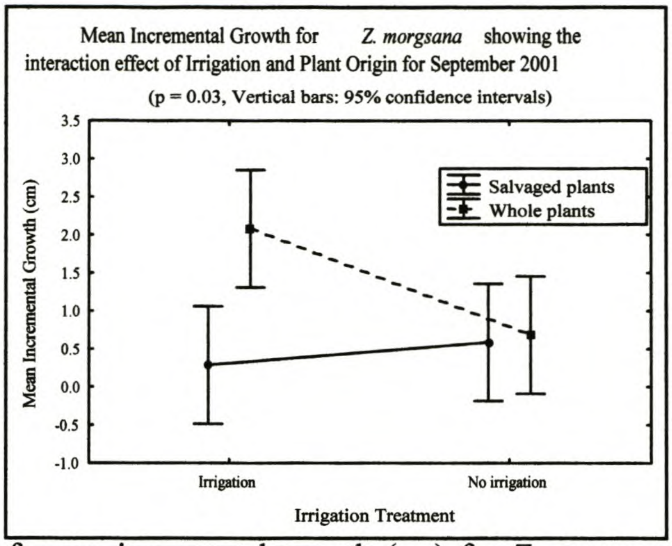

Figure 5.11: Plot of mean incremental growth (cm) for *Z. morgsana* for irrigation for September 2001 showing the interaction effect between irrigation and plant origin. (Vertical bars below 0-cm mean incremental growth is a statistical anomaly due to working with a low mean value.)

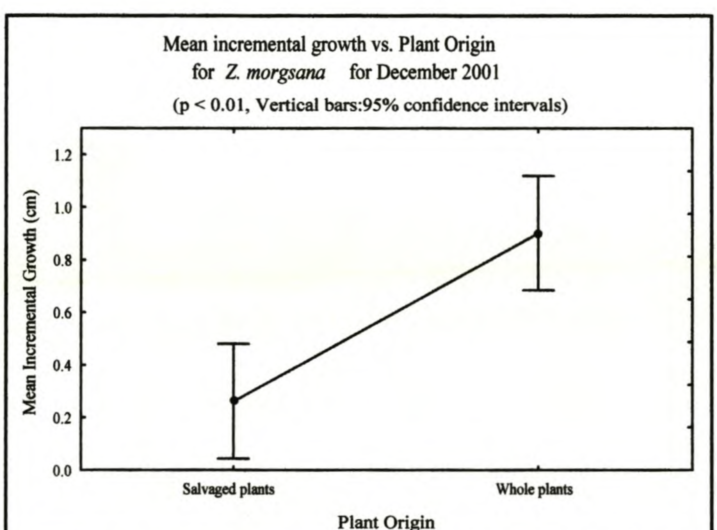

Figure 5.12: Plot of mean incremental growth (cm) for *Z. morgsana* versus plant origin for December 2001.

Clump size

For clump size it is important to give an indication of the trend observed over the data collection periods. These results have been summarised in Table 5.4. In June 2001, September 2001 and December 2001 salvaged-plant clumps were significantly larger than whole-plant clumps. For April 2002 and July 2002 the significant difference between the average size of salvaged-plant clumps versus whole-plant clumps is no longer observed.

Table 5.4: Summary of p-values obtained for all data collection periods for clump size for the factor of plant origin.

Date	Effect	Fixed or random effect	p-value
June 2001	Plant Origin	Fixed	0.03
September 2001	Plant Origin	Fixed	0.02
December 2001	Plant Origin	Fixed	0.03
April 2002	Plant Origin	Fixed	0.07
July 2002	Plant Origin	Fixed	0.44

The regression tree analyses for clump size analysis give an indication of the most important factors splitting data obtained. Regression trees are given for June 2001 and July 2002 to give an overall idea of the changes in the important factors determining clump size. The regression tree for June 2001 (Figure 5.13) shows whole-plant clumps had the lowest average clump size, no matter the irrigation or soil treatment factors. Salvaged-plant clumps planted on stockpiled topsoil spread over tailings and salvaged-plant clumps planted on tailings that received irrigation had similar average clump size. Salvaged-plant clumps planted onto tailings and not irrigated had the largest average clump sizes in June 2001. This is an indication of the different sizes of clumps when planting took place.

The regression tree for July 2002 (Figure 5.14) shows that salvaged-plant clumps that did not receive irrigation (no matter the soil treatment) as well as whole-plant clumps that were planted on tailings and received irrigation had a slightly larger average clump size compared to the first group. Salvaged-plant clumps planted on tailings and receiving irrigation had slightly larger average clump size than the first three groups. Whole-plant and salvaged-plant clumps planted onto stockpiled topsoil spread over tailings that were irrigated had the largest average clump size for July 2002.

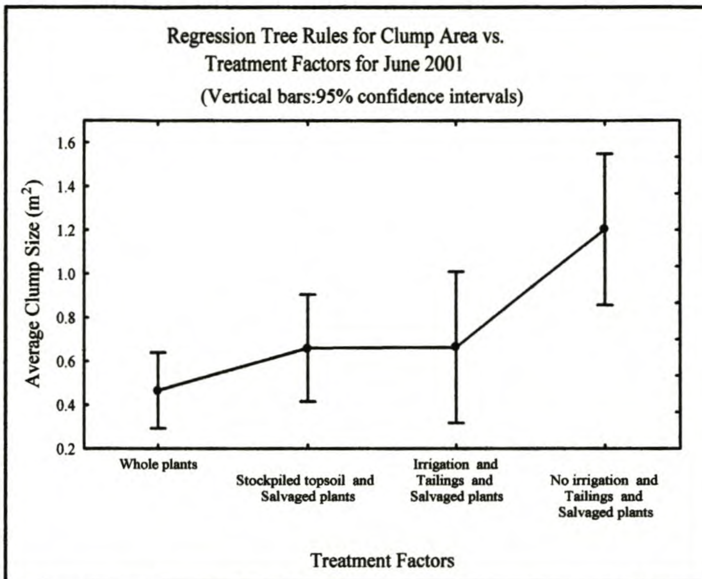

Figure 5.13: Plot of average clump size (m^2) versus the treatment factors as determined by the regression tree for June 2001.

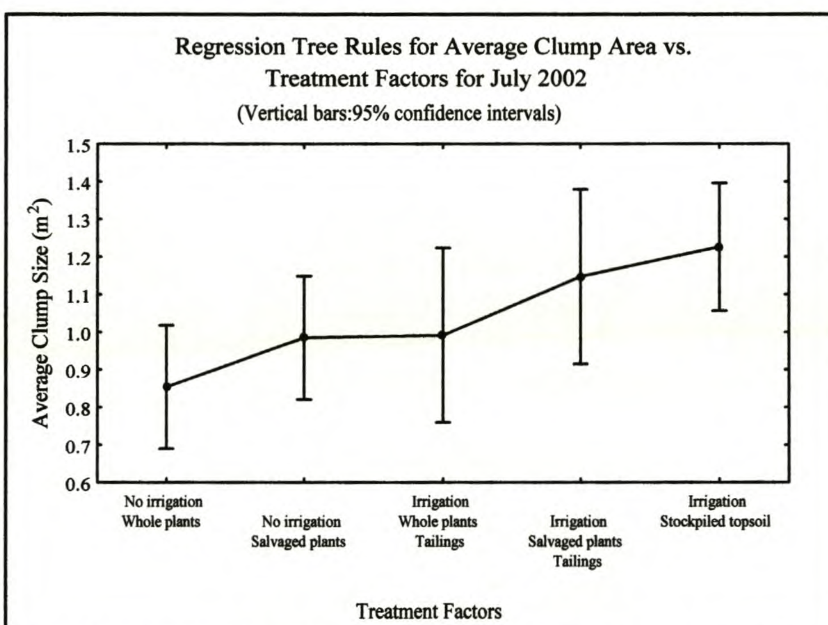

Figure 5.14: Plot of average clump size (m^2) versus the treatment factors as determined by the regression tree for July 2002.

Time series graphs of average clump size give an idea of how average clump size changed over the duration of the study. Where irrigation was applied (Figure 5.15) it can be seen how salvaged-plant clumps planted on stockpiled topsoil spread over tailings retained a steady growth over time, salvaged-plant clumps on tailings decreased in size before increasing and maintaining a steady increase in average clumps size growth. Whole-plant clumps on tailings maintained a steady growth over the duration of the study period. Whole plants on stockpiled topsoil spread over tailings maintained a steady growth until April 2002. After April 2002 there was a dramatic increase in whole-plant clump cover on stockpiled topsoil.

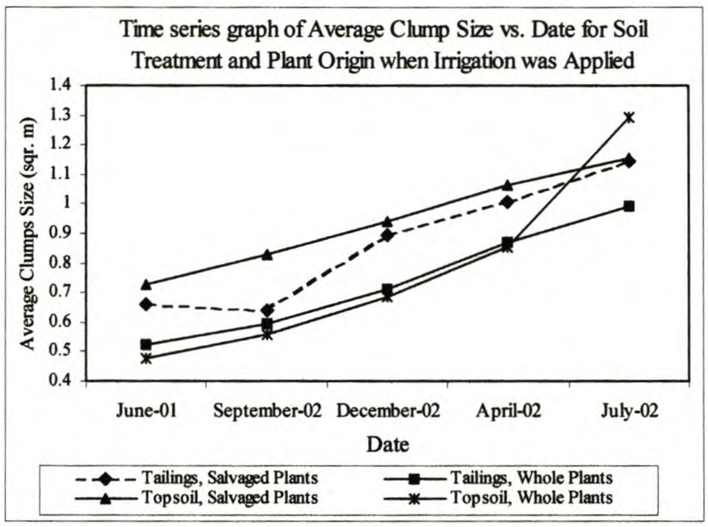

Figure 5.15: Time series graph of clump size versus date to indicate the change in clump size over time for different soil treatments and plant origins when irrigation was applied.

Where irrigation was not applied (Figure 5.16) it can be seen how salvaged-plant clumps planted on tailings decreased in size before increasing in size. In July 2002 these clumps reduced in size again. Salvaged-plant clumps planted onto stockpiled topsoil spread over tailings showed a steady increase in clump size over time. Whole-plant clumps planted on to tailings showed a steady increase in average clump size, except for the time period between December 2001 and April 2002, where average clumps size remained relatively constant. Whole-plant clumps planted on stockpiled topsoil spread over tailings showed a steady increase in average clump size over time, with most growth occurring in the period from April 2002 to July 2002.

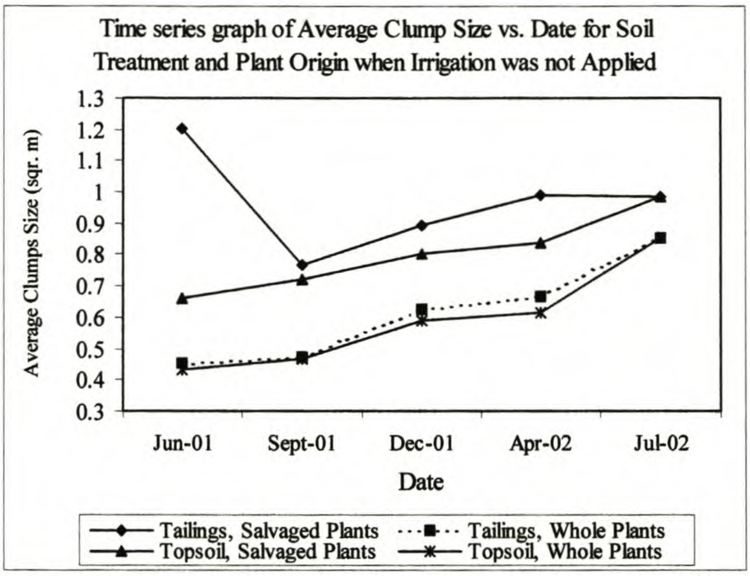

Figure 5.16: Time series graph of clump size versus date to indicate the change in clump size over time for different soil treatments and plant origins when irrigation was applied.

DISCUSSION

During a pre-mining vegetation benchmark study (de Villiers *et al.* 1999) it was recommended that the rehabilitation programme at Namakwa Sands should concentrate on perennial species, as these species would help to stabilise post-mined areas during the hot, dry and windy summer months. The life-history strategy of annuals is such that they are able to colonise open or disturbed habitats easily, provided the habitat is suitable for germination and seeds can be disseminated from the surrounding vegetation. However, the usefulness of annual species in the revegetation programme is restricted to the wet, cool winter months (de Villiers *et al.* 1999). This translocation study investigated the effectiveness of transplanting five perennial species onto post-mined areas as a form of facilitating rehabilitation.

Indigenous species represent the best choice in plants when one of the goals in reclamation is to facilitate succession and a self-sustaining vegetation. Indigenous seedlings commonly result in communities that are open to colonisation by other indigenous species and are less inhibitory to the process of plant community change that leads to the development of later communities (Redente and Keammerer 1999).

A year after translocations took place a high percentage of plants for all species were still present. *Asparagus* spp. showed poor survival, which could be due to root storage organs not carrying sufficient water and nutrient reserves to allow this species to cope with the relocation stress. During stockpile formation damage to plants is mainly caused by the shearing off of roots, the storage organ in *Asparagus* spp., which could have been a cause of this species' high mortality.

For the remaining species, whole plants had better survival than salvaged plants. *O. cylindrica* showed the highest rates of survival, followed by *L. suavissimus*, then *R. versicolor* with *Z. morgsana* showing relatively poor survival. Soil treatment did not appear to influence *O. cylindrica* survival, while *R. versicolor*, *L. suavissimus* and *Z. morgsana* showed better survival when planted on stockpiled topsoil spread over tailings than when planted on tailings alone. This indicates that the spreading of stockpiled topsoil may enhance survival of selected translocated species. Fey (1996) suggests that the use of topsoil in rehabilitation may be of vital importance in determining the success of rehabilitation, and should not be underestimated.

O. cylindrica is an evergreen leaf and stem succulent, with an extensive shallow (between 0 and 10-cm below ground) root system. *L. suavissimus* and *R. versicolor* are both evergreen leaf succulents. *R. versicolor* was observed to have a few deeper penetrating roots with an extensive shallow lateral root network (Figure 5.17). This root architecture has been noted for other *Ruschia* spp. (Midgley and van der Heyden 1999). *L suavissimus* did not have deeper penetrating roots, but did have an extensive, shallow root system. The summer deciduous stem succulent *Z. morgsana* appeared to have an extensive lateral root system, which was deeper than that of *O. cylindrica*, *R. versicolor* and *L. suavissimus*. *Asparagus* spp. had a shallow root system (up to 30-cm deep), with storage organs occurring some distance from the aboveground plant parts. When the morphological features of the species used in the translocation trials are compared, it appears that species with permanent aboveground storage organs and shallow root systems show the best survival.

Burke and Dauth (2000) found that arid zone perennial species with leaf and stem succulence could undergo *in situ* translocation successfully in early spring (September 1999). However, Burke and Dauth (2000) also found that *O. cylindrica* did not perform well if transported over large distances (southern Namibia to Windhoek), as this species appeared to suffer from dehydration, indicating that transplantation of this species should take place as quickly as possible after collection. In propagation trials on *O. cylindrica* when tip- and soft wood cuttings were kept moist, after a period of seven weeks all cuttings had produced roots outside of this species normal growing season (Burke and Dauth 2000), indicating a potential for *O. cylindrica* to re-root if transplanted.

Figure 5.17: Photograph of a whole *R. versicolor* collected for use in the translocation trials, showing the root system.

O. cylindrica, *R. versicolor* and *L. suavissimus* produce attractive flowers and could attract insect fauna back to the site. *O. cylindrica* is not regarded as a grazing species, however the flowers are grazed. Although *R. versicolor* and *L. suavissimus* are not regarded as having a grazing potential, grazed plants have been observed on the mine site. These species alone may not directly achieve the end goal of the Namakwa Sands rehabilitation programme, to restore the land to small stock grazing, however they may provide micro-climates and conditions more conducive to seed germination and growth of palatable species. A potential negative effect of only using palatable species in translocation efforts is that when rehabilitation is complete, if vegetation is dominated by palatable species, the existing vegetation could be decimated by overgrazing, with no protection from soil erosion and trampling being provided by non-palatable species. If translocation of indigenous plant species is used in conjunction with other rehabilitation techniques, such as seeding with palatable species the end goal of the rehabilitation programme may be facilitated.

Although not all plants survived, dead plants do contribute to the rehabilitation process (Milton 2001). Plants that die contribute organic material to the soil and can assist in the reduction of wind speed. Dead branches remaining upright may provide perches for birds and refuge to insects crossing the area. These birds and insects also add to the rehabilitation process by returning organic material and seeds to the site. Branches may also assist by collecting water from mist and may increase rainwater infiltration by slowing surface water flow. Dead branches provide habitats for fauna returning to the site. Insects and mammals that dig or burrow will assist the rehabilitation process by bringing seeds onto the site, burying seeds on the site and by digging, these fauna may create microhabitats more conducive to seed germination and survival (van Rooyen 1999; Schmidt 2002).

Whole plants grew significantly better than salvaged plants. Whole plants were collected as intact as possible and salvaged plants were collected from stockpiled topsoil. During the process of stockpile formation approximately the top 5-cm of soil is scraped together using heavy machinery, causing many of the roots, leaves and stems of plants to be sheared off. Salvaged plants from stockpiles may be damaged to such an extent that survival is not possible. Added to damage from the stockpiling process, plants may also become dehydrated while in stockpile, further limiting the ability of these plants to recover if transplanted.

Irrigated *R. versicolor* plants grew better than non-irrigated plants. Irrigation and plant origin had an interaction effect for *Z. morgsana* for September 2001. Both effects show a potential for irrigation to improve growth, however, due to the uneven application of irrigation, further investigation is needed to determine the true effect irrigation may or may not be having on the survival and growth of species tested in the translocation trials. At this stage irrigation was still being applied to the translocation trials.

Clump size was significantly affected by plant origin. Results indicate that when planting took place, salvaged-plant clumps were significantly larger than whole-plant clumps. This discontinuity in size was probably a result of plants collected during the translocation trial. When collecting salvaged plants for translocation, larger specimens within the stockpiles were more easily recognised and handled and were therefore collected, where whole plants collected from the pre-mining areas were easily recognised, no matter the size, subsequently more smaller plants were collected. However this discontinuity in original clump size reduced over time, indicating that whole-plant clumps provided a greater increase in plant cover compared to salvaged-plant clumps.

Factors affecting clump size also changed over time. In June 2001 the smallest clumps were whole-plant clumps and the largest clumps were salvaged-plant clumps. However, by July 2002 this situation had shifted to where non-irrigated whole-plant clumps remained the smallest, but irrigated whole-plant clumps planted on tailings were bigger than non-irrigated salvaged-plant clumps. Whole- and salvaged-plant clumps that were planted on stockpiled topsoil spread over tailings and irrigated where the largest clumps in July 2002. This indicates that the spreading of topsoil and the use of whole plants provide a faster increase in cover than salvaged plants when irrigation is applied.

Whole-plant clumps grew more rapidly with the onset of the 2002 winter season. The reliable winter rainfall and mild winter temperatures of Namaqualand select for a winter growth phenology. Both perennial and annual species begin vegetation development with autumn rains and continue active growth to reproductive maturity during the winter months (Milton *et al.* 1997; Cowling *et al.* 1999). Lubke and van Eeden (1994) found that better survival was obtained when transplantations took place in early winter.

CONCLUSION

Asparagus spp. should not be considered for large-scale translocation purposes. Irrigation had inconsistent effects on the species used in the translocation trials, and because of the uneven application of irrigation in this experiment further investigation is required to determine if irrigation is having a beneficial effect on plant growth and survival. A cost-benefit analysis of irrigation should also be carried out to determine whether irrigation is warranted, as Namakwa Sands does not have a large fresh water supply and water for irrigation has to be pumped from the nearest town (approximately 70-km away) to Namakwa Sands at great cost. The fresh water supply in the winter season is also inconsistent.

The use of stockpiled topsoil improved the survival of *R. versicolor, L. suavissimus* and *Z. morgsana*, and clumps appear to provide better cover when planted on stockpiled topsoil.

It is therefore recommended that spreading of topsoil continue being implemented as part of the rehabilitation programme at Namakwa Sands.

The most successful species used in terms of survival appears to be the shallow rooted leaf and stem succulent *O. cylindrica,* followed by the shallow rooted leaf succulents *L. suavissimus* and *R. versicolor*. From the results obtained on the survival of species it is recommended that *O. cylindrica, L. suavissimus* and *R. versicolor* could be used in future large-scale translocation projects on Namakwa Sands.

It is recommended that large-scale translocations of indigenous plants at Namakwa Sands should only take place in the winter growing season, the natural growing season in Namaqualand, as this should give plants a full growing season to stabilise in the new environment of a post strip-mined area.

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APPENDIX 5.1

SUMMARY OF CLASSIFICATION TREE METHODOLOGY

In the case of classification trees the dependent (response) variable y is a discrete variable consisting of 2 or more classes (e.g. yes/no, present/not present, low/medium/high). (For continuous response variables, a similar technique called regression trees can be used.)

<u>The concept of entropy</u>

The concept of entropy (chaos) is used as basis for constructing classification trees. To explain entropy in the framework of classification trees, consider a response variable with 2 classes namely yes/no. If a data set consists of 50% yes and 50% no responses, then the entropy of that data set is a maximum because the data will have only a 50% chance of correctly predicting the class of the response variable. As the proportion of one of the classes tends to 100%, the lower the entropy becomes, and it reaches a minimum when a data set consists of 100% of one class. In this case the data will have a 100% chance of correctly predicting the class of the response variable.

Entropy can be calculated from a dataset using various methods of which the Gini measure is probably the most common in classification trees.

The aim of a classification tree is to divide the data set into subsets such that the subsets have a lower entropy than the full data set. Thus it strives to group the classes together into subsets as best possible based on the independent or predictor variables. This is achieved as follows:

<u>Case 1: One continuous independent variable(x)</u>

The method selects a point x_p between the minimum and maximum of x that splits the data into two sets (or nodes in a tree). All the cases for which $x \leq x_p$ goes to the left node and all the cases where $x > x_p$ goes to the right node.

The point where the split is made is the point that decreases the entropy from the parent node to the child nodes the most.

The procedure above is then repeated for each of the two nodes. Thus a binary split is made on each node using the criteria mentioned above.

Stopping rules are used to decide when the splitting process should stop. For example a minimum number of cases per node can be specified, and if that minimum number is reached, the node will split no further.

Case 2: One categorical independent variable

In the case of a categorical independent variable, all combinations of binary splits of the levels of the variable are considered and the combination that most successfully decreases the entropy are used as splitting criteria. For example if a variable has three levels namely *a*,*b* and *c* then the following combinations of splits will be considered:

Left node	Right node
a	*b*,*c*
a,*b*	*c*
a,*c*	*b*

Case 3: More than one independent variable (combination of continuous and discrete)

The procedure described above is applied to each variable independently. Then the variables are compared with one another and the one that provides the best split over all the variables is used as the splitting variable.

Variable importance

A variable importance factor in terms of its effect on the response variable can be derived once the tree has been built. This variable importance is calculated based on the number of times the variable was used as splitting variable and how well it separated the classes of the response variable.

APPENDIX 5.2

SUMMARY OF REGRESSION TREE METHODOLOGY

In the case of regression trees the dependent (response) variable y is a continuous variable. (For categorical response variables, a similar technique called classification trees can be used.)

1 Case 1: One continuous independent variable(x)

The method selects a point x_s between the minimum and maximum of x that splits the data into two sets (or nodes in a tree). All the cases for which $x \leq x_p$ goes to the left node and all the cases where $x > x_p$ goes to the right node.

The point where the split is made is the point that most successfully separates the high response values from the low ones.

The procedure above is then repeated for each of the two nodes. Thus a binary split is made on each node using the criteria mentioned above.

Stopping rules are used to decide when the splitting process should stop. For example a minimum number of cases per node can be specified, and if that minimum number is reached, the node will split no further.

2 Case 2: One categorical independent variable

In the case of a categorical independent variable, all combinations of binary splits of the levels of the variable are considered and the combination that most successfully separates the high response values from the low ones are used as splitting criteria. For example if a variable has three levels namely *a*,*b* and *c* then the following combinations of splits will be considered:

<u>Left node</u>	<u>Right node</u>
a	*b*,*c*
a,*b*	*c*
a,*c*	*b*

<u>Case 3: More than one independent variable (combination of continuous and discrete)</u>

The procedure described above is applied to each variable independently. Then the variables are compared with one another and the one that provides the best split over all the variables is used as the splitting variable.

3 Variable importance

A variable importance factor in terms of its effect on the response variable can be derived once the tree has been built. This variable importance is calculated based on the number of times the variable was used as splitting variable and how well it separated the low values from the high values.

CHAPTER 6

IS THE RETURN OF BIODIVERSITY AND SOIL QUALITY AFFECTED BY REHABILITATION TECHNIQUE?

ABSTRACT

It is thought that soil treatment during the mining as well as post-mining rehabilitation processes influences the return of biodiversity to rehabilitation areas. In this study, on the arid West Coast of South Africa, I compared biodiversity and soil quality for combinations of top-soiling, irrigation, plant translocation and unmodified tailings. Irrigation may negatively affect the biodiversity and number of seedlings/m^2 on rehabilitation areas and can therefore not be recommended as a way of increasing biodiversity. For certain soil properties, an improvement took place over a period of 15 months following back filling and topsoil spreading. pH levels were slightly more neutral than the slightly acidic levels found in topsoil and sub-soil from undisturbed areas. Resistance appeared to have increased indicating a decrease in the salinity of the soils being used in rehabilitation, most likely due to leaching of free salts. Phosphorus levels did not return to those of undisturbed topsoil and sub-soil. Sodium, potassium and calcium for back-filled, shaped tailings appear to have returned to levels observed for topsoil and subsoil from undisturbed areas. Magnesium concentrations appear to remain lower than in topsoil and sub-soil from undisturbed areas. In general soil conditions may be more conducive for plant establishment and rehabilitation after back-filling of tailings and spreading of stockpiled topsoil. Further investigation is needed to determine the time taken and mechanisms at play for returning soil chemical conditions to those similar to pre-mining conditions. Carbon remained below pre-mining levels for at least 15 months after the rehabilitation programme was initiated and remains a potential limiting factor in rehabilitation. Further investigation should be made into potential causes for the decrease in carbon and means of alleviating the reduced carbon levels.

Key Words: strip-mines, rehabilitation techniques, seed banks, seedling emergence, biodiversity indices, arid areas, restoration ecology.

INTRODUCTION

During the strip-mining process large areas of natural vegetation are destroyed, and rehabilitation becomes essential to return damaged areas to a condition similar to the pre-mining capabilities of post-mined areas. Strategies for rehabilitation and restoration typically centre on augmenting, enhancing or accelerating changes in species composition and therefore in successional processes (Pyke and Archer 1991). A newly degraded landscape can be considered as a raw skeleton of soil materials with no plants. As plants begin to colonise the bare soil and contribute organic material to the soil; the environment becomes more able to sustain different and larger species, and progressively a more substantial and complex ecosystem develops (Bradshaw 1984). It must be remembered that processes involved in the production of many materials when industry or other activities degrade land create systems that have become extreme in both physical and chemical characteristics, precluding the growth of many common species (Bradshaw 1984). The rehabilitation processes at Namakwa Sands aims to restore the post-mined areas to a vegetation type and productivity equivalent to the pre-mining capabilities of the mine site, which supported small stock farming (Environmental Evaluation Unit 1990). However, to date the mine has had a slow increase in the occurrence of natural vegetation on post-mined areas (T. Hälbich 2001, personal communication).

Numerous studies have shown that processes involved in strip-mining negatively affect soil seed banks (Koch *et al.* 1996; Rokich *et al.* 2000; Schmidt 2002) and soil chemical, physical and biological processes (Rivers *et al.* 1980; Visser *et al.* 1984a).

Seeds are a crucial and integral part of desert ecosystems. Desert plants have developed various mechanisms to ensure that seed release and germination are coupled with sufficient moisture supply, and most seeds that are dormant during dry periods, require complex triggers to stimulate germination (Günster 1994). Seeds of most desert plant species represent the only means of dispersal in space and time (Kemp 1989), especially as a means of escape from unfavourable conditions and during long periods of drought annual species may persist as seeds for several years (Venable and Brown 1988). Seed size has been negatively correlated to longevity, with persistent seeds generally being small compact and well-defined, both physically and chemically. However, increased seed persistence is not always associated with reduced seed size, as persistence is not dependent on seed size only, but also on many other seed traits, including seed physiology. Annual and biennial species are thought to almost always have more persistent seeds than related perennials (Thompson *et al.* 1998). In general the winter annuals of Namaqualand have small compact seeds, which are easily buried (Fenner 1987; van Rooyen 1999).

If seeds are to persist in the seed bank, predation and decomposition have to be counteracted. Chemical defence mechanisms play a role in this regard, probably by decreasing the rate of decomposition by microbes, as well as defending against herbivory (van Rooyen 1999). For annuals and perhaps many of the short-lived leaf succulent shrubs in the succulent karoo, germination and recruitment are the critical life-cycle stages (Esler 1999). The differences in life-strategies between annual and perennial species is important to consider, as one is likely to find a larger seed bank for annuals than for perennials, as found by de Villiers (2000). Milton (1994) showed that changes in the species composition of shrub populations in arid rangelands could be a function of seed availability. The effects of mining could be changing the composition of the seed bank, which in turn would change the structure of vegetation returning to the post-mined areas. Schmidt (2002) found that seed bank numbers and diversity were negatively affected by the stockpiling of soil.

Until plants arrive, ecosystem development cannot take place. It is taken for granted that plants are readily dispersed over quite a distance. Although this applies to a few species with light seeds, or special organs to aid dispersal by wind or animals, it does not apply to all species (Bradshaw 1984). A characteristic of many desert plants is the relatively short seed dispersal distances (de Villiers 2000), suggesting that dispersal in space may be a limited means of rehabilitation on large strip-mines in arid areas. Seed dispersal in space plays a role in the potential for rehabilitation to occur on a disturbed area. If seeds are not designed for long distance dispersal, seeds may not necessarily reach areas that are undergoing rehabilitation and it may be necessary to supplement the seed bank. The use of topsoil is considered to be the most effective (and cost-effective) means of returning biodiversity to rehabilitation areas (Australian Mining Industry Council 1990; Fey 1996; de Villiers 2000). Kemp (1989) suggests that seeds in desert soils are distributed mostly near the soil surface, with between 80 and 90% of soil seeds in the upper 2-cm of soil. A seed bank study carried out at Namakwa Sands Mine found that there was a significant decrease in the number of seeds occurring with increased soil depth (De Villiers *et al.* 1993), reiterating this idea.

De Villiers (2000) found that the number of species recorded for the seed bank (109 species) was markedly lower than the number of species recorded in the standing vegetation (230 species) in the Strandveld Succulent Karoo, in which the mine occurs. Of the 109 species recorded in the soil seed bank 58 species were perennials and 51 were annuals, although annual species dominated the soil seed bank in terms of emerged seedlings. In light of these findings and the fact that the standing vegetation of the study area is dominated by perennial vegetation, de Villiers (2000) suggested that topsoil replacement would return large numbers of annual and perennial species to post-mined areas. However, de Villiers (2000) did not consider the effects that stockpiling might have on soil seed banks, as the mine was not stockpiling topsoil when the study was carried out. Koch *et al.* (1996) found that when topsoil was stockpiled prior to re-spreading, seed content was reduced by 31% in freshly created stockpiles and was reduced to 13% after ten months in stockpile. The process of stockpiling could have negative effects on the soil seed bank either by causing a dilution of the seed bank when topsoil and subsoils mix or by the use of poor techniques during stockpile creation and re-spreading (Rokich *et al.* 2000) or due to seed destruction in the stockpile.

Soil properties such as pH, salinity, nutrient cycling and soil aggregation may be affected by soil treatments involved in strip mining operations (Abdul-Kareem and McRae 1984; Visser *et al.* 1984a; Visser *et al.* 1984b; Galajda 1999; Strohmayer 2002). This change could affect germination and survival of seedlings, causing an overall change in the quantity and biodiversity of returning vegetation, which could influence the establishment of a self sustaining vegetation cover on post-mined areas. The use of topsoil is vital to achieving a suitable plant cover on post-mined areas and has been promoted on numerous occasions (Rethman *et al.* 1999, Rokich *et al.* 2000). Maximising the value of topsoil as an amendment is necessary to ensure that while soil is in stockpiles no significant losses in chemical, physical and biological properties occurs (Visser *et al.* 1984a). The testing and inventorying of post-mined soils and tailings to anticipate potential rehabilitation problems is recommended (Sharma and Gough 1999), as the full effects of storing topsoil are not known (Rivers *et al.* 1980). During the mineral extraction process at Namakwa Sands seawater is used to wash sub-soil being mined. The washing process has been shown to significantly increase the salinity of tailings (see Chapter 4). This may influence seedling establishment and nutrient cycling on post-mined areas, as leaching due to rain is unlikely (de Villiers *et al.* 1997). The mining process also acts as a soil filter where residues left after mineral extraction are separated into a sand (tailings) fraction and a clay (slimes) fraction. The clay fraction is stored in slimes dams and the fine grained sand tailings fraction is back-filled into the mined out area (Environmental Evaluation Unit 1990).

In this study I investigate whether combinations of top-soiling, irrigation, plant translocation and unmodified tailings influence the return of biodiversity to post-mined areas and whether the application of irrigation affects the soil quality of spread topsoil and unmodified tailings 15 months after rehabilitation begins.

METHODS

Study Site

The location, climate and physical conditions of Namakwa Sands Mine have been described fully in Chapter 2 and will therefore not be discussed here. However, information on the vegetation and seed banks of the study site, with particular reference to this study will be discussed.

In a pre-mining vegetation study of Namakwa Sands by de Villiers *et al.* (1999) the vegetation of the study area was described and divided into six vegetation units, some of which included several variants. The standing vegetation on the mine site, situated in the Strandveld Succulent Karoo, is dominated by perennial vegetation (de Villiers 2000). All vegetation units had a shrub stratum, dominated by perennial species and a herbaceous stratum dominated by ephemeral and grass species. The rehabilitation study site is situated within "Dwarf Shrub Strandveld" (as described in Chapter 2). A total of 171 plant species were recorded for this vegetation unit, which is the highest, compared to other vegetation units on the mine site. Dwarf Shrub Strandveld has a shrub stratum canopy cover of 16.8% and the herbaceous stratum canopy cover of 15.5%.

Prior to mining, analysis of soil-stored seed bank densities at Namakwa Sands were carried out (de Villiers 2000). Seed bank densities obtained varied between vegetation units, and are summarised in Table 6.1. Annual taxa (excluding grasses) yielded the highest similarity between vegetation and seed banks (67.9%), while perennial (excluding grasses) and grass taxa had similarities of 34.2% and 40.0% between their standing vegetation and seed banks, respectively.

Table 6.1: Mean number of emerged seedlings/m^2 of different plant types, for samples taken in six vegetation units (seasonal data were lumped (de Villiers 2000)). The number in brackets indicates the percentage either perennials, annuals or unidentified makes up of the total number of seedlings/m^2.

Plant type	Vegetation unit						Mean for study area
	1	2	3	4	5	6	
Perennials	225.0 (14%)	253.8 (9%)	170.0 (5%)	221.6 (7%)	187.8 (6%)	115.9 (5%)	195.7 (7%)
Annuals	742.6 (46%)	1767.8 (62%)	1870.2 (60%)	1717.1 (55%)	1826.2 (56%)	1056.5 (44%)	1496.7 (55%)
Unidentified	644.5 (40%)	842.5 (29%)	1060.7 (34%)	1155.4 (37%)	1262.0 (39%)	1232.4 (51%)	1032.9 (38%)
All Species	1612.1	2864.0	3100.9	3094.1	3276.0	2404.8	2725.3

The mining process involved at Namakwa Sands has been described in detail in Chapter two and will not be described here.

Experimental Design

A rehabilitation technique being investigated by Namakwa Sands involves the translocation of indigenous plants onto post-mined areas to facilitate the rehabilitation process. Fifteen months after translocations were initiated; this biodiversity study was carried out to determine if treatments used in the translocation trial influence the return of biodiversity to translocation areas.

The biodiversity and chemical analysis studies were carried out on the same experimental site and with the same experimental design as the translocation trials described in Chapter 5. Full details of the experimental design are given there.

Data Collection

Seedling Counts and Biodiversity

Seedling counts were carried out in September 2002; 15 months after the translocation trials were initiated. Seedlings were counted in each of the three blocks of the experiment (Chapter 5) within a minimum of five randomly selected 5x5-m sub-blocks for each of the treatments:

1. irrigated stockpiled topsoil spread over tailings with whole plants;
2. irrigated tailings with whole plants;
3. non-irrigated stockpiled topsoil spread over tailings with whole plants;
4. non-irrigated tailings with whole plants;
5. irrigated stockpiled topsoil spread over tailings with salvaged plants;
6. irrigated tailings with salvaged plants;
7. non-irrigated stockpiled topsoil spread over tailings with salvaged plants; and
8. non-irrigated tailings with salvaged plants.

The same randomly selected 5x5-m blocks were used for all main-blocks to ensure there was no edge effect. A metal ring (diameter of 1-m with two perpendicular cross wires) was randomly placed within the 5x5-m sub-block. The location of the ring was marked with the use of two wooden dowels approximately 30-cm in length) marking the centre and northern outer edge of the ring. All seedlings within the metal ring were counted and, where possible, identified.

Soil Samples

Soil was collected from four treatment sites (irrigated stockpiled topsoil spread over tailings; irrigated tailings; non-irrigated stockpiled topsoil spread over tailings and non-irrigated tailings). Three samples, consisting of 8 soil cores (50mm-deep, 47-mm in diameter) per sample, were collected for each treatment from each of the main-blocks over a two-day period (8th and 9th September 2002) with a total of 36 samples being collected. Each core was collected within the treatment site, with 2-m intervals between core collection points. All soil was collected from the upper 60-mm of soil. Samples were marked and sent for analysis at BemLab (Pty) Ltd[1]. The treatment of plant origin (whole and salvaged plants) was excluded, as soil samples were collected at least one meter away from clumps within the 5x5-m sub-block.

[1] BemLab (Pty) Ltd. 2002. AECI Building W21, De Beers Road, Somerset West, Western Cape.

STATISTICAL ANALYSIS

Seedling Counts

A split-split-plot design, which falls within the category of nested designs was used (Snedecor and Cochran 1989). This design is explained fully in Chapter 5 and will therefore not be explained here.

Seedling counts for each treatment per main-block (Block effect) were pooled and averaged (i.e., seedling counts for each of the five 5x5-m sub-block per treatment were pooled). The average of seedlings/m^2 was used to indicate number of emerged seedlings for each treatment. The general linear model ANOVA (Analysis of Variance) was applied to data for number of seedlings/m^2. Independent factors were irrigation, soil treatment and plant origin. Treatment factors were assigned either a random or fixed effect for all analyses (Table 6.2).

Table 6.2: Assignment of fixed and random effects for treatment factors applied in the general linear model design for seedling emergence and biodiversity analysis.

Effect	Fixed or Random
Block	Random
Irrigation	Fixed
Block * Irrigation	Random
Soil Treatment	Fixed
Irrigation * Soil Treatment	Fixed
Block * Irrigation * Soil Treatment	Random
Plant Origin	Fixed
Irrigation * Plant Origin	Fixed
Soil Treatment * Plant Origin	Fixed
Irrigation * Soil Treatment * Plant Origin	Fixed

If a significant ANOVA result was obtained, a univariate F-test was carried out for each variable to determine which single or interaction effects were significant (StatSoft Incorporated 2002). A result was regarded as significant at the 95% confidence level. All analyses were carried out with the use of the STATISTICA program (StatSoft Incorporated 2002)

Biodiversity Indices

To determine biodiversity indices for each treatment site, data obtained from the seedling counts were pooled as described for the number of seedlings/m^2. The Species Diversity and Richness Program (Henderson and Sealby 2001) was used to determine Simpson's D index for each of the pooled data sets. D is a diversity index proposed by Simpson (1949) to describe the probability that a second individual drawn from a population should be of the same species as the first. The larger D's value the greater the diversity.

Once Simpson's D Index was determined for all treatments, comparisons were made using a general linear model ANOVA. Treatment factors were assigned either a random or fixed effect for all analyses (Table 6.2). If a significant ANOVA result was obtained, a univariate F-test was carried out for each variable to determine which single or interaction effects were significant. The ANOVA and univariate F-tests were carried out in the STATISTICA program (StatSoft Incorporated 2002). A result was regarded as significant at the 95% confidence level.

Soil Samples

Analyses were carried out for soil pH, electrical resistance, exchangeable cations, available phosphorus and organic carbon for each of the three samples, per treatment per main-block. Results from the chemical analysis for the three samples from the same treatment and same main-block were then averaged to give a single value for each chemical property for each treatment for the main-block. A general linear model ANOVA was applied to data. Treatment factors were assigned either a random or fixed effect for all analyses (Table 6.3). If a significant ANOVA result was obtained, a univariate F-test was carried out for each variable to determine which single or interaction effects were significant (StatSoft Incorporated 2002). A result was regarded as significant at the 95% confidence level. Analyses were carried out with the use of the STATISTICA program (StatSoft Incorporated 2002).

Table 6.3: Assignment of fixed and random effects for treatment factors applied in the general linear model design for soil analysis.

Effect	Fixed or Random
Block	Random
Irrigation	Fixed
Block * Irrigation	Random
Soil Treatment	Fixed
Irrigation * Soil Treatment	Fixed

RESULTS

Significant differences were found for the block factor. However, block was not a factor of interest, as block represents replicates within the experimental design and not a factor being tested. It was later determined that irrigation was not applied evenly to all replicates (Table 6.4). This difference in irrigation together with other unknown factors may have caused the significant differences observed in results for the Block effect. For these reasons, limited results will be given for block effects and block interaction effects.

Table 6.4: Quantities of irrigation applied for the 2001 winter and spring seasons at Namakwa Sands (T. Hälbich 2002, personal communication).

Date	Block	Quantity	Comment
August 13, 2001	1	25mm	
August 13, 2001	3	25mm	
August 16, 2001	2	25mm	
September 19, 2001	1	25mm	
September 25, 2001	2	25mm	
October 24, 2001	2	50mm	
October 25, 2001	1	50mm	Block 3 not irrigated due to lack of water
November 26, 2001	1	50mm	
November 28, 2001	2	50mm	Block 3 not irrigated due to lack of water

After the trials were set out it was discovered that block 1 with irrigation had been top-soiled before all other blocks. This was an unavoidable logistical problem on the mine site that may affect results of the biodiversity trials undertaken in this study and must be considered when results are presented.

Seedling Counts

The average number and the range (minimum and maximum) of seedlings/m^2 are given in Table 6.5. A significant difference in the number of seedlings/m^2 was found for the interaction effect of block and irrigation (Figure 6.1). Block 1 had significantly more seedlings/m^2 when irrigation was applied compared to when irrigation was not applied. Block 2 had significantly more seedlings/m^2 when irrigation was not applied. Block 3 did not show a significant difference. The average number of seedlings/m^2 for block 1 is significantly higher than for block 2 and 3 when irrigation is applied, and significantly lower than block 2 and 3 when irrigation is not applied.

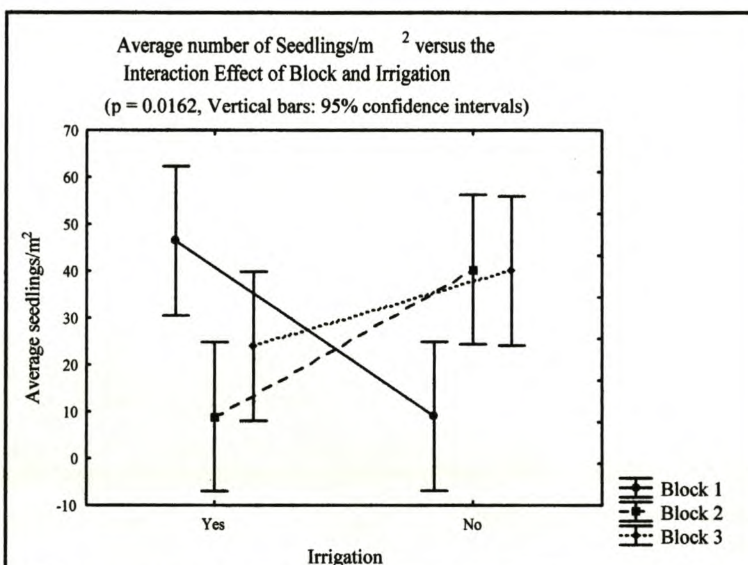

Figure 6.1: Plot of the interaction effect of block and irrigation on the number of seedlings/m^2. Vertical bars indicate the 95% confidence intervals. (Vertical bars below 0 seedlings/m^2 is a statistical anomaly due to working with averages.)

Table 6.5: Average number of seedlings/m^2, pooled for soil, irrigation, and plant origin treatments, with range of seedlings/m^2 (minimum – maximum), arranged from highest to lowest average seedlings/m^2.

Irrigation	Soil Treatment	Plant Origin	Average seedlings/m2	Range (Min-Max)
No	Stockpiled topsoil	Whole plants	39.30	8.91 - 118.41
Yes	Stockpiled topsoil	Whole plants	31.24	3.82 - 90.4
No	Stockpiled topsoil	Salvaged plants	30.47	0.00 - 94.22
Yes	Stockpiled topsoil	Salvaged plants	27.84	3.82 - 68.75
No	Tailings	Whole plants	26.82	3.82 - 53.48
Yes	Tailings	Whole plants	25.21	3.82 - 67.48
No	Tailings	Salvaged plants	22.66	6.67 - 49.66
Yes	Tailings	Salvaged plants	21.39	2.55 - 59.84

Biodiversity Indices

Number of species per treatment as well as the Simpson's D Index of biodiversity is given in Table 6.6. Block 1 had significantly more species when irrigation was applied, compared to when irrigation was not applied. Block 2 had significantly more species when irrigation was not applied and block 3 did not show a significant difference in the number of species when irrigation was or was not applied (Figure 6.2). When irrigation was not applied Simpson's D Index was significantly higher than when irrigation was applied (Figure 6.3).

Table 6.6: Species Richness as number of species per treatment and the Simpson's D Index of biodiversity for the treatment factors of Block, Irrigation, Soil treatment and Plant origin.

Treatment Factor				Number of Species	Simpson's D Index
Block	Irrigation	Soil Treatment	Plant Origin		
1	Yes	Tailings	Salvaged plants	15	3.44
1	Yes	Tailings	Whole plants	18	5.29
1	Yes	Stockpiled topsoil	Whole plants	16	3.92
1	Yes	Stockpiled topsoil	Salvaged plants	16	3.94
1	No	Tailings	Salvaged plants	12	5.88
1	No	Tailings	Whole plants	10	6.70
1	No	Stockpiled topsoil	Whole plants	12	4.06
1	No	Stockpiled topsoil	Salvaged plants	12	12.00
2	Yes	Tailings	Salvaged plants	9	4.68
2	Yes	Tailings	Whole plants	9	5.08
2	Yes	Stockpiled topsoil	Whole plants	12	8.82
2	Yes	Stockpiled topsoil	Salvaged plants	17	2.85
2	No	Tailings	Salvaged plants	16	6.82
2	No	Tailings	Whole plants	26	8.16
2	No	Stockpiled topsoil	Whole plants	22	6.28
2	No	Stockpiled topsoil	Salvaged plants	22	8.43
3	Yes	Tailings	Salvaged plants	15	6.21
3	Yes	Tailings	Whole plants	14	3.46
3	Yes	Stockpiled topsoil	Whole plants	21	8.94
3	Yes	Stockpiled topsoil	Salvaged plants	22	8.22
3	No	Tailings	Salvaged plants	22	8.81
3	No	Tailings	Whole plants	23	9.89
3	No	Stockpiled topsoil	Whole plants	24	7.42
3	No	Stockpiled topsoil	Salvaged plants	21	6.85

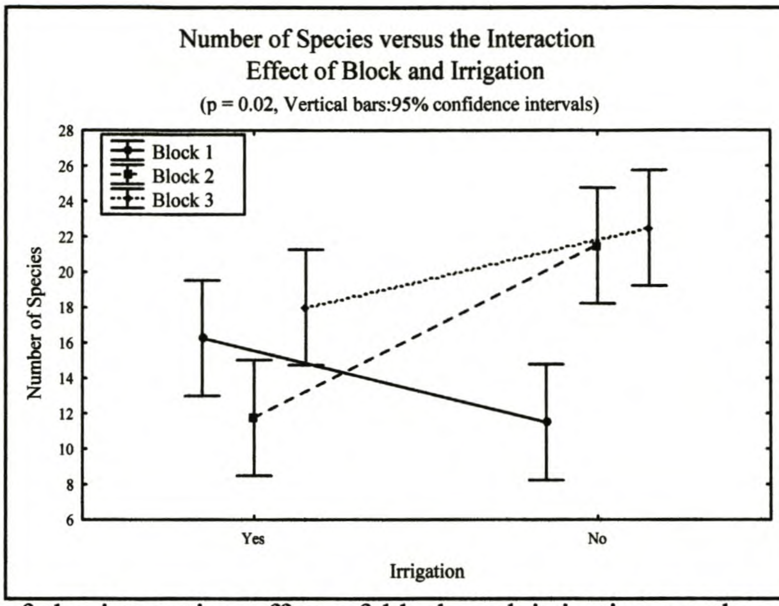

Figure 6.2: Plot of the interaction effect of block and irrigation on the number of species observed. Vertical bars indicate the 95% confidence intervals.

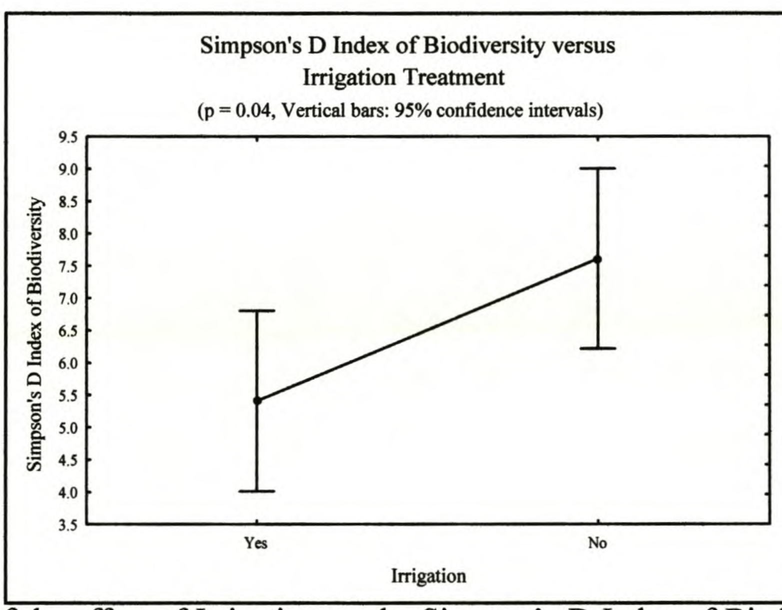

Figure 6.3: Plot of the effect of Irrigation on the Simpson's D Index of Biodiversity. Vertical bars indicate the 95% confidence intervals.

Of the species that were identified (Table 6.7), 9 species were perennials and 10 species were annuals. Of all species identified as either annual or perennial there were a total of 2 053 plants counted. Of these plants counted 82.85% were annuals and 17.15% were perennials. Only one geophyte was identified. For perennial species there was a range of between 7 and 5 different species observed for the different treatments examined, with 5 species being the mode. Non-irrigated topsoil spread over tailings with whole plants had more individuals than all other treatments. These results are summarised in Table 6.8.

Table 6.7: A summary of perennial and annual species that were identified, according to life history strategy, with the total number of plants counted per species. (This table excludes species that were not identified.)

Species	Life History Strategy	Total Individuals Counted
Amellus tenuifolius	Perennial	39
Chaetobromus involucratus	Perennial	2
Conicosia pugioniformis	Perennial	50
Crassula expansa	Perennial	3
Drosanthemum hispidum	Perennial	3
Herrea elongata	Perennial	2
Manochlamys albicans	Perennial	29
Othonna cylindrica	Perennial	185
Tetragonia fruticosa complex	Perennial	39
Oxalis obtusa	Geophyte	14
Arctotheca calendula	Annual	38
Atriplex lindleyi sp. *inflata* *	Annual	12
Ehrharta brevifolia	Annual	747
Karroochloa schismoides	Annual	1
Mesembryanthemum guerichianum	Annual	344
Molluga cerviana	Annual	81
Oncosiphon grandiflorum	Annual	426
Salsola kali *	Annual	12
Wahlenbergia paniculata	Annual	6
Zaluziansky benthamiana	Annual	28
	Total Perennials	352
	Total Geophytes	14
	Total Annuals	1695
	TOTAL	2061

*Indicates exotic species.

Table 6.8: Number of perennial plants and number of perennial species, listed from highest to lowest for various treatments investigated.

Treatment	Number of Plants	Number of Species
Non-irrigated Topsoil, Whole plants	103	5
Non-irrigated Tailings, Whole plants	47	6
Irrigated Topsoil, Whole plants	46	7
Non-irrigated Tailings, Salvaged plants	41	5
Non-irrigated Topsoil, Salvaged plants	39	5
Irrigated Tailings, Whole plants	30	5
Irrigated Topsoil, Salvaged plants	24	5
Irrigated Tailings, Salvaged plants	22	5

For annual species there was a range of between 10 and 7 species observed for the different treatments investigated, with 8 species being the mode. Non-irrigated topsoil spread over tailings with whole plants had more individuals and more species than all other treatments investigated. These results are summarised in Table 6.9.

Table 6.9: Number of annual plants and number of perennial species, listed from highest to lowest for various treatments investigated.

Treatment	Number of Plants	Number of Species
Non-irrigated Topsoil, Whole plants	273	10
Irrigated Topsoil, Whole plants	255	7
Irrigated Topsoil, Salvaged plants	235	9
Non-irrigated Topsoil, Salvaged plants	222	8
Irrigated Tailings, Whole plants	210	9
Non-irrigated Tailings, Whole plants	179	8
Irrigated Tailings, Salvaged plants	172	7
Non-irrigated Tailings, Salvaged plants	150	8

Soil Results

A full list of soil chemical analysis results, as supplied by BemLab (Pty) Ltd. is given in Appendix 6.1.

pH (KCl)

Analysis of pH showed no significant difference between any of the treatments investigated.

Electrical Resistance (Ohm)

Electrical resistance did not show significant results at the 95% confidence level. However, a result that should be considered was obtained for soil treatment, where tailings had a higher resistance than stockpiled topsoil spread over tailings (Figure 6.4). This result should be considered as it may indicate that tailings has a lower salinity than that of stockpiled topsoil spread over tailings, indicating more free salts in stockpiled topsoil spread over tailings than in tailings only.

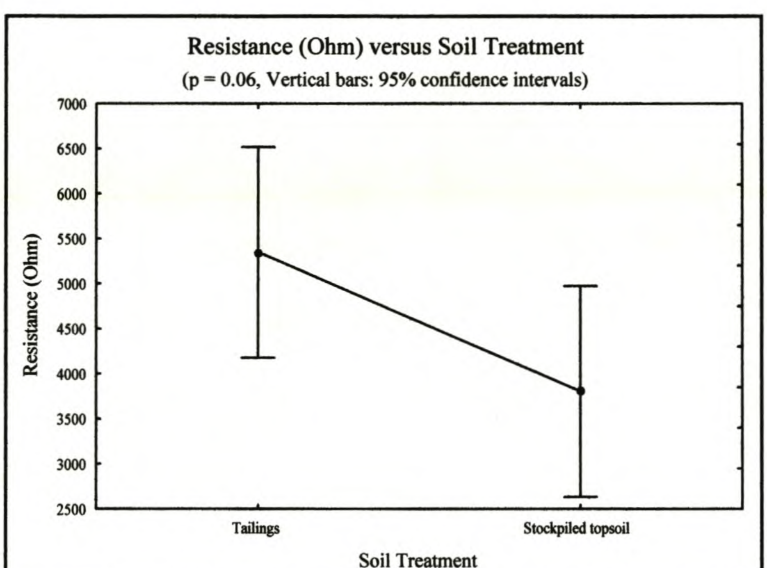

Figure 6.4: Plot of the effect of soil treatment on electrical resistance (Ohm). Vertical bars indicate the 95% confidence intervals.

Available Phosphorus (mg/kg)

Available phosphorus did not show any significant differences for any treatment factors or combination of treatment factors.

Sodium (Percentage)

Analyses of exchangeable sodium percentage did not indicate a significant result at the 95% confidence level; however, results obtained for irrigation have been included to indicate patterns within results obtained for other chemicals in the analysis. When irrigation was applied percentage sodium was significantly lower than when irrigation was not applied (Figure 6.5).

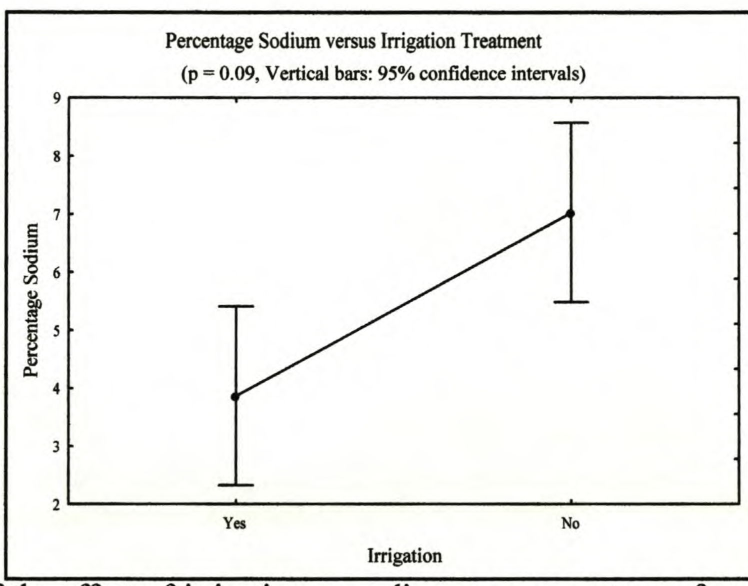

Figure 6.5: Plot of the effect of irrigation on sodium as a percentage of exchangeable cations. Vertical bars indicate the 95% confidence intervals.

Potassium (Percentage)

Potassium analyses revealed a significant difference for Block effect. Block 3 had significantly more potassium than either Block 1 or Block 2. There was no significant difference between exchangeable potassium percentage for Block 1 and Block 2 (Figure 6.6).

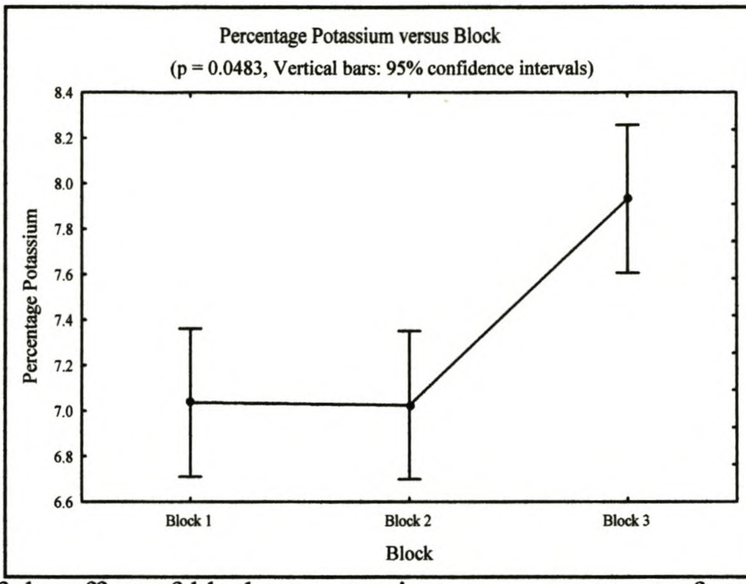

Figure 6.6: Plot of the effect of block on potassium as a percentage of exchangeable cations. Vertical bars indicate the 95% confidence intervals.

Calcium (Percentage)

Analyses found no significant differences between exchangeable calcium percentage for any of the treatment factors.

Magnesium (Percentage)

Results obtained for exchangeable magnesium percentage did not show any significant differences at the 95% level. A result that should be considered in the context of results obtained for the complete soil chemical analysis is included. For the factor of soil treatment percentage magnesium was higher in tailings than in stockpiled topsoil spread over tailings (Figure 6.7).

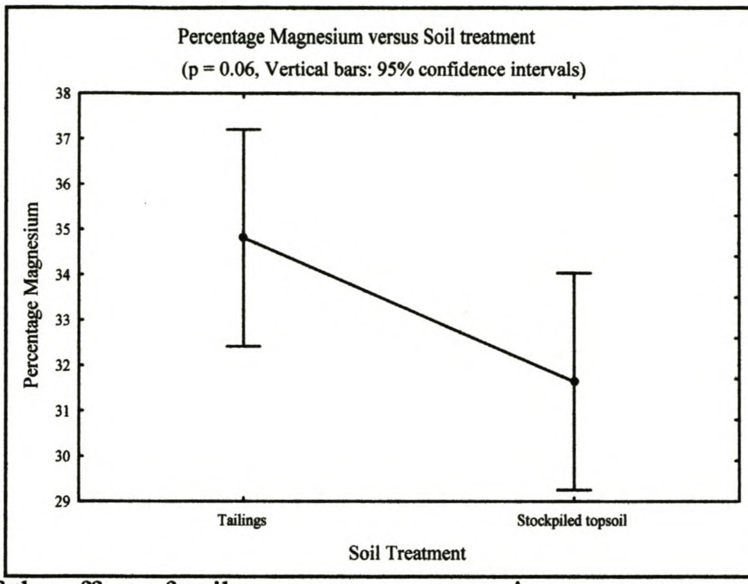

Figure 6.7: Plot of the effect of soil treatment on magnesium as a percentage of exchangeable cations. Vertical bars indicate the 95% confidence intervals.

Carbon (Percentage)

No significant results were obtained for analyses carried out on percentage organic carbon in soils within the four treatments analysed.

Chemical Change Over Time

To highlight changes that may have occurred from the time soils were first disturbed to a point 15 months after rehabilitation began, data from analyses carried out are compared to results from Chapter 4 and are summarised in Tables 6.10a and 6.10b.

Table 6.10a: Average value of soil chemical properties analysed (± Standard Deviation) for the treatments analysed 15 months after topsoil spreading.

Soil Treatment	Average pH ± SD	Average Resistance ± SD	Average P (mg/kg) ± SD	Average %Na ± SD	Average %K ± SD	Average %Ca ± SD	Average %Mg ± SD	Average %C ± SD
Irrigated Tailings	6.278±0.04	7016±2292.40	22.000±3.84	3.730±1.26	7.310±0.89	54.372±2.15	34.587±2.50	0.289±0.053
Irrigated Stockpiled topsoil	6.256±0.13	4760±2673.48	26.889±9.35	4.011±0.89	7.137±0.70	56.886±2.29	31.969±3.68	0.266±0.068
Non-Irrigated Tailings	6.344±0.16	3680±1697.71	20.778±9.43	7.278±3.06	7.462±0.53	48.647±4.15	35.032±1.58	0.298±0.042
Non-Irrigated Stockpiled topsoil	6.200±0.19	2850±1143.72	23.333±11.20	6.776±2.36	7.414±0.52	52.146±9.52	31.320±4.03	0.363±0.145

Table 6.10b: Average value of soil chemical properties analysed (± Standard Deviation) for the treatments of undisturbed topsoil, undisturbed subsoil, stockpiled topsoil and tailings prior to spreading (taken from Chapter 4).

Soil Treatment	Average pH ± SD	Average Resistance ± SD	Average P (mg/kg) ± SD	Average %Na ± SD	Average %K ± SD	Average %Ca ± SD	Average %Mg ± SD	Average %C ± SD
Undisturbed topsoil	5.614±0.45	1695±391.23	18.286±5.65	3.920±1.31	8.236±1.57	52.114±7.25	35.731±5.34	0.729±0.13
Undisturbed subsoil	4.829±0.66	1178±345.71	8.429±3.69	7.426±2.78	7.630±0.95	44.164±9.66	40.780±7.56	0.713±0.11
Stockpiled topsoil	6.357±0.17	914±172.90	12.143±2.61	7.287±0.75	9.383±0.31	57.927±1.39	25.401±0.67	0.619±0.09
Tailings	6.114±0.04	225±15.12	4.286±0.49	54.683±0.82	6.377±0.24	15.639±0.69	23.300±0.35	0.254±0.06

pH levels have not returned to levels of topsoil and subsoil from undisturbed areas. Fresh tailings had a low resistance compared to tailings measured 15 months after spreading. Resistance levels in stockpiled topsoil 15 months after spreading appeared to be much higher than resistance in stockpiled topsoil in piles. Resistance levels in rehabilitation areas appear to be higher than for pre-mining soil conditions. Phosphorus levels appear to be higher in rehabilitation areas than in pre-mining soil conditions. Sodium levels observed is soils tested in this study are similar to those observed for pre-mining soil conditions. Potassium 15 months after rehabilitation began, appear to be at similar levels to undisturbed areas. The high levels of potassium in stockpiled topsoil prior to spreading and the low levels in tailings are no longer observed. Percentage calcium and magnesium in 15 month old rehabilitation areas appears to have returned to levels observed in pre-mining soil conditions. Carbon in soils of rehabilitation areas 15 months after rehabilitation began appears to be at lower levels than those observed in pre-mining as well as stockpiled topsoil in piles, but appears to be higher than carbon in tailings.

DISCUSSION

It has been shown in numerous studies that one of the most effective ways to encourage the revegetation of disturbed areas is through the use of topsoil spreading (Australian Mining Industry Council 1990; Rethman *et al.* 1999; de Villiers 2000). The effectiveness of stockpiled topsoil spreading has not been tested for Namakwa Sands. The establishment and growth of vegetation at any point in the landscape occurs in response to the availability of seed and three basic resources: water, nutrients and solar energy. The availability of these resources is influenced by a complexity of environmental factors: soil, topography, aspect, rainfall, fire, competition with other plants and with other organisms (Palmer *et al.* 1999). All these factors are affected differently by the mining process. Results obtained in this study should elucidate some of the factors affecting the return of biodiversity to post-mined areas on Namakwa Sands.

Results indicate that the interaction between block and irrigation do play a role in differences of average number of seedlings/m^2 and species richness. This effect is likely to be caused by the slightly older age of irrigated block 1 compared to all other blocks, combined with the fact that irrigated block 3 received less irrigation that blocks 1 and 2. The Simpson's D Index for biodiversity indicated a higher diversity when irrigation was not applied. This indicates that in general irrigation may be decreasing the return of diversity to the rehabilitation areas.

It is well documented that up to 90% of soil seed banks are stored in the upper 5 to 10-cm of topsoil (Kemp 1989). Overall findings for number of seedlings/m^2 for stockpiled topsoil spread over tailings and tailings only was far lower than found by de Villiers (2000), compared to any of the vegetation units assessed (Table 6.1). Decreases in seedling recruitment have been noted in stockpiled topsoil for other mine sites (Koch *et al.* 1996; Rokich *et al.* 2000; Schmidt 2002).

De Villiers (2000) noted that the standing vegetation at the study site was not well represented in the soil seed banks, however seed banks were well represented in the standing vegetation. Those species recorded only in the seed bank were mainly annuals with relatively low densities and frequencies. Most samples used in the seed bank trials had few or no seeds and only a minor proportion had a large number of seeds. This general spatial heterogeneity may in part be the result of the relatively short seed dispersal distances characteristic of the majority of desert plants, or the consequence of directed dispersal by ants or rodents, or trapping of wind-blow seeds by shrubs (de Villiers 2000). This indicates that alternate methods should be applied to facilitate the return of biodiversity to Namakwa Sands. The technique of seeding rehabilitation areas with indigenous seeds has been suggested before (de Villiers 2000) and should be examined further.

In terms of biodiversity, Simpson's D Index is negatively affected by irrigation. It is recommended that irrigation not be used in rehabilitation efforts were increased biodiversity is the main objective.

The treatment of stockpiled topsoil with whole plants produced the greatest number of annual species as well as the greatest number of annual and perennial individuals. The number of perennial species observed does not appear to be greatly influenced by soil treatment. These results indicate that the spreading of topsoil and the use of whole translocated plants (compared to salvaged translocated plants) may be facilitating the return of perennial and annual vegetation to the rehabilitation site. It is highly recommended that stockpiled topsoil be used in rehabilitation to return biodiversity to post-mined areas. Annual species tend to dominate the returning vegetation, not only in the number of different species returning, but also notably through the number of annual individuals returning.

The mine site has continuing rehabilitation efforts across post-mined areas at Namakwa Sands. These treatments are applied at different times and to different degrees, depending on climatic conditions and various other management constraints. This made it difficult to access an area of the mine that had not undergone any rehabilitation efforts at all and subsequently a control could not be found for the biodiversity study. For this reason, I was not able to determine if translocation of indigenous plant species is facilitating the return of biodiversity to rehabilitation areas or not.

This study has revealed changes in the chemical composition of fresh tailings and stockpiled topsoil in piles from the time rehabilitation begins to a period of time 15 months later.

pH values 15 months after rehabilitation began were not affected by rehabilitation technique. Due to the slight changes in pH observed in Chapter 4, it is unlikely that the changes observed in soil pH would influence plant growth on post-mined areas. If long-term studies reveal that pH is affecting rehabilitation, cost effective means of ameliorating pH levels may be considered by the mine.

Sodium levels measured 15 months after rehabilitation trials began indicated that sodium in back-filled tailings returned to levels observed for undisturbed subsoil, indicating that amelioration of sodium levels in tailings is occurring. Irrigation may not be needed to ameliorate sodium levels in fresh tailings. At this stage it is unclear how or why sodium decreased in tailings and further investigation into the mechanisms involved in this amelioration process is needed to determine constraints that may influence amelioration.

Fifteen months after rehabilitation trials were initiated resistance appeared to increase above levels observed in undisturbed topsoil and subsoil. These higher levels indicate a reduction in the free salts and therefore the salinity of post-mined soils. Resistance is known to differ between certain Strandveld plant communities (Eccles 2000). Inconsistencies observed on the rehabilitation study site may be due to soil from one vegetation unit being deposited onto a different vegetation unit area, reflecting inherent differences in soil chemistry which become evident after free salt levels in post-mined soils are normalised. It is likely that free salts were washed out of post-mined soils during the winter rain season or through irrigation that was applied during the study. However, further investigation is needed to determine if resistance will continue to increase over time on rehabilitation areas.

Phosphorus appear to increase (above levels observed in undisturbed soils) in back-filled tailings and spread topsoil 15 months after rehabilitation trials were initiated, indicating that phosphorus levels may be accumulating in rehabilitation areas. However, if irrigation was applied phosphorus appeared not to increase as much when irrigation was applied. Fey (1996) suggests that due to marine influences on soils of the area, phosphorus availability could be more appropriately determined by means of an alkaline extract rather than an acidic Bray II solution, which was used in this case. Conclusions about phosphorus based on these data should be regarded as tentative. Further investigation is needed to determine if observed increases are a trend, causing phosphorus to accumulate in rehabilitation areas over time. Irrigation may be leaching phosphorus from rehabilitation areas.

Potassium showed significantly higher levels in block 3 than in blocks 1 or 2. This may be due to the effect of block 3 not receiving the same amount of irrigation as blocks 1 and 2. Potassium and calcium levels for back-filled tailings 15 months after rehabilitation began, appear to have returned to levels observed for topsoil and subsoil from undisturbed areas. Magnesium levels appear to remain lower than levels observed in undisturbed soils, although levels appear to be higher than for fresh tailings and stockpiled topsoil still in piles. Improved soil conditions indicate that after back-filling of tailings and spreading of stockpiled topsoil takes place soil conditions may become more conducive for plant establishment and rehabilitation over time. These ameliorated conditions should be investigated further to determine the long term effect of the changes that occur from the time tailings are back-filled and stockpiled topsoil spread to the point where potassium levels return to levels equivalent to pre-mining conditions.

No significant differences were found for percentage carbon for the four treatments examined in this study. However, comparisons of carbon in pre-mining conditions indicate that carbon levels are not returning to levels observed before mining took place. Further studies are needed to determine why carbon levels are not increasing in post-mined areas. The mining process of washing and separating mine tailings into a clay slimes fraction and a sand fraction is likely to be the cause of lowered organic carbon levels in rehabilitation areas, as much of the carbon remains in the slimes fraction which is not used in rehabilitation. Subsequent rehabilitation processes may also be a limiting factor in rehabilitation.

Although not noted in analyses carried out for Namakwa Sand (Chapter 4), carbon has been shown to decrease in stockpile (Abdul-Kareem and McRae 1984). The fact that carbon does not decrease in stockpiles at Namakwa Sands may be because of the short time that soils are in stockpile. The spreading of stockpiled topsoil over tailings on post-mined areas is unlikely to alleviate reduced carbon levels. Reduced carbon levels have been shown to be a limiting factor in stimulating microbial metabolic activities (Galajda 1999). Levels of microbial activities in both pre-mining soils and post-mining soils have not been examined at Namakwa Sands. It is recommended that further investigation be carried out to determine if reduced carbon in post-mined rehabilitation areas is affecting microbial activities. It has been noted that for soils to be productive, a continuous flow of energy in the form of carbon compounds through soil organisms is needed (Strohmayer 2002).

CONCLUSION

Results indicate that winter and spring irrigation may be negatively affecting the return of biodiversity and the number of seedlings/m^2 on rehabilitation areas. It is suggested that irrigation on post-mined areas not be used as a rehabilitation mechanism in respect of attempting to increase biodiversity. Results also indicate that there are more annual species and more annual individuals returning to rehabilitation sites than perennials. It is recommended that rehabilitation techniques, such as seeding with perennial species, be implemented to facilitate the return of perennial biodiversity to rehabilitation areas. It is suggested that further trials be carried out to determine the effects translocation may be having on the return of biodiversity to rehabilitation areas, with measures in place to control for rehabilitation work being applied to other areas of the rehabilitation areas.

Findings indicate that certain soil properties have been ameliorated from the time tailings back filling and stockpiled topsoil spreading took place and the time soil analyses were carried out 15 months later. pH remained similar to conditions in topsoil stockpiles and fresh tailings, although these levels are slightly more neutral than the slightly acidic levels found in undisturbed topsoil and sub-soil. Resistance appeared to have increased during the 15 months since rehabilitation was initiated. These higher levels indicate a lowered salinity level on rehabilitation areas, most likely due to free salts being leached out of soils on rehabilitation areas. Phosphorus levels appear not to have returned to levels found in undisturbed topsoil and sub-soil, however, levels in back-filled tailings appear to be higher than for fresh tailings. Levels of sodium, potassium and calcium for back-filled, shaped tailings after 15 months appear to have returned to levels observed for undisturbed topsoil and subsoil. These results indicate that the use of salt water in the mining process may not have a long-term effect on soil salinity levels. Magnesium levels appear to remain lower than levels observed in undisturbed topsoil and sub-soil. However, the levels do appear to be higher than for fresh tailings and stockpiled topsoil still in piles. Soil conditions may be more conducive for plant establishment and rehabilitation after tailings back-filling and stockpiled topsoil spreading takes place. Further investigation is needed to determine the time taken and mechanisms at play for soil amelioration to take place returning soil chemical conditions to those similar to pre-mining conditions. More investigation is also needed into the high levels of observed resistance.

Decreased carbon levels in rehabilitation areas remain a potential limiting factor for rehabilitation, as levels have not increased to pre-mining levels in the 15 months that rehabilitation programme was initiated. Carbon levels appear to remain low, most likely due to the potential concentration of organic carbon in clay slimes. Further investigation is needed into the composition of the clay slimes and possible mechanisms for the use of clay slimes in the rehabilitation process, to potentially ameliorate low carbon levels.

Largely unknown, however, are the long-term (>10 years) changes in the chemical and physical nature of the tailings materials and the sustainability of the developed landscape and the vegetation community. Long-term studies are needed regarding the chemical changes that occur in soils once tailings are back-filled and stockpiled topsoil is spread (Sharma and Gough 1999).

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APPENDIX 6.1

COMPLETE SOIL ANALYSIS RESULTS OBTAINED FROM BEMLAB (Pty)Ltd.

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De Beers Road
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P O Box 12457
Die Boord, Stellenbosch 7613

BemLab (Pty) Ltd

Reg. Nr. 2002/017933/07

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E-Mail akotze@adept.co.za

VAT Reg. No. 4160185577

Dear Kirsten Mahood

The results of your soil analyses are as follows:

Date received: 12/09/2002

Orchard No.	Lab. No.	Depth (cm)	Soil	pH (KCl)	Resist. (Ohm)	H (cmol/kg)	P Bray II	K	Exchangeable cations (cmol(+)/kg)				C
							mg/kg		Na	K	Ca	Mg	%
Topsoil Block 1	11604	0	Sand	6.6	4440	0.00	36	59	0.05	0.15	1.24	0.60	0.31
Topsoil Block 1	11605	0	Sand	6.3	3940	0.00	33	68	0.14	0.17	1.41	0.71	0.33
Topsoil Block 1	11606	0	Sand	6.3	1400	0.00	44	85	0.20	0.22	1.77	0.84	0.33
Topsoil Block 2	11607	0	Sand	6.3	7150	0.00	23	39	0.06	0.10	0.65	0.44	0.20
Topsoil Block 2	11608	0	Sand	6.4	1890	0.00	22	41	0.15	0.11	0.64	0.44	0.26
Topsoil Block 2	11609	0	Sand	6.4	3380	0.00	22	38	0.12	0.10	0.74	0.49	0.24
Topsoil Block 3	11610	0	Sand	6.2	6810	0.00	23	28	0.03	0.07	0.66	0.42	0.15
Topsoil Block 3	11611	0	Sand	6.1	9900	0.00	20	28	0.03	0.07	0.66	0.43	0.21
Topsoil Block 3	11612	0	Sand	6.2	6830	0.00	23	44	0.06	0.11	0.82	0.56	0.21
Topsoil Block 4	11613	0	Sand	6.1	2730	0.00	33	80	0.09	0.20	1.87	0.80	0.50
Topsoil Block 4	11614	0	Sand	6.3	1430	0.00	30	97	0.19	0.25	2.24	0.97	0.60
Topsoil Block 4	11615	0	Sand	6.3	1720	0.00	42	89	0.13	0.23	2.10	0.88	0.46
Topsoil Block 5	11616	0	Sand	6.1	3280	0.00	27	52	0.06	0.13	0.92	0.53	0.26
Topsoil Block 5	11617	0	Sand	6.2	3360	0.00	20	55	0.05	0.14	1.13	0.57	0.30
Topsoil Block 5	11618	0	Sand	6.3	2880	0.00	16	49	0.08	0.13	0.91	0.50	0.29
Topsoil Block 6	11619	0	Sand	6.0	3500	0.24	11	54	0.10	0.14	0.80	0.59	0.32
Topsoil Block 6	11620	0	Sand	5.9	920	0.15	14	52	0.26	0.13	0.64	0.63	0.29
Topsoil Block 6	11621	0	Sand	6.1	2930	0.00	13	76	0.10	0.19	1.14	0.73	0.40
Tailings 1	11622	0	Sand	6.4	5140	0.00	28	39	0.06	0.10	0.94	0.53	0.34
Tailings 1	11623	0	Sand	6.2	6880	0.00	20	35	0.05	0.09	0.92	0.57	0.34
Tailings 1	11624	0	Sand	6.3	7050	0.00	29	49	0.05	0.13	0.95	0.59	0.32

Orchard No.	Lab. No.	Depth (cm)	Soil	pH (KCl)	Resist. (Ohm)	H (cmol/kg)	P Bray II	K	Exchangeable cations (cmol(+)/kg)				C %
							mg/kg		Na	K	Ca	Mg	
Tailings 2	11625	0	Sand	6.5	3580	0.00	24	44	0.10	0.11	0.72	0.49	0.21
Tailings 2	11626	0	Sand	6.6	5250	0.00	23	38	0.08	0.10	0.84	0.52	0.27
Tailings 2	11627	0	Sand	6.5	4160	0.00	23	47	0.12	0.12	0.93	0.61	0.34
Tailings 3	11628	0	Sand	6.3	8270	0.00	21	39	0.03	0.10	0.68	0.47	0.25
Tailings 3	11629	0	Sand	6.2	9180	0.00	22	43	0.04	0.11	0.64	0.46	0.22
Tailings 3	11630	0	Sand	6.2	11250	0.00	24	32	0.03	0.08	0.68	0.50	0.22
Tailings 4	11631	0	Sand	6.5	4190	0.00	42	47	0.10	0.12	0.99	0.61	0.33
Tailings 4	11632	0	Sand	6.4	3920	0.00	34	59	0.11	0.15	1.15	0.73	0.25
Tailings 4	11633	0	Sand	5.9	6760	0.24	10	54	0.07	0.14	0.65	0.59	0.24
Tailings 5	11634	0	Sand	6.1	6910	0.00	12	48	0.08	0.12	0.59	0.45	0.30
Tailings 5	11635	0	Sand	6.7	3050	0.00	29	57	0.10	0.14	1.79	0.66	0.31
Tailings 5	11636	0	Sand	6.1	5420	0.00	13	57	0.08	0.15	0.80	0.59	0.30
Tailings 6	11637	0	Sand	6.3	1080	0.00	11	56	0.24	0.14	0.81	0.67	0.22
Tailings 6	11638	0	Sand	6.2	1580	0.00	9	76	0.25	0.19	0.99	0.84	0.51
Tailings 6	11639	0	Sand	6.2	2600	0.00	11	51	0.14	0.13	0.75	0.61	0.31

If the pH > 7.0 the Olsen method is used to determine P.

Base Saturation

Orchard No.	Lab. No.	Na %	K %	Ca %	Mg %	T-Value cmol/kg
Topsoil 1	11604	2.41	7.44	60.57	29.59	2.04
Topsoil 1	11605	5.87	7.17	57.95	29.01	2.43
Topsoil 1	11606	6.62	7.21	58.29	27.88	3.03
Topsoil 2	11607	4.70	8.00	52.15	35.15	1.25
Topsoil 2	11608	11.18	7.87	47.86	33.08	1.33
Topsoil 2	11609	8.28	6.71	51.17	33.83	1.44
Topsoil 3	11610	2.92	6.00	55.51	35.58	1.18
Topsoil 3	11611	2.54	5.96	55.21	36.29	1.20
Topsoil 3	11612	4.12	7.20	52.52	36.16	1.56
Topsoil 4	11613	3.14	6.86	62.88	27.12	2.97
Topsoil 4	11614	5.17	6.84	61.50	26.49	3.64
Topsoil 4	11615	3.84	6.84	62.87	26.45	3.33
Topsoil 5	11616	3.68	8.01	55.84	32.47	1.64
Topsoil 5	11617	2.75	7.45	59.73	30.07	1.89
Topsoil 5	11618	5.19	7.79	56.35	30.67	1.62
Topsoil 6	11619	5.58	7.31	42.87	31.44	1.88
Topsoil 6	11620	14.29	7.36	35.49	34.58	1.81
Topsoil 6	11621	4.80	8.94	52.52	33.74	2.17

Orchard No.	Lab. No.	Na %	K %	Ca %	Mg %	T-Value cmol/kg
Tailings 1	11622	3.59	6.08	57.69	32.64	1.64
Tailings 1	11623	2.88	5.54	56.52	35.06	1.63
Tailings 1	11624	3.02	7.32	55.47	34.18	1.72
Tailings 2	11625	6.73	7.95	50.67	34.66	1.42
Tailings 2	11626	4.98	6.41	54.90	33.72	1.53
Tailings 2	11627	6.76	6.73	52.35	34.16	1.78
Tailings 3	11628	2.50	7.72	52.93	36.85	1.29
Tailings 3	11629	3.50	8.68	51.02	36.81	1.26
Tailings 3	11630	2.54	6.30	52.80	38.36	1.29
Tailings 4	11631	5.25	6.66	54.62	33.46	1.82
Tailings 4	11632	5.12	7.06	53.87	33.95	2.14
Tailings 4	11633	4.42	8.18	38.37	34.79	1.68
Tailings 5	11634	6.78	9.78	47.06	36.38	1.25
Tailings 5	11635	3.88	5.35	66.29	24.47	2.70
Tailings 5	11636	4.88	9.02	49.57	36.53	1.61
Tailings 6	11637	12.94	7.71	43.33	36.03	1.86
Tailings 6	11638	10.97	8.51	43.47	37.05	2.28
Tailings 6	11639	8.33	7.95	46.24	37.47	1.63

CHAPTER 7

ECONOMICS OF STRIP-MINE REHABILITATION WITH SPECIFIC REFERENCE TO TRANSLOCATION TRIALS

ABSTRACT

In South Africa the rehabilitation of post-mined areas is mandatory for commercial mines. Techniques employed in rehabilitation efforts should take mine location and end use of the mine site once rehabilitation is complete into account. Each rehabilitation technique that a mine employs has costs and benefits, and it is becoming increasingly important that insights from ecology and economics are brought together if restoration efforts are going to succeed. Here I evaluate what is currently being spent on rehabilitation in various countries around the world and I review valuation systems. It was found that rehabilitation spending ranges from R44 560/ha to R161 400/ha and I conclude that the use of Discounted Cash Flow Techniques (DCF) is suitable for valuation of rehabilitation operations. Restoration activities are inextricably embedded within an economic framework, as a mine has to be economically viable, while adhering to environmental regulations.

Key Words: restoration ecology, rehabilitation techniques, strip mines, arid areas, financial analysis

INTRODUCTION

In recent years there has been a growing awareness of the importance of the environment in which we live (Rolfe 2000; Allen *et al.* 2001). These concerns have been focused on the activities of the agricultural and mining industries in particular (Rolfe 2000). Environmental impacts, particular to mining, can be classified into three broad categories: air and noise pollution, water quality flowing off the mine site, and environmental losses at the mine site (Rolfe 2000). Namakwa Sands (Pty) Ltd., a subsidiary of Anglo American PLC, situated in the arid, winter rainfall west coast of Namaqualand, South Africa, is currently strip mining large areas for heavy mineral concentrate (ilminite, rutile and zircon). In the mining process large areas of natural vegetation are destroyed, there are changes in the topography (with the potential to increase soil erosion) and changes in the topsoil and subsoil characteristics (Brink *et al.* 1990). According to the Mining Rights Act No. 20 of 1967, the Environment Conservation Act of 1988 and the Minerals Act No. 50 of 1991, rehabilitation of mined areas is mandatory for commercial mines in South Africa. This has led the mining industry to introduce a rigorous programme of land rehabilitation, and for this purpose the Chamber of Mines has drawn up a set of guidelines for surface mine rehabilitation, with specific reference to coal mining. The recommended rehabilitation programme makes provision for characterisation of the pre-mining environment, management and protection of water resources, top-soiling and revegetation of the area and long-term monitoring and recording of conditions (Brink *et al.* 1990). Once the rehabilitation programme proposed by the mine has been accepted by the Inspector of Mines, the rehabilitation programme becomes binding upon the owner of the mine. The idea of mandatory rehabilitation of mine sites is not exclusive to South Africa and is practised in, amongst others, Australia and New Zealand (Australian Mining Industry Council 1990; UNDESA and UNEP 1994). Both the Federal and State Governments of Australia supported the inclusion of environmental costs in decision-making as sound economic management (Victorian Auditor-General 1999).

It is normal to weigh up the benefits and costs of different rehabilitation options, though some benefits may be difficult to measure and compare. Zero rehabilitation is not regarded as an option, however full restoration of a landscape to its original natural state is also not always an option. The extremely high costs involved in moving from rehabilitation to full restoration often precludes full restoration as a viable option. It is therefore essential that mining companies and regulatory bodies find a middle ground, where both economic and environmental constraints can be met (Rolfe 2000).

According to the Minerals Act No. 50 of 1991, the rehabilitation of the surface used in mineral extraction must be carried out by the holder of the mining authorisation concerned, according to the approved rehabilitation programme as an integral part of the prospecting or mining operations concerned (Wells *et al.* 1999). It is becoming increasingly important that insights from ecology and economics are brought together if restoration efforts are going to succeed, as restoration activities are inextricably embedded within an economic framework (Holl and Howarth 2000). Draft as well as current regulations require that, unless exemption is granted, all topsoil removed at any open cast mine must be deposited at a specially selected site for replacement during rehabilitation of the surface. However, where rehabilitation is carried out simultaneously with mining operations topsoil may be replaced directly in accordance with the rehabilitation programme (Wells *et al.* 1999).

In the past environmental expenditure was not seen as essential to the ongoing mine operations. Environmental works were therefore competing against funding for non-discretionary operational works, and it may have been the case that the annual level of funding may not have been sufficient to meet minimum requirements for environmental considerations (Victorian Auditor-General 1999). It has been noted before that the major limitation in any mine rehabilitation process is the amount of money made available by the mining company (Lubke and Avis 1998; Holl and Howarth 2000). Each rehabilitation process has costs and benefits. However, at present the costs of rehabilitation efforts have not been studied in relation to the benefits of rehabilitation. For example the benefits of improved or increased biodiversity have been studied in biological terms, but have not been described or quantified fully in financial terms. The questions of how much to spend on rehabilitation and the benefits obtained from rehabilitation remain. Holl and Howarth (2000) have suggested techniques for determining the amount of money that should be allocated to rehabilitation efforts, including ecosystem replacement costs, quantifying ecosystem services, contingent valuation and surrogate market price techniques. There must be a reasonable balance between relatively successful rehabilitation efforts and the cash outlay to achieve a sustainable ecosystem. On one hand if insufficient funds and expertise are applied rehabilitation may fail; however, if extensive funds are applied success is not ensured, unless the process is well planned and managed (Lubke and Avis 1998). The question that remains is what constitutes successful rehabilitation? The answer to which depends on the end goal set for a particular rehabilitation programme and how success of rehabilitation is measured.

In this chapter I intend to review current valuation methods used to determine the allocation of funds for rehabilitation and the use reclamation bonds within the mining industry. I identify available methods for comparisons of cost effectiveness of rehabilitation options and review what is currently being spent on rehabilitation in the mining industry. I discuss the value of land once rehabilitation efforts have been completed and further production is to commence on the land.

DETERMINATION OF ALLOCATION OF FUNDS FOR REHABILITATION

The question of importance remains how one integrates ecological and economic considerations in deciding the level of resources to allocate to restoration. Six methods have been put forward by Holl and Howarth (2000) and are listed in Table 7.1.

Table 7.1: Methods of evaluating the costs and benefits of ecological restoration (Holl and Howarth 2000)

METHOD	DESCRIPTION
Replacement cost	Cost of restoring a damaged ecosystem
Replacement cost multiplier	Cost of restoring a damaged ecosystem plus additional funding for lost values during damage and uncertainty
Valuing ecosystem goods and services	Evaluate economic benefits of restoring a given good or service using a tradable substitute *e.g., watershed for restoration vs. water treatment plant to improve water quality*
Contingent valuation	Evaluate amount to allocate based on surveys of peoples' willingness to pay for restored areas
Travel cost method	Estimate the value that people place on a site by their willingness to spend time and money travelling to an area
Hedonic price method	Estimate the value of a restored area by evaluating the effect of a restored area on nearly property values

Replacement Cost

At first the most obvious and apparently simplest way to allocate funds appears to be an estimation of the cost of restoration or replacement of the ecosystem. This approach has the implicit assumption that ecosystem health is highly valued by society and is not to be traded off against economic considerations. This idea is not as simple as it first appears. The first consideration is that different parties (e.g., mining company and interested and affected parties) have to agree on what constitutes restoration in a given situation (Holl and Howarth 2000). Law as to what degree of rehabilitation or restoration is required may govern this agreement. Estimated project costs often fail to account for the resources required to support planned restoration efforts. Many projects also experience cost overruns as needs to adapt preconceived plans to suit circumstances emerge (Holl and Howarth 2000).

Replacement Cost Multiplier

To cope with uncertainties described above planners may scale up their best estimate of restoration costs to account for contingencies. The use of cost multipliers is linked to United States environmental law, which requires the polluter to cover the cost of restoring publicly owned resources that are damaged by their activities (polluter pays principle) (Holl and Howarth 2000).

Valuing Ecosystem Goods and Services

From an economic perspective it is important to know whether restoration costs generate environmental benefits of equal or greater magnitude. If benefits of a project exceed its costs and the net benefits are distributed equally amongst members of society the project can be said to enhance social welfare. Increasingly, decision-makers are recognising that goods and services are provided by relatively intact ecosystems. Although such services are often difficult to quantify, they are increasingly being used to justify the commitment of resources to restoration projects. This approach, of quantifying both direct use values (product harvested from the ecosystem) and indirect use values (ecosystem function), serves to justify an amount of money to dedicate to restoration in narrow economic terms. However, so-called "existence" values such as aesthetics, community pride and a sense of stewardship are overlooked. These existence values are a primary driver behind environmental law and management practices (Holl and Howarth 2000).

Contingent Valuation

Contingent valuation has been used to quantify all of the values people place on an ecosystem, including the so-called existence values. Survey instruments include the use of surveys of the public to determine peoples' willingness to pay to maintain or restore an ecosystem. Although the contingent valuation approach has been commended as the only approach that includes both non-use and use values, it has been criticised. These criticisms are in terms of peoples' ability to make quantitative evaluations of how much they would be willing to pay for non-market environmental goods; people often giving the same answer, regardless of the size or significance of the project; and discrepancies in terms of peoples stated willingness and observed actions. These problems have been partially addressed by asking people to rank the relative importance of different conservation alternatives (Holl and Howarth 2000).

Travel Costs and Hedonic Price Methods

This method aims at estimating peoples' willingness to pay for restoration through surrogate market prices. The travel cost method uses the time and money actually spent by people in terms of travel to and meals, lodging, entrance fees and equipment at the site. Hedonic pricing considers the effects of improved or degraded environmental quality on the value of land surrounding the affected area. The travel cost and hedonic price methods have not been widely used in determining the economic benefits of restoration and are only useful in certain situations (Holl and Howarth 2000).

Each of the six methods described above has strengths and weaknesses. The most appropriate method to use depends on factors such as magnitude of the cost and who is paying for the restoration. When there is a clear individual party causing the damage, ideally, that party would be charged with the full costs of restoring the system. This is the case in mining operations (Holl and Howarth 2000).

RECLAMATION BONDS IN THE MINING INDUSTRY

The legacy of abandoned mines, especially in the United States of America (USA) and Australia is attributed to both a lack of concern about potential hazards and an absence in the past of regulations (Gerard 2000; Rolfe 2000). Various forms of bonds are now used to ensure performance or payment in a number of situations, for example: to subcontractors and labourers that work on construction projects, for projects affecting public health or safety and services that are rife with unscrupulous business practitioners. Environmentalists have been known to advocate bonding as an instrument for regulating activities with uncertain future costs (Gerard 2000). The use of bonding to ensure site reclamation is pervasive in the mining industry on a worldwide scale. Performance guarantee bonds, as they are known in Australia, have two quite different functions. The first is to ensure compliance in the case of a company's solvency and the second is for insuring governments for rehabilitation costs in the case of a company's insolvency. The key rationale for using bonds is as an economic incentive mechanism to enforce rehabilitation standards and rests on the expected efficiencies that bonds have over other enforcement mechanisms available to regulators, such as court action and other forms of "punishment" (Allen *et al.* 2001). To a large extent, direct regulation has been very successful in ensuring that mining companies address environmental issues. In Australia, in economic terms, the downside of direct regulation is that environmental outcomes are often set with little regard for the costs and benefits incurred by firms in achieving them. It is generally required that land be converted to agricultural productive use, often on land that would not necessarily be suited for agricultural use. In certain regions of Australia rehabilitation objectives are shifting away from the idea of pastoral lands towards the development of natural vegetation (Rolfe 2000).

In general there are two ways to determine bond amounts. The first is a per-area calculation. The second bond value is set according to the expected rehabilitation costs, usually including administrative costs and a profit margin for a third-party contractor. In the USA the Bureau of Land Management sets an uppermost limit of US$1000 (±R10 000)/acre for exploration and $2000 (±R20 000)/acre for development. However, contracts with the potential for acid mine drainage are set a bond of the expected costs of rehabilitation (Gerard 2000).

In earlier research on the minimum bond necessary to provide companies with the incentive to comply with their rehabilitation obligations it was suggested that the bonds should be set near the expected rehabilitation costs. This holds true if the probability of a company being detected as non-compliant is 100% (Allen *et al.* 2001). Recent work on the benefits of bonds as instruments of enforced compliance of rehabilitation standards suggest that the expected costs to companies who shirk rehabilitation requirements was likely to be greater than the forfeited bond due to powers that government authorities have to recover damages though court action, to block future permits of a company that has a record of non-compliance or to use other forms of administrative punishment (Gerard 2000). For very large firms, where reputation and associated administrative penalty costs of non-compliance would be very high, the bond necessary to force compliance is likely to be considerably less than expected rehabilitation liabilities for that company. This would not necessarily be the case for smaller companies. It may be more financially attractive for smaller companies to shirk rehabilitation obligations, through for example "strategic bankruptcy", to minimise company outlays and maximise returns during the life of the mine, if their bond amounts were set well below expected rehabilitation costs.

The Western Australian Department of Minerals and Energy (1999) suggest that the primary role of performance guarantee bonds in Australia is to ensure that government authorities are not left with rehabilitation costs in the event that a company becomes insolvent before rehabilitation is completed.

Currently, reclamation bonding is not in use in South Africa. However, the Minerals Act No. 50 of 1991 does make provision for the establishment of a "rehabilitation trust fund" by a mining organisation, which is a fund into which a mining company deposits money annually for the life of the mine. The value of the annual deposit is determined during the environmental impact assessment for the mining operation. Trust fund money is used to cover the cost of final mine closure, including any rehabilitation that needs to be completed and the break-down of any mine infrastructure left at the end of the mine life. The trust fund is administered by the mining organisation (T. Hälbich 2002, personal communication).

FINANCIAL ANALYSIS

Read (1998) has suggested that a business oriented approach to environmental management should be adopted. This approach would see that environmental management would be expanded to include quantitative techniques such as economic planning, risk assessment and technology design to assist in decision making. Only once environmental and the management thereof is valued or quantified in financial terms can the relative importance of this concept be realised.

Rehabilitation managers must continuously choose between alternative courses of action, in terms of which rehabilitation techniques to employ. Most of these choices have financial implications. For example the alternatives may be to irrigate or not to irrigate or to apply fertiliser at different rates. The decision making process can be simplified if values can be assigned to the different alternatives, as these values can give a guide to environmental managers in making their decisions (Uys 2000). However, the costs of restoration efforts are rarely published in academic articles (Holl and Howarth 2000) and in South Africa the latest data available for environmental expenditure by the mining industry was compiled in a relatively informal survey in 1998, and is out of date (Chamber of Mines 2002).

It is generally recognised in current financial literature that the most acceptable means for assigning values to a long term project such as mining (Namakwa Sands has an expected mine life of 30 years) is Discounted Cash Flow (DCF) analysis. This technique recognises that money has a time value, a value that cannot be ignored in long term projects (Uys 2000). A long-term project starts at zero point in time (inception of the project) and runs to the end of the project, which for Namakwa Sands would be when the mine closure certificate is granted by the Department of Minerals and Energy Affairs and the previously mined land is sold (i.e., rehabilitation is complete).

In order for a DCF analysis to be performed a number of steps are necessary.

- A schedule of activities for the project that is being analysed, or for each of a number of alternative projects being considered should be developed.
- Choice of a DCF criterion to judge a single project or to rank a number of alternative projects
- Determination of a discount rate to use in the calculations
- Calculation of the value of the chosen criterion for the project or projects under consideration; and
- Decisions about the acceptance, rejection or ranking of projects.

A schedule of activities (also known as a cash flow table) indicates the points in time when the various activities occur as well as the cost of and/or revenue from each of those activities. This schedule can be visualised as a time line, from time zero at project inception to time *n*, the cessation of all incomes and expenditures associated with the project. These activities include the "general annual costs" such as maintenance, administration, management and taxes. General annual costs are related to the general welfare of that enterprise, forming an annual recurring cost (Uys 2000). Costs that could be incurred include (but are not restricted to) salaries, machinery and transport and revenues would include income from product sold. The inclusion of land value is also important, as when the land is being used for mining it cannot be used for anything else at that stage and an opportunity cost is incurred for the use of the land. This opportunity cost must be included in the cash flow of a project. Although it is only the annual interest cost on the land value which should be included, the same result is obtained when the market value of land forms a cost item at time zero (start of project) and a revenue item at the end of the project. It is generally accepted that all cash flows occur at the end of the specific years, except the initial outlay, which occurs at the beginning of the first year (zero point in time). Discounting is usually done to the zero point in time. Income and expenditure is usually expressed in Rands/hectare (R/ha) (Uys 2000).

Net Present Value (NPV) is the most commonly used DCF criteria. NPV is the sum of the annual net discounted cash flows and is formulated as follows:

$$\text{NPV} = \sum_{t=0}^{n} \left[A_t / (1+i)^t \right] \qquad (1)$$

Where:

NPV = Net Present Value;

$\sum_{t=0}^{n}$ = Sum of equation from t = 0 to t = n)

A_t = net cash flow in year t;

i = real discount rate;

n = duration of project.

When NPV is used to evaluate viability, the decision rules are as follows:

NPV>0: Accept the project;

NPV<0: Reject the project (Uys 2000).

In summary, NPV takes the magnitude and timing of all the expenses and all of the revenue from a project, from the first expenditure until final expenditure, including final sale of land and any other income from the project, into account. The calculation then determines whether the project is viable or not.

If the rehabilitation options are mutually exclusive with different lives, NPV cannot be used as a selection criterion. Equivalent Annual Income (EAI) which yields a value expressed in R/ha/annum is the correct criterion to use in these cases.

As regards rehabilitation, this calculation can be used to first determine NPV including all rehabilitation costs and revenues and then to recalculate NPV excluding rehabilitation costs, or various combinations of rehabilitation options. If NPV excluding rehabilitation is subtracted from NPV including rehabilitation the cost of rehabilitation over the life of the project can be determined. These same calculations can be used to compare rehabilitation techniques. For example the effect the application of irrigation would have on the overall cost of rehabilitation for the life of the mine could be determined. However, the value of a particular rehabilitation technique, in terms of success of rehabilitation has not been determined. It may be that a very inexpensive rehabilitation technique is selected for large-scale use due to its low cost, but that technique is unsuccessful in achieving rehabilitation goals set (e.g., return of biodiversity). The opposite may also be true, where a rehabilitation technique that is more costly is selected by the value this technique adds in terms of improved rehabilitation is not worth the cost incurred.

One way to overcome this problem would be to select a standard mechanism for measuring success on rehabilitation areas such as return of biodiversity or vegetation cover. Once a standard mechanism has been selected various rehabilitation techniques potentially suited to the site where rehabilitation is to take place could be tested at the site. Success of rehabilitation could be measured according to the standard criteria of either returned biodiversity or cover. The increase in cover or/and biodiversity could be compared together with the NPV calculations for the various rehabilitation techniques. This may allow for a more informed decision regarding the most cost effective rehabilitation technique that should be applied to a particular situation. These comparisons would be site specific. However, if wider research was carried out in similar environments trends may emerge that could be used in future rehabilitation programmes. These rehabilitation techniques could be monitored over time and compared on a biological basis, for example through biodiversity indices to determine which technique improves original biodiversity the most. A cost benefit analysis could then be carried out to determine which rehabilitation technique might be best suited for particular constraints.

WHAT IS BEING SPENT ON REHABILITATION IN MINING?

Currently there is not much literature available on the costs involved in rehabilitation. A number of reasons have been suggested for this lack of information. One reason is that often these costs are not known or are incorporated into the running costs of the mine and are not known as individual values for the different processes involved in rehabilitation (T. Hälbich 2002, personal communication). Costs are rarely documented in academic articles (Holl and Howarth 2000).

The general sequence of events for the rehabilitation of strip mines around the world follows a similar pattern, depending on the mining process. The processes generally involved in strip-mining are as follows:

- Pre-mining surveys: this may include vegetation and soil surveys (Tanner 1998).
- Planning of mine closure and final land use (setting of rehabilitation goals, in South Africa often to an agricultural land use) (Tanner 1998; Mentis 1999; Rethman *et al.* 1999)
- Stripping and stockpiling of topsoil and, where necessary, overburden to access the ore body, in long parallel strips (hence strip-mining).
- Removal and mining of the ore body.
- Back-filling of removed overburden or tailings: overburden or tailings are placed in rows of spoil piles in the preceding strip from which the ore body has been removed. Once the mining strip has been moved spoil piles are landscaped (overburden or tailings back-filling is often considered the start of the rehabilitation process).
- Spreading of stockpiled topsoil (or soil brought directly from the un-mined side of the mine) is placed on top of the landscaped overburden or tailings and landscaped.
- Agronomic amelioration techniques are applied to "New ground" (includes activities such as liming and fertilisation).
- Revegetation of the "new ground" through seedling or planting operations (Wells *et al.* 1999).
- Post-mining surveys and monitoring to ensure rehabilitation is successful and sustained.
- Mine closure.

The conceptual starting point of the rehabilitation process is still debated. The question remains whether rehabilitation begins with the back-filling of tailings or does rehabilitation begin with the spreading of stockpiled overburden and topsoil? It may be that the rehabilitation process begins with a pre-mining vegetation survey of the site to be mined. For this study the rehabilitation processes of interest are the stripping and stockpiling of topsoil, the back-filling and contouring of tailings, the spreading of stockpiled topsoil over tailings and revegetation processes that follow from that point forward. Currently within the rehabilitation processes in strip-mining, the major differences in rehabilitation occur once stockpiled topsoil is spread over tailings. One of the questions regarding the cost of rehabilitation is which operations are part of the mining operations and which operations are strictly rehabilitation. For example the back-filling of mined out areas may be considered as part of the rehabilitation process, while some mines see this operation as part of the mining process (T. Hälbich 2002, personal communication). Costs may also increase due to different environmental hazards that need to be dealt with in the rehabilitation process for different mines. Costs of rehabilitation that are available for mining are generally given in rands or dollars/hectare (R/ha or $/ha).

Information is available for Alcoa Australia Limited; a mining operation in Queensland, and the State Electricity Commission of Victoria (SECV) in Australia; Bowers Coal, West Pen Coal and The Laurel Coal Company in United States of America (USA); and Amcoal and Namakwa Sands, in South Africa. Limited information was also available for Richards Bay Minerals of South Africa. It is difficult to compare or benchmark the given costs, as it is not known what rehabilitation techniques these costs were used for in the rehabilitation process.

Alcoa Australia Limited (Australia)

More than 10,500 hectares have been revegetated since the start of the mining process at the Alcoa mine project, an aluminium-mine situated in Western Australia (Alcoa Australia Limited 2002). Current rehabilitation costs to Alcoa Australia Limited are averaging AUS$20,000/hectare (R109 200/ha; Exchange rate for November 2002). A total of AUS$13 million is being spent annually on research, planning, environment operations and rehabilitation at the Alcoa mine. The Alcoa rehabilitation project is specific to the mine and research has been carried out to determine rehabilitation mechanisms that best suite the specific soil and climatic conditions in the area of the mine, which consists of jarrah forest. The current rehabilitation objective of the Alcoa mine is to re-establish a jarrah forest ecosystem after bauxite mining. More than 96% of floral species, including all the dominant tree species, are currently being successfully re-established on rehabilitation areas (Alcoa Australia Limited 2002).

State Electricity Commission on Victoria (SECV) (Australia)

The SECV is an electricity supply company in Australia that also has brown coal mining operations. A report by the Victorian Auditor-General (1999) stated that in 1999 the SECV had not assessed the level of total funding required for the rehabilitation of land disturbed by open cut mining as SECV still had to develop plans for rehabilitation. However, the SECV has assessed the cost to fully rehabilitate a 300 hectare overburden dump site at approximately AUS$7.5 million or AUS$25 000/hectare (R103 500/ha using the 1999 exchange rate of R4.14 to the Australian dollar). This estimate was comparable with NSW (New South Wales) rehabilitation costs, where security deposits of up to AUS$32 000/hectare (R132 480/ha using 1999 exchange rates) were required to cover the full estimated cost of rehabilitation, with funds released progressively by the Department of Minerals and Energy as rehabilitation was successfully completed. If the NSW model was to be adopted by the SECV, total funding of $160 million would be necessary for the 5 000 hectares of open cut area requiring rehabilitation over the 30-year life of the operation. (In 1991-1992 the SECV were spending less than 1 percent of total expenditure on environmental management at the mine face) (Victorian Auditor-General 1999). (Note: these values are for 1999 and inflation has not been accounted for to give current values.)

Queensland (Australia)

Data for the Queensland mining operation is a final rehabilitation cost of R120 000/ha (T. Hälbich 2002, personal communication). This cost appears to be far higher than previous costs mentioned. This may be due to specialised operations, which may be necessary at this mine. The high cost of rehabilitation may also be due to the inclusion of some standard operational costs as part of the rehabilitation costs.

United States of America

The costs of rehabilitation for the United States of American are given in Table 7.2, as data for these mines gives only a final rehabilitation cost.

Table 7.2: Final rehabilitation costs associated with strip-mining. Costs are given in R/ha (T. Hälbich 2002, personal communication).

NAME	FINAL REHABILITATION COST
Bowers Coal (USA)	R73 606/ha
West Pen Coal (USA)	R44 560/ha
The Laurel Coal Company (USA)	R127 530/ha

Amcoal (South Africa)

Amcoal is situated on the Highveld of South Africa. Final rehabilitation costs associated with strip-mining at Amcoal are estimated at R161 400/ha. This is a final rehabilitation cost and includes all rehabilitation that was carried out on the mine (T. Hälbich 2002, personal communication).

Richards Bay Minerals (South Africa)

At Richards Bay Minerals situated in Richards Bay (South African East Coast), the cost of rehabilitation of indigenous vegetation in 1999 was in the order of R25 000 to R30 000/hectare. These costs included the spreading of topsoil, establishing wind breaks, seeding and limited ongoing management. It is unclear if these costs included the cost of spreading and contouring tailings (Lubke and Avis 1998).

REHABILITATION OPERATIONS AND COSTS AT NAMAKWA SANDS (South Africa)

A pre-mining vegetation survey was carried out for Namakwa Sands as part of the Environmental Impact Assessment for mining operations at Namakwa Sands (de Villiers *et al.* 1999). This vegetation survey serves as a benchmark for returning biodiversity and vegetation structure to the post-mined site. In the past sand tailings were transported from the mineral concentration plant to the mine pit via tip-truck. Recently a new conveyor belt system has been brought into operation, which transports the ore body to the concentration plant and transports tailings to the pit for back-filling (T. Hälbich 2002, personal communication). The sand tailings are deposited into the mined out area (Environmental Evaluation Unit 1990). Deposited sand tailings are shaped to fit the contours of the surrounding land. The reshaping and grading of a site is an essential aspect of rehabilitation. Unless slopes are stabilised, the effectiveness of subsequent topsoil spreading and revegetation can be greatly reduced due to erosion and movement of surface soil. The final landform should be hydrologically and if possible, visually compatible with the surrounding area (Australian Mining Industry Council 1990). The stockpiled topsoil is spread over the contoured tailings. Wind has been identified as the major form of potential erosion at Namakwa Sands (Washington 1990). Windbreaks are erected on rehabilitation areas to reduce wind damage to plants that emerge on rehabilitation areas. Windbreaks also act as seed and fog traps on areas that are undergoing rehabilitation. Windbreaks consist of polyethylene shade net (40% shade) approximately 1-m high, with vertical pockets sown into the net to hold metal droppers. These droppers are then hammered into the sand to keep the nets upright. Windbreak nets are placed at 4 to 5-m intervals perpendicular to the dominant wind directions. The best spacing and height of the windbreak net with the aim to reduce wind speed and sand erosion was tested in trials carried out at Kleinzee (T. Hälbich 2002, personal communication).

From this point forward Namakwa Sands uses various techniques to revegetate rehabilitation areas. Techniques vary due to the extreme weather conditions at Namakwa Sands, which are extremely windy and dry in the summer (although summer temperatures are ameliorated by summer fog) and only moderately wet in the winter growing season (de Villiers 2000; Eccles *et al.* 1999). These techniques include seeding with indigenous seed, which takes place throughout the year, planting and irrigation of teff (*Eragrostis tef*) grass to stabilise surface soil in the summer season (dry season). The mine is currently testing whether translocation of selected perennial species in winter would facilitate rehabilitation of previously mined areas. Namakwa Sands has a rehabilitation cost of R39 635/ha, excluding the cost of conveying tailings for back-filling of mined out areas. The cost of conveying tailings to backfill areas is R50 400/ha. This would give a total cost of R90 035/ha (T. Hälbich 2002, personal communication).

Namakwa Sands feel that the operation of back-filling should be seen as part of the operating cost of the mine. This is due to the fact that by law the mine is required to rehabilitate mined areas and part of that rehabilitation process is the back-filling of tailings and the spreading of topsoil (T. Hälbich 2002, personal communication). If back-filling was not a legal requirement the mine would still have to do something with the tailings and an alternative could be the construction of a single tailings dump. A single tailings dump would also have a rehabilitation cost in that a dump would have to be sloped to a reasonable angle and stabilised in some manner. A further breakdown of costs for rehabilitation operations at Namakwa Sands can be seen in Table 7.3. A graphic comparison of selected mines' rehabilitation costs can be seen in Figure 7.1.

Table 7.3: Costs of rehabilitation operations at Namakwa Sands in 2001/2002, given in Rands/hectare (T. Hälbich 2002, personal communication).

OPERATION	COST
Pushing of topsoil into stockpile	R914/ha
Hauling of topsoil stockpiles to rehabilitation areas	R1 054/ha
Hauling of tailings to rehabilitation areas (excluding conveying)	R21 072/ha
Spreading tailings in back-fill areas	R1 016/ha
Spreading stockpiled topsoil over tailings	R508/ha
Cost of windbreak installation	R10 529/ha
Windbreak maintenance	R294/ha
Revegetation costs:	
Seed collection and spreading	R775/ha
Production and planting of *Chrysanthemoides* seedlings	R600/ha
Collection of indigenous plants from un-mined areas, transportation and re-planting in rehabilitation areas	R2 818/ha
Irrigation	R50/ha
Monitoring return of biodiversity	R55/ha
TOTAL:	**R39 635/ha**

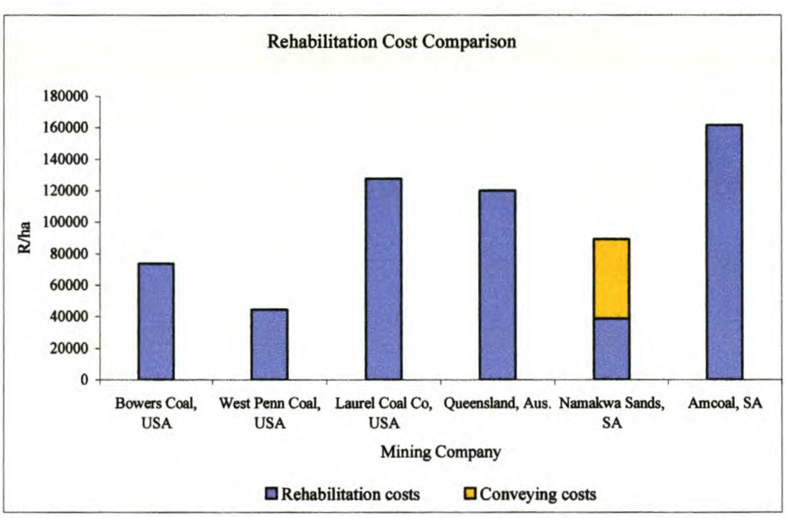

Figure 7.1: Graph indicating the benchmarking costs of Australian, American and South African mines in terms of money spent on rehabilitation given as Rands/hectare (T. Hälbich 2002, personal communication).

LAND EXPECTATION VALUE AFTER MINING AND REHABILITATION

Most of the proposed mining area at Namakwa Sands is uncultivated and was used for small stock grazing (mainly sheep) before mining. There were a few isolated cultivated lands in the north eastern sector of the mine area. Stocking rates are generally low, varying from 10 to 20 hectares per small stock unit. This is due to the fact that the carrying capacity of the vegetation is limited by low rainfall (Environmental Evaluation Unit 1990). During the approximately 30-year life of the mine the areas that were being used for small stock grazing and cultivation will be completely devastated due to the operations involved in the strip mining process. The aim of the overall rehabilitation program for Namakwa Sands is to return the area to a vegetation cover and productivity that is equivalent to the pre-mining condition. This implies that the vegetation that is re-established on the post-mined areas should have a carrying capacity of between 10 and 20 hectares per small stock unit.

The question may be asked that if a mining company is spending between R25 000/hectare and R161 400/ha on rehabilitation, does that mean that once rehabilitation is complete that land should be valued at the rehabilitation cost per hectare? The answer should be no. Property value is based on what income can be earned from the land, either before or after rehabilitation, and should not be based on the cost of rehabilitation once rehabilitation is completed. If the stocking rate was set at between 10 and 20 hectares per small stock unit prior to mining and this stocking rate can be achieved after rehabilitation is complete, the land value will remain equivalent (inflation rate should be taken into account, as the life of the mine is 30 years. One could say that if the market value of the land prior to mining was in the region of R200/ha) for grazing land (M. Du Rand 2002, personal communication) and if stocking rates are returned to pre-mining conditions, land value should follow an inflation adjusted value of R200/ha. However, if the mine does not rehabilitate the vegetation quality to suit a stocking rate of 10 – 20 hectares per small stock unit, with no sign of this stocking rate being achieved in the near future, the land value will decrease. If the mine rehabilitates vegetation on post-mined areas to have a higher stocking rate than the 10 –20 hectares per small stock unit, the land value may increase.

Traditionally the maximum price for bare land is determined by calculating the so-called Land Expectation Value (LEV) with the use of the Faustmann formula (Uys 1993). Bare land is considered as the land as it stands before production of any kind is initiated, including natural vegetation, soils and micro-organisms. This value can be regarded as the natural vegetation production potential as occurring on the property, without improvements. LEV was first used for the determination of the price companies could be expected to pay for forestry land. However, the Faustmann formula could be used for any LEV calculation. The formula has changed through the years, however the basic mathematics of compounding all items in the cash flow of a planned project, except the cost of land, to the end of the project life, and discounting this terminal value to the present time as if the project would be repeated infinitely, have remained unchanged.

This calculated Present Value forms the LEV and gives an indication of the maximum price payable for the land. In its simplest form the Faustmann formula can be written as:

$$\text{LEV} = \frac{\sum_{t=0}^{n} P_t (1+i)^{n-t}}{(1+i)^n - 1} - \frac{E}{i} \qquad (2)$$

where

P_t = net cash flow in year t of the project, expressed in today's prices (land cost and general annual costs excluded);

E = general annual costs

n = duration of rotation

i = real (inflation-free) discount rate.

The Faustmann formula assumes that:

- The land value is zero. This does not restrict the use of the formula for land valuation purposes. Land is deliberately assigned a zero value (not included in the formula) because land value forms the decision variable in a land valuation calculation.
- There are no standing crops (value of vegetation for grazing is included, however any stock on the land is excluded) or other activities on the land. The value of operations already in action on the land can be taken into consideration through standing value or expectation values.
- The cash flow of the project will be repeated unaltered in each of the successive rotations (a rotation can be determined for small stock farming. For example 1 rotation is the time from purchasing first lambs to the time those lambs (or sheep) are sold and would include income from additional lambs produced on the land in that period).
- The land will be used for that particular purpose as indicated in the calculations indefinitely.

The final two assumptions are unrealistic, as most projects do not have an infinite planning horizon. The reasons for this include fluctuating economy, changes in ownership and conversion of land to other uses (Uys 1993). Uys and Kotze (1992) suggest an equivalent for equation (2) (NPV_p or Net present value for specific project duration) which is more appropriate and is formulated below:

$$\mathrm{NPV_p} = \sum_{t=0}^{n} P_t(1+i)^{n-t}\left[\frac{(1+i)^{pn}-1}{(1+i)^{pn}\left[(1+i)^{n}-1\right]}\right] - E\left[\frac{(1+i)^{pn}-1}{i(1+i)^{pn}}\right] \qquad (3)$$

where

NPV_p = Net Present Value for p rotations (rotations can be determined for small stock farming, for example 1 rotation is the time from purchasing first lambs to the time those lambs or sheep are then sold and would include income from additional lambs produced on the land in that period).

P_t = net cash flow in year t of the project, expressed in today's prices (land cost and general annual costs excluded)

p = number of rotations within the planning horizon

Other symbols have the same meaning as in equation (2).

It must be remembered that LEV and NPV_p are calculated values, entirely controlled by the data used in their determination and results obtained can only be as reliable as the input data. This means that when determining LEV for a particular piece of land; values that are used must reflect the true potential use of the land. For example, if the land can only accommodate small stock grazing, it is pointless to use information for sugar cane plantations as inputs. LEV should be calculated depending on what can be reasonably produced on the land (Uys 1996).

CONCLUSION

Although strip-mining is an efficient means of mining, rehabilitation is essential to restore the capabilities of the land (Mentis 1999). The question that has to be answered in rehabilitation is what are the costs and benefits of various rehabilitation options. This is not an easy question to answer, as many of the benefits of rehabilitation are not tangible. However, mechanisms have to be developed to suit the needs of the mining industry in determining the most economically and environmentally well suited rehabilitation mechanisms to be used on different mine site locations. The concept of NPV together with the testing of the success of different rehabilitation techniques could be used to good effect to determine which rehabilitation options provide a cost effective rehabilitation programme for mining organisations. However, suitable measures and standards are needed to determine when rehabilitation should be considered as successful. Rethman *et al.* (1999) consider rehabilitation to be successful when the recreated land is capable of being used in an economically and ecologically sustainable manner.

The concept of land value changing due to rehabilitation is valid, however, not in terms of the cost of rehabilitation determining the future land value. Rather the costs of rehabilitation should be seen as an environmental obligation due to the destruction of the environment through mining operations. This environmental cost could be determined through the use of NPV calculations. Land value should be determined by what can be produced on the land after mining. If a mining company rehabilitates post-mined land to a state equivalent or better than the pre-mining conditions, land value of post-mined areas can be expected to reach an equivalent value or to increase. However, if the mining company rehabilitates post-mined land to a state regarded as degraded compared to the pre-mining capabilities of the site, over the long term, land value can be expected to drop.

LEV and NPV_p provide a means to determine land value for a new project. However, LEV and NPV_p are guidelines to future projects and these land values cannot be forced onto the market. They give an indication of the price an investor could be expected to pay for bare land. These values should always be seen in relation to the particular assumptions upon which they were determined (Uys 1996).

Much research and investigation is still needed to establish effective ways of determining cost-benefit ratios of rehabilitation methods within the mining industry.

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CHAPTER 8

GENERAL CONCLUSIONS AND RECOMMENDATIONS

INTRODUCTION

Strip-mining results in the destruction of natural vegetation (Wells *et al.* 1999) and damage to stockpiled topsoil (Abdul-Kareem and McRae 1984) so that repair involves capital intensive mine site rehabilitation. Under South African law, mining companies are compelled to rehabilitate mined areas (Mining Rights Act No. 20 of 1967, Minerals Act 50 of 1991 and National Environmental Management Act 1998). There is still much to be learnt regarding the rehabilitation of strip-mines in the arid winter rainfall areas of the West Coast of South Africa. Pilot studies should be used to develop cost-effective rehabilitation techniques that could be applied to best suit the environment in which a mine is found (Lubke and Avis 1998).

Namakwa Sands (Pty) Ltd., a subsidiary of Anglo American PLC, is strip-mining large tracts of the arid, winter rainfall areas of coastal Namaqualand for heavy mineral concentrate (ilminite, rutile and zircon minerals). During a pre-mining vegetation survey, six vegetation units were identified, described and mapped. These descriptions should serve as a starting point from which revegetation efforts can depart, as an understanding of the pre-mining vegetation structure is of fundamental importance for devising rehabilitation, management and conservation strategies (de Villiers 2000). The aim of the Namakwa Sands rehabilitation programme is to restore the mined areas as closely as possible to the original natural condition as soon as possible after mining has been completed, to support the pre-mining land-use of small stock farming and to obtain a vegetation cover, containing plant species from all the pre-mining plant communities of the mine site (Environmental Evaluation Unit 1990). The creation of indigenous plant communities on post-mined landscapes allows grazing management strategies to be consistent with surrounding indigenous communities. With the rehabilitation programme at Namakwa Sands aimed at returning post-mined areas to a small stock grazing system, the use of indigenous plant species becomes crucial for successful rehabilitation.

In this chapter I summarise my findings relating to the effectiveness of top-soiling, irrigation and translocations of indigenous plants, for facilitating the cost-effective return of a mined landscape to its former land-use.

SOILS

The stockpiling of topsoil and the mining of subsoil, as shown in the fertility bioassay and soil chemical analysis, decreased soil fertility at the mine site. Nitrogen and carbon levels decreased significantly in mined soil (tailings). Fresh tailings showed decreased levels of phosphorus, potassium, calcium and magnesium. There was a slight increase in pH, creating a slightly more acidic rehabilitation environment. The most severely affected cation in tailings was sodium, which increased to highly toxic levels in fresh tailings, with a reciprocal decrease in resistance. Topsoil was not as severely affected by stockpiling compared to the effects of mining the sub-soil.

Nutrient deficiencies are a common problem during the reclamation of mined soils (Abdul-Kareem and McRae 1984), and it was initially assumed that remedial action would be needed to decrease the toxic sodium levels in fresh tailings. However, in soil analyses 15 months after the rehabilitation trials began it was found that soil chemical properties had been ameliorated. Sodium, potassium and calcium appear to return to levels observed in pre-mining soil conditions. Magnesium, although not at pre-mining levels, also appears to have increased in soils 15 months after rehabilitation trails began. Available phosphorus and resistance appeared to increase above pre-mining soil conditions. This indicates that, even though soil conditions are not of pre-mining quality, some amelioration has taken place and certain soil properties may be more conducive to seedling germination and growth than at the start of the rehabilitation trials. However, carbon did not return to levels of pre-mining conditions and remains a potential limiting factor in rehabilitation efforts. Further investigation is needed to determine the mechanisms involved in the amelioration of certain soil conditions and to determine why carbon remains a limiting factor. Mechanisms that could potentially be implemented to alleviate reduced carbon levels, such as the addition of humified organic materials or the use of clay slimes in rehabilitation efforts should be investigated. Investigation is also needed to determine if electrical resistance is a potential limiting factors to rehabilitation and, if so, what measures can be taken to alleviate this limiting factor. Further investigation is needed into the changes that may occur in nitrogen levels in stockpiled topsoil as nitrogen may be in a volatile state in stockpiled topsoil, and may be lost to the environment when spreading takes place.

Soils of the Strandveld vegetation are known to have inherent differences and show degrees of heterogeneity for various soil properties (Eccles 2000). Inconsistencies observed on the rehabilitation study site may be due to soil from one plant community being deposited onto a different plant community area, reflecting an inherent difference in soil chemistry which becomes evident after sodium levels in post-mined areas are normalised. It is likely that free salts were leached from rehabilitation soils after winter rains, which would account for the increase in electrical resistance observed. Further investigation, however, is needed to determine if this increase in electrical resistance is a trend over time. The effect that inherent differences in soils may have on plant growth should also be investigated. The activity of separating mine residue into a sand and clay fraction may be having a significant effect on rehabilitation efforts and these potential effects should be investigated further, especially with regard to changes in the chemical and nutrient makeup of the soils.

Further long-term studies are needed into the chemical changes that occur in soils once tailings are back-filled and stockpiled topsoil is spread. It is recommended that methods used in the striping and spreading of topsoil be refined to reduce the effects of stockpiling of topsoil. Removing the topsoil from an area to be mined and placing it directly onto contoured tailings reduces the need for stockpiling. In this way soil chemical and physical properties will not be as adversely affected.

TRANSLOCATION TRIALS

In studies carried out on rehabilitation techniques and associated biological processes at Namakwa Sands it was found that the transplantation of indigenous plants from pre-mined areas to post-mined areas can be successful for shallow rooted evergreen leaf and stem succulent species in the arid winter rainfall area of coastal Namaqualand.

Irrigation gave inconsistent results across all species and treatments and due to the fact that irrigation was not applied equally to all replicates further investigation is required into the potential use of irrigation in rehabilitation efforts. Irrigation was shown to decrease the return of biodiversity to rehabilitation areas. The potential for irrigation, when considered in terms of the inconsistent results obtained in the translocation trials, and results obtained in the biodiversity study, together with the potentially high cost of irrigation due to the location of the mine must be weighed up carefully. It is recommended that a cost-benefit analysis of irrigation be conducted in conjunction with further closely regulated irrigation trials to determine if irrigation does hold any benefit for rehabilitation efforts.

Topsoil spread over tailings improved the survival of *Asparagus* spp., *R. versicolor*, *L. suavissimus* and *Z. morgsana*. In winter whole-plant clumps planted on stockpiled topsoil grew better than whole-plant clumps planted on tailings and all salvaged-plant clumps. This indicates that topsoil spreading does have an advantage for species used in the translocation trials. The most successful species in terms of survival appears to be the leaf and stem succulent *O. cylindrica*, followed by the leaf succulents *R. versicolor* and *L. suavissimus*, all three of which are shallow rooted. The summer deciduous leaf succulent *Z. morgsana* and *Asparagus* spp., with root tubers, but no succulent above ground stems or leaves showed very poor survival.

Whole plants grew better than salvaged plants for *O. cylindrica*, *L. suavissimus* and *Z. morgsana,* indicating that the process of stockpiling damages plants to such an extent that these plants cannot be used successfully in translocation efforts. Damage is mainly in the form of roots being sheared from the rest of the plant and damage to some stems. Leaves are also broken off plants. The desiccation of plants and while in stockpile may also be a factor reducing the survival potential of salvaged plants.

From the results obtained from the survival of species as well as in the differences in growth of whole and salvaged plants it is suggested that plants with permanent (evergreen) above-ground storage organs and shallow root systems will be successful in large-scale translocation trials in arid areas. It is recommended that *O. cylindrica*, *R. versicolor* and *L. suavissimus* be used in future large-scale translocation projects on Namakwa Sands. Whole plants of each species should be used, as whole plants show better survival and growth than salvaged plants. This difference in survival and growth of whole and salvaged plants could be attributed to the damage caused to salvaged plants when topsoil stockpiles are made.

O. cylindrica, *R. versicolor* and *L. suavissimus* produce attractive flowers and could attract insect fauna back to the site, ensuring that vegetation processes also return to rehabilitation areas. *O.*

cylindrica is not regarded as a high quality fodder species, however the flowers are grazed. Although *R. versicolor* and *L. suavissimus* are not regarded as having a high grazing potential, grazed plants have been observed on the mine site. These species may not directly achieve the end goal of the Namakwa Sands rehabilitation programme, to restore the land to small stock grazing, however they may act as seed traps and provide micro-climates and conditions more conducive to seed germination and growth (as discussed in Chapter 3). The use of palatable species only in translocation could have a negative effects, whereby when rehabilitation is completed and the land is returned to small stock grazing the vegetation will be dominated by palatable species. All palatable species will be grazed, creating a reduced vegetation cover and allowing soil erosion and trampling to occur. By using unpalatable species in translocation refuge sites may be provided for palatable species. Refuges provide safe sites for the germination and survival of more palatable species (Todd 2000). Milton (1994) showed that changes in the species composition of shrub populations in arid rangelands could be a function of seed availability. If all palatable species are grazed, seed production could be reduced thereby reducing the carrying capacity of the rehabilitated areas. If translocation of non-palatable indigenous plant species is used in conjunction with other rehabilitation techniques, such as seeding with palatable species, the end goal of the rehabilitation programme could be facilitated far better than by creating a system that may be prone to overgrazing.

Z. morgsana, being a summer deciduous leaf succulent, may take longer to recover after the translocation process. It is recommended that further studies be carried out on this species, as *Z. morgsana* does have some grazing potential, early in the growing season (Le Roux and Schelpe 1988).

Lubke and van Eeden (1994) found that when indigenous plants were used in strip-mine rehabilitation trials in the arid West Coast of South Africa, better survival was obtained from plants planted in early winter. In light of these findings and due to the fact that the West Coast of South Africa has a winter growth phenology, it is recommended that large-scale translocations of indigenous plants at Namakwa Sands only take place in the winter growing season.

BIODIVERSITY RESULTS

The return of biodiversity and seedling densities on rehabilitation areas were decreased by the application of irrigation, and, as mentioned previously, irrigation should not be used as a rehabilitation mechanism in attempting to increase biodiversity. However, in extremely dry winter seasons irrigation may have a positive effect on seedling emergence and biodiversity, and further trials are required to determine the application of irrigation in drought years.

Due to ongoing rehabilitation efforts, such as hand seeding, on all other rehabilitation areas of Namakwa Sands, it could not be determined if the translocation of indigenous species facilitated the return of biodiversity on rehabilitation areas, or not. It is suggested that experiments with strict controls be carried out to determine if large-scale translocation is facilitating the return of biodiversity to rehabilitation areas. This may be difficult as Namakwa Sands has made a valuable commitment to ongoing rehabilitation on post-mined areas and control experiments could limit their management strategy.

It was found that there were far more individuals of both annual and perennial species on spread topsoil. This finding again reiterates the importance of using topsoil as an amendment in rehabilitation efforts. Annuals dominated in terms of number of emerged species, this finding is similar to that of de Villiers (2000) for pre-mined areas.

Monitoring of the translocation trials should be ongoing in the summer and winter seasons to determine the long-term (> 10 years) effects rehabilitation options are having on the return of biodiversity and seedling densities to the study site. Further studies are needed to elucidate information on the germination strategies and dormancy breaking mechanisms of plants within the Strandveld vegetation as these mechanisms play an important role in the rehabilitation process.

FINANCIAL ANALYSIS

The determination of the costs and benefits of rehabilitation is becoming an essential part of sound financial and environmental management and many benefits of rehabilitation such as the return of biodiversity and aesthetic values are not considered to be tangible. In the past environmental management was considered as a separate part of operations in various industries that impact on the environment. However, today more than ever, environmental management is starting to be included as an integral part of any operation. Mechanisms to determine the most cost effective and environmentally suitable techniques to be used in rehabilitation on different post-mined sites have to be developed for the mining industry. The use of Discounted Cash Flow (DCF) techniques, and NPV (Net Present Value) in particular, together with testing the success of different rehabilitation techniques according to standardised measures could be used to good effect to determine which rehabilitation options provide a cost effective rehabilitation programme for mining organisations. Suitable standardised measures are needed to determine when a rehabilitation option should be considered as successful.

The concept of land value change due to rehabilitation (or lack thereof) is valid, however, not in terms of the cost of rehabilitation efforts, but rather according to the success of rehabilitation. The cost of rehabilitation should be seen as an environmental obligation due to the destruction of the environment by mining operations. Land value should be determined by what can be produced on the land after mining. Where rehabilitation improves land condition land value could be increased. However, if rehabilitation of post-mined land is in a degraded state compared to the pre-mining capabilities of the site, land value can be expected to decline. LEV (Land Expectation Value) and NPV_p (Net Present Value for specific project duration) provide a means to determine land value for a post-mining project. LEV and NPV_p are guidelines to future projects and give an indication of the price an investor could be expected to pay for bare land. These values should always be seen in relation to the particular assumptions upon which they were determined (Uys 1993).

FURTHER REHABILITATION STRATEGIES

A functioning rehabilitation project will interact biologically with surrounding areas, with the exchange of species and genes being particularly important. Analyses of the microbial and invertebrate communities that have invaded the installed plant community may be accurate determinants of the ecological function of rehabilitation areas. Research is needed into the return of the invertebrate and microbial communities to rehabilitation areas to determine if form as well as function is being rehabilitated on the mine site.

Mining companies within the grassland biome of South Africa, in co-operation with regulatory bodies and a wide range of interested and affected parties have developed successful strategies to deal with the disturbances of topography, soil and vegetation associated with strip-mining. The development of such strategies within an adaptive management approach is dependent on thorough and regular monitoring to assess success over time (Rethman *et al.* 1999). Success though adaptive management is possible for any mine site and is within reach for Namakwa Sands. Continued research and development of successful rehabilitation techniques and strategies specific to Namakwa Sands should lead to the successful achievement of rehabilitation goals.

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