STUDY OF PHYSICAL AND CHEMICAL SOIL PROPERTIES AND POTENTIAL OF POST-MINING SUBSTRATES AS A HABITAT FOR PLANTS DURING RESTORATION AT SENDELINGSDRIF MINE

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Abstract

Soils influence the growth and performance of plants. Sendelingsdrif is a new area in Sperrgebiet National Park that had been identified by NAMDEB for diamond mining. Little is known about soil properties in this area yet after mining, it will be important to have good knowledge of soil properties and post-mining substrate to facilitate restoration of the mined and surrounding sites. The main aim of the study was to determine how the physical and chemical properties of post-mining substrates differ from that of natural soils and how these properties among substrates relate to plant performance. Field and greenhouse studies of soil properties and post-mining substrates was carried out at Sendelingsdrif mine in the Tsau //khaeb (Sperrgebiet National Park) from September 2012 to June 2013. In the greenhouse, ten substrates (including two natural soils and potting soil as reference) were prepared and plants (Radish (*Raphanus sativus*), *Juttadinteria albata* (L. Bolus) L. Bolus and *Cephalophyllum herrei* L. Bolus) performances were tested across them. Lucerne was added to some of the prepared mixes of post-mining substrates to act as nutrients and the plants performances were assessed. During fieldwork, environmental data such as infiltration rate, soil texture and rock cover were recorded. Seventy soil samples were collected from seven habitats in the study area. The analysis of soil properties revealed that water infiltration rate and soil texture differed significantly ($H = 48.15$, $df = 9$, $P < 0.05$) between natural soils and post-mining substrates in the study area. Soil chemical properties such as pH, total nitrogen, organic matter, phosphorus, calcium and iron were not significantly different ($F = 1.82$, $F = 2.05$, $H = 7.51$, $F = 0.35$, $H = 12.41$, $H = 17.89$, $df = 6$, $P > 0.05$) across the landscape in the study area. Soil chemical properties such as calcium carbonate, potassium, copper and electrical conductivity differed significantly ($H = 21.13$, $F = 2.56$, $F = 3.02$, $H = 16.59$, $df = 6$, $P > 0.05$) between habitats across the landscape. Chemical properties of natural soils such as nitrogen, organic matter, phosphorus, calcium, potassium and conductivity was significantly different from that of post-mining substrates. The post-mining substrates lacked essential nutrients such as nitrogen, organic matter and phosphorus that are needed by plants for growth. Post-mining soils had significantly high content of salt; this salt was significantly high in content in comparison to that of natural soils ($H = 31.21$, $df = 9$, $P < 0.05$). The experiment revealed that the germination of the *Juttadinteria albata* and *Cephalophyllum herrei* differed significantly between natural soils and post-mining substrates ($F = 6.55$, $H = 35.56$, $df = 9$, $P < 0.05$). Plants used in the greenhouse showed improved growth in substrates where Lucerne (*Medicago sativa L.*) was added. The study concluded that there are major differences in the physical and chemical properties between natural soils and post-mining substrates. The study also concluded that the addition of Lucerne to post-mining substrate improves the performance of plants.

Key words: Soil, Sendelingsdrif, restoration, post-mining substrate, natural soil, Sperrgebiet, mining, radish, *Juttadinteria albata* and *Cephalophyllum herrei*

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Dedication

I would like to dedicate this thesis to my lovely grandmother Hilka Shinana Ndeilenga and my entire family for standing by my side during my studies.

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Chapter 1

1.1 Introduction

The Succulent Karoo is an arid winter rainfall area of southern Africa and is one of the most diverse biomes of the region (Hoffman, Schmiedel & Jürgens, 2010). It is the only biodiversity hot spot found in an arid system in the world and about 40% of plant species found are endemic to the region (Beukes and Cowling, 2003). In comparison to other hyper arid areas of the world, it has high levels of endemism in both plants and animals (Burke, 2005). The reasons for this high level of endemism have not yet been explained adequately, but some hypotheses have been put forward. A study done by Burke (2005) suggested that the factors such as the unusual substrates, climatic fluctuations, and fast speciation among groups of different plants species in the area could be used to explain the high level of speciation among plants as well as endemism in the Succulent Karoo. Moreover, the geology of the area played a major role in how different plant species are dispersed in the area (CEPF, 2003). Soil is one of the important abiotic components of ecosystems that support biodiversity (Hoffman et al., 2010). Soil determines the distribution of plants and other organisms that directly or indirectly depend on the soil for their existence (Esler & Cowling, 1993). Studies have indicated that the structure and process of terrestrial ecosystems vary largely as a function of soil properties (Hoffman et al., 2010). Whitford (2002) suggested that the most important factor that seems to affect the structure of vegetation in ecosystems is soil. Soil is the basic resource of global ecosystems and dry ecosystems are no exception.

There are several human activities that can that can alter the soil properties of ecosystems such as, agricultural practices, urbanization and mining. Due to the nature (aridity) and climate of Namibia the most common practice that has an adverse effect on the soil or ecosystems on the larger scale is mining (Linus, 2010). Mining involves the removal of precious minerals or other geological materials from the earth, from an ore body, host rock, vein or seam (Montgomery, 2011; Angula, 2007; Linus, 2010). There are two main common mining techniques that are employed in order to recover the precious minerals such as, surface or strip mining and underground mining.

Strip mining (open pit or open cast) is employed in areas or places where the ore body is located close enough to the earth's surface (Montgomery, 2011). Minerals such as diamonds, coal and bauxite are often mined in this manner. Underground mining method is performed when an ore body is too deep beneath the earth's crust or in areas where strip or surface mining is not applicable (Cooke & Johnson, 2002; Montgomery, 2011). Most of the minerals that contain metals are mined using this technique.

Mining is one of the human activities that disturb soil components such as soil horizons, soil microbes, nutrient cycle and structure (Sheoran et al., 2010). Mining disturbs ecosystem processes and functioning through the removal of soil and all organisms of which some may be of conservation importance. Cooke and Johnson (2002) stated that mining can destroy natural ecosystems via the removal of soil and vegetation and burial under waste materials. Mining activities may reduce the availability of soil nutrients (Sheoran et al., 2010) and increase soil compaction (Squillace, 1990). After mining is done, soil organic matter, seeds and crucial nutrients for plants disappear. The disruption of the soil profile results in leaching of nutrients and moisture loss (Cummings et al., 2005).

Sendelingsdrif Mine is a new extension of the NAMDEB group located on the Orange River near Rosh Pinah within the Succulent Karoo Biome. Mining of diamonds at Sendelingsdrif will entirely be carried out in the form of strip mining. At sites where strip mining is employed, plants and animals are removed because the process involves the removal of layers of soil overlaying the minerals to access buried deposits of useful minerals (Squillace, 1990; Montgomery, 2011). Mining affects soil surface and vegetation particularly because in surface mining, the land surface have to be removed to get at the mineral resource being mined and in deep mining any waste material has usually had to be deposited at the surface (Bradshaw, 2000). In areas where topsoil is thin and poorly developed often the case in hyper arid areas (Burke, 2008), this means that the application of top soil from somewhere else could be used to restore the area but this is usually expensive and unaffordable. The cheaper option will be to take and manipulate the available waste materials in order to rehabilitation and restoration of ecosystem properties. At Sendelingsdrif, fine tailings is one of the post-mining substrate that will be used to replace natural soils and serve as some sort of artificial topsoil (restoration) once mining is done. Fine tailings refers to as all the waste materials that are left over after the mining process of separating the valuable fraction from the uneconomic fraction of an ore body, which are usually below 2mm in diameter.

Strip mining for titanium, diamonds, gypsum, silver and other industrial minerals is expanding in the arid winter rainfall areas of South Africa and Namibia (Milton, 2001). Although mining is economically important as it contributes to economic development of the country via income generation (GDP), employment creation, and export earnings (Angula, 2007), mining damages thousands of hectares of biologically diverse environments where vegetation growth and recovery is limited by aridity, wind and nutrient-poor soils.

It is expected that most plants including endemic plants will be removed during mining at the proposed Sendelingsdrif mine (Mannheimer, 2010). To mitigate the impact of mining on the soil and organisms, restoration is an important management tool (Anonymous, 2004).

Ecological restoration is an activity undertaken to facilitate the recovery of ecosystems that are degraded, damaged or entirely destroyed (Burke, 2001). Restoration includes a range of activities, such as engineering of soils and introduction of organisms (SER, 2004). According to SER (2004), ecological restoration aims at facilitating natural processes in disturbed areas that will sooner or later lead to self-sustaining ecosystems related to what was there before disturbance. The ecosystem is said to be recovered and restored when it contains sufficient biotic and abiotic resources to continue its development without further assistance.

Restoration in the Succulent Karoo Biome has received increasing attention, because of the biomes' global importance for biodiversity conservation (Burke, 2008). Soil erosion and incompatible soil properties are some of the problems arising during the restoration of areas disturbed by mining (Sheoran et al., 2010; Potthoff et al., 2005).

The emphasis of this study was to determine and understand properties of natural soils and waste materials that are relevant for ecological restoration. The acquired knowledge from the study will be used to understand how to re-engineer a type or types of substrates where plants can grow again after mining. Additionally, this knowledge will also be used later on to measure the extent of the success of restoration at the proposed Sendelingsdrif mine.

1.1.1 Orientation of the proposed study

There is a knowledge gap regarding soils at Sendelingsdrif mining area because not many studies have been conducted in this area. Cumming et al., (2005) stated that viable restoration techniques for abandoned mines, where fresh topsoil is not available have not been documented. Burke (2008a) tested the application of topsoil in deeply excavated areas in Skilpadberg in Namibia section of the Succulent Karoo Biome in Southern Africa and found out that it leads to re-growth of plants. In addition, areas with shallow excavations in turn showed re-establishment of plants, even without topsoil application. Beukes & Cowling (2003) tested the possibility of initiating the restoration of bare areas using gypsum and organic mulch in the Succulent Karoo and found that both gypsum and mulch improves rain water infiltration. Burke (2008b) also carried out an experiment in-situ at Sendelingsdrif to test the survival of *Juttadinteria albata* in waste materials through transplanting and propagation techniques but there were no follow ups. The experiment was very basic, because there was no replication and the watering of plants was done twice only. An analysis of the available data revealed high mortality and poor plant health in all treatments but it was at that stage still unknown why plant mortalities were high (Wassenaar, 2010). The present study was designed to fill in the knowledge gap that existed on which properties of soil are related to plant performance, in order to determine how best to manipulate the properties of mining waste material in order to get as close as possible to natural soil. The study used several approaches such as the usage of crop plants (radish) and indigenous plants (*Juttadinteria albata* and *Cephalophyllum herrei*) in the greenhouse experiment as bio-indicators of soil fertility and suitability.

1.1.2 Statement of the problem

Mining alters soil properties of ecosystems, via the removal of large quantity of soils and the dumping of waste materials. At Sendelingsdrif, in the Succulent Karoo biome, the proposed strip mining for diamonds by NAMDEB, will remove the topsoil, which supplies essential nutrients for plant growth. Knowledge of properties of soils in the mined areas will facilitate effective and successful restoration of plant species. After decommissioning of the mines, waste materials are returned to the open pit. It is largely unknown whether plant species that were removed can grow on the mining waste, yet in many areas, the mining waste may be the only medium in which plants will be expected to grow to enable restoration.

1.1.3 Aim of the study

The overall aim of the study was to determine how physical and chemical properties of natural soils differ from that of the post-mining substrates and how these properties are related to plant performances.

1.1.4 Specific objectives

1. To determine and compare the difference in infiltration rate, soil texture, and rockiness between the natural soils and waste materials in the proposed Sendelingsdrif mine area.

2. To determine and compare the difference between pH, percentage organic matter, total N, $CaCO_3$ and other macro (P, K and Ca)-and micro (Fe and Cu)-nutrients between natural soils and post-mining substrate.

3. To determine and compare the difference between: - i) germination rate, ii) growth rate, iii) phenology, iv) biomass and v) survival rate of radish, *Juttadinteria albata* and *Cephalophyllum herrei* between natural soils and post-mining substrates.

4. To determine and assess which of the available mixtures of waste materials will have properties that best support plant growth and survival.

1.1.5 Research questions

1. What are the physical characteristic of natural soils and mining waste materials (in terms of infiltration rate, soil texture, and rockiness) and how do they differ between the two substrates?

2. What are the chemical characteristic of natural soils and mining waste materials (in terms of pH, percentage organic matter, absolute levels of nitrogen, carbonate, electrical conductivity and other macro (phosphorus, potassium and calcium)-and micro (iron and copper)-nutrients) and how do they differ between the two substrates?

3. Do different mining waste material mixes and natural soils differ in terms of i) timing of germination, ii) rate of germination, ii) rate of growth, iii) phenology, iv) biomass and v) rate of survival of a crop indicator species and the indigenous plants?
4. Which of the available waste materials or mixes of post-mining substrates facilitate plant growth and survival as good as the natural soils?

1.1.6 Hypotheses of the study

1. There is no significant difference in the physical properties between post-mining substrates and natural soil.

2. There is no significant difference in the chemical properties between post-mining substrates and natural soil.

3. The performance (germination rate, growth rate, phenology, and biomass and survival rate) of plants grown in the natural soil will not be significantly better than that grown in waste material due to adequate nutrients in the natural soil.

4. There is no significant difference in plant growth and survival between different mixes of post-mining substrates.

1.1.7 Significance of the study

The study will determine the physical and chemical properties of the soil that promote growth of plants in the mine area. This information will serve as important baseline that will be useful during restoration of Sendelingsdrif mined area, for post-mining substrates amelioration and for plant growth and monitoring.

1.1.8 Limitation of the study

The sensitivity of the diamond mining area restricts the amount of soils that can be collected and used for analysis. Funds were not adequate to undertake analysis of all the essential macro-and-micro nutrients. Additionally, the current study did not look at the biological soil properties due to lack of funds, especially looking at the presence or action of mycorrhizal fungi and rhizobia which can assist in the uptake of some essential nutrient elements beyond their depletion zones. This could have helped to explain the apparent lack of phosphorus and other essential nutrient elements in post-mining substrates. The study site was far from accommodation (about 90km) hence this restricted the amount of time spent in the field for data collection. During the period of study the mine had only one heap of mining waste materials, so replication could not be done for mining waste materials that were sent to the laboratory for analysis of chemical and physical properties. The limited availability of mining waste materials from different habitats that are going to be impacted by mining, made it difficult to compare and detect the differences in physical and chemical properties that exist between natural soils and mining waste materials.

Chapter 2

Literature Review

2.1 Introduction

This chapter will review soil properties of arid environments, properties of post mining substrates and a short description of Lucerne. Soil refers to the combination of loose weathered minerals, rock materials and decayed organic matter, which are found on the earth's surface (Wild, 1993). Soil plays an important role in ecosystems such as providing a medium for plant roots and supplying nutrients that are crucial to the entire plant (Brady and Weil, 1999). Soil properties are divided into physical, chemical and biological properties. Physical properties of the soil include soil texture, infiltration rate, and soil structure (Brady and Weil, 2008). Organic matter, cation and anion exchange capacity, pH, level of nitrogen, and carbonate are some of the important chemical properties of the soil (Brady and Weil, 2008). Biological properties refer to the living component, which consists of micro-organisms (such as microbes, fungi, collembola and helminths), macro-organisms (e.g. isopods and earthworms) and plant roots (Lee & Foster, 1991; McClauley & Jacobson, 2005). Post mining substrates (tailings) refers to what is left behind after minerals of interest have been extracted from the soils/gravels that have been excavated (Franks et al., 2011). Tailings are different from overburden, which is the waste rock covering or the ore body. The composition and fractions of tailings depends on the composition of the ore body and the process of mineral extraction used on the ore body (Franks et al., 2011). In general larger proportion of tailings consists of unwanted rocks that are crushed to a fine size ranging from coarse sands down to a very fine powder (Davies & Rice, 2001).

Lucerne (*Medicago sativa L.*) is one of the plants that has been used as fodder for decades, because it is rich in nutrients especially proteins (Mustafa et al., 2001). *Medicago sativa* is a leguminous plant with the nitrogen-fixing Rhizobium bacteria that are capable of fixing nitrogen in the soil (Török et al., 2011). Lucerne was harvested on a farm in Oranjemund. It was dried for use in the greenhouse experiment. The aim of adding Lucerne to post-mining substrates was to test whether Lucerne can improve the growth of plants. In three different mixes of post mining substrates that were prepared Lucerne was added on the surface with the idea of it becoming the source of nutrients in these substrates. Literatures have indicated that post mining substrates contains low or no organic matter or macronutrients (Johnson et al., 2002; Cooke & Johnson, 2002; Carrick & Krüger, 2007); in the present study, therefore post mining substrates were enriched with Lucerne in order to ameliorate them and assess how well plants would grow. There are no particular studies describing or reporting on the addition of Lucerne to post-mining substrates in order to enhance plants, germination, growth and development.

Each of the different properties of soils and post-mining materials are described in detail in the following sections.

2.2 Chemical properties of soil

2.2.1 Soil pH

In soils that have a pH near neutral or are alkaline, the exchange sites on soil particles can be occupied by base cations that can be exchanged between soils and plants, such as calcium (Ca+), sodium (Na^+), magnesium (Mg^{2+}) and potassium (K^+) (Gu & Crouse n.d). Laura and Jodi (2009) and Killham (1994) stated that the growth of roots in the soil can lead to short-term acidification of the soil by removing base cations in exchange for hydrogen ions.

Soil pH affects the growth of plants through the control of nutrient availability (Killham 1994). Soils with high pH tend to affect plants by reducing the amount of manganese and iron in the roots (Gu & Crouse n.d). Studies have indicated that in arid regions the soil pH is usually neutral or alkaline and calcium is abundant making liming undesirable (Al-Khaier, 2003; Brady and Weil, 2009; Plaster, 2009). Low pH tends to affect plants harmfully through increasing the amount of aluminium, manganese (Brady and Weil, 2009). Alkaline soils are found mainly in semi-arid to arid regions (Lukama, 2006). Studies done in arid and semi-arid areas of the world (Namibia included) concluded that most of the soils found in this areas are basic (alkaline) or nearly neutral for various reasons such as the ions derived from weathering of minerals are predominantly base-forming, and there is not enough precipitation to leach the m from the soil, high evaporation and winds (Eash, et al., 2008; Coetzee, 2009; Hartemink & Huting, 2008; Bertram, 1999). Hoffman et al., (2010) found that soil pH values increase with soil depth (0-1cm, 1-5cm and 5-10cm) in the lowlands of the Succulent Karoo. Similarly, Prinsloo (2005) found that the soils of the Succulent Karoo tend to be neutral to alkaline with pH values in water mostly between 6 and 8. According to Beukes & Cowling (2003), soils of the Succulent Karoo are rich in lime and are alkaline (pH 8.0), and have low electrical conductivity and high sodium content. Determining and understanding the pH of natural soils and post-mining wastes and how it is related to the growth of plants in the study area could improve the restoration success at Sendelingsdrif mine. The factors that are affecting soil pH in the study area are not yet documented.

2.2.2 Soil Organic Matter

Soil organic matter is any material of biological origin that decomposes and becomes part of the soil (Bot & Benites, 2005). Plants and animals maintain the presence of organic matter in the soil by constantly adding their remains. Organic matter plays a vital role in increasing water holding capacity of the soil and the proportion of water available to plants for growth (McCauley & Jacobsen, 2005). Soil nutrients and organic matter have a propensity to be concentrated in the upper 2-5 cm of the soil with the greatest amounts beneath the canopies of individual shrubs in the desert (Ward, 2009). Organic matter found on the soil surface helps to protect the soil from the effects of wind, rainfall and sun (Bot & Benites, 2005).

According to Du Preez et al., (2011), most of the South African soils have low organic matter levels, because of low rainfall that leads to poor growth of plants. They also found out that there are large differences in soil organic matter content within and between soil forms depending on climatic conditions, vegetation cover, topographical position and soil texture. Similarly Brown (1974) mentioned that the accumulation of soil organic matter is very slow in most of Southern African soils due to a lack of plants, which is caused by aridity. In a study conducted by Heathcote (1983), he found out that the lack of available moisture in arid environment may not only slow down the chemical processes but also the breakdown of plant materials into organic matter and humus, therefore the depth and quantity of both organic matter and humus in the arid soils is low and decline rapidly down the rainfall gradient. Organic matter is the major source of nutrients such as nitrogen and available phosphorus and potassium in unfertilized soils such as desert soils (Sheoran et al., 2010). Succulents of the family Mesembryanthemacea found in Succulent Karoo are associated with low percentage organic matter (Boom et al., 2005).

However, the percentage organic matter in hyper-arid soils varies spatially, depending on position in the landscape and on the vegetation cover in upstream regions (Whitford, 2002). In this way, soil samples from the same landscape, but taken from different positions in the catena, may vary between 0.013% and 0.062% (Jacobson, 1997). A study done by Hoffman et al., (2010) in the Succulent Karoo has indicated that leaf-succulent dwarf shrubs affect their environment by creating fertility islands underneath their canopies. The study also found out that the topsoils that are underneath the crowns of the plants in comparison with the adjacent open soils was enriched with organic matter, had increased pH-values and high coarse soil fraction, and they were partly enriched with nutrients. Similarly, Abrahams et al., (1995) also mentioned that the soil chemistry of arid lands is associated with islands of fertility (the accumulation of organic matters under perennial shrubs and trees). In the study area it is not yet understood on how organic matter accumulates and how it is distributed within the landscape. But based on the knowledge gathered from several studies or literatures on how organic matter accumulates in arid environments and the role it plays in the soil, this information could be very useful during the restoration of the Sendelingsdrif mine. During the restoration of Sendelingsdrif mine this could mean that the establishment of annuals or fast growing opportunistic perennials on mined substrates could be used to protect the exposed soil and may in time add to organic matter of the soil, and this could trigger a succession towards long-living species.

2.2.3 Cation and Anion Exchange capacity

Cation exchange capacity (CEC) is a measure of the soil’s ability to hold cation nutrients (Laura & Jodi, 2009). Clay particles and organic matter in the soil are negatively charged, attracting positively charged cations and making the cations resistant to leaching. Due to the high cation exchange properties of organic matter, it is able to bind soil particles together in a more stable structure (Killham, 1994). Cation nutrients include: iron (Fe^+), hydrogen ion (H^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and sodium (Na^+).

High cation exchange capacity is a good measure of a soil's ability to retain and supply nutrients to plants (Jones & Jacobsen, 2001), and thus of fertility. CEC is limited in arid environments, with the result that not all the nutrients in the soil are available to plants (Hartmann et al., 1988). Soils in arid areas tend to be sandy, with low nutrients and low cation exchange capacity (Whitford, 2002). Some studies done in the central Namib and in the southern part of Namibia have indicated that most of the soils (especially in dry areas) have low cation exchange capacity and they are sandy (Hartemink & Huting, 2008; Bertramis, 1999; Coetzee, 2009). CEC is an important soil factor especially in dry area because it can determine which nutrients are available in the soil for plants. In the study area CEC is not yet understand or determined, therefore the current study will focus on determining the CEC of natural soils and post-mining substrates.

Anion exchange capacity is the degree to which a soil can attract and exchange anions (Dean & Rubins 1947; Brady & Weil, 2009). Anions are negatively charged ions that include: phosphate (PO_4^{3-}), sulfate (SO_4^{2-}), chlorine (Cl^-), and nitrite (NO_3) .The exchange capacity of anions increases as soil pH decreases. Most agricultural soils have small anion exchange capacity compared to cation exchange capacity, because anions are constantly repelled by negatively charged clay particles and organic matter (Amador et al., 2000).

2.2.4 Carbonates

Brian (1973) defines carbonate as a salt of carbonic acid, characterized by the presence of the carbonate (CO_3) ion. The concentration of carbonates is common in all arid soils because of the shallow penetration of water into the soil column (Brown, 1974). Calcium carbonate and other salts accumulate in arid soils due to the downward penetration of salts as they leach from flying dust that settles and are caught in rainstorms. The concentration and size of carbonate particles in the soil affects the water holding capacity (Brady, 1974). The distribution and amount of carbonates influence soil fertility, erodibility and available water capacity by binding the soil together in a more stable fashion (Dixon & Weed, 1989). The presences of lime in arid soils serve as the source of carbonates, which are very crucial in the structuring of the soil. According to Ward (2009) calcium carbonates in arid and semi-arid soils serve as a source of soil nitrogen.

2.2.5 Soil salinity

Soil salinity refers to the state of accumulation of the soluble salts in the soil column (Al-Khaier, 2003). Soils are considered to be saline if they contain salt in the concentration that is enough to interfere with the growth of most crop species (Bui, 2013). Additionally, saline soils are usually having an electrical conductivity greater than $4dSm^{-1}$ (~36mM Nacl) measured on a saturated soil paste extract at 25°C. When salinity levels are high, plants struggle to extract water from the soil, because salt reduces the rate and the amount of water that the plant roots can take up from the soil (Al-Khaier, 2003). High levels of salinity in the soil can also cause an uneven distribution of nutrients, which can lead to accumulation of toxic elements in plants (Bui, 2012). A study has shown that high salinity can reduce the rate of water infiltration in the soil if the level of salt elements such as sodium is high (Abuduwaili, Liu & Wu, 2010). Salinity is common in arid and semi-arid environments because of low precipitation, high evaporation rates and low levels of leaching (Eash et al., 2008). According to Hartmann at el., (1988), saline soil is associated with high pH, which reduces the availability of plant nutrients such as zinc, iron, manganese, and copper (trace elements). In the study area is unclear to as whether the natural soils are saline or not, therefore the current study will determine whether the soils at Sendelingsdrif are saline or not.

2.3 Physical properties of the soil

2.3.1 Soil texture

Soil texture is determined by the proportion of three mineral particles—sand, silt and clay—in the soil (Wild, 1993; McCauley & Jacobsen, 2005). Clay particles found in the soil play a crucial role in imparting specific physical properties to the soils, to microbial communities, and to plants through nutrient availability (Coleman, Crossley & Hendrix, 2004). Additionally, soil texture properties are affected by soil organic matter. According to Whitford (2002), soil texture, landscape position and organic matter content in arid ecosystems have a remarkable effect on the population densities, species richness and biomass of soil biota such as plants, bacteria and fungi. Soil texture determines the rate at which water will infiltrate and how much water is available to plants (Foth, 1990). The breaking down of rocks and minerals either by physical or chemical weathering results in a particular texture (Wild, 1993). A field study conducted by Wassenaar (2010) at Sendelingsdrif (study area) has indicated that there are several factors that influence the soil's hydraulic conductivity such as soil texture. Soil texture has a larger influence on water infiltration because it determines the basic pore size. He also mentioned that plant roots and organic matter cause the difference in macro- and micropore sizes and they influences the waterrepellent properties of the soil. Soil texture of different natural soil is not yet determined in the study area and their relationship to plant growth is unknown. Therefore knowledge that will be acquired from the present study in combination with knowledge from previous studies can be used as a starting point for restoration of the Sendelingsdrif mine. Understanding the soil texture of natural soil from the study area can give us more options of amending the texture of mined substrates in such a way that it comes closest to that of natural soils.

2.3.2 Soil structure

Soil structure is defined by the way individual particles of sand, silt and clay soils are arranged (Brady & Weil 1999; 2002). Soil scientists currently divided soils into twelve (12) soil orders such as alfisols, andisols, aridisols, entisols, gelisols, histosols, inceptisols, mollisols, oxisols, spodosols, ultisols and vertisols (Plaster, 2009). Arid soils are classified as aridisols, which are often associated with alkaline, low organic matter and salted horizons. Organic matter content in the soil influences soil structure (Wild 1993). The presence of organic matter in the soil leads to good or improved soil structure (Eash et al., 2008); good structure allows the soil to retain adequate water for plants growth as well as drain excess water. Soil structure and its stability play an important role in a variety of processes in the soil, such as flood and erosion prevention, water infiltration and root penetration (Jury & Horton, 2004). Soil structure also has an effect on air movement and water through the soil (Coleman at al., 2004). The spaces between individual soil particles (aggregate) are micropores and those that are between the groups of soil particles (aggregates) are macropores (Eash et al., 2008). The macropores allow water and air movement through the soil profile, whereas micropores act as sponge and retain water for use by plants. According to USDA (2008) and Colenman et al., (2004), soil pores exists among and within aggregates and they are occupied by water and air. Macropores are large soil pores, generally between aggregates, that are usually greater than 0.08 mm in diameter (Brady and Weil 1999; Eash et al., 2008). Whereas micropores are small soil pores, usually found within structural aggregates (USDA, 2008). According to Bradshaw (2000), good soil structure is crucial for the proper functioning of terrestrial ecosystems.

2.3.3 Infiltration rate of water

Infiltration is the movement of water into the soil column from the surface by downward or gravitational flow (Brady and Weil, 2009). Infiltration rate is the speed at which water enters the soil column (Jury and Horton, 2004). Rate of water infiltration can be affected by factors such as moisture content in the soil, condition of the surface, hydraulic conductivity of the soil, soil texture, organic matter, vegetation cover and biological crusting (Osuji et al., 2010). In many semi-arid ecosystems there is strong evidence that the infiltration of rain water into the soil is positively correlated with vegetation biomass (Sherratt & Synodinos, 2012). They also mentioned that, on bare ground, much of the water that falls as rain simply runs off, but higher levels of organic matter in the soil, and the presence of roots, increases the proportion of rain water infiltrating into the soil. A study done in Nigeria stated that different land use practices such as urban development, mining, agricultural practices affect infiltration rate in many different ways (Osuji et al., 2010). The building of infrastructures (urban development), clearing of natural vegetation, and mining can lead to a reduced infiltration rate and high runoff, while agricultural practices such planting of crops and other vegetation can lead to an improved infiltration rate. When land is put to a certain use such as agricultural practices and mining activities, there is accompanying changes in both physical and chemical soil properties and therefore the hydrological balance of the soil is altered. Studies in the arid area have demonstrated that water infiltration in the desert is mainly influence by both biological and physical crusting, and the vegetation cover (Osuji et al., 2010). According to Wassenaar (2010) there are many aspects of soils that influence plant establishment and growth, the soil's hydraulic conductivity (its ability to absorb water) is probably the key property to understand in terms of restoration. Infiltration rate of natural soil in the study area is not yet determine, therefore the current study will for the first time determine the infiltration rate of natural soil at Sendelingsdrif. Understanding the soil's hydraulic conductivity of natural soil and the factors influencing it in the study area will help to improve the establishment of plant communities on post mining substrates and hence the restoration success at Sendelingsdrif mine.

2.4 Biological properties of soil

2.4.1 Soil flora

In most ecosystems soil flora plays a fundamental role in the process of soil formation. Flora breaks up the rock particles and enriches the soil with organic matter from the aerial (leaves) and subterranean (roots) parts (McCauley & Jacobsen, 2005). After the death and decomposition of roots, they leave channels in the soil that allow air and water movement in the soil. Roots stabilize the soil through aggregation of particles and extensive root systems help to decrease soil erosion (Amador et al., 2000). However, the role of soil flora in both soil formation and addition of organic matter diminishes in arid zones, because of the sparse canopy cover and limited development of aerial parts (Whitford, 2002). It is understood that the severe environmental constraints affects the distribution of plants in arid environments (Pointing and Belnap, 2012). Studies in arid and semiarid ecosystems have indicated that soil flora plays a major role in supplying the soil with organic matter, soil erosion prevention, improves water infiltration, nutrients cycling, supplying habitat and food for animals (Whitford, 2002; Abrams et al., 1995; Hoffman et al., 2010). Studies done in the Succulent Karoo have indicated that the occurrence of several species of plants is closely related to high diversity of soil features (Petersen, 2010; Hoffman, et al., 2010). These studies also highlighted the importance of soil flora such as their contribution to nutrients in the soil, soil formation process, and their interaction with soil microbes. Additionally, the high diversity of vegetation patterns in the Succulent Karoo is closely related to patterns of soil types. The importance of soil flora and their interaction with other organisms, and the soil properties that are affecting them are not yet known at Sendelingsdrif. Therefore the current study in conjunction with the knowledge gathered from other related studies will help us to determine which soil properties that are related to plant growth in the study area. The gathered information will then be used later during restoration at Sendelingsdrif mine to help ameliorate post mining substrates to make the more conducive for plant establishment and growth.

2.4.2 Soil fauna

According to Lee and Foster (1991), soil fauna refers to all organisms that live in or on the soil such as earthworms, rodents, ants, and termites. Soil fauna are soil engineers, starting the breaking down of dead plant and animal material, ingesting and processing soil particles, burrowing channels for water and air movement, mixing of different soil layers, and promoting aggregation (Davies, 1973).

Ecosystem engineers directly affect soil physical properties and decomposition, by their digestion and transfer of organic matter and soil (Lavelle et al., 1997). They digest crop residues and other organic matter enzymatically, and they move the residues from one place to the other mixing it with the soil (Hartmann et al., 1988). According to Bradshaw (2000), it is evident that without appropriate soil micro-organisms there would be no organic matter breakdown and cycling of nutrients.

Fauna are therefore important part of ecosystem development. Earthworms, nematodes, rodents, insects and arthropods are among the important soil fauna on earth. Through the process of burrowing, soil fauna provides channels that increases water holding capacity, porosity and water infiltration (McCauley & Jacobsen, 2005). Generally, studies have indicated that soils in arid regions have different and fewer soil organisms compared to other regions (Hartmann et al., 1988). Whitford (2002) stated that the soil fauna in arid regions is nearly as diverse as the soil fauna of semi-arid areas. A study done by Burke (2001) in the Succulent Karoo found out that animal activity (soil fauna) can positively alter physical and chemical soil properties. Burrowing animals such as rodents, reptiles and other invertebrates contributes to the loosening of the soil, breaking down of the nutrients, and as a result fertilization of the soil. In another study done by Burke (2003) she mentioned that as in many shrub-dominated communities, in Succulent Karoo natural processes such as cyclic succession are aided by animal activities, such as burrowing animals and herbivores that help with seed dispersal and soil nutrients enrichment. The cyclic succession process involves vegetation naturally under going through changes from bare areas to herb- and later shrub- dominated communities (Burke, 2003). A study done by Desmet and Cowling (1999) in the arid west coast of southern Africa (part of Succulent Karoo) found out that the fossorial rodent *paratomys brantsii* on overburden dumps initiated the natural re-vegetation of plants. The colonization of plants was facilitated by rodent burrowing activities which created soil patches (islands) containing organic matter and soil microbial propagules. Furthermore, the study disclosed that the activities of these rodents on the waste dumps increased the microbial activities. The presence of microbials in the soil can facilitate the establishment and growth of plants. The role of soil fauna are not yet known at Sendelingsdrif. Burke (2001) also mentioned that the southern Namib's invertebrate fauna is poorly known, but potentially very important for ecological processes. Therefore the knowledge that will be gathered from the present study coupled with knowledge gathered from various studies can be used at Sendelingsdrif mine during restoration to restore the fauna communities back into the area. During restoration of the Sendelingsdrif mine, burrowing animals such as rodents can be re-introduced in the area (on waste dumps) in order to help with the process of soil formation, accumulation of organic matter, re-establishment of microbial communities, mixing of soil particles, and hence the facilitation of plant colonization.

2.4.3 Soil microbes

In desert ecosystems, microbes form a thin layer or crust of biological activity that occurs within the top few centimeters of most soils and rock surface (Pointing and Belnap, 2012). Microbes are invisible with the naked eye but their effects on numerous soil properties are considered to be very important (Carter, 1986). Microbes improve soil structure by surrounding particles of the soil and gluing them together via the secretion of sugars. In arid ecosystems soil microbes play a vital role in facilitation of weathering of rocks, water retention on the surface of the soil, improves infiltration and nutrients cycle (Pointing and Belnap, 2012).

Bacteria play an important role in decomposing of soil organic matter, clay aggregation and nutrients transformation (White, 1997; Brady & Weil, 2009). Microbes such as *Rhizobia* form a symbiotic association with legumes in order to fix nitrogen (Hopkins and Huner, 2004). Plant roots and fungi form a symbiotic association known as mycorrhiza. In this association, the plant supplies the fungus with necessary energy and in return the fungus takes up nutrients for the plant and improves plant growth (Carter, 1986). Mycorrhiza increase water availability and reduces plant diseases, as well as improving soil aggregation stability.

Burke (2001) mentioned that in the Succulent Karoo not all plants are capable of forming mycorrhiza. Many members of the mesembryanthemacea and the dominant leaf-succulent shrubs are not mycorrhizal. In semi-arid regions the diversity of soil microbes are higher than those that are found in arid areas (Pointing & Belnap, 2012). Moreover, soil microbes are evenly distributed in semi-arid regions whereas they are found in patches in arid region (Belnap, 2005). Soil microbes in arid areas tend to colonise less extreme places and that is how they end up forming patches (Pointing & Belnap, 2012). The study done by Belnap (2005) indicated that the activities of microbial activities in semi-arid and arid areas are closely related to the timing, intensity, and amount of precipitation. Soil microbes carry out crucial ecosystem functions in all biomes, even in extreme arid environments where higher plants cannot grow. In the study area the activities of soil microbes is not yet known.

2.5 Nitrogen Cycle

Of all the soil nutrients required for plant growth, nitrogen appears to be the most important limiting nutrient in semi-arid and arid environments (Whitford, 2002). Like oxygen and carbon dioxide, nitrogen exists in a number of inert forms in the environment (Pidwimy, 2006). It is found in the atmosphere, in soils and in the biomass pool (Whitford, 2002). Plants lack a gene that codes for the enzyme capable of fixing nitrogen; therefore, nitrogen fixation is done by microbial organisms found in the soil in the process called “biological nitrogen fixation” (Burdass, 2002; Hopkins & Huner, 2004).

Nitrogen that is derived from the soil is generally in the form of nitrate (NO^-_3) and the nitrogen found in the atmosphere needs to be reduced to ammonia (NH_4^+) by the prokaryotes in the soil to produce amino acid and proteins (Dennis & Turpin, 1990). Nitrogen is an important building block for proteins and other organic compounds (Burdass, 2002).

2.5.1 Biological Nitrogen Fixation

Microbes such as soil bacteria and cyanobacteria, in association with fungi or roots, carry out the reduction of dinitrogen (N_2) to ammonia (NH_4^+) (Killham, 1994). Prokaryotic organisms have a gene that codes for an enzyme called dinitrogenase, which they use to facilitate the reduction of atmospheric dinitrogen to ammonia (Hopkins & Huner, 2004).

Booi (2011) carried out a study in Succulent Karoo *heuweltjie* soils where he found out that nutrient such as nitrogen, carbon and phosphorus accumulate to higher levels due to the effect of termites in the biome. He also discovered that plant material which is high in nitrogen and phosphorus is collected by termites, digested and excreta produced enrich the soil of Succulent Karoo. The patterns of nitrogen distribution maybe as elsewhere, be related to the presence of shrubs (Allsop, 1999), but for now there is no information available for Sendelingsdrif. Soil nutrients such as nitrogen and organic carbon are determined by microbial activity, which is in itself closely related to the timing, intensity and the amount of precipitation (Belnap, 2005). According to Wassenaar (2010) when the soil profile is disturbed, the availability of many nutrients changes abnormally. Especially nitrogen becomes less available and if biological activities are lost, it may drop to very low levels.

2.5.2 Nitrification

The process of nitrification in arid and semi-arid ecosystems is carried out by the cynobacterial found in soil crusts (Araniba et al., 2003) whereas in some other ecosystems the nitrification process happens in legumes of leguminous herbs (Whitford, 2002). Nitrification is a biological conversion of ammonium to nitrate (Focht & Verstraet, 1977). Nitrosomonas is a bacterium that carries out the conversion of ammonium and ammonia to nitrite (Sharma & Ahlert, 1977). The translation of nitrite to nitrate is finalized by a bacterium called Nitrobacter. The reactions are coupled and proceed rapidly to the nitrate form (ammonium to nitrite and nitrite to nitrate). Bacteria involved in this process require oxygen; therefore it only occurs under strict aerobic condition (Anthonisen *et al*., 1976). The process of nitrification produces acid as a by-product and the formed acid lowers the pH. Furthermore a decrease in pH can cause a reduction of the growth rate of nitrifying bacteria. Nitrosomonas and Nitrobacter have optimum pH between 7.5 and 8.5. pH that is below 6.0 can stop nitrification reaction. The conversion of ammonium to nitrate (nitrification reaction) consumes 7.1mg/L of calcium carbonate ($CaCO_3$) for each mg/L of ammonia nitrogen oxidized (Focht & Verstraet, 1977).

The rate of nitrification reaches its maximum at temperatures between 30 and 35°C. At temperatures of 40°C and higher, the rate of nitrification decreases to nearly zero (Sharma & Ahlert, 1977). At temperatures below 20°C, nitrification proceeds at slow rate. The process of nitrification is not yet documented at Sendelingsdrif (study area).

2.5.3 Denitrification

The process of denitrification results from the microbial reduction of nitrate (NO_3) or nitrite (NO_2) to either N_2O or dinitrogen (N_2). Ammonia volatilization and denitrification are the mechanisms by which nitrogen is lost from the soil pool back into the atmosphere (Whitford, 2002). In arid environments nitrogen is lost from soil back into the atmosphere in the form of ammonia (Fleisher et al., 1987). The loss of ammonia is greatest from coarse, dry soils with limited cation exchange capacity (Whitford, 2002).

The process of denitrification occurs when oxygen levels are low and nitrate becomes the most important oxygen supply for microorganisms (Seitzinger, 1988). During the process of denitrification, bacteria break down nitrate (NO_3) to nitrite in order to acquire the oxygen molecule (O_2) (Knowles, 1982).

This process has an optimum pH which is between 7.0 and 8.5 (Focht & Verstraete, 1977). Factors such as the presence of sufficient organic matter as source of carbon has an effect on the rate of the denitrification reaction. In addition to this, nitrate concentration, anoxic conditions, presence of organic matter, pH, temperature alkalinity and the effects of trace metals affects the efficiency of the denitrification process (Takaya et al., 2003). Arid soils are low in carbon and nitrogen content, are frequently basic and subjected to extreme temperatures (Korom, 1992). In most arid watersheds, losses of nutrients in litter and plant debris transported into ephemeral streams are a spatial occurrence, which means the concentration of organic materials is high at the end of watershed (Whitford, 2002). Nutrient losses from desert watersheds only occur in those few watersheds that are drained by perennial streams. Thus in most desert landscapes, denitrification is the most prominent means of loss of nitrogen. The process of denitrification is not yet understood and documented in the study area.

2.6 Properties of post-mining substrates

In comparison to natural soils, post-mining substrates are excavated from depths of thirty metres or from just below the surface or from the processing of minerals and therefore their physical and chemical properties differ drastically from that of the natural soils (Cooke & Johnson, 2002). Understanding the physical and chemical properties of post-mining substrates is very important, because post-mining substrates are the fundamental starting point for restoration of an ecosystem for vegetation establishment. Colonization of mining substrates can be very difficult due to the absence of either organic matter or other nutrients and good physical, chemical and biological properties of top soil, the re-application of suitable growth medium such as topsoil or dilution of mining substrates (Johnson et al., 1994). The presences of fine texture and no organic matter in mining substrates may lead to extreme compaction, low water infiltration rates and surface water logging (Sheoran et al., 2010).

All mining substrates generally have low levels of macronutrients such as nitrogen, phosphorus, and potassium (Cooke & Johnson, 2002). Post-mining substrates can exhibit extreme pH depending on what type of mineral is being mined. This extreme pH of post-mining substrates can pose serious growth problems to plants (Cooke & Johnson, 2002). Carrick & Krüger (2007) considered that most of the post-mining substrates lack nutrients that are essential for plant growth and they are often high in saline content. They further added that these substrates consist of unsuitable media for establishment of plants except for fewer salt-tolerant species.

In arid and semi-arid environments, establishment plants on post-mining substrates (tailings) is affected by physical and chemical factors such as low precipitation, extreme temperatures especially on the surface of tailings, and high winds (Munshower, 1994). The above mentioned factors contribute to the development of extremely high salt concentrations ranging up 22 dS/m due to high evaporation and low water infiltration (Mendez and Maier, 2008). There is a knowledge gap when it comes to which of the crucial soil nutrients will be affected by mining in the study area and which of these crucial nutrients is lacking in post-mining substrates. Burke (2008) did an experiment in-situ at Sendelingsdrif to test the survival of *Juttadinteria albata* in waste materials (post-mining substrate) through transplanting and propagation techniques but there no follow ups. The experiment was very basic, because there was no replication and the watering of plants was done twice only. An analysis that was done in 2010 (Wassenaar, 2010) revealed that there was high mortality and poor plant health in all treatments but it is still unknown to as why plants mortalities were high. Therefore, the current study will fill in the knowledge gap that exist on which properties of soil are related to plant performance, so that it can be decided how best to manipulate the waste material properties to get as close as possible to natural soil in terms of plant growth.

Summary

Arid soils are generally sandy to sandy loamy with low cation exchange capacity, fertility, and organic matter. Salinity is common in arid and semi-arid environments due to low precipitation, high evaporation and low levels of leaching. The Succulent Karoo has various soil patterns (different soil types) that occur at various spatial scales, caused by different processes such as climatic variability, history, weathering and the geology, and they are closely related to the high diversity of vegetation (Hoffman et al., 2010). Moreover, all post-mining substrates generally have low levels of macronutrients such as nitrogen, phosphorus, and potassium. Post-mining substrates tend to have high salt contents due to the fine-texture fraction within them that are capable of binding the salts within the soil.

Chapter 3

Methodology

3.1 Study area

Sendelingsdrif mine is a new extension of the Orange River Mines Mining Licence ML42. The mine is located in the Sperrgebiet National Park in the Karas region in the heart of the arid Succulent Karoo Biome about 20 km southeast of Rosh Pinah, along the Orange River, in the Tsau //khaeb (Figure 1). The Succulent Karoo covers an area of approximately 116,000 km^2 in Namibia and South Africa (CEPF, 2003). The Succulent Karoo is one of the only world’s top 25 biodiversity hotspots found in the arid area (Beukes and Cowling, 2003; CEPF, 2003). The Succulent Karoo includes 851 Red Data Book plant species, 685 (about 40%) of which are endemic to this ecoregion (Loots, 2005).

The Succulent Karoo is characterized by winter rainfall, beautiful landscapes, and low-growing succulents such as the endemic *Juttadinteria albata* and other dwarf shrubs (Petersen, 2008). The climate is arid with long-term average rainfall of approximately 50 mm pa (Burke, 2008; Pallet et al., 1995). Many species are habitat specialists, with specialization generally related to soil type, and have limited range size (CEPF, 2003). Local endemism is mainly evident among bulbs, Mesembryanthemaceae and other succulents (CEPF, 2003). Succulent Karoo has surfaces of dry, shallow and rocky soil with most of the vegetation growing on the slopes or in sheltered gullies (Pallet et al., 1995). The underlying rock type is mainly quartzite and soils are very shallow lithosols, usually not deeper than a few centimetres (Burke, 2008; Elser et al., 2006).

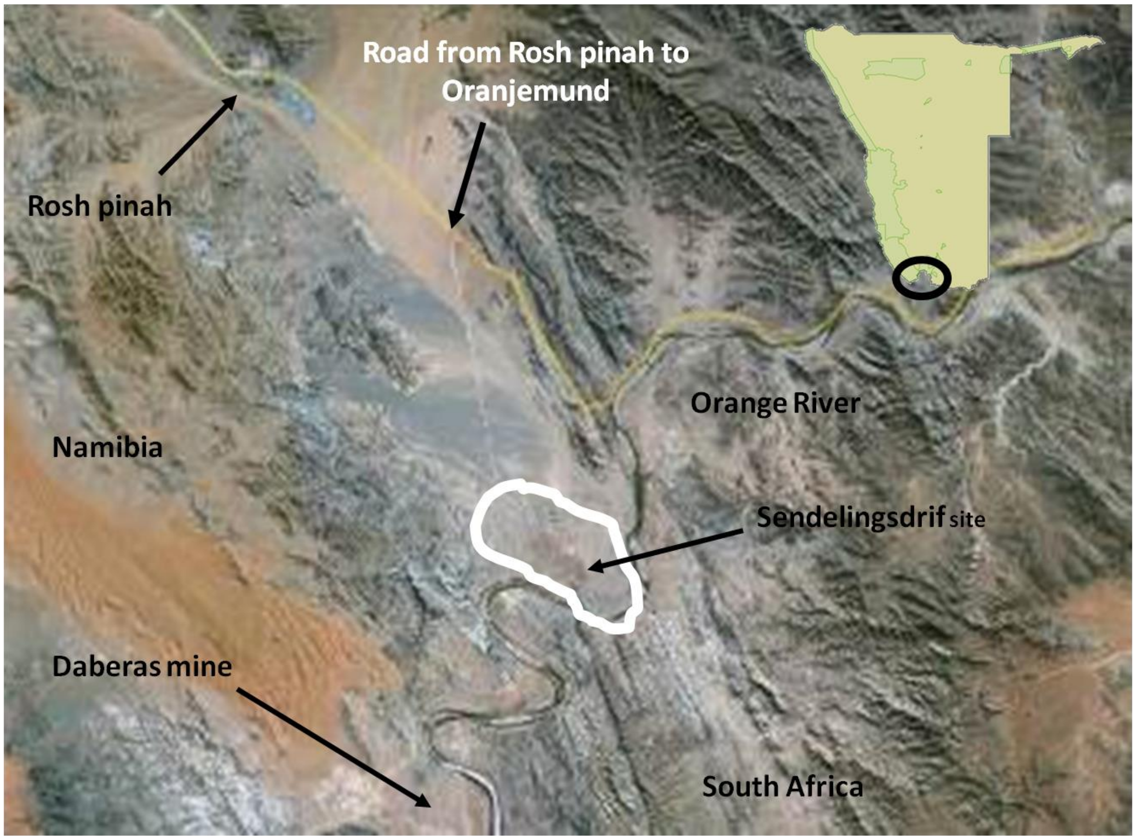

Figure 1: Map of Namibia showing the location of the study area of proposed Sendelingsdrif mine (Reproduced from Wassenaar, 2010).

3.2 Research design

The present study comprised a fieldwork phase during which surveys were conducted at and around the mine site of the natural conditions under which plants grow, and a greenhouse experiment, to test the utility of different waste mixes as growth medium for plants. The greenhouse experiment followed a randomised block design.

3.2.1 Field study

Thirteen different habitats (Figure 2) were previously identified in the study area based on geology, topography and soil depth (Wassenaar, 2010). For the present study, fieldwork was conducted in seven habitats that will be impacted by mining activities. These included the lower terrace, broad sandy wash, meso-terrace, sheltered gullies, proto-terrace, rocky hills and shallow soil on ridges at Sendelingsdrif. ArcGIS software was used to generate ten random points in each of the seven habitats. All the random points were loaded on the GPS and the GPS was used to navigate to each of the generated random points on site. A total of 70 quadrats were sampled for all of the seven habitats. In each habitat a total of ten quadrats were sampled. At each random point, a 4 x 4 m quadrat was set up for sampling. In each quadrat the following variables were measured: rock cover, aspect and altitude, slope, description of landscape. All plants in each quadrat were identified to species level.

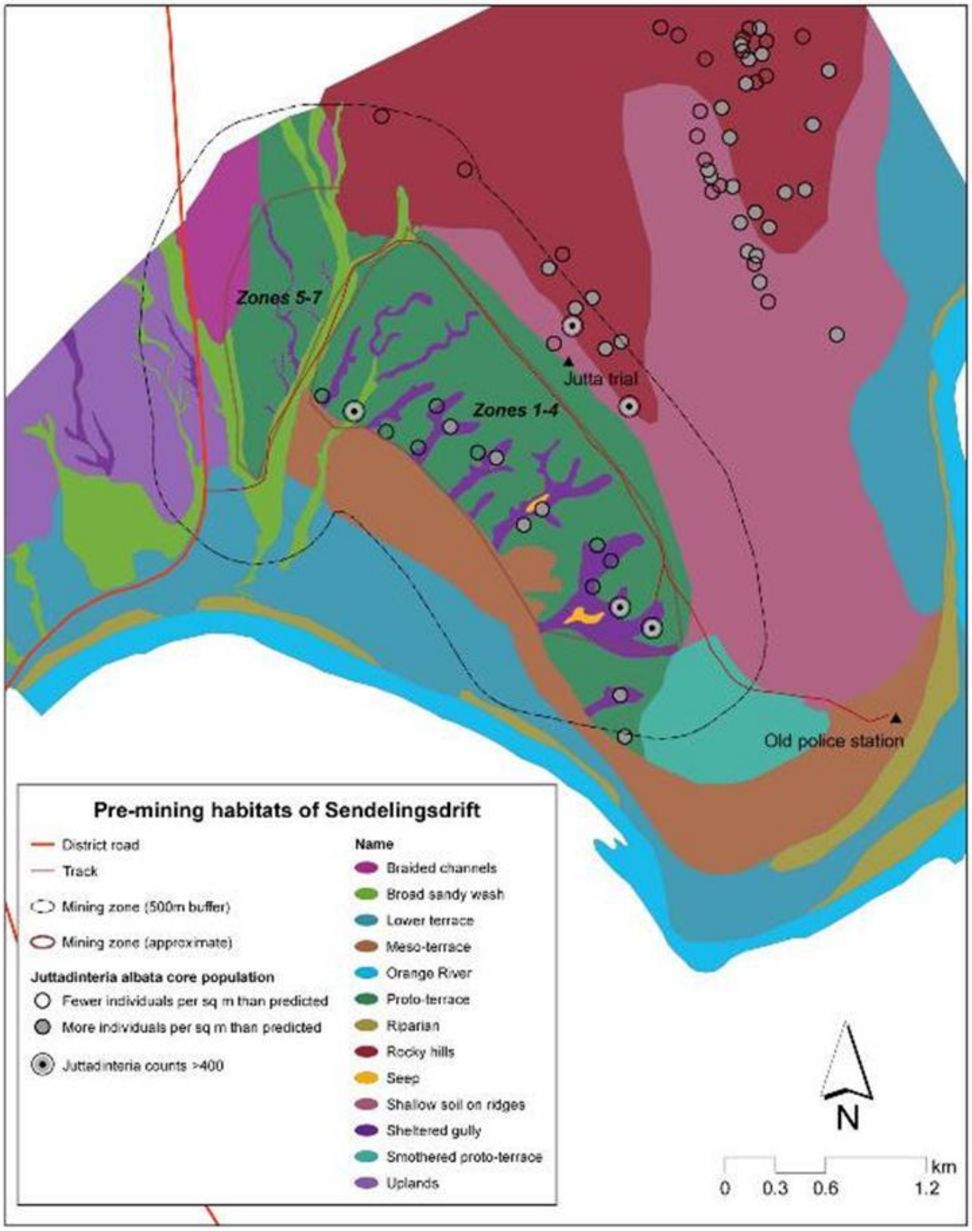

Figure 2: A map of the area where Sendelingsdrif mine is located, showing the location of several habitats that will be impacted by mining for Diamonds. The *Juttadinteria albata* core

population refers to the first trial that was done in the study area prior to my study to identify the location of *J. albata* population in the area.

3.2.2 Sampling design

3.2.2.1 Collection of soil samples

One sub-sample was collected from each of the four corners of every quadrat and the fifth from the centre (Figure 3). A total of five sub-samples were taken at the depth of 0-10 cm using a garden shovel, away from the nearby plants in the open area. Plants affect physical and chemical soil properties through the alteration of infiltration and runoff (Esler & Cowling, 1993), therefore samples were taken away from them. The soil samples were then sieved through a 2mm sieve to remove stones and large pebbles. Sub-samples were then mixed together in a bucket to get one collective soil sample of 4 kg; this was done for all the surveyed quadrats (70 quadrats).

The Sendelingsdrif mine is currently still being constructed and at the time of the study, only trial mining had been conducted. Hence there was, only one heap of fine tailings, available with properties close to what will be available in the future after mining. This was used both in greenhouse and in the laboratory for analysis, therefore only one collective sample from the available heap was sent to the laboratory for the analysis of physical and chemical properties of post-mining substrates.

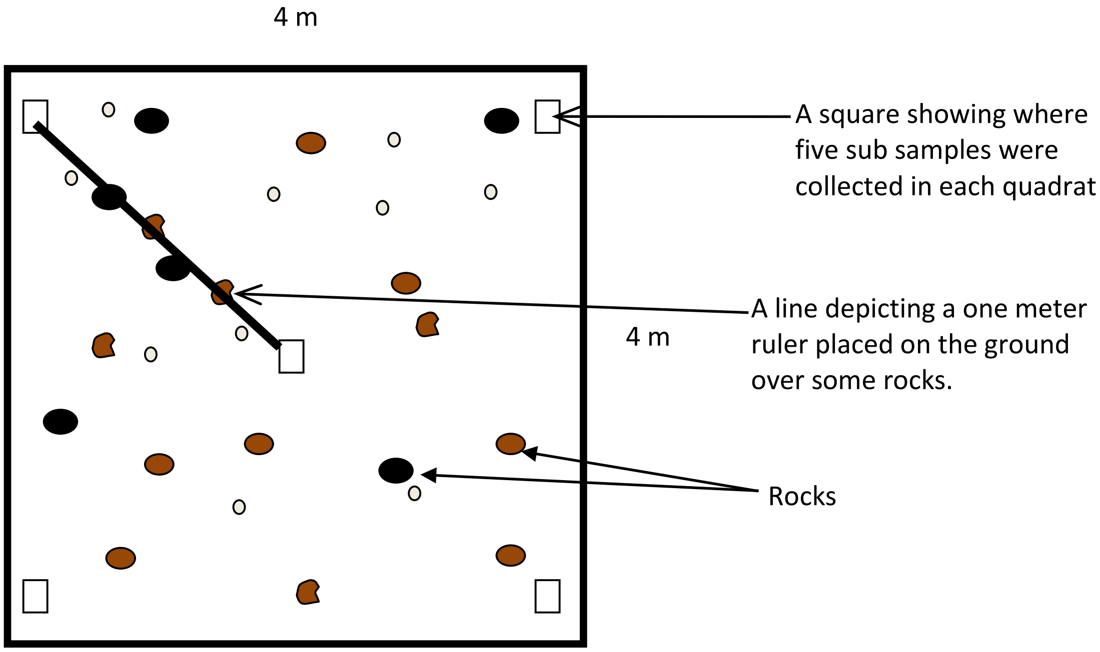

Figure 3. The quadrat showing how soil samples were collected in each habitat and how line intercept method was employed in order to compute rock percentage cover in each quadrat at Sendelingsdrif mine.

3.2.3 Variables measured

Field variables

3.2.3.1 Rock cover in each quadrat

In the present study, percentage rock cover was defined as a portion of the quadrat that was covered by rocks that were greater than 2 cm in each quadrat using a line intercept technique (Esler & Cowling, 1993). A wooden ruler was laid down in all four corners of each quadrat and at the centre of the quadrat (Figure 3). The diameters of all rocks that intercepted the ruler were recorded (adopted from Esler & Cowling, 1993). The rock diameters from all four corners and the centre were summed and converted to percentage to represent the percentage rock cover per quadrat. This was repeated for 70 quadrats in each of the 7 habitats (lower terrace, broad sandy wash, meso terrace, sheltered gullies, proto terraces, rocky hills and shallow soil on ridges).

3.2.3.2 Aspect and Altitude

In each of the 70 quadrats in the 7 sampled habitats, aspect and altitude was determined. Aspect is the positioning of the slope in a particular direction such as north, west, east and south (Huggett & Cheesman, 2002). Aspect of slopes was determined using a hand-held compass (TFA, R1100646). Altitude is the height (measured in meters) above the sea level of a specific point. A handheld GPS Unit (Garmin III Plus) was used to determine the altitude in meters.

3.2.3.3 Slope

Slope is the angle of a flat surface tangent to the topography surface represented by a Digital Elevation Model (DEM) at any given point (Huggett and Cheesman, 2002). The slope of each of the (70) surveyed random points in each habitat was measured using a clinometer (angle locator) and the readings were recorded in degrees (Figure 4). The clinometer was home-made (by Dr Wassenaar) using hardware-bought components (hence no model name or number). The clinometer constructed from a camera tri-pod, and a straight-edge and cheap angle measurer bought as a home builder's set. The angle measuring device comprised a simple semi-circular scale with a weighted needle that pointed to the degrees off-horizontal, in 1-degree increments. The angle measurer was tied on to the spirit level using cable ties, and the combined instrument was screwed onto the tripod. With the tripod providing a stable platform that was at a constant height above the ground, the top surface of the straight-edge was used to aim the whole device to an equal-height target, providing a line of sight parallel to the surface of the slope. At that point the needle would be pointing to the appropriate number of degrees away from horizontal.

Figure 4. Using a clinometer to determine the slope angle for a survey plot at Sendelingsdrif diamond mine.

3.2.3.4 Position in the landscape

The description of landscape was done in order to understand how the physical and chemical soil properties vary in different positions and how this variation affects plant growth within the landscape (Coetzee, 2009). The position of each quadrat was determined on a hypothesised catena, and it was recorded as either crest, upper mid slope, lower mid slope and bottom, respectively. In the present study, crest refers to the flat area on top of the hill, upper mid slope refers the area just below the crest, lower mid slope refers to the area just below the upper mid slope and slightly above the bottom of the slope or valley, and bottom refers to the flat area at the bottom of the slope. Catena refers to the sequence of soil types that are linked together like chains from hill to valley floor (Bertram, 1999). Catena is an important feature of landscapes because catena allows or helps people to accurately predict soil locations, understand the hydrology of water catchments, and learn the history of land forms (Coetzee, 2009).

3.2.3.5 Coordinates

The latitude and longitude of surveyed sampled quadrats in each of the 7 habitats were recorded in degrees, minutes and seconds using a handheld GPS Unit (Garmin III Plus).

3.2.3.6 Infiltration rate

In each of the surveyed quadrats in the present study, a mini-disc infiltrometer (WA 99163) containing a volume of 80 mm of water was placed on the surface of soil in each habitat and the time taken for water to move from 80 mm at intervals of 10 mm till 30 mm was recorded (Figure 9). The manufacturer recommends distinguishing of soil types when working with a mini-disc infiltrometer, because different soil types differ in their suction rates (Decagon Devices, 2007). In the field, soil types were identified using a soil texture chart adopted from Thien (1979).

The water infiltration rate was also measured in different post-mining substrates (those that were mixed with Lucerne and those without Lucerne), natural soils and potting soils that were used in the greenhouse experiment.

The curve of cumulative infiltration against the square root of time was used to determine water infiltration rate of different soil samples (after Olorunfemi & Fasinmirin, 2011). The slope of this curve was determined using a basic Microsoft excel spreadsheet macro provided by Decagon (Decagon Devices, 2007).

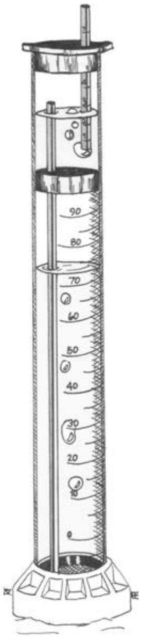

Figure 5. Illustration of mini-disc infiltrometer for determining water infiltration rate in different soil types and post-mining substrates (reproduced from Decagon, 2007)

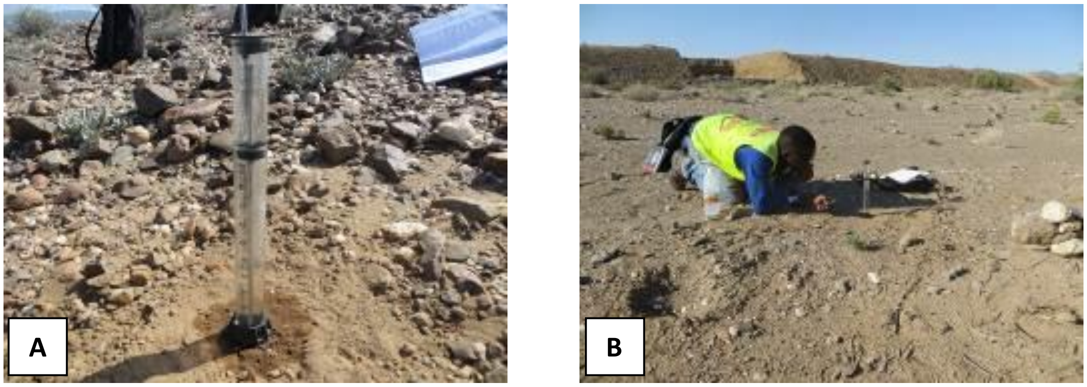

Figure 6. Picture **A** illustrates the set-up of mini-disc infiltrometer in the natural habitat and picture **B** demonstrates how the measurement of water infiltration rate was carried out in the field at Sendelingsdrif.

3.3 Soil chemical and physical properties

3.3.1 Storage of soil samples

Seventy soil samples that were collected during fieldwork were kept in brown paper bags in a store room at Sendelingsdrif at ambient temperature. Samples that were moist were air dried at ambient temperature for 4 to 5 days before storage.

Permission was granted by Ministry of Mines and Energy for the transportation and analysis of soil samples out of the diamond area.

3.3.2 Laboratory method

3.3.2.1 Preparation of soil samples

Soil samples were analysed at Analytical Laboratory for chemical analysis. Soil samples were air dried at room temperature for two days in aluminium dishes before they were sieved through a 2mm sieve. Then each soil sample was divided into two portions or subsamples to yield a laboratory subsample and an original subsample. The laboratory subsamples were placed in labelled plastic bags. Analysis of all soil samples described below was carried out on these laboratory subsamples. They are henceforth below referred to as soil samples.

Analysis of the 70 soil samples was carried out in order to measure the following: pH, percentage organic matter, total nitrogen, carbonate, potassium, magnesium, calcium, iron, copper and soil texture.

3.3.2.2 pH

The pH of soil was measured on all the collected soil samples (70 soil samples) on saturated paste using an electrometric method at Analytical Laboratory Services (Bower & Wilcox, 1965).

3.3.2.3 Percentage organic matter

The Walkely Black method was used to determine the percentage organic matter in all samples of soil and post-mining waste materials (Nelson & Sommers, 1982). A subsample of 2.5g of soil per sample was prepared and 10ml of potassium chromate was added. Ten (10) ml of concentrated sulphuric acid was added to this solution under a fume hood. The mixture was left to react for 30 minutes. After the reaction, the solution was cooled down by adding 200ml of distilled water and was allowed to cool down for 10-15 minutes. After cooling, 10ml of concentrated orthoplosponic acid and 0.5ml barium diphenylamine sulphumate indicator was added to the solution in the Erlenmeyer flask. The solution was then titrated in the burette titration flask. At the beginning of the titration process, the solution was blue. The indicator solution was added to the solution until a green colour appeared. The titration process was done in order to find out the presence or absence of organic carbons in the sample.

3.3.2.4 Total nitrogen

The content of nitrogen in the 70 soil samples collected during field work and post-mining waste materials was determined at the analytical laboratory. A modified Kjeldahl method was used to determine total nitrogen of soil samples (Shaenau & Karamanos, 1993; Soil Science Society of South Africa, 1990). The procedure determines the total nitrogen, specifically ammonium N, nitrate-N, nitrite-N and organic N content of the soil. Five (5) grams of the soil sample was weighed using microsep scale (AE ABAM model) and placed into a digestion tube, after which 20ml of salicylic sulfuric acid was added. The solution was placed in the freezer overnight. The next morning, 0.5 grams of sodium was added to the solution and the solution was placed in a digestion chamber which was heated to 200°C for 30 minutes. After heating, the sample was left to cool down and two tablets were then added to the solution. The solution was heated again to 400°C for 120 minutes. After the sample cooled down, it was placed on the distillation unit. Distilled water was added and left for 5 minutes in order to neutralize the acid. The distilled solution was poured into 20ml of boric acid and then 0.1 grams of indicator solution was added (0.2 grams of Methyl red plus 100ml of ethanol plus 0.1 grams of methylene blue). The solution was subsequently titrated against 0.1 molar of HCl until the solution turned from green to purple.

The whole digestion process took three to four hours to be completed. The content of total nitrogen was determined on the ICP-OES (Optical Emission Spectrometer).

3.3.2.5 Carbonate

In order to determine the amount of carbonates in each of the 70 soil samples twenty (20) grams of the sample was weighed and placed into a 250ml Erlenmeyer flask with 50ml of 1 molar of hydrochloric acid. The solution was left to stand for 30 minutes for the reaction to take place.

After the reaction, 50ml of 0.5 molar KHP solution (KHP determines the molarity of sodium hydrogen solution) was added to the solution in the Erlenmeyer flask. A blank was prepared from 25ml of 1 molar of hydrochloric acid. A blank is normally used as a standard in a titration process (International Soil Reference and Information Centre, 1992). Six drops of phenolphthalein indicator was added to the solution before titration. The titration was carried out using 1 molar of hydrogen sulphate; hydrogen sulphate was added to the solution until a pink colour was observed. When the solution turns pink in the process of titration, it is an indication that carbonate is present in the sample. The content of carbonate was determined on the ICP-OES (Optical Emission Spectrometer).

3.3.2.6 Extractable macronutrients (Mg, K and Ca)

Fifty (50) millilitres of 1 molar of acetate at pH 7 was added to 5 grams of the soil sample. The solution/mixture was shaken for 1 hour on the shaker (Model 1346) and thereafter filtered via gravity. The filtered extract was placed in the freezer overnight, on the following day, 20 ml of the extract was placed in a vial and 1ml of 65% nitric acid was added. A dilute solution (1:10) of the extract was prepared from 1 molar of ammonium acetate blank (1,000 ml of ammonium extraction solution plus 50ml of 65% nitric acid). The prepared dilute solution was analysed via ICP-OES (Soil Science Society of South Africa, 1990; Shoenau & Karamanos, 1993). The content of macronutrients was determined on the ICP-OES (Optical Emission Spectrometer).

3.3.2.7 Extractable micronutrients (Fe and Cu)

Fifty millilitres of 1 molar of acetate at pH 4.6 was added to 5 grams of the soil sample. The solution/mixture was shaken for 1 hour on the shaker and subsequently filtered via gravity. The filtered extract was placed in the freezer overnight, on the next day; 20 ml of the extract was placed in a vial to which was added 1ml of distilled water. The prepared diluted solution was analysed via ICP-OES (International Soil Reference and Information centre, 1992). The content of micronutrients was determined on the ICP-OES (Optical Emission Spectrometer).

3.3.2.8 Plant-available phosphorus

Five grams of soil sample was prepared, to which 0.3g of charcoal was added. The charcoal was first washed with hot water before adding it to the 5 grams of the sample. Charcoal was added to the sample to act as a decolouring agent (Shoenau & Karamanos, 1933). The mixture of 5g of the sample and charcoal was placed on a shaker for 30 minutes. The sample was then filtered via gravity and was placed in the freezer for 24 hours to let all the suspended particles to settle. Five millilitres of extracted solution was placed in the test tube to which 5 drops of 4 molar sulphuric acid was added using a glass pipette. Distilled water was added to the solution and 10 ml was extracted from that solution. The extracted 10 ml solution was added to phosphate reagent and the solution was left to react for 15 minutes. After the reaction, the solution was placed in the cuvette and it was pipetted in the UVmini 1240 (instrument for measuring the amount of light) at a wavelength of 825 nm. This method of analysis is only applicable to soils with the pH greater than 6.5 (alkaline to neutral soils). The extraction solution for phosphorus is an alkaline solution made up of sodium hydrocarbon with a pH of 8.0. The Olsen method of extraction was used, namely a 0.5 M sodium bicarbonate solution at pH 8.5 (Shoenau & Karamanos, 1933). This method is suitable for alkaline to neutral soils. Phosphate in the extract was measured calorimetrically following spectrophotometric analysis (International Soil Reference and Information centre, 1992).

3.3.2.9 Soil texture

A pipette method was used to determine soil texture (Figure 7). Soil texture was determined in terms of particle size analysis and percentage of sand, silt and clay was recorded. Twenty (20) g of soil sample was placed in a 250ml volumetric flask then 20ml of a dispersing agent was added to the sample. The dispersing agent was made up of 40g of sodium hexametaphosphate in 100ml of distilled water and 10g of sodium carbonate mixed in a volumetric flask to yield 1 litre solution. The prepared dispersing solution was shaken manually for 30 minutes and it was left to stand overnight. Eighty (80) millilitre of distilled water was added to the extract and then it was shaken for 30 seconds. After shaking the solution, 5ml was extracted from the solution into an aluminium dish using a pipette. Five (5) millilitre of the solution that was extracted came from a depth of 6 cm, in order to extract silt and clay particles. The extracted solution was placed in the oven at 100°C for 3 hours, after which the silt content was weighed to the nearest grams. After 5 hours the same method was repeated to get the clay content. For sand, the whole extract was poured onto a 5µm sieve and it was washed through the sieve with distilled water into the aluminium dish. The extract was then placed in the oven at 100°C for 3 hours after which the sand content was weighed to the nearest grams.

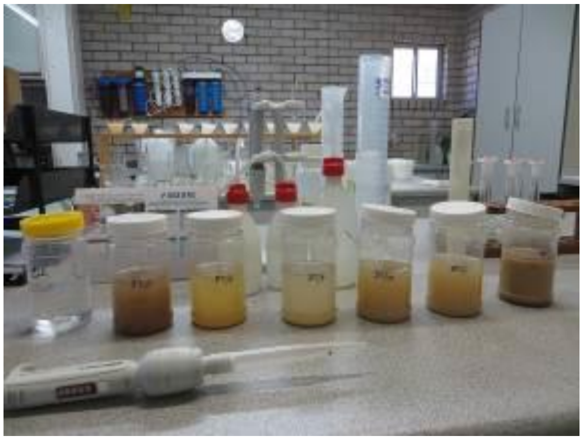

Figure 7. A photograph showing the bottles and the pipette that were used to determine the texture of soil samples at Analytical Laboratory Services in Windhoek.

3.3.2.10 Salinity

For each soil sample, a saturated paste was prepared to determine the electrical conductivity. A saturated paste was prepared by mixing the soil sample with 150ml of water in a polyethylene plastic bottle and was left to stand overnight. The next morning, the paste solution was poured into the funnel for filtering. The funnel was placed on the vacuum extraction utilizing a re-usable extraction tube (SAMPLETEK) connected to a syringe. The extract was placed in the funnel for extraction for 1 hour. Approximately 60ml of the sample was extracted. The pH and electric conductivity (EC) was determined for the extracted solution using an electric pH meter (multi lab, model 540). After determining the pH and EC, 20ml of the extract was placed in a vial plus 1ml of 65% nitric acid, and then the concentration of cations were determined on the ICP-OES (Optical Emission Spectrometer) (Bower & Wilcox, 1965).

3.4 Greenhouse study

Two greenhouse experiments were conducted in order to investigate which natural soil and waste material will give optimal growth for different plant species. In the first greenhouse experiment, commercially-available radish (*Raphanus sativus*) plants were used as a bio-indicator for soil quality, while in the second greenhouse experiment, two indigenous plants namely *Juttadinteria albata* and *Cephalophyllum herrei* (Figure 8) were planted. *Juttadinteria albata* (focal species) was identified by Namibian Botanical Research Institute (NBRI) as species with narrow range, threatened, endemic and most of its significant population is going to be affected by mining at Sendelingsdrif. *Cephalophyllum herrei* was also identified as a second focal species, because of its dominance (i.e it is found growing in most of the habitats at Sendelingsdrif). The two experiments tested the same basic set of response variables, namely the response of plants (in terms of variables such as germination rate and growth rate) to different mixes of waste materials, natural soils and potting soil (as an indication of the fertility of the substrate). Two different watering regimes were employed for indigenous local plants and for radish. All the greenhouse experiments were run concurrently.

Figure 8. A picture illustrating three different plants species that were used in the greenhouse potting experiment at Sendelingsdrif.

For the purpose of this study, a greenhouse was constructed on site by NAMDED, to a standardized design. The greenhouse experiments commenced at the end of January 2013 and ran till December 2013. Two different types of natural soils were collected during the field work from the proto terraces; these were used as reference soils in the greenhouse experiment. The natural soils for the greenhouse experiment were collected from Proto terraces, because it is where most of the indigenous plants are growing and it was easier (in terms of distance) to access and carry them to the greenhouse. The first natural soil was excavated from an area where there was a high growth of indigenous plant species, while the second natural soil came from an area that was bare. Waste materials were collected from a heap stockpile available on site, specifically fine tailings (FT) and coarse tailings (CT). The tailings are stockpiled according to their size fractions with fine tailings referred to as all particles that were less or equal to 2mm (≤ 2 mm) and coarse tailing classified as all the particles between 2mm and 25mm respectively. Additionally, commercially available potting soil used in the greenhouse experiment was purchased at a general dealer in Oranjemund and was used as a reference substrate in addition to natural soils. Mixing of fine tailings and coarse tailings was done as a volume ratio using plastic pots (Figure 9).

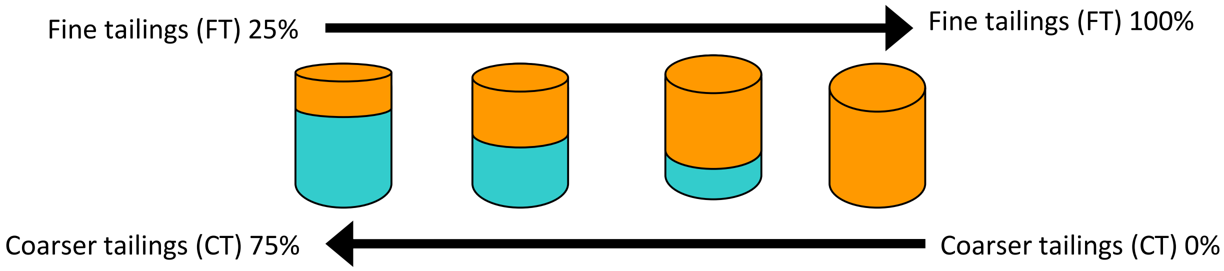

Figure 9. A diagram showing how the available fine tailings and coarse tailings were mixed in four volumetric ratios (FT 25%: CT75%, FT50%: CT50%, FT75%: CT25% and FT100: CT0%) that were used in the greenhouse potting experiment at Sendelingsdrif mine.

The greenhouse experiments were conducted with ten levels of substrate, namely natural soil 1, natural soil 2, potting soil and a number of mixes of different waste materials (7.5 fine [FT]: 2.5 coarse [CT], 1/2 FT: 1/2 CT, 2.5 FT: 7.5 CT), as well as 1/2 FT: 1/2 CT plus three different levels of Lucerne (3g [L1], 6g [L2] and 12g [L3]) and three plant species (*Raphanus sativus, Juttadinteria albata and Cephalophyllum herrei*). Each of the substrates had six replicates in total. Natural soils and potting soil were used as reference substrate to compare performance and the ability of different mixtures of post-mining wastes to support plant growth.

3.4.1 Experimental design

The greenhouse experiments followed a randomized block design (Weiss, 2008), to control spatial variation that might exist in terms of growing conditions (Figure 10). Ten substrates (treatment) were randomly placed in blocks, while plant species were used as blocks and the blocks where replicated three times. The experiment was conducted using 180 plastic pots (20.5 cm height, 25 cm diameter at the top and 17.5 cm diameter at the bottom).

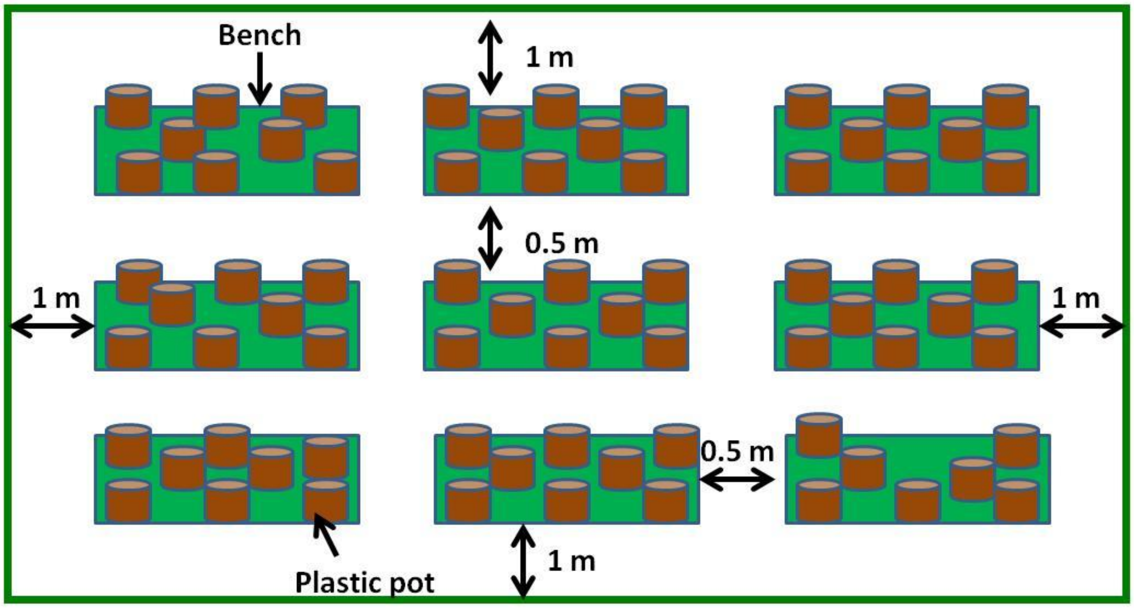

Figure 10. Illustration of a randomized block design of the greenhouse potting experiment which took place at Sendelingsdrif mine.

3.4.2 Experiment 1

In the first greenhouse experiment, the growth of radish (*Raphanus sativus*) was tested in ten different substrates as they are described in Figure 5. Radish was used as an indicator species for soil quality because radish is sensitive to soil properties (Mann & Schumann, 2010). In each pot, five seeds of radish were planted in each of the ten substrates. Radish was watered three times a week with 250 ml of water using a watering can till maturity and then it was harvested for biomass determination.

3.4.3 Experiment 2

In the second greenhouse experiment, the growth of *Juttadinteria albata* and *Cephalophyllum herrei* was tested in ten different substrates as described in Figure 5. *Juttadinteria albata* and *Cephalophyllum herrei* are local plants that were identified in the study area, with *J. albata* being a focus plant for the restoration project because of its limited range and the high level of threat it is experiencing as a result of mining. In 60 plastic pots as described under experimental design, 50 seeds of *J. albata* were planted in each pot in ten different substrates. For *C. herrei,* ten seeds were sown in each of the pots in ten different substrates using 60 plastic pots. Using a watering can, all indigenous plants and radish were watered three times a week with 500 ml till germination. After germination, frequency of watering was reduced to just once a week, to avoid over-watering and possible fungal infections. Mesembs such as *J. albata* are very sensitive to over-watering and they can easily drown or die (Burke & Mannheimer, 2004).

3.4.4 Greenhouse variables

Germination rate was expressed as the mean percentage of germinated seedlings per substrate. After the germination of radish, to prevent competitive effects from obscuring the soil effects, one healthy plant was selected from each pot, in order to collect height data over time that was later used to calculate growth rate of each plant. Radish was used as a standard indicator for substrate quality to support plant growth and development. This was adopted from Mann and Schumann (2010) who in a similar study, thinned out some radish plants leaving only one to few plants per pot to determine the potential of substrates in supporting plant growth. For indigenous plants, the selected plant (based on the height) was marked and the rest were left to let nature takes it course (no thinning was done). No thinning was done for local plants, because the current study was also interested in determining other population dynamics of local plants. Certain measurements such as plant height using a ruler, number of leaves, the stretched length of the longest leaf and the number of flower. The survival rate of plants was calculated as the number of pots out of the total per substrate containing a live, healthy plant at the end of the experiments.

4.4.5 Determining biomass

At the end of the greenhouse experiment 1, all the plant material for radish, namely leaves, shoots, stems, and roots, were harvested using a kitchen fork. During the harvesting of plants in each pot, excess sand was gently washed off the roots and the harvested material was placed in labelled brown paper bags. The biomass for local plants was not recorded because at the end of the greenhouse experiment local plants did not reach maturity (harvestable mass) due to their growth rate; therefore it was not possible to harvest them.

The fresh mass of the harvested plant material was recorded using a balance scale (precision electronic digital, 7250 model) in the laboratory at Daberas mine (a mine close to Sendelingsdrif). The weighed fresh plant material was then placed in a drying oven (GERMINI CORDOIL BLEU) at 60°c for 24 hours and the dry mass of plant material was recorded using a balance scale (Precision Electronic Digital, 7250 model).

3.5 Data analysis

In the present study, the following data were collected: for objective one; Infiltration rate, soil texture and rock cover was collected, for objective two; Total nitrogen, Copper, pH, Phosphorus, Potassium, Calcium carbonate, Organic matter, Organic carbon, Calcium, Iron, and Conductivity were determined, for objective three and four; germination rate and growth rate of plants were determined. The data for population dynamics for local plants were not obtained, because plants did not reach maturity and hence no data analysis was performed.

A Shapiro-Wilk test was used to test all data for normality (infiltration, rock cover, total nitrogen, Copper, pH, Phosphorus, Potassium, Calcium carbonate, Organic matter, Organic carbon, Calcium, Iron, Conductivity, germination rate, and growth rate) for normality (Dytham, 1999). Data that met all assumptions of normality, for example soil properties of natural soils and different mixtures of waste materials, were compared using a one way analysis of variance (ANOVA) (Zar, 1999). Data that did not meet the assumptions of normality were tested using non-parametric tests such as Kruskall-Wallis and Chi-square. The Tukey HSD was used as post-hoc test to reveal where the major difference were between the groups of means that were being compared. Backward selection was performed in R statistical program using linear model in order to see which of the predictable factors influenced the response variables. All statistical tests were performed using the statistical package SPSS (Field, 2009), R Statistical program (Im-R version 2.8.0) and Statistica 7 (Statsoft Inc., 1985-2005).

3.6 Outcomes of normality tests

The outcome of normality test for all the variables are presented in table 1 below.

Table 1. Normality test (Shapiro-Wilk test) for physical and chemical soil properties, and growth of plants in the greenhouse.

Variable	**D**	**P-value**	**Distribution normal or non-normal**
Infiltration rate in field	0.205	P < 0.001	Non-normal
Infiltration rate in greenhouse	0.106	0.046	Non-normal
Percentage rock cover	0.077	0.200	Normal
Total nitrogen	0.092	0.200	Normal
Copper	0.117	0.161	Normal
pH	0.113	0.199	Normal
Phosphorus	0.111	0.200	Normal
Potassium	0.115	0.181	Normal
Calcium carbonate	0.157	0.010	Non-normal
Organic carbon	0.315	P < 0.001	Non-normal
Organic matter	0.324	P < 0.001	Non-normal
Calcium	0.200	P < 0.001	Non-normal
Iron	0.155	0.011	Non-normal
Conductivity	0.319	P < 0.001	Non-normal

Germination rate of radish	0.260	P < 0.001	Non-normal
Germination rate of *C. herrei*	0.226	P < 0.001	Non-normal
Germination rate of *J. albata*	0.119	0.200	Normal
Growth rate of radish	0.776	P < 0.001	Normal
Growth rate of *C. herrei*	0.104	P < 0.001	Normal
Growth rate of *J. albata*	0.107	P < 0.001	Normal

Chapter 4

Results

In the current study, the natural habitats are plotted on the figure based on their position in the study area in relation to the Orange River (Lower terraces being close to the river and Shallow soil on ridges being far from the river).

4.1 Soil physical properties

4.1.1 Water infiltration rate

Water infiltration rate of seven habitats and post-mining substrates in the study area is presented in Figure 11. There was no significance difference in infiltration of water amongst habitats in the study area (Kruskal-Wallis: H = 8.24, df = 6, P = 0.22) (Figure 11). However, there was a significant difference in infiltration rate between natural soils and post-mining substrates that were used in the greenhouse experiment (Kruskal-Wallis: H = 48.15, df = 9, P =0.001). The infiltration rate in natural soil two (NS2) and potting soil (PS) used in the greenhouse differed significantly from that of FT1/2:CT1/2+L1 and FT7.5:2.5CT (multiple comparison post hoc test, $P < 0.05$).

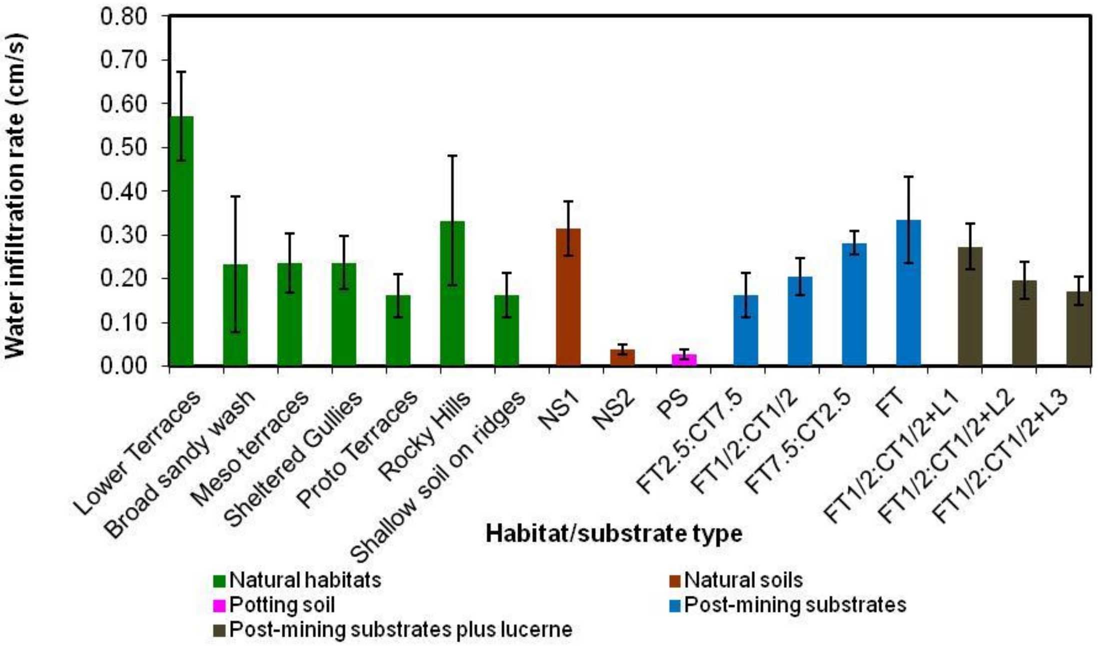

Figure 11. Water infiltration rate (cm/s) in natural habitats, natural soils (NS1 and NS2), potting soil (PS) and post-mining wastes (Fine Tailings (FT)/ Coarse Tailings (CT) plus Lucerne (L) of different ratios) at Sendelingsdrif mine. Error bars denote 95% confidence interval level.

4.1.2 Rockiness

Percentage rock cover of seven natural habitats in the study is presented in Figure 12. There was a significant difference in the percentage rock cover between habitats (ONE WAY ANOVA: df = 6, F = 3.35, P = 0.006) (Figure 12). The percent rock cover on sheltered gullies was significantly higher than that of shallow soil on ridges (Tukey HSD test, $P < 0.05$).

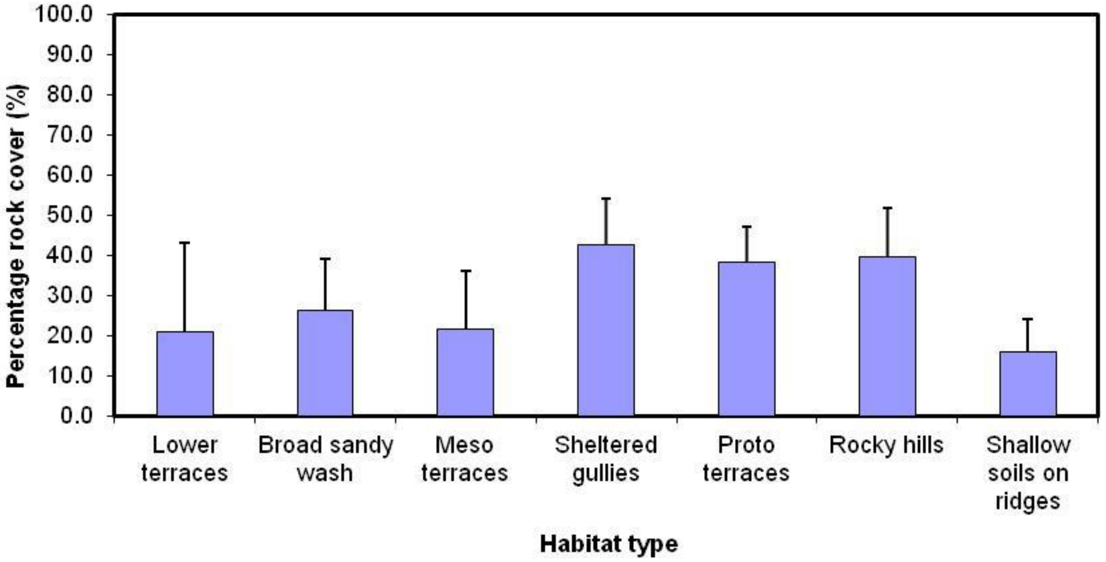

Figure 12. Percentage (%) rock cover in seven different habitat types at Sendelingsdrif mine. Error bars denote 95% confidence interval level.

4.1.3 Soil texture

The particle soil analysis was performed on 70 soil samples (from natural soils and post mining substrate) from the study area. The laboratory analysis (particle size analysis) revealed that the most dominant soil type at Sendelingsdrif was sand while sandy loam was the least dominant soil type in all the habitats (Table 2). Results in Table 2 further revealed that natural soil types that were used in the experiment were mainly sandy and sandy loam while the post-mining substrates consisted of sand only.

Table 2. The comparison of soil types (based on particle analysis at Analytical Laboratory services) between natural soil and post-mining substrates used in the greenhouse experiment.

Type of substrate	**Soil types**						
	Clay loam	**Sand**	**Loamy sand**	**Sandy loam**	**Loam**	**Silt loam**	**Sandy clay loam**
Natural soils (Natural habitats)	Absent	Present	Absent	Present	Absent	Absent	Absent
Post-mining substrates	Absent	Present	Absent	Absent	Absent	Absent	Absent

4.2 Soil chemical properties

4.2.1 Soil pH

The pH of 70 soil samples from the study area ranged from 7.6 (meso terrace) to 8.0 (lower terrace). The pH of the soil from the 7 habitats in the study area is presented in Figure 13. Statistical analysis revealed that there was no significant difference in pH of soils amongst the 7 habitats sampled in the present study (ONE WAY ANOVA: F = 1.82, df = 6, P = 0.12). The linear model outcome revealed that in the present study there is no factor or variable that is affecting pH in the study area.

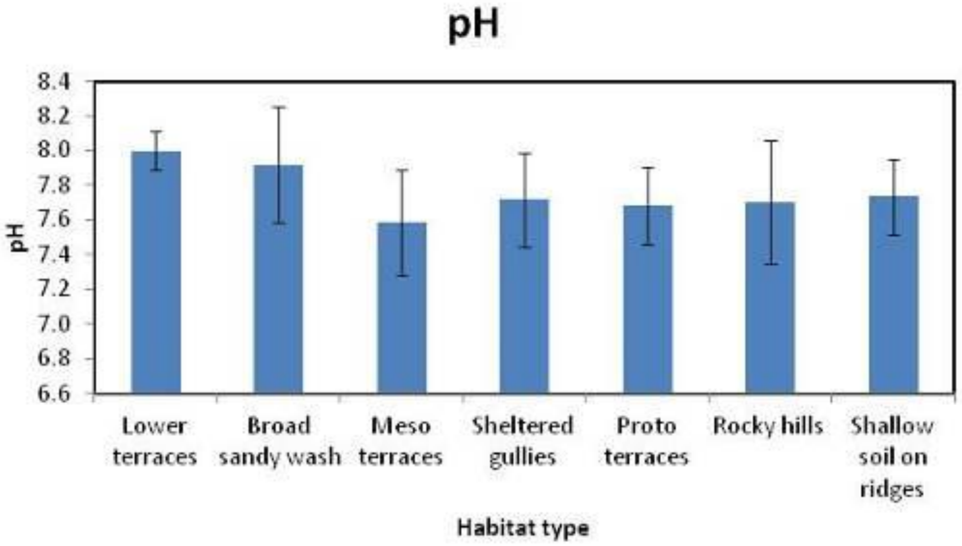

Figure 13. pH of the soils sampled from seven different habitats at Sendelingsdrif. Error bars denote 95% confidence interval level.

4.2.2 Soil total nitrogen content

In the present study the total nitrogen content of 70 soil samples ranged from 164 mg N/kg (rocky hills) to 401 (shallow soil on ridges) mg N/kg. Figure 14 illustrates total nitrogen (mg N/kg) in seven different habitats at Sendelingsdrif. There was no significant difference in the total nitrogen amongst the 7 habitats (ONE WAY ANOVA: F = 2.05, df = 6, P = 0.08). The linear model outcome revealed that in the present study the content of total nitrogen in the soil was influenced by habitat type ($F_{6, 33} = 2.88$, P = 0.02), organic matter ($F_{1, 33} = 10.78$, P = 0.002), phosphorus ($F_{1, 33} = 4.76$, P = 0.04) and potassium ($F_{1, 33} = 4.41$, P = 0.04).

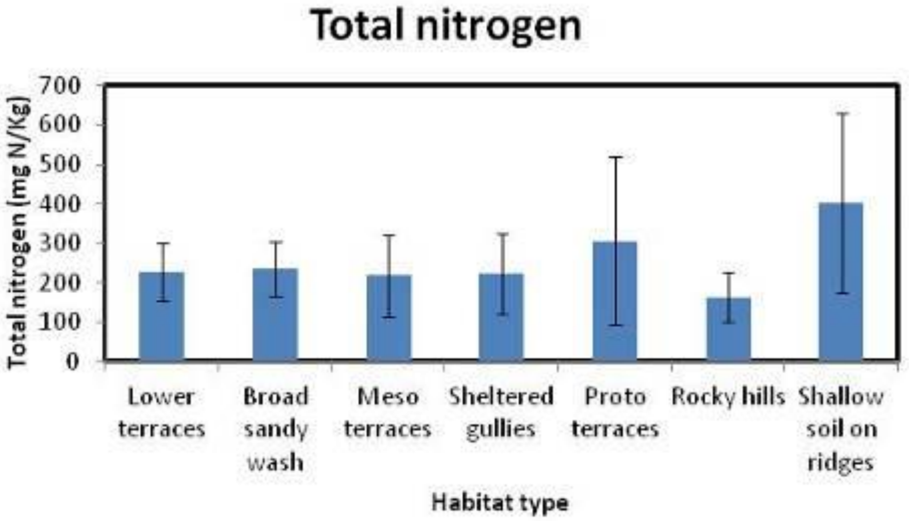

Figure 14. The total nitrogen (mg N/kg) in soils from seven different habitats at Sendelingsdrif. Error bars denote 95% confidence interval level.

4.2.3 Soil Organic Matter

The soil organic matter (SOM) content of 70 soil samples from the study area ranged from 0.02-0.16% m/m organic matter (OM) (Figure 15). There was no significant difference in the content of organic matter in soils sampled from the 7 different habitats in the present study (Kruskal-Wallis: $H = 7.51$, $df = 6$, $P = 0.28$). The linear model outcome revealed that in the present study the content of soil organic matter was significantly influenced by habitat type ($F_{6, 28} = 75.87$, $P < 0.001$), total nitrogen ($F_{1, 28} = 319.41$, $P < 0.001$) , calcium carbonate ($F_{1, 28} = 4.53$, $P = 0.04$), phosphorus ($F_{1, 28} = 43.54$, $P < 0.001$), calcium ($F_{1, 28} = 70.89$, $P < 0.001$), potassium ($F_{1, 28} = 51.59$, $P < 0.001$) , iron ($F_{1, 28} = 51.79$, $P < 0.001$), pH ($F_{1, 28} = 13.10$, $P = 0.001$) and organic carbon ($F_{1, 28} = 985.51$, $P < 0.001$).

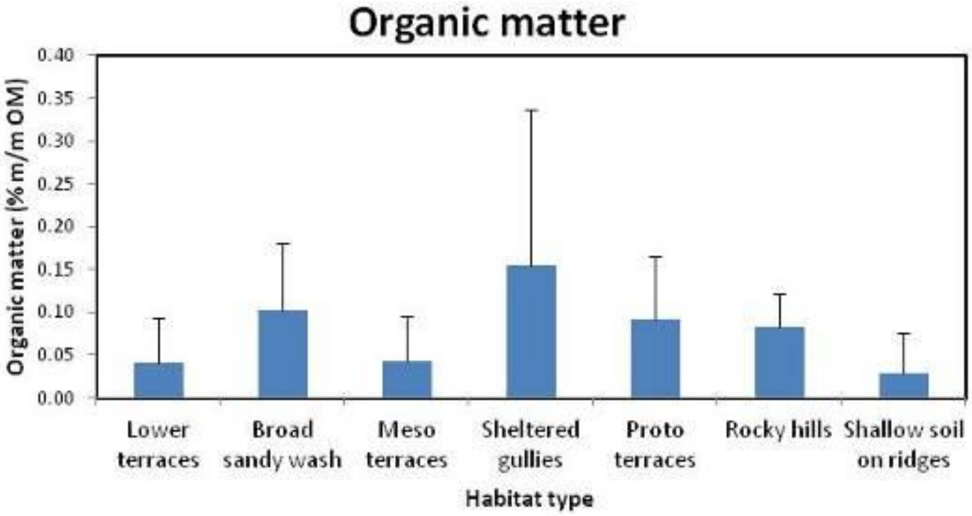

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Figure 15. Percentage (%) SOM in soils from seven different habitats at Sendelingsdrif. Error bars denote 95% confidence interval level.

4.2.4 Soil Organic Carbon

The organic carbon (C) content of 70 soil samples from the study area ranged from 0.02 (shallow soil on ridges) to 0.09 (sheltered gullies) %m/m C (Figure 16). There was no significant difference in the content of organic carbon in soils sampled from the 7 different habitats in the present study (Kruskal-Wallis: H = 7.86, df = 6, P = 0.25). The linear model outcome revealed that the content of organic carbon in the soil was influenced by habitat type ($F_{6, 35} = 61.04$, $P < 0.001$) and organic matter ($F_{1, 35} = 1197.48$, $P < 0.001$).

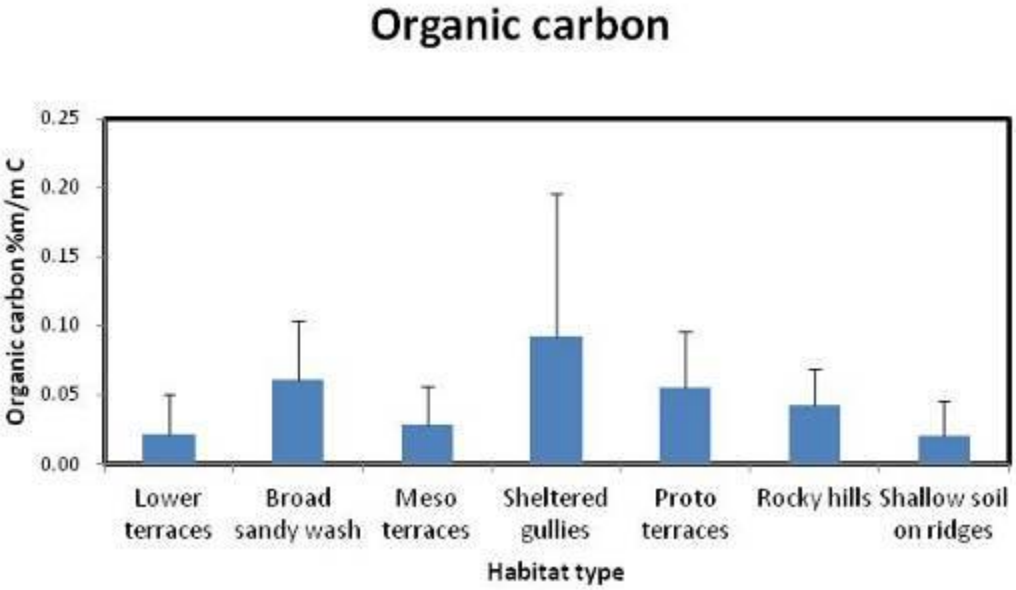

Figure 16. Content of organic carbon (% m/m C) in soils from seven different habitats at Sendelingsdrif. Error bars denote 95% confidence interval level.

4.2.5 Soil Calcium carbonate

Calcium carbonate content of 70 soil samples from the study area ranged from 0.4% (meso tarrace) to 3.5% (broad sandy wash) as presented in Figure 17. There was a significant difference in the percentage calcium carbonate amongst habitats in the study area (Kruskal-Wallis: H = 21.13, df = 6, P = 0.02). Post Hoc Test (Multiple comparison post hoc test, $P < 0.05$) revealed that Calcium carbonate content in broad sandy wash and meso terraces was significantly higher than in the lower terraces. The linear model outcome revealed that in the present study the content of calcium carbonate in the soil was significantly influenced by habitat type ($F_{6, 36} = 6.28$, $P < 0.001$).

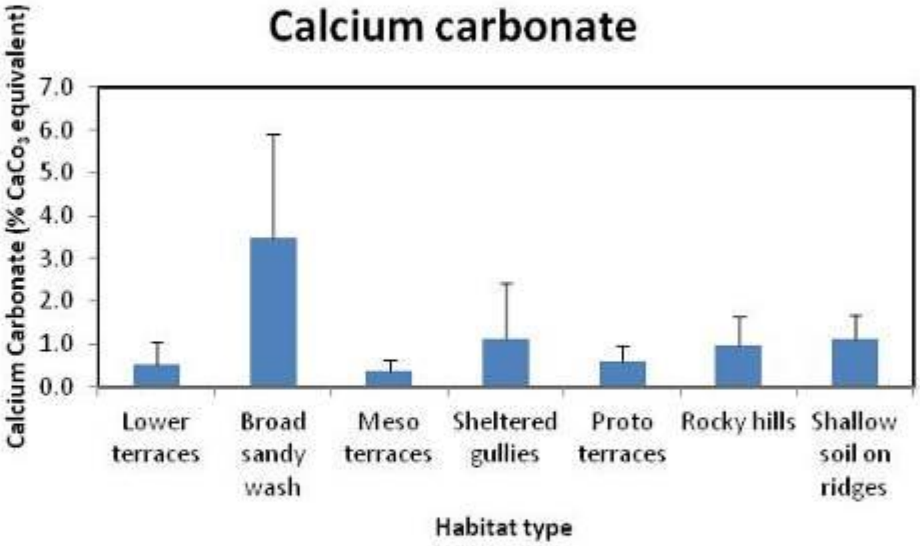

Figure 17. Calcium carbonate equivalent (% $CaCo_3$ equivalent) in soils from seven different habitats at Sendelingsdrif. Error bars denote 95% confidence interval level.

4.2.6 Soil Phosphorous

The phosphorus content of 70 soil samples from the study area ranged from 3.65 (broad sandy wash) to 5.26 (proto terrace, rocky hills and shallow soil on ridges) mg/kg (Figure 18). There was no significant difference in the content of phosphorus in soils sampled from the 7 different habitats in the present study (ONE WAY ANOVA: F = 0.35, df = 6, P = 0.91). The linear model outcome revealed that in the present study the content of phosphorus in the soil was not significantly influenced by any variable (pH, total nitrogen, calcium carbonate, organic matter, organic carbon, potassium, calcium, copper, and iron).

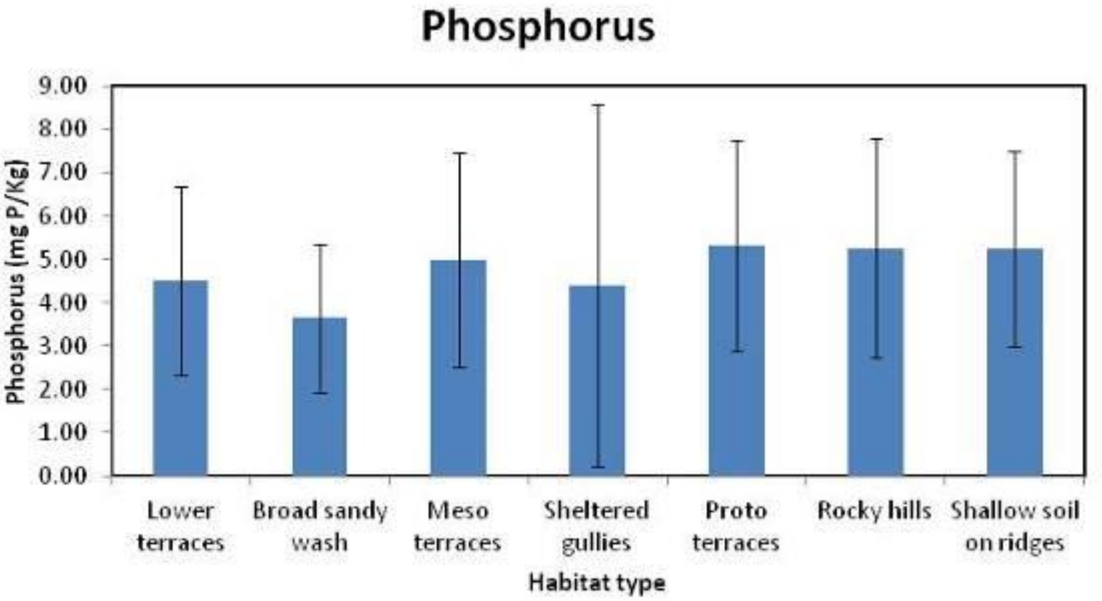

Figure 18. Content of phosphorus (mg P/kg) in soils from 7 different habitats at Sendelingsdrif. Error bars denote 95% confidence interval level.

4.2.7 Soil Potassium

The potassium content of 70 soil samples from the study area ranged from 65 to 108 mg/kg as presented in Figure 19. There was a significant difference in the levels of potassium in soils sampled from the 7 different habitats in the present study (ONE WAY ANOVA: F = 2.56, df = 6, P =0.04). The potassium content in proto terraces was significantly higher than in Shallow soil on ridges (Tukey HSD post hoc test, $P < 0.05$). The linear model outcome revealed that in the present study the content of potassium in the soil was influenced by habitat type ($F_{1, 33} = 4.70$, P = 0.001), organic matter ($F_{1, 33} = 10.54$, P = 0.003), phosphorus ($F_{1, 33} = 4.96$, P = 0.03) and copper ($F_{1, 28} = 17.72$, $P < 0.001$).

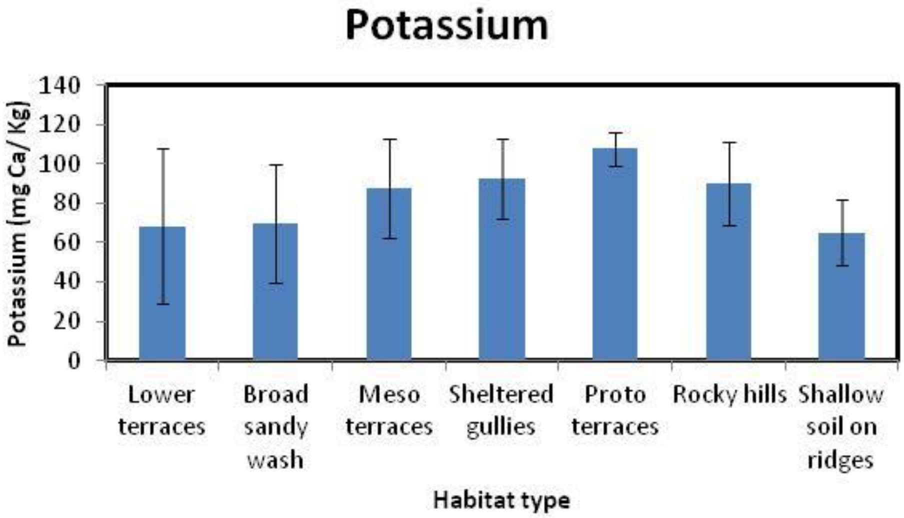

Figure 19. Showing the levels of potassium (mg K/kg) in soils from seven different habitats at Sendelingsdrif. Error bars denote 95% confidence interval level.

4.2.8 Soil Calcium

Figure 20 presents the calcium content of 70 soil samples from the study area which ranged from 2326 (lower terrace) to 16951 (shallow soil on ridges) mg/kg. There was no significant difference in the levels of calcium in soils sampled from the 7 different habitats in the present study (Kruskal-Wallis: H = 12.41, df = 6, P =0.05). The linear model outcome revealed that in the present study the content of calcium in the soil was significantly influenced by habitat type ($F_{6, 35} = 8.98$, $P < 0.001$), organic matter ($F_{1, 35} = 11.78$, $P = 0.002$), iron ($F_{1, 35} = 38.70$, $P < 0.001$) and calcium carbonate ($F_{1, 35} = 12.79$, $P = 0.001$).

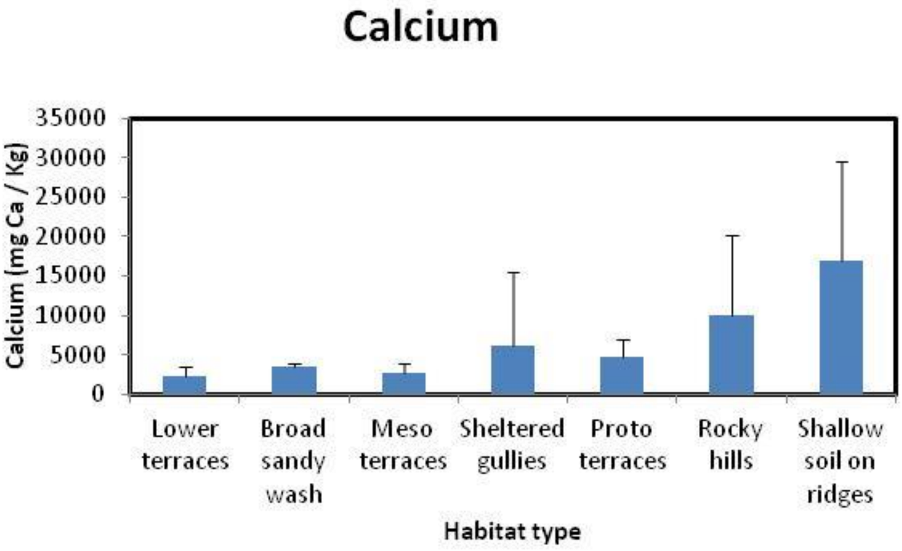

Figure 20. Content of calcium (mg Ca/kg) in soils from seven different habitats at Sendelingsdrif. Error bars denote 95% confidence interval level.

4.2.9 Soil Copper

The Copper content of 70 soil samples from the study area ranged from 0.3 to 1.4 mg/kg (Figure 21). ONE WAY ANOVA revealed that there was a significant difference in the content of copper in soils sampled from the 7 different habitats in the present study (ANOVA: F = 3.02, df = 6, P=0.017). The content of copper level in proto terraces was significantly higher than copper levels in shallow soil on ridges (Tukey HSD post hoc test, $P < 0.05$). The linear model outcome revealed that in the present study the content of copper in the soil was significantly influenced by habitat type ($F_{6, 33} = 9.47$, $P < 0.001$), phosphorus ($F_{1, 33} = 15.02$, $P < 0.001$) and potassium ($F_{1, 33} = 17.72$, $P < 0.001$).

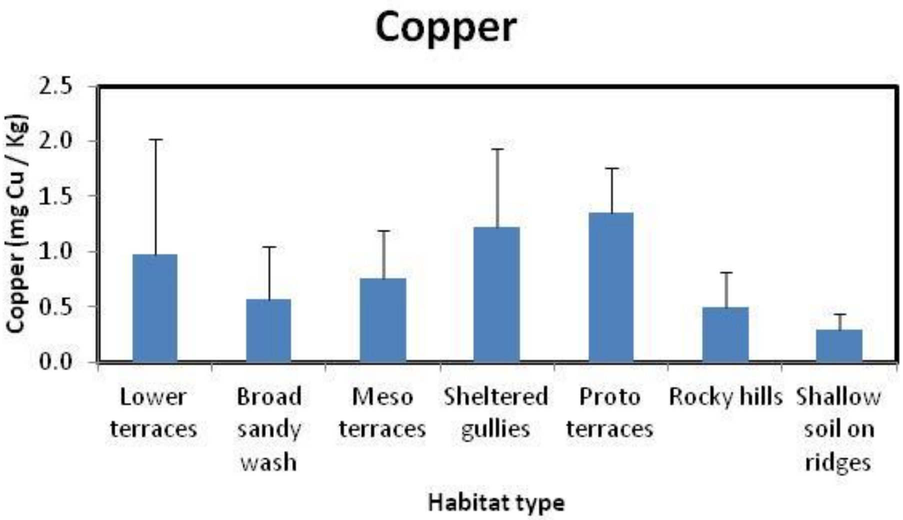

Figure 21. Content of copper (mg Cu/kg) in soils at seven different habitats at Sendelingsdrif. Error bars denote 95% confidence interval level.

4.2.10 Soil Iron

The iron content of 70 soil samples from seven different habitats in the study area is presented in Figure 22. The iron content ranged from 19 mg/kg (proto terrace) to 152 (rocky hills) mg/kg and was significant difference amongst habitats (Kruskal-Wallis: H = 17.89, df = 6, P =0.01). Further analysis revealed that the content of iron in rocky hills was significantly higher than that found in proto terraces (multiple comparison post hoc test, $P < 0.05$). The linear model outcome revealed that in the present study the content of iron in the soil was significantly influenced by habitat type ($F_{6, 34} = 7.27$, $P < 0.001$), conductivity ($F_{1, 34} = 4.39$, $P = 0.04$) and calcium ($F_{1, 34} = 32.79$, $P < 0.001$).

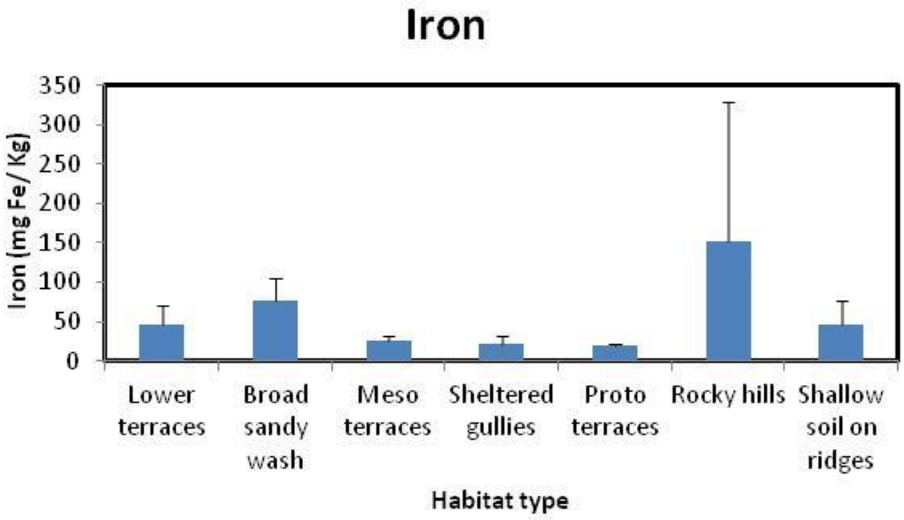

Figure 22. Content of iron (mg Fe/kg) in soils from seven different habitats at Sendelingsdrif. Error bars denote 95% confidence interval level.

4.2.11 Electrical conductivity

The electrical conductivity of 70 soil samples from seven different habitats (presented in Figure 23) in the study area ranged from 124 mS/m to 1,232 mS/m. A Kruskal-Wallis test revealed that there was a significant difference in electrical conductivity amongst different soils from seven habitats ($H = 16.59$, $df = 6$, $P = 0.01$). The electric conductivity was significantly higher in the shallow soil on ridges than in the lower terraces (multiple comparison post hoc test, $P < 0.05$). The linear model outcome revealed that the electrical conductivity of the soil was significantly influenced by habitat type ($F_{6, 36} = 2.94$, $P = 0.02$)

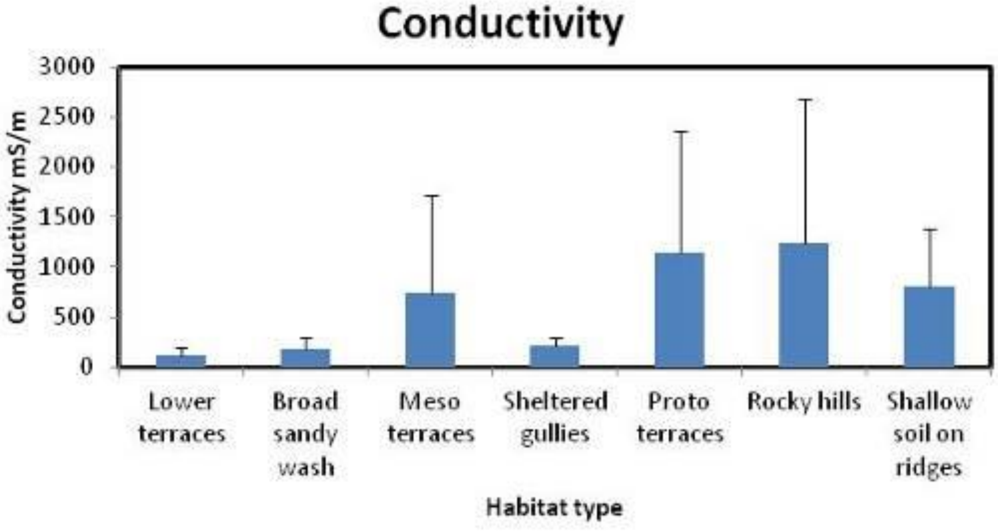

Figure 23. Electrical conductivity (mS/m) of soils in seven different habitats at Sendelingsdrif. Error bars denote 95% confidence interval level.

4.3 Chemical properties of post-mining substrates

The chemical properties of fine tailings, natural soils and post-mining waste are presented in Table 3. The comparison made between natural soils and post-mining substrates used in the greenhouse experiment are primarily subjective because no statistical tests were carried out. Moreover, the present study only had one heap of mining wastes to work with, which made it difficult to replicate the number of samples that were sent for analysis. It is evident from Table 3 that the fine tailings had low total nitrogen, low organic matter, low organic carbon, low phosphorus, low potassium and low conductivity compare to natural and potting soil. Additionally, fine tailings had exceptionally high calcium content compare to all other substrates.

Table 3. Chemical properties of a single sample of post-mining substrate (fine tailings), natural soil one and two (NS1 & NS2) and the potting soil that were used in the greenhouse experiment at Sendelingsdrif mine and no means were computed, because there was no replication.

	Substrate type			
Chemical properties	**Fine tailings**	**Natural soil one**	**Natural soil two**	**Potting soil**
pH	7.7	7.5	7.5	7.7
Total nitrogen (mg N/kg)	115	402	258	3310
Calcium carbonate (% $CaCo_3$ equivalent)	0.9	0.5	0.4	0.5
Organic matter (% m/m OM)	<0.1	0.2	<0.1	17.2*
Organic carbon (% m/m C)	<0.1	0.1	<0.1	---
Phosphorus (mg P/kg)	3	4	4	201
Potassium (mg K/kg)	6	65	61	1745
Calcium (mg Ca/kg)	26083	7463	7093	2273
Copper (mg Cu/kg)	0.2	1.4	1.4	3.1
Iron (mg Fe/kg)	7.4	18	19	251
Conductivity (mS/m)	479	1812	1539	1197

4.4 Greenhouse experiment

4.4.1 Germination rate

The germination of radish was tested across ten substrates in the greenhouse experiment at Sendelingsdrif mine. There was no significant difference in the percentage germination of radish sown on natural soils, potting soils, post-mining substrates and post mining substrates mixed with lucerne ((Kruskal-Wallis: H = 11.72, df = 9, P =0.23) (Figure 24).

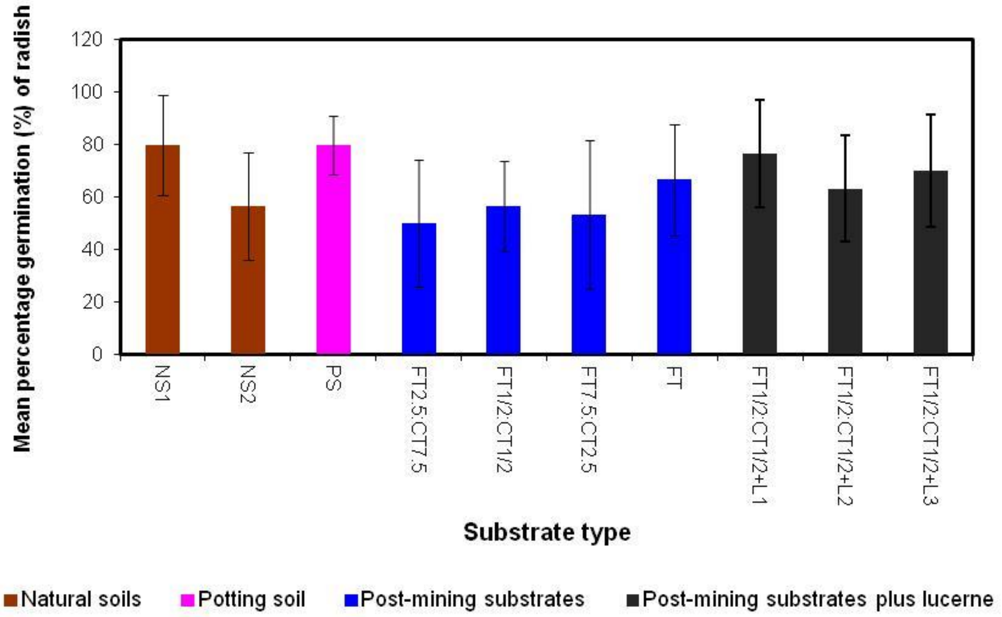

Figure 24. Percentage (%) germination of Radish in various mixes of post-mining substrates (FT = Fine tailings & CT = Coarse tailings), post-mining substrates plus Lucerne (L1-L3), potting soil (PS) and Natural soils (NS1 & NS2) at Sendelingsdrif mine**.** Error bars denote 95% confidence interval level.

The germination of *Juttadinteria albata* was tested across ten substrates in the greenhouse experiment at Sendelingsdrif mine. Figure 25 shows the mean percentage germination of *J. albata* in various substrates. There was a significant difference in the mean percentage germination of *J. albata* across ten substrates (ONE WAY ANOVA: df = 9, F = 6.55, $P < 0.001$). Further analysis revealed that the mean percentage germination of *J. albata* in natural soil one (NS1) differed significantly from that of the rest of the substrates used in the greenhouse (Tukey HSD post hoc test, $P < 0.05$) (Figure 25). Moreover, the mean percentage germination in natural soil two (NS2), fine tailings (FT) and FT7.5: CT2.5 also differed significantly from that of the post-mining substrate mixture of FT2.5: CT7.5 (Tukey HSD post hoc test, $P < 0.05$).

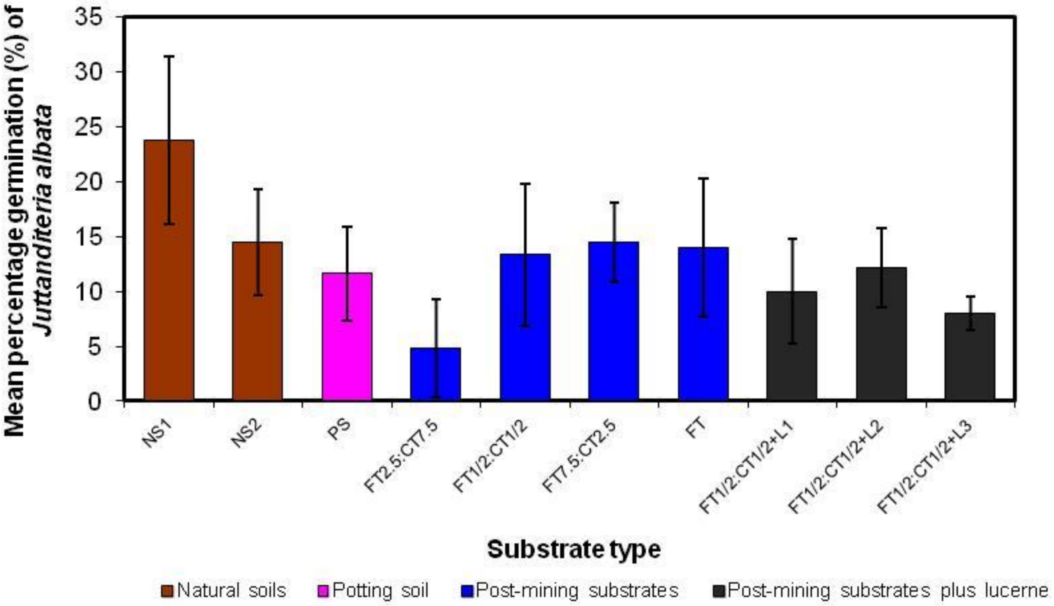

Figure 25. Mean percentage (%) germination of *Juttadinteria albata* in various mixes of post-mining substrates (FT = Fine tailings & CT = Coarse tailings), post-mining substrates plus lucerne (L 1-L3), potting soil (PS) and Natural soils at Sendelingsdrif mine. Error bars denote 95% confidence interval level.

The germination of *Cephallophyllum herrei* was tested across ten substrates in the greenhouse experiment at Sendelingsdrif mine (Figure 26). There was a significant difference in the mean percentage germination of *C. herrei* across ten different substrates (Kruskal-Wallis: $H = 35.56$, df $= 9$, $P < 0.001$). The mean percentage germination of *C. herrei* differed significantly in natural soil one (NS1) and two (NS2) from that of the FT2.5: CT 7.5 and FT1/2: CT1/2+L3 (multiple comparison post hoc test, $P < 0.05$).

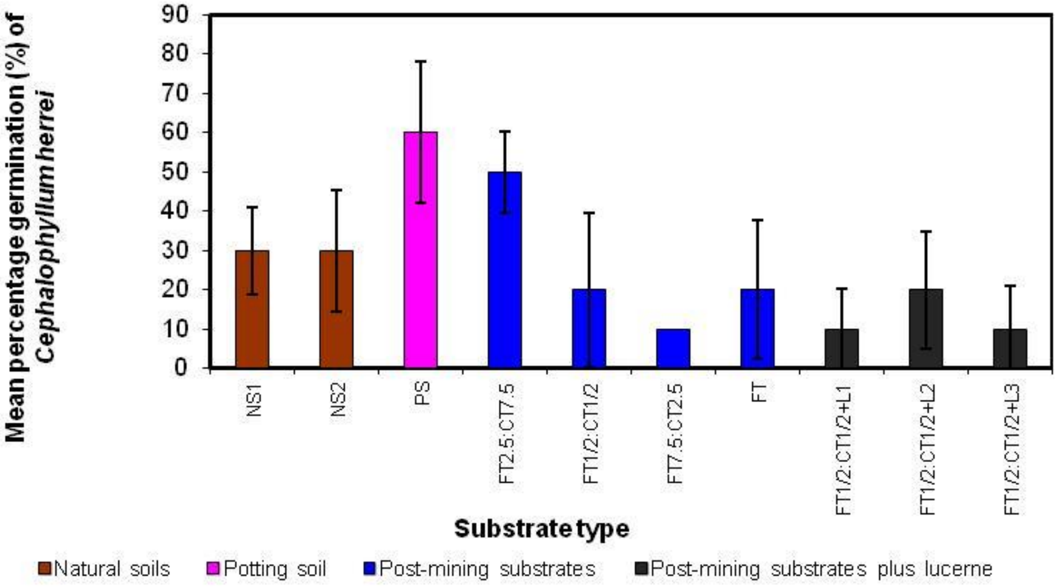

Figure 26. Percentage (%) germination of *Cephalophyllum herrei* in various mixes of post-mining substrates (FT = Fine tailings & CT = Coarse tailings), post-mining substrates plus Lucerne (L1-L3), potting soil (PS) and Natural soils (NS1 & NS2) at Sendelingsdrif mine. Error bars denote 95% confidence interval level.

4.4.2 Growth in plants

4.4.2.1 Change in height of plants over time

A growth curve was obtained by plotting the mean height of radish, *J. albata* and *C. herrei* plants as a function of time. The growth of plants was compared across ten different substrates in order to find out which substrate gives the optimum growth of radish, *J. albata* and *C. herrei*.

Figure 27 shows the change in the mean height of radish in various substrates in the greenhouse. There was a significant difference in the height of radish across ten substrates (ONE WAY ANOVA: $F = 31.31$, $df = 9$, $P < 0.001$). The growth (change in mean height) of radish in FT1/2:CT1/2+L3 significantly differed from that of the rest of substrates used in the greenhouse in exception of the natural soils (NS1 & NS2) (Tukey HSD post hoc, $P < 0.05$).

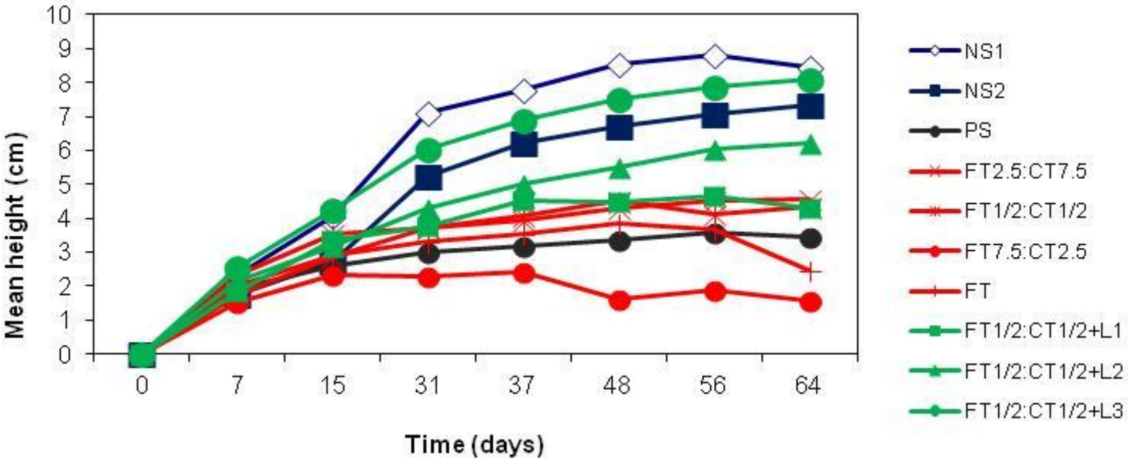

Figure 27. Growth (change in mean height in cm) of radish (*Raphanus sativa*) obtained by plotting the mean height (cm) of radish over a period of 64 days. Radish was grown on various mixes of post-mining substrates, post-mining substrates plus Lucerne (L1-L3), potting soil (PS) and Natural soils (NS1 & NS2) in a greenhouse at Sendelingsdrif mine.

Figure 28 shows the change in height of *J. albata* in various substrates in the greenhouse. There was a significant difference in the height of *J. albata* across ten substrates (ONE WAY ANOVA: df = 9, F = 17.18, P < 0.001). Post Hoc test (Tukey HSD, P < 0.001) revealed that the change in mean height of *J. albata* in natural soil (NS1) differed significantly from that of the rest of the substrates used in the greenhouse in exception of natural soil two (NS2), FT1/2:CT1/2+L2 and FT1/2:CT1/2+L3. The change in mean height of *J. albata* in natural soil two (NS2), FT1/2:CT1/2+L2 and FT1/2:CT1/2+L3 also showed similar growth as that in natural soil one (NS1). Moreover, the growth of *J. albata* in potting soil (PS) differed significantly from the rest of the substrates in the greenhouse.

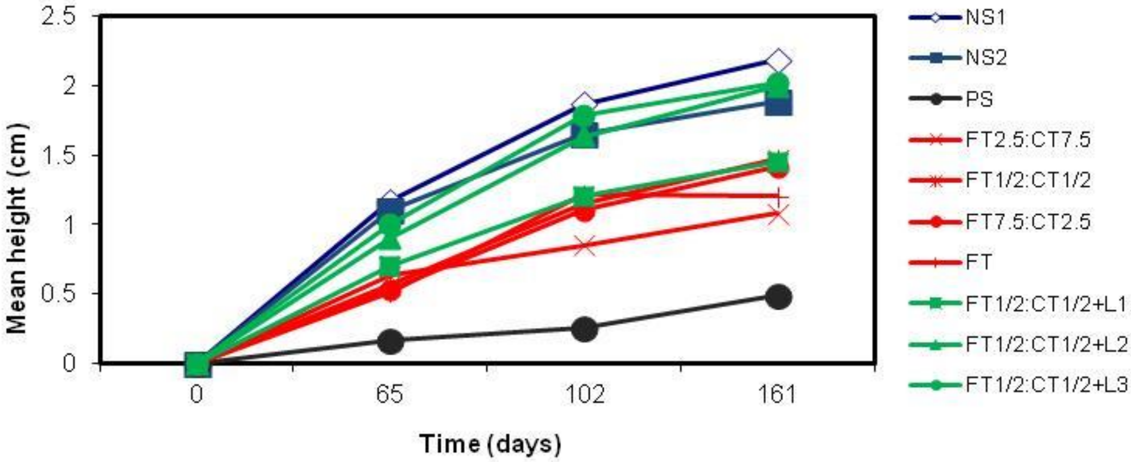

Figure 28. Growth (change in mean height in cm) of *Juttadinteria albata* obtained by plotting the mean height (cm) of *J. albata* over a period of 161days. *Juttadinteria albata* was grown on various mixes of post-mining substrates, post-mining substrates plus Lucerne (L1-L3), potting soil (PS) and Natural soils (NS1 & NS2) in a greenhouse at Sendelingsdrif mine.

The growth (change in mean height) for *C. herrei* is presented in Figure 29. There was a significant difference in the mean height of *C. herrei* across ten substrates (ONE WAY ANOVA: df = 9, F = 15.50, $P < 0.001$). The Tukey HSD test ($P < 0.05$) revealed that the mean height of *C. herrei* in natural soils (NS1 & NS2) differed significantly to that of the rest of the substrates used in the greenhouse (Post Hoc test). Moreover, the mean height of *C. herrei* in FT1/2:CT1/2+L2 differed significantly from that of FT2.5:CT7.5 and FT1/2:CT1/2.

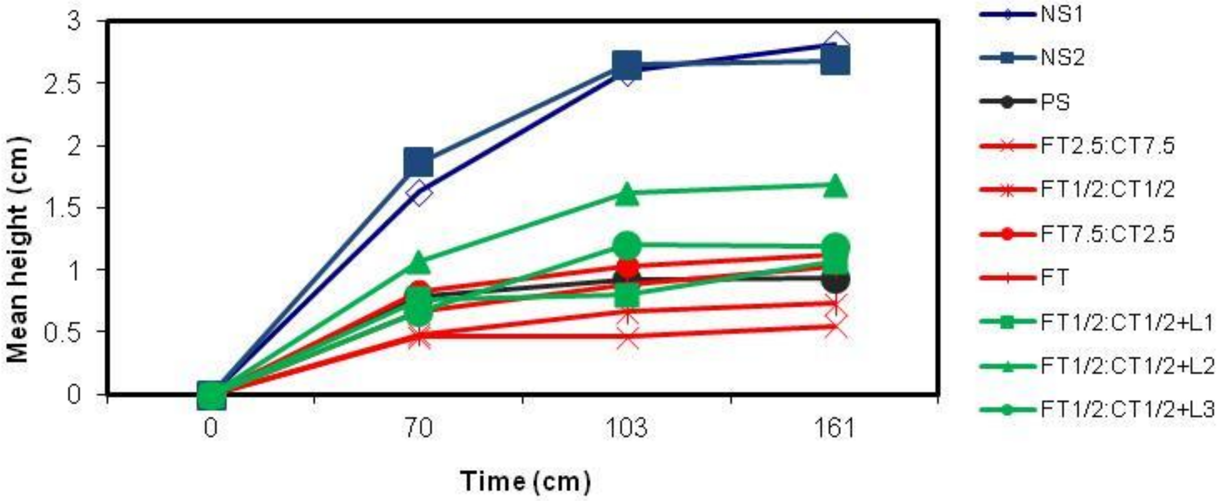

Figure 29. Growth curve of *Cephalophyllum herrei* obtained by plotting the mean height (cm) of *C. herrei* over a period of 161days. *Cephalophyllum herrei* was grown on various mixes of post-mining substrates, post-mining substrates plus Lucerne (L1-L3), potting soil (PS) and Natural soils (NS1 & NS2) in a greenhouse at Sendelingsdrif mine.

4.4.2.2 Growth rate curves

The growth rate of radish is presented in Figure 30. There was no significant difference in the growth rate of plants in all treatments by day 7 (ONE WAY ANOVA: F = 1.37, df = 9, P = 0.23). There was a significant difference in the growth rate of plants across ten substrates by day 15 (ONE WAY ANOVA: F = 3.36, df = 9, P = 0.003). The post hoc test revealed that the growth rate of the plants (day 15) in FT1/2:CT1/2+L3 and NS1 differed significantly from that of the plants grown in PS and FT7.5:CT2.5 (Tukey HSD, $P < 0.05$). The test also showed that the growth rate of plants in NS1 differed significantly from that of NS2. There was a significant difference in the growth rate of plants across ten substrates by day 31 (ONE WAY ANOVA: F = 15.33, df = 9, P < 0.001). The post hoc test revealed that the growth rate of plants in NS1 differed significantly from the rest of the substrates that were used in the greenhouse in exception of FT1/2:CT1/2+L3 (Tukey HSD, P < 0.05). The growth rate of plants in FT1/2:CT1/2+L3 also differed significantly (Tukey HSD, P < 0.05) from the rest of substrates in exception of the natural soils (NS1 & NS2) and FT1/2:CT1/2+L2. Furthermore, the test revealed that the growth rate of plants in NS2 differed significantly from that of the FT, PS, NS1 and FT7.5:CT2.5.

There was a significant difference in the growth rate of plants across ten substrates by day 37 (ONE WAY ANOVA: F = 21.27, df = 9, P < 0.001). Post hoc test revealed that the growth rate of plants in natural soils (NS1 & NS2) and FT1/2:CT1/2+L3 differed significantly from that of the rest of the substrates used in the greenhouse (Tukey HSD, P < 0.05). There was a significant difference in the growth rate of plants across ten substrates by day 48 (ONE WAY ANOVA: F = 18.67, df = 9, P < 0.05). Post hoc test revealed that the growth rate of plants in NS1 differed significantly from that of the rest of the substrates in exception of the NS2 and FT1/2:CT1/2+L3. The test also revealed that the growth rate of plants in NS2 differed significantly from that of the FT, PS, FT7.5:CT2.5, FT2.5:CT7.5, and FT1/2:CT1/2+L1 (Tukey HSD, P < 0.05).

There was a significant difference in the growth rate of plants across ten substrates by day 56 (ONE WAY ANOVA: F = 13.48, df = 9, P < 0.001). The post hoc test revealed that the growth rate of plants in natural soils (NS1 & NS2) and FT1/2:CT1/2+L3 differed significantly from that of the rest of the substrates used in the greenhouse (Tukey HSD, P < 0.05). There was a significant difference in the growth rate of plants across ten substrates by day 64 (ONE WAY ANOVA: F = 12.53, df = 9, P < 0.001). Tukey HSD post hoc test revealed that the growth rate of plants in NS1, FT1/2:CT1/2+L2 and FT1/2:CT1/2+L3 differed significantly from the rest of the substrates used in the greenhouse in exception of NS2 (P < 0.05).

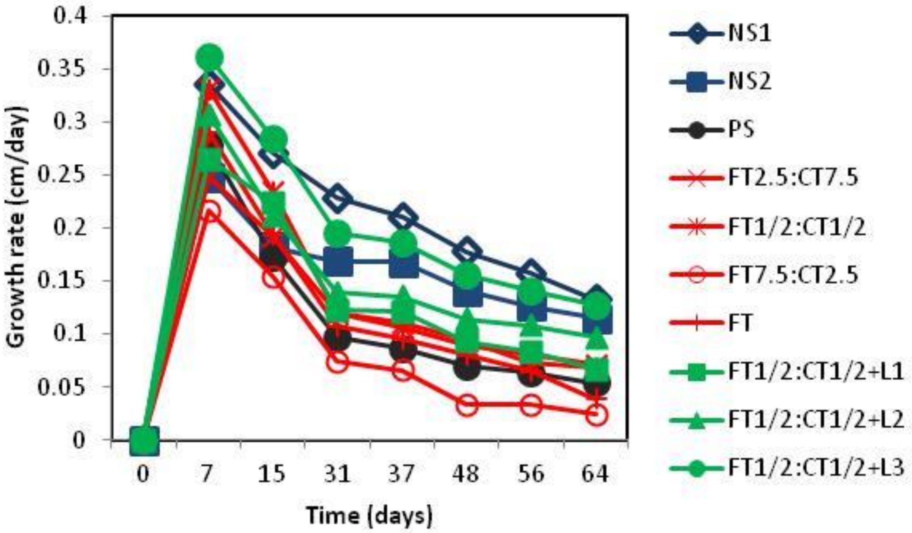

Figure 30. The growth rate (cm/day) of radish plants for 64 days. Radish was grown on various mixes of post-mining substrates, post-mining substrates plus Lucerne (L1-L3), potting soil (PS) and Natural soils (NS1 & NS2) in a greenhouse at Sendelingsdrif mine.

Figure 31 shows the growth rate of *J. albata* in various substrates. There was a significant difference in the growth rate of plants across ten substrate by day 65 (ONE WAY ANOVA: F = 16.87, df = 9, P <0.001). The post hoc test revealed that the growth rate of plants in natural soils (NS1 & NS2) and FT1/2:CT1/2+L3 differed significantly from that of the rest of the substrates in exception of FT1/2:CT1/2+L2 (Tukey HSD, P < 0.05). There was a significant difference in the growth rate of plants across ten substrates used in the greenhouse by day102 (ONE WAY

ANOVA: df = 9, F = 13.25, P < 0.001). Post hoc test revealed that the growth rate of plants in NS1 differed significantly from that of the rest of the substrates in exception of NS2, FT1/2:CT1/2+L2 and FT1/2:CT1/2+L3 (Tukey HSD, P < 0.05). The test also revealed that the growth rate of plants in NS1 differed significantly from that of the rest of the substrates in exception of NS2, FT1/2:CT1/2+L2 and FT1/2:CT1/2+L3. The test also showed that the growth rate of plants in FT1/2:CT1/2+L2 and FT1/2:CT1/2+L3 differed significantly to that of the FT, PS, FT7.5:CT2.5 and FT2.5:CT7.5.

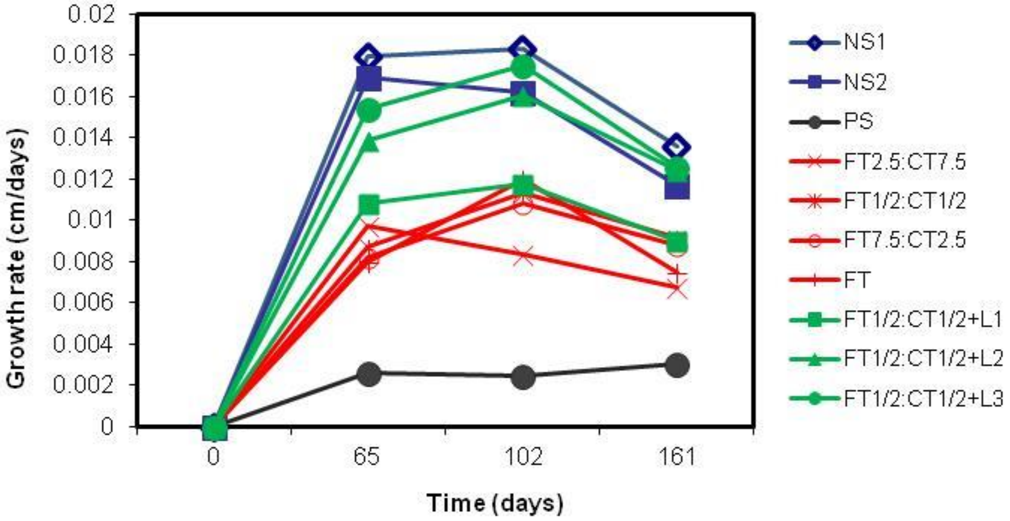

Figure 31. The growth rate (cm/day) of *J. albata* for 161 days. *Juttadinteria albata* was grown on various mixes of post-mining substrates, post-mining substrates plus Lucerne (L1-L3), potting soil (PS) and Natural soils (NS1 & NS2) in a greenhouse at Sendelingsdrif mine.

Figure 32 shows the growth rate of *C. herrei* in various substrates. There was a significant difference in the growth rate of plants across ten substrates by day 70 (ONE WAY ANOVA: F = 4.20, df = 9, P < 0.001). The post hoc test revealed that the growth rate of plants in NS2 differed significantly from that of the FT, PS, and FT2.5:CT7.5, FT1/2:CT1/2, FT1/2:CT1/2+L1 and FT1/2:CT1/2+L3 (Tukey HSD, P < 0.05). The test also revealed that the growth rate of plants in NS1 differed significantly from that of the FT2.5:CT7.5 and FT1/2:CT1/2.

There was a significant difference in the growth rate of plants across ten substrates by day 103 (ONE WAY ANOVA: df = 9, F = 5.59, P < 0.001). The post hoc test revealed that the growth rate of plants in natural soils (NS1 & NS2) differed significantly from that of the FT, PS, FT7.5:CT2.5, FT2.5:CT7.5, FT1/2:CT1/2 and FT1/2:CT1/2+L1 (Tukey HSD, P < 0.001). There was a significant difference in the growth rate of plants across ten substrates by day 161 (ONE WAY ANOVA: F = 6.10, df = 9, P < 0.001). The post hoc test revealed that the growth rate of plants in Natural soils (NS1 & 2) differed significantly from that of the FT, PS, and FT7.5:CT2.5, FT2.5:CT7.5, FT1/2:CT1/2 and FT1/2:CT1/2+L1 and FT1/2:CT1/2+L3 (Tukey HSD, P < 0.001).

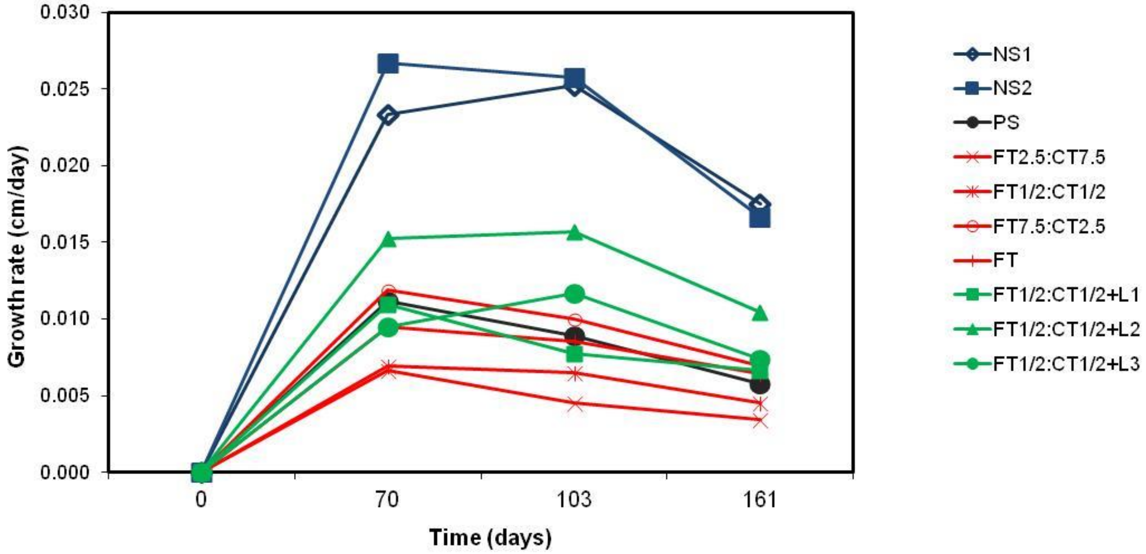

Figure 32. The growth rate (cm/day) of *Cephalophyllum herrei* for 161 days. *Cephalophyllum herrei was* grown on various mixes of post-mining substrates, post-mining substrates plus Lucerne (L1-L3), potting soil (PS) and Natural soils (NS1 & NS2) in a greenhouse at Sendelingsdrif mine.

4.4.3 Biomass of Radish

At the end of the greenhouse experiment, the wet biomas of radish plants were recorded and the results are presented in Figure 33. Statistical analysis revealed that there was a significant difference in the biomass of radish across ten different substrates (Kruskal-Wallis: H = 24.58, df = 9, P=0.004). The biomass of radish in FT7.5: CT2.5 differed significantly to that of potting soil and FT2.5: CT7.5 (multiple comparison post hoc test, $P < 0.05$).

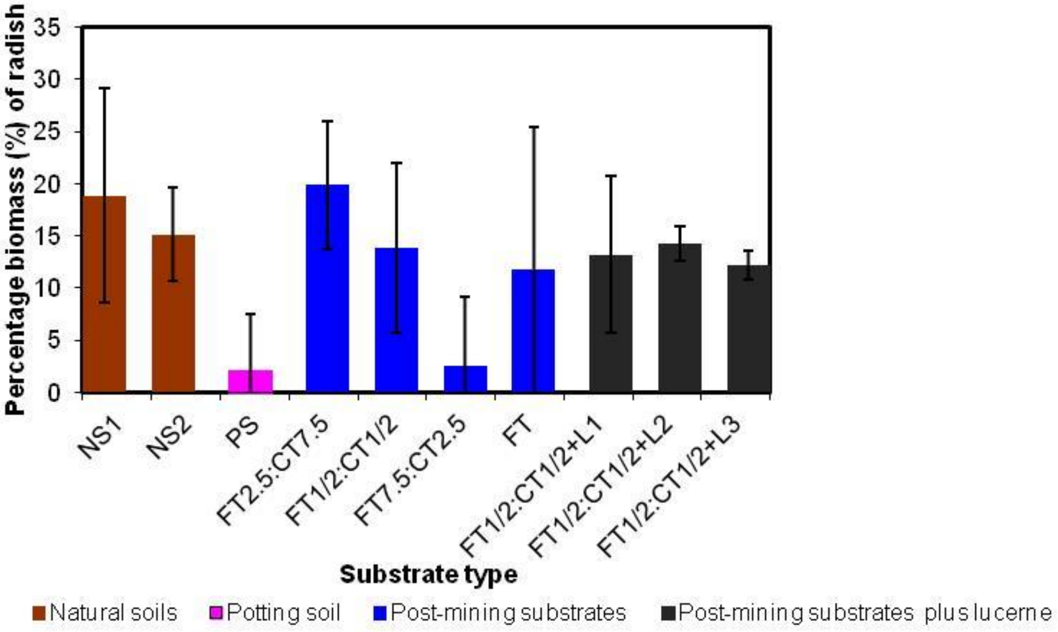

Figure 33. Percentage (%) biomass of radish across grown on various mixes of post-mining substrates, post-mining substrates plus Lucerne (L1-L3), potting soil (PS) and Natural soils (NS1 & NS2) in a greenhouse at Sendelingsdrif mine**.** Error bars denote 95% confidence interval level.

4.4.4 Survival rate

In the present study, survival rate was calculated as number of pots per substrate that contains a live plant at the end of the greenhouse experiment (i.e after 64 days). Statistical analysis revealed that there was no significant difference in survival rate of radish grown on ten different substrates (Kruskal-Wallis: H = 16.06, df = 9, P =0.07) (Figure 34).

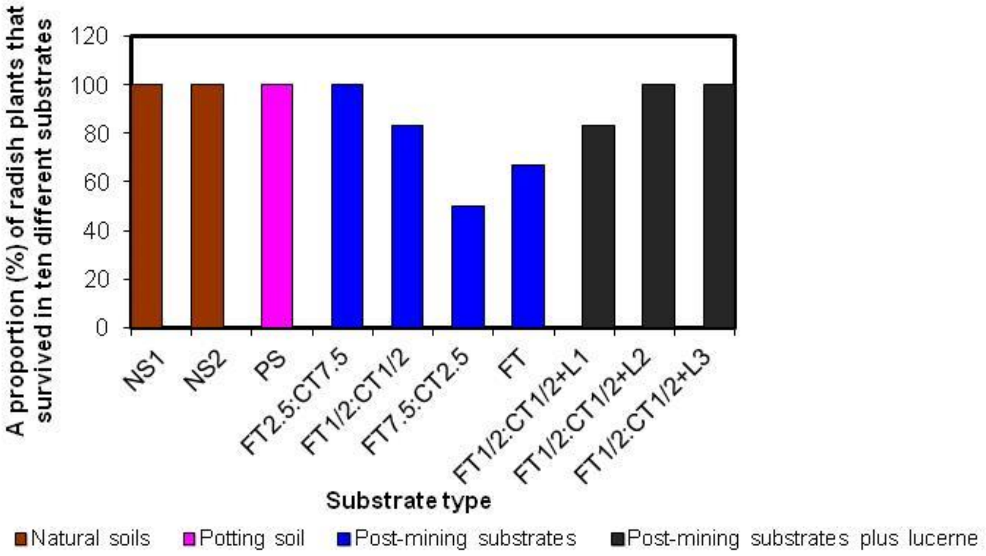

Figure 34. Proportion (%) of radish plants that survived at the end of the experiment in ten different substrates.

Hundred percent survival rate of *J.albata* and *C.herrei* was recorded across ten substrates at the end of the greenhouse experiment. Wet biomass of these two plants could not be determined because plants did not reach the harvestable masses.

Chapter 5

Discussion

5.1. Field study

The first objective of the study was to determine and compare the difference in infiltration rate, soil texture, and rockiness between the natural soils and waste materials in the proposed Sendelingsdrif mine area. The study found that water infiltration rate was not significantly different across the whole landscape in the study area, but it differed significantly between natural soils and post mining substrates in the greenhouse. Infiltration rate was highest in natural soil one and it was lowest in natural soil two (Figure 11). The addition of Lucerne to mine tailings seems to slow down the water infiltration, because it appears that the Lucerne modifies the structure of the tailings by filling the pore spaces within them. The slowing down of infiltration rate in mine tailings may cause runoff or erosion, but however it may also give abundant chance to plants to absorb enough water before seeping deep into the ground. The study also showed that the natural soil found in the study area has several soil types (sand, loamy sand and sandy loam), whereas post-mining substrates only have one soil type, which is sand and the rest is coarse materials. Unfortunately the study could not compare rockiness or infiltration rate between soils in the natural environment (i.e. the habitats) and mining substrates statistically because these variables could not be measured in a similar way in the greenhouse and in the field.

The similar infiltration rate depicted by different habitats in the study area can be due to various factors such as soil type (texture), soil nutrients, position in landscape and plants. Similarly, Osuji (et al., 2010) found out that water infiltration rate can be affected by several factors such as moisture content in the soil, condition of the surface, hydraulic conductivity of the soil, soil texture, organic matter, vegetation cover and biological crusting. The soil analysis revealed that most of the soils in the study area are sandy soils with low nutrient content (Table 2 and 3). The water infiltration rate of natural soils differed significantly from that of mixture of FT1/2:CT1/2+L1 and FT7.5:CT2.5 in the greenhouse. It appears that the infiltration rate and soil texture of post-mining substrates have been altered due to mining activities at Sendelingsdrif mine, through the moving of the sand, gravels and the processing of them. Mining alters soil texture either by re-arrangement of soil particles (silt, clay and sand) or by completely changing the soil from one soil type to the other. For example mining can change sand loamy or loam sandy soils into sandy soils. The findings of the present are also supported by Sadhu (et al., 2012) who found out that mining methods changes the soil texture from silt loam to loamy sand texture which has direct impact on climate. Their study revealed that the texture of mine wastes are mainly sandy or sand loamy. They also mentioned that the silt loamy type soil is the indicator of availability of water and nutrients to the plants and thereby affecting the plant growth and sandy soil holds less water and nutrients which affect the plant growth. Normally infiltration rate of water in the natural environment may be affected by several factors such as: position of habitat in the landscape, soil texture, the number of available plants (roots) and the organic matter (Wassenaar, 2010; Whitford, 2002). A study done by Guzman and Al-Kaisi (2011) revealed that water infiltration rate was affected differently by soil organic carbon and other soil surface parameters at different slope positions. Landscape slope effect on water infiltration rate showed that the summit and mid-slope positions had lower infiltration rates in comparison bottom slope position. They reported that the differences in water infiltration rate at different slope position can be explained by slope position effect on soil organic matter pool size.

Results of the present study suggest that during mining of diamonds at Sendelingsdrif mine, the soil texture is likely to be altered through moving of sand and gravel from the natural environment to the processing plant and separation of soil particles according to their fraction sizes. This separation will lead to changes in the soil texture, structure and hence infiltration rate. Soil texture and infiltration rate are the most important soil physical properties that can affect the abundance and the distribution of plants in an area (Whitford, 2002; Whitford, 1986). A study carried out by Dean and Milton (1999) in the Succulent Karoo showed that the activities of ants, soil texture, nutrients in the soil and infiltration rate influence the water retention capacity of the soil and hence the spatial distribution of vegetation’s in the area. Soil texture and structure are dominant factors that determine water holding capacity in the soil for plant growth (Esler & Cowling, 1993; Wassenaar, 2010). Therefore changes in these two important soil physical properties can or may negatively affect the presences or the amount of water in the soil, and hence the abundance, distribution and the survival of plants in an area.

It appears that water infiltration rate in natural soils depends on factors such as texture, position in landscape, the slope and rock cover while in post-mining substrates it depends textural properties of waste material (Guzman and Al-Kaisi, 2011; Sadhu et al., 2012). The addition of Lucerne slows down the water infiltration rate. The slowing down of water in substrates where Lucerne was added can be an advantage, because more water will be available in the first few centimetres of the soil where most of the biological processes take place (Pointing & Belnap, 2012).

The second objective of the study was to determine and understand whether the pH, percentage organic matter, total nitrogen, calcium carbonate, and other macro (P, K and Ca)-and micro (Fe and Cu)-nutrients differ between natural soils and post-mining substrates. Most of the soil chemical variables such as pH, total nitrogen, organic matter, phosphorus, calcium and iron were not significantly different across the landscape in the study area. Apart from the similarities that were found between the habitats across the landscape, the study also showed that soil chemical variables such as calcium carbonate, potassium, copper and electrical conductivity differed between habitats across the landscape. Additionally, the study found out that there were major differences in the chemical properties between the natural soils and post-mining substrates (Table 3). These differences found between natural soils and post-mining substrates may have an effect on the success of the restoration of the area after mining. For instance, if the chemical properties of post-mining substrates differs significantly form that of natural soils, which means post-mining substrates having very low levels of nutrients in comparison to natural soils. The plants might find it difficult to grow if no adjustments are made on post-mining substrates. Furthermore, plants will grow much more easily on post-mining substrates if their chemical properties are not significantly different from that of natural soils.

It was evident from results that the contents of major nutrients that are essential for plant growth such as nitrogen, organic matter and phosphorus are very low in the study area and calcium contents are high in comparison to other areas that are not arid (Whitford, 2002). Furthermore, the soils in the study area are sandy soil will low cation exchange capacity. Low cation capacity of the soil means that most of the cation nutrients are not available to plants for growth. Studies done in the central Namib and in the southern part of Namibia have showed that most of the soils (especially in dry areas) have low cation exchange capacity and they are sandy (Hartemink & Huting, 2008; Bertramis, 1999; Coetzee, 2009). A study carried out by Jacobson (1997) in the

Namib Desert, showed that soil nutrient levels were quite low with the soil organic matter ranging from 0.013-0.062%.

The similarities in amounts of nutrients in different habitats in the study area may be attributed to possibility that they are all equally affected by similar climate, topography, soil types and soil biota (Dean & Milton, 1999). In addition to this, it appears that prolonged periods of high evaporation and low precipitation seem to promote the accumulation of salt elements such as calcium and sodium that are responsible for raising the pH of the soil in the study area (Dean & Milton, 1999; Brandy & Weil 1999).

Soil pH controls the availability of nutrients in soil to plants (Killham, 1994). Soils with high pH (the case with the study area) especially those that are found in dry arid environments limits the availability of some micronutrients (such as manganese and iron) in the soil to plants (Whitford, 2002; Gu & Crouse, n.d). Additionally, other factors such as low precipitation, low decomposition rate and high evaporation rate can also affect the availability of nutrients in the soil and this factor are often coupled with low primary productivity and low biomass production (Jacobson, 1997; Jacobson & Jacobson, 1997; Dean and Milton, 1999). Limited soil nutrients can affect the abundance, the types, the distribution of plants in area, and hence the available organic matter on the soil surface. Furthermore, Ward (2009) mentioned that the distribution and concentration of soil nitrogen and other nutrients such as potassium and phosphorus are strongly associated with the presence of shrubs in arid environment, because organic matter from the plants accumulates there. According to Whitehead (2000), nitrogen concentrations are highest in the upper few centimetres of the soil due to the presence of nitrogen containing plant litter and animal droppings and it decreases drastically with depth.

Soil nutrients such as calcium carbonate, potassium, copper and conductivity were significantly different across the whole landscape in the study area (Figure 17, 19, 21 and 23). In comparison to other habitats, most of these soil nutrients were different in the shallow soil on ridges in the study area. It appears that the content of calcium carbonate, potassium and electrical conductivity seem to be influenced by the habitat type, altitude, water movement and surface evaporation in the study area. Studies by Lukam (2006), Coetzee (2009) and Al-Khaier (2003) reported that the presence and the content of soil nutrients such as calcium carbonate, calcium, potassium, iron, copper and electrical conductivity are influenced by altitude, pH, weathering of parental material, water flow, evaporation and the presences of plants. Generally, the levels of potassium and the electrical conductivity were high while calcium carbonate and copper contents were very low in the study area (Figure 17, 19, 21 & 23). A study done by Beukes & Cowling (2003) reported low electrical conductivity in the Succulent Karoo. This is different from the results of the present study in which high levels of electrical conductivity were reported (Figure 23), Furthermore, Beukes & Cowling (2003) reported that the soils of Succulent Karoo were very rich in lime and hence alkaline (pH 8.0) which is supported by results of the present study (Figure 13).

It was not possible to compare the chemical properties of post-mining substrate directly to that of the natural soils statistically, because post-mining substrates only had one sample that was analyse (no replication), unlike natural soils were several soil samples were analysed. Moreover, during the duration of the study at Sendelingsdrif the mine only had one heap of mine tailings which was used as a source of mining substrates. But according to the results obtained so far, it appears that post-mining substrates have low total nitrogen, low organic matter, low phosphorus, low copper, low iron and low electrical conductivity in comparison to natural soils (Table 3).

Additionally, post-mining substrates have exceptionally high calcium content compare to natural soils. Studies have shown that establishment plants on post-mining substrates (especially in dry areas) is affected by physical and chemical factors such as low precipitation, extreme temperatures especially on the surface of tailings, and high winds (Munshower, 1994; Mendez & Maier, 2008). The studies also showed that the physical and chemical factors mentioned above contributes to the development of extremely high salt concentrations ranging up 22 dS/m in post-mining substrates due to high evaporation and low water infiltration.

The deficiency in nutrients depicted by post-mining substrate may be caused by the processing and treatment of sand and gravels to extract diamonds. At treatment plant, gravels undergo a lot of washing processing stages until the diamonds are recovered. This washing may remove nutrients from the soils and therefore this can be used explain the very low levels of nutrients in post-mining substrates. In a similar study by Cooke and Johnson (2002) soil analysis revealed that all mining substrates had very low contents of macronutrients such as nitrogen, phosphorus and potassium. Carrick & Krüger (2007) reported that most of the post-mining substrates in their study lacked nutrients and that the salinity of these substrates was often high. High salinity content in post-mining substrates is unfavourable for plant growth. Such salinity is caused by the fine-texture fraction that is within them, which are capable of binding the salts to the soil (Lanz, 1999). Munshower (1994) contended that the establishment of plants on mine tailings especially in arid and semi-arid ecosystems is very difficult, because of factors such as low precipitation, extreme temperatures especially at the surface of tailings, and high winds. These contribute to the development of extremely high salt concentration in tailings up to 22 dS/m as a result of high evaporation and low water infiltration and hence low plant growth or establishment.

5.2 Greenhouse study

The third objective of the study was to compare and understand whether the germination rate, growth rate, biomass and survival rate of radish, *Juttadinteria albata* and *Cephalophyllum herrei* differ amongst natural soils and post-mining substrates.

Radish together with *J. abata* and *C. herrei* was used at Sendelingsdrif in potting experiment in order to test the capability of post-mining substrates in terms of its germination, growth and survival rate. Mann and Schumann (2010) used radish together with sorghum in greenhouse experiments as a bioassay, because it is a good indicator of soil properties. *Juttadinteria albata* was used in the greenhouse experiment, because mining at Sendelingsdrif is going to destroy about 39% of *J. albata* population and other plants and a lot of waste materials will be generated. After mining, plant communities are expected to establish themselves on mining waste material with the help of human interventions.

The percentage germination of radish was not significantly different across ten different substrates in the greenhouse (Figure 24). Addition of Lucerne to some of the post-mining substrates did not influence or contribute to germination of radish across the substrates. Several studies have indicated that the germination and the growth of radish is likely to be affected by several environmental factors such sun light intensity, soil quality, depth at which seeds are sown, moisture content of the soil, and length of day and night (Williams, 1995; Code & Donaldson, 1996). In the present study, one could look at factors such as temperature, wind and water to explain the similar germination depicted by different substrates in the greenhouse. Radish pots were watered three times a week to increase chances of germinating. We also learned from the pilot experiment that radish is not likely to germinate or survive the extreme daily conditions at Sendelingsdrif unless the frequency of watering is increased.

In addition to this, even though post-mining substrates on their own tend to dry up very quickly in comparison to natural soils and potting soil, this factor did not affect their germination. Carrick and Krüger (2007) found that the germination of seeds in post-mining substrates and natural habitats is mainly affected by moisture availability but not by the nutrients content in the soil. Even though it was suspected that Lucerne is capable of improving the structure of post-mining substrates and hence water retention, this effect was not felt because radish has shorter germination period (4-5 days) (personal observation).

The germination of local species (*J. albata* and *C. herrei)* differed significantly across ten substrates in the greenhouse. Percentage seed germination was significantly higher in natural soil one and two than in the rest of the substrates (Figure 25 & 26). Additionally, the germination of seeds in the mixture of FT2.5:CT7.5 was significantly higher than in the rest of the substrates used in the greenhouse. Laboratory tests showed that the substrates that were used in the greenhouse potting experiment differed in terms of nutrient content and texture (Water retention). The natural soils (NS1 & NS2) and potting soil (PS) showed the highest percentage germination for both *J. albata* and *C. herrei.* This may have been due to the fact that the natural soils still have the natural structure and texture intact to hold water for long enough to support germination of seeds in comparison to post-mining substrates that are entirely altered. On the other hand potting soil had high content of organic matters (Table 3) that are capable of retaining moisture for longer period of time and hence supports better germination of the seeds (McCauley & Jacobsen 2005, Önemli, 2004). A study by Önemli (2004) showed that soil organic matter and the environmental conditions have a significant effect on the germination of the seedlings. The study further revealed that decreasing soil organic matter content results in a decrease of seedling emergence due to the decrease in water content of the soil.

Infiltration could also explain the difference in germination that exists between natural soils, post-mining substrates and post-mining substrates with Lucerne. It was observed that water infiltration rate was high in natural soils whereas it was lowest in both post-mining substrates (Figure 11).This could be due to the fact that post-mining substrates were so altered that their water holding capacity was reduced and hence water infiltrated quickly. This could also be due to the fact that Lucerne altered post-mining substrates by not only adding nutrients but also altered the texture of post-mining substrates to hold water a bit longer through slow infiltration. A study by Cooke and Johnson (2002) showed that the fine texture found in post-mining substrates coupled with no organic matter leads to high bulk densities, extreme compaction, low infiltration rate, poor water

Results of this study suggests that addition of Lucerne to post-mining substrates will not only improve the nutrients content of post-mining substrates but it will also alter the texture to hold water longer through slow infiltration and hence more water will be available to plants. There are no specific studies that are describing or reporting on the role of Lucerne to seed germination of plants when added to post-mining substrates.

The growth rate of three plant species used in the greenhouse was significantly better than in post-mining substrates with Lucerne than in post-mining substrates on their own (Figure 30, 31 & 32). The growth of plants in the greenhouse across ten substrates was mostly high in the mixture of FT1/2:CT1/2+L3 in exception of the natural soils (NS1 & NS2) and lowest in the mixture of FT2.5:CT7.5 and potting soil. These results suggest that addition of Lucerne to post-mining substrate boasted the growth rate of plants. It is likely that Lucerne may have added some nutrients (e.g. nitrogen) to the post-mining substrates, or altered its texture such that this aided in the growth and development of plants in the greenhouse. Lucerne is a leguminous plant that is very rich in nutrients such as, nitrogen (protein) and phosphorus that can improve the growth of plants when added to the soil (Mann & Schumann, 2010). There are no particular studies describing or reporting on the addition of Lucerne to post-mining substrates in order to enhance plants growth and development.

A laboratory analysis indicated that the post-mining substrates have deficiency or low levels of essential nutrients such as nitrogen, phosphorus, organic matter and organic carbon that are crucial for plant growth (Table 3). Studies have showed that post-mining substrates generally have low levels of macronutrients such as nitrogen, phosphorus, and potassium which prohibits the growth and establishment of plants on them (Cooke & Johnson, 2002; Carrick & Krüger, 2007; Sheoran et al., 2010). Therefore, it is likely that plant growth in post-mining soils was poor because these soils are nutrient deficient. Additionally, substrate analysis in this study revealed that the post-mining substrates have high concentration of calcium (Table 3). According to literature, high level of salt related elements such as calcium or sodium in the soil can inhibit the growth of plants, by making it difficult for the roots to absorb water and it also limits the availability of other nutrients that are needed by plants (Al-Khaier, 2003). High levels of calcium in post-mining soils could prevents plants from absorbing water from the soils ,because salt tend to make the soil dry up quickly and the salt can also force the water to diffuse out of the plant roots in the process called osmosis.

The high nutrient content in potting soils (such as nitrogen, organic matter, and phosphorus, and potassium) may have led to poor growth and development of *J. albata* and *C. herrei*. Boom *et al.* (2005) studies plants growth in Succulent Karoo and reported that mesembs such as *Juttadinteria albata* and others grow in this area associated with low soil nutrients content. Local plants especially *J. albata* were growing poorly in potting soil because soil with high nutrients (e.g organic matter) can retain water for a very long period of time (Önemli, 2004). Mesembs in general do not like wet places or too much water because they can rot easily due to fungal infections in the presence of water. A study by Hammer (1995) reported that mesembs can tolerate poor soil conditions and dim light, but nothing spoils them so quickly and thoroughly as thoughtless general watering.

In summary, the growth rate of all plant species used in the greenhouse potting experiment was highest or improved in the post-mining substrates that were enriched with Lucerne.

The biomass production of radish differed significantly between natural soils and post-mining substrates. The major differences were between the potting soil, mixture of FT7.5:CT2.5 and the mixture of FT2.5:CT7.5. We expected substrates such as natural soils and potting soil to have higher biomass production compared to the post-mining substrates with and without Lucerne, because they are rich in nutrients that can support growth of plants but this was not the case. Substrates with enough soil nutrients essential for plant growth (e.g natural soils) could support better growth of plants and hence high biomass production, whereas substrates with low levels of nutrients essential for plant growth (post-mining substrates) might struggle to support plant growth and hence low biomass production.

The biomass production in different post-mining substrates without Lucerne also differed significantly from that of natural soils and potting soil. The difference in biomass production that exist between the different substrates could be explained using difference in nutrients content, the structure, moisture retention, and survival rate of radish across ten different substrates. It could be that substrates with sufficient nutrients content promotes good soil structure and improves water holding capacity, and hence improves the growth and development of plants. Furthermore, improved plant growth and development leads to high biomass production.

There was no significant difference in survival rate of radish across ten different substrates in the greenhouse. Other studies have shown that the type of substrate has an effect on the growth and the survival of the plant (Carrick & Krüger, 2007).

Post-mining substrates tend to dry up very quickly in comparison to natural soils and potting soil. (Munshower, 1994) However, this did not affect the survival rate of radish in post-mining substrates. Moreover radish grow very fast and reach maturing in 20 to 30 days (Code & Donaldson, 1996) and after that they needed to be harvested because they begin to lose leaves or die even. From the experiment, it is evident that water played a crucial role to explain why the survival of radish did not differ across all the substrates.

Even though it was hypothesized that Lucerne is capable of improving the structure of post-mining substrates, the nutrients and hence water retention, it appears that Lucerne did not play much role in the survival of radish. Hundred percent survival rate of *J.albata* and *C.herrei* was recorded across ten substrates at the end of the greenhouse experiment. Wet biomass of these two plants could not be determined because plants did not reach the harvestable masses.

5.3 Implication of the findings to the restoration project

The difference in infiltration and soil texture that was revealed between natural soil and post-mining substrate implies that mining at Sendelingsdrif will change the soil physical properties. These induced changes in soil properties may affect the establishment of local plants during the restoration.

The study showed that there was a major difference in soil chemical properties between natural soils and post-mining substrates. Nutrients such as nitrogen, phosphorus, potassium and organic matters were very low in post-mining substrates and calcium was very high in comparison with the natural soils. These findings imply that mining at Sendelingsdrif is likely to drain or remove all crucial nutrients from the soil, which are needed by plants. Moreover, if no adjustments are made to the post-mining substrates then plants will find it difficult to establish themselves on post-mining substrates. The application of organic matter to post mining substrates can help improve the establishment of plants back into the area and hence the restoration success.

The greenhouse experiment has demonstrated that post-mining substrates that are enriched with Lucerne have the highest growth of plants. This implies that Lucerne could perhaps be added to post-mining substrates to help support or improve the growth of plants during the restoration of Sendelingsdrif mine.

Chapter 6

Conclusion and Recommendations

6.1 Conclusion

The present study concluded that water infiltration rate did not differ across the landscape in Sendelingsdrif mining area. However, infiltration rate differed significantly between post-mining substrates and natural soil. The study concluded that there is a significant difference in physical and chemical properties of the natural soils and post-mining substrates. Post-mining substrates have a deficiency in essential nutrients needed by plants for growth. The addition of Lucerne to post-mining substrates slows down the infiltration of water in post-mining substrates. Furthermore, the study found that post mining substrates have low nutrients content and high salt content. The high salt content in post-mining substrates could be caused by various factors such as high temperature, high evaporation and winds experienced on the surface post-mining substrate due to lack of plants. Hence post mining substrate will pose a challenge after decommissioning of mining, during the time of restoration to enable re-establishing plants on them. The present study concluded that the addition of Lucerne to post-mining substrate improves the plants performance in these waste substrates. The study also concluded that the growth of plants in post-mining substrates that are enriched with Lucerne came closest to the natural soils in terms of plants performances.

6.2 Recommendations

1. The mine needs to come up with a way of mixing all the post-mining substrates together regardless of their fraction sizes instead of putting them in stock piles.
2. The mine also needs to consider rescuing plants from all the zones that are being mined or going to be impacted by mining and keep them in the greenhouse. The rescued plants can be transplanted back to the mined areas instead of germinating seeds in the field. The present study showed that germinating of seeds require a lot of water that we do not have in the desert.
3. The mine should consider mixing the post-mining wastes with lucerne to help improve the growth of plants.
4. If there is a budget, gypsum and mulch needs to be added to post-mining substrates in order to eliminate salt and to act as source of nutrients for plants in post-mining substrates.
5. There is a need for field trials at the mined sites to test whether what students find out can be applied in the field on a large scale. Additionally, there is a need to investigate more on the properties of waste material, because when the present study was conducted the mine only had one heap of waste material present as a source of post mining substrate.
6. There is a need for another research or studies primarily focusing on the biological soil properties of natural soils and post-mining substrates at Sendelingsdrif.

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Appendices

Appendix 1. The data of water infiltration rate and percentage rock cover in different seven habitats in the study area.

Site	**K (cm/s)**	**Total rock cover %**
Broad sandy wash	0.002366393	16
Broad sandy wash	0.000194714	30.5
Broad sandy wash	0.071485691	0
Broad sandy wash	0.013178681	18.32
Broad sandy wash	0.047469641	27.12
Broad sandy wash	0.001261468	45.16
Broad sandy wash	0.140429896	28.06
Broad sandy wash	0.005771381	45.38
Lower terraces	0.082948384	23.86
Lower terraces	0.007397633	0
Lower terraces	0.004796557	0
Lower terraces	0.101678395	100
Lower terraces	0.007999268	30.94

Lower terraces	0.014141706	31.26
Lower terraces	0.001359057	0
Lower terraces	0.100056983	0
Lower terraces	0.030425911	22.14
Lower terraces	0.050748358	0
Meso terraces	0.050923765	0
Meso terraces	0.001946673	0
Meso terraces	0.013053863	0
Meso terraces	0.022902602	24.98
Meso terraces	0.013751785	51.76
Meso terraces	0.016369479	9.36
Meso terraces	0.007210810	29
Meso terraces	0.004229764	48.18
Meso terraces	0.010148254	15.16
Meso terraces	0.000769834	38.96
Proto terraces	0.046046589	28.92

Proto terraces	0.004211202	43.92
Proto terraces	0.045903078	39.78
Proto terraces	0.060196098	14.52
Proto terraces	0.002488964	38.58
Proto terraces	0.028270426	59.16
Proto terraces	0.002187287	52.92
Proto terraces	0.016298232	29.44
Proto terraces	0.063639054	38.96
Proto terraces	0.008185793	36.08
Rocky hills	0.010935565	8
Rocky hills	0.018097514	55.04
Rocky hills	0.006584194	41.94
Rocky hills	0.001380763	43.48
Rocky hills	0.013008304	21.68
Rocky hills	0.008667174	50.9
Rocky hills	0.000869692	53.64

Rocky hills	0.030132363	61.2
Rocky hills	0.036432133	29.9
Rocky hills	0.080410620	29.24
Sheltered gullies	0.067696007	15.2
Sheltered gullies	0.056488790	28.92
Sheltered gullies	0.066492353	50.6
Sheltered gullies	0.030466576	63.18
Sheltered gullies	0.021106949	31.02
Sheltered gullies	0.018696214	36.38
Sheltered gullies	0.060851823	57.54
Sheltered gullies	0.041549736	6.64
Sheltered gullies	0.013297931	35.96
Sheltered gullies	0.020768679	49.58
Sheltered gullies	0.002170455	48.42
Sheltered gullies	0.008619881	54.88
Sheltered gullies	0.002552768	19.7

Sheltered gullies	0.000181440	84.46
Sheltered gullies	0.002483065	56.72
Shallow soils on ridges	0.021537196	16.74
Shallow soils on ridges	0.039765887	16.56
Shallow soils on ridges	0.003173346	5
Shallow soils on ridges	0.043161418	0
Shallow soils on ridges	0.020104489	19.08
Shallow soils on ridges	0.000785483	29.36
Shallow soils on ridges	0.006438389	13.6
Shallow soils on ridges	0.021452734	39.56
Shallow soils on ridges	0.011889587	6
Shallow soils on ridges	0.007268087	12.3

Appendix 2. Plot code, latitude, longitude, elevation and plant species all describing where and what types of plants were found in the study area

Plot code	**Latitude**	**Longitude**	**Elevation**	**Species**
BSW17S	-28.15945499	16.83879303	34.49	L. boscifolium
BSW17S	-28.15945499	16.83879303	34.49	L. boscifolium
BSW17S	-28.15945499	16.83879303	34.49	L. boscifolium
BSW17S	-28.15945499	16.83879303	34.49	L. boscifolium
BSW17S	-28.15945499	16.83879303	34.49	L. boscifolium
BSW17S	-28.15945499	16.83879303	34.49	L. boscifolium
BSW17S	-28.15945499	16.83879303	34.49	D. carnosa
BSW18S	-28.15773804	16.83292301	46.03	C. royenii
BSW18S	-28.15773804	16.83292301	46.03	D. carnosa
BSW19S	-28.16159002	16.83572299	36.42	L. boscifolium
BSW19S	-28.16159002	16.83572299	36.42	L. boscifolium
BSW19S	-28.16159002	16.83572299	36.42	L. boscifolium
BSW19S	-28.16159002	16.83572299	36.42	L. boscifolium

BSW19S	-28.16159002	16.83572299	36.42	S. obtusa
BSW19S	-28.16159002	16.83572299	36.42	L. boscifolium
BSW21S	-28.14647402	16.838126	79.19	S.ciliata
BSW21S	-28.14647402	16.838126	79.19	
BSW22S	-28.15894302	16.83324002	46.99	C. royenii
BSW22S	-28.15894302	16.83324002	46.99	D. carnosa
BSW23S	-28.16121301	16.83526601	36.42	Z. microcarpum
BSW24S	-28.14507701	16.85036299	76.79	S.ciliata
BSW24S	-28.14507701	16.85036299	76.79	S. obtusa
BSW25S	-28.16184098	16.83345996	39.06	B. arenosus
BSW25S	-28.16184098	16.83345996	39.06	B. arenosus
LT027S	-28.16085996	16.841937	43.14	D. carnosa
LT027S	-28.16085996	16.841937	43.14	S.ciliata
LT028S	-28.143351	16.88751896	45.55	E. pseudo
LT028S	-28.143351	16.88751896	45.55	E. pseudo
LT028S	-28.143351	16.88751896	45.55	E. pseudo

LT029S	-28.14204502	16.88419503	47.23	E. pseudo
LT029S	-28.14204502	16.88419503	47.23	E. pseudo
LT030S	-28.15856701	16.88069098	120.53	M. guerichianum
LT030S	-28.15856701	16.88069098	120.53	M. guerichianum
LT030S	-28.15856701	16.88069098	120.53	M. guerichianum
LT030S	-28.15856701	16.88069098	120.53	M. guerichianum
LT030S	-28.15856701	16.88069098	120.53	M. guerichianum
LT030S	-28.15856701	16.88069098	120.53	M. guerichianum
LT030S	-28.15856701	16.88069098	120.53	M. guerichianum
LT030S	-28.15856701	16.88069098	120.53	M. guerichianum
LT030S	-28.15856701	16.88069098	120.53	M. guerichianum
LT030S	-28.15856701	16.88069098	120.53	M. guerichianum
LT030S	-28.15856701	16.88069098	120.53	M. guerichianum
LT030S	-28.15856701	16.88069098	120.53	M. guerichianum
LT030S	-28.15856701	16.88069098	120.53	S.ciliata
LT031S	-28.17941699	16.87358798	33.29	

LT032S	-28.16360302	16.85273699	43.63	E. ambiguus
LT033S	-28.17811604	16.86992702	34.49	
LT034S	-28.16757697	16.853889	28.72	
LT035S	-28.15931702	16.84493998	42.66	
LT036S	-28.16366304	16.85145297	37.14	E. ambiguus
LT036S	-28.16366304	16.85145297	37.14	Z. microcarpum
LT036S	-28.16366304	16.85145297	37.14	S. spartea
MT037S	-28.17487098	16.87866499	44.59	
MT038S	-28.17095504	16.88147401	51.32	Z. microcarpum
MT039S	-28.174557	16.877819	46.75	
MT040S	-28.15871897	16.85320102	64.77	S.ciliata
MT041S	-28.16176001	16.85639997	59.25	S. obtusa
MT042S	-28.15736001	16.85405597	63.81	S. obtusa
MT042S	-28.15736001	16.85405597	63.81	S.ciliata
MT043S	-28.17436203	16.87647698	53	E. ambiguus
MT043S	-28.17436203	16.87647698	53	E. ambiguus

MT043S	-28.17436203	16.87647698	53	E. ambiguus
MT043S	-28.17436203	16.87647698	53	Z. microcarpum
MT044S	-28.158667	16.85541602	66.94	Z. patenticaule
MT044S	-28.158667	16.85541602	66.94	Z. patenticaule
MT044S	-28.158667	16.85541602	66.94	Z. patenticaule
MT044S	-28.158667	16.85541602	66.94	Z. patenticaule
MT044S	-28.158667	16.85541602	66.94	Z. patenticaule
MT044S	-28.158667	16.85541602	66.94	Z. patenticaule
MT044S	-28.158667	16.85541602	66.94	Z. patenticaule
MT044S	-28.158667	16.85541602	66.94	Z. patenticaule
MT044S	-28.158667	16.85541602	66.94	Z. patenticaule
MT044S	-28.158667	16.85541602	66.94	Z. patenticaule
MT044S	-28.158667	16.85541602	66.94	Z. patenticaule
MT044S	-28.158667	16.85541602	66.94	Z. patenticaule
MT044S	-28.158667	16.85541602	66.94	E. gummifera
MT044S	-28.158667	16.85541602	66.94	S.ciliata

MT045S	-28.16397903	16.85793	56.84	K. cynanchia
MT045S	-28.16397903	16.85793	56.84	S.ciliata
MT046S	-28.158263	16.85357602	63.33	E. ambiguus
MT046S	-28.158263	16.85357602	63.33	S.ciliata
PT047S	-28.15976	16.86090801	94.33	S. flavescens
PT047S	-28.15976	16.86090801	94.33	S. obtusa
PT047S	-28.15976	16.86090801	94.33	S.ciliata
PT048S	-28.14748999	16.84372704	0	
PT049S	-28.15513303	16.85645697	87.12	S.ciliata
PT049S	-28.15513303	16.85645697	87.12	S. obtusa
PT050S	-28.16712904	16.86594704	75.11	K. cynanchia
PT051S	-28.14180404	16.84717401	80.4	E. ebrateata
PT052S	-28.15499498	16.85883701	87.12	S.ciliata
PT052S	-28.15499498	16.85883701	87.12	S. obtusa
PT053S	-28.14844603	16.85250197	87.61	B. marlothii
PT053S	-28.14844603	16.85250197	87.61	B. marlothii

PT053S	-28.14844603	16.85250197	87.61	B. marlothii
PT053S	-28.14844603	16.85250197	87.61	B. marlothii
PT053S	-28.14844603	16.85250197	87.61	B. marlothii
PT053S	-28.14844603	16.85250197	87.61	S.ciliata
PT053S	-28.14844603	16.85250197	87.61	B. marlothii
PT053S	-28.14844603	16.85250197	87.61	B. marlothii
PT053S	-28.14844603	16.85250197	87.61	B. marlothii
PT053S	-28.14844603	16.85250197	87.61	B. marlothii
PT053S	-28.14844603	16.85250197	87.61	B. marlothii
PT053S	-28.14844603	16.85250197	87.61	B. marlothii
PT053S	-28.14844603	16.85250197	87.61	B. marlothii
PT053S	-28.14844603	16.85250197	87.61	B. marlothii
PT054S	-28.16337202	16.86125804	71.26	E. gummifera
PT054S	-28.16337202	16.86125804	71.26	D. carnosa
PT054S	-28.16337202	16.86125804	71.26	T. polycephala
PT054S	-28.16337202	16.86125804	71.26	S.ciliata

PT055S	-28.15458996	16.86008801	87.12	S. obtusa
PT055S	-28.15458996	16.86008801	87.12	S.ciliata
PT056S	-28.15886297	16.863165	82.8	Z. patenticaule
PT056S	-28.15886297	16.863165	82.8	Z. patenticaule
PT056S	-28.15886297	16.863165	82.8	T. polycephala
PT056S	-28.15886297	16.863165	82.8	S.ciliata
PT056S	-28.15886297	16.863165	82.8	S. obtusa
RH057S	-28.13943598	16.85651899	92.41	S. beetzii
RH057S	-28.13943598	16.85651899	92.41	S. beetzii
RH057S	-28.13943598	16.85651899	92.41	B. arenosus
RH057S	-28.13943598	16.85651899	92.41	T. polycephala
RH057S	-28.13943598	16.85651899	92.41	D. carnosa
RH058S	-28.12696497	16.87524601	70.78	B. arenosus
RH058S	-28.12696497	16.87524601	70.78	B. arenosus
RH058S	-28.12696497	16.87524601	70.78	B. arenosus
RH058S	-28.12696497	16.87524601	70.78	B. arenosus

RH058S	-28.12696497	16.87524601	70.78	B. arenosus
RH058S	-28.12696497	16.87524601	70.78	B. arenosus
RH058S	-28.12696497	16.87524601	70.78	B. arenosus
RH059S	-28.13790604	16.85454204	105.87	E. chersina
RH059S	-28.13790604	16.85454204	105.87	E. chersina
RH059S	-28.13790604	16.85454204	105.87	M. guerichianum
RH060S	-28.14302796	16.86571604	79.43	
RH061S	-28.14331203	16.857513	96.02	B. arenosus
RH061S	-28.14331203	16.857513	96.02	S. beetzii
RH061S	-28.14331203	16.857513	96.02	Little succulent
RH061S	-28.14331203	16.857513	96.02	B. marlothii
RH062S	-28.13078896	16.87034503	82.32	
RH063S	-28.14314699	16.85349799	74.39	
RH064S	-28.13349799	16.86295998	86.64	T. polycephala
RH065S	-28.13868698	16.86401401	87.12	B. arenosus
RH065S	-28.13868698	16.86401401	87.12	B. arenosus

RH065S	-28.13868698	16.86401401	87.12	B. arenosus
RH066S	-28.14008298	16.85602999	99.86	
SG002S	-28.16129096	16.86432104	63.09	River grass
SG003S	-28.15808496	16.86252203	71.5	Z. patenticaule
SG003S	-28.15808496	16.86252203	71.5	Z. patenticaule
SG003S	-28.15808496	16.86252203	71.5	Z. patenticaule
SG003S	-28.15808496	16.86252203	71.5	Z. patenticaule
SG003S	-28.15808496	16.86252203	71.5	Z. patenticaule
SG003S	-28.15808496	16.86252203	71.5	Z. patenticaule
SG003S	-28.15808496	16.86252203	71.5	S. obtusa
SG003S	-28.15808496	16.86252203	71.5	S.ciliata
SG004S	-28.15270202	16.85487103	79.91	
SG005S	-28.15233104	16.84776996	66.22	T. polycephala
SG005S	-28.15233104	16.84776996	66.22	D. carnosa
SG005S	-28.15233104	16.84776996	66.22	S. obtusa
SG005S	-28.15233104	16.84776996	66.22	S.ciliata

SG006S	-28.14824704	16.84658904	0	E. chersina
SG006S	-28.14824704	16.84658904	0	D. carnosa
SG006S	-28.14824704	16.84658904	0	T. polycephala
SG006S	-28.14824704	16.84658904	0	L. boscifolium
SG006S	-28.14824704	16.84658904	0	Z. microcarpum
SG006S	-28.14824704	16.84658904	0	S.ciliata
SG007S	-28.15311098	16.84375101	0	D. carnosa
SG007S	-28.15311098	16.84375101	0	T. polycephala
SG007S	-28.15311098	16.84375101	0	P. modesta (seedlings)
SG007S	-28.15311098	16.84375101	0	Z. microcarpum
SG007S	-28.15311098	16.84375101	0	S.ciliata
SG007S	-28.15311098	16.84375101	0	S. obtusa
SG008S	-28.15020204	16.845374	0	S.ciliata
SG008S	-28.15020204	16.845374	0	S. obtusa
SG009S	-28.14985301	16.85434598	77.99	L. boscifolium
SG009S	-28.14985301	16.85434598	77.99	L. boscifolium

SG009S	-28.14985301	16.85434598	77.99	L. boscifolium
SG009S	-28.14985301	16.85434598	77.99	L. boscifolium
SG009S	-28.14985301	16.85434598	77.99	L. boscifolium
SG009S	-28.14985301	16.85434598	77.99	L. boscifolium
SG009S	-28.14985301	16.85434598	77.99	B. arenosus
SG009S	-28.14985301	16.85434598	77.99	B. arenosus
SG009S	-28.14985301	16.85434598	77.99	Z. patenticaule
SG009S	-28.14985301	16.85434598	77.99	Z. patenticaule
SG010S	-28.15196902	16.85382698	86.4	S.ciliata
SG010S	-28.15196902	16.85382698	86.4	S. obtusa
SG011S	-28.15781096	16.85701202	77.27	Z. patenticaule
SG011S	-28.15781096	16.85701202	77.27	Z. patenticaule
SG011S	-28.15781096	16.85701202	77.27	Z. patenticaule
SG011S	-28.15781096	16.85701202	77.27	Z. patenticaule
SG011S	-28.15781096	16.85701202	77.27	Z. patenticaule
SG011S	-28.15781096	16.85701202	77.27	Z. patenticaule

SG011S	-28.15781096	16.85701202	77.27	Z. patenticaule
SG011S	-28.15781096	16.85701202	77.27	Z. patenticaule
SG011S	-28.15781096	16.85701202	77.27	Z. patenticaule
SG011S	-28.15781096	16.85701202	77.27	Z. patenticaule
SG011S	-28.15781096	16.85701202	77.27	Z. patenticaule
SG011S	-28.15781096	16.85701202	77.27	Z. patenticaule
SG011S	-28.15781096	16.85701202	77.27	Z. patenticaule
SG011S	-28.15781096	16.85701202	77.27	Z. patenticaule
SG011S	-28.15781096	16.85701202	77.27	Z. patenticaule
SG011S	-28.15781096	16.85701202	77.27	P. modesta
SG011S	-28.15781096	16.85701202	77.27	P. modesta
SG011S	-28.15781096	16.85701202	77.27	P. modesta
SG011S	-28.15781096	16.85701202	77.27	P. modesta
SG011S	-28.15781096	16.85701202	77.27	S. obtusa
SG012S	-28.14961497	16.83201701	73.43	C. royenii
SG012S	-28.14961497	16.83201701	73.43	C. royenii

SG012S	-28.14961497	16.83201701	73.43	T. polycephala
SG012S	-28.14961497	16.83201701	73.43	Z. microcarpum
SG013S	-28.15632401	16.85778801	79.91	Z. patenticaule
SG013S	-28.15632401	16.85778801	79.91	Z. patenticaule
SG013S	-28.15632401	16.85778801	79.91	Z. patenticaule
SG013S	-28.15632401	16.85778801	79.91	Z. patenticaule
SG013S	-28.15632401	16.85778801	79.91	Z. patenticaule
SG013S	-28.15632401	16.85778801	79.91	Z. patenticaule
SG013S	-28.15632401	16.85778801	79.91	Z. patenticaule
SG013S	-28.15632401	16.85778801	79.91	Z. patenticaule
SG013S	-28.15632401	16.85778801	79.91	Z. patenticaule
SG013S	-28.15632401	16.85778801	79.91	Z. patenticaule
SG013S	-28.15632401	16.85778801	79.91	Z. patenticaule
SG013S	-28.15632401	16.85778801	79.91	Z. patenticaule
SG013S	-28.15632401	16.85778801	79.91	Z. patenticaule
SG013S	-28.15632401	16.85778801	79.91	J. albata

SG013S	-28.15632401	16.85778801	79.91	J. albata
SG013S	-28.15632401	16.85778801	79.91	J. albata
SG013S	-28.15632401	16.85778801	79.91	J. albata
SG013S	-28.15632401	16.85778801	79.91	J. albata
SG013S	-28.15632401	16.85778801	79.91	E. gummifera
SG013S	-28.15632401	16.85778801	79.91	S. flavescens
SG013S	-28.15632401	16.85778801	79.91	S.ciliata
SG014S	-28.14636396	16.84785202	67.42	S. spartea
SG014S	-28.14636396	16.84785202	67.42	B. arenosus
SG014S	-28.14636396	16.84785202	67.42	B. arenosus
SG014S	-28.14636396	16.84785202	67.42	Z. microcarpum
SG014S	-28.14636396	16.84785202	67.42	Z. microcarpum
SG014S	-28.14636396	16.84785202	67.42	Z. microcarpum
SG014S	-28.14636396	16.84785202	67.42	Z. microcarpum
SG014S	-28.14636396	16.84785202	67.42	Z. microcarpum
SG014S	-28.14636396	16.84785202	67.42	T. polycephala

SG015S	-28.15019701	16.85084	74.87	B. marlothii
SG015S	-28.15019701	16.85084	74.87	B. marlothii
SG015S	-28.15019701	16.85084	74.87	B. marlothii
SG015S	-28.15019701	16.85084	74.87	B. marlothii
SG015S	-28.15019701	16.85084	74.87	B. marlothii
SG015S	-28.15019701	16.85084	74.87	B. marlothii
SG015S	-28.15019701	16.85084	74.87	B. marlothii
SG015S	-28.15019701	16.85084	74.87	B. marlothii
SG015S	-28.15019701	16.85084	74.87	B. marlothii
SG015S	-28.15019701	16.85084	74.87	B. marlothii
SG015S	-28.15019701	16.85084	74.87	B. marlothii
SG015S	-28.15019701	16.85084	74.87	B. marlothii
SG015S	-28.15019701	16.85084	74.87	B. marlothii
SG015S	-28.15019701	16.85084	74.87	B. marlothii
SG015S	-28.15019701	16.85084	74.87	E. gummifera
SG015S	-28.15019701	16.85084	74.87	T. polycephala

SG016S	-28.15174104	16.84494501	61.65	B. marlothii
SG016S	-28.15174104	16.84494501	61.65	B. marlothii
SG016S	-28.15174104	16.84494501	61.65	E. chersina
SG016S	-28.15174104	16.84494501	61.65	S. flavescens
SG016S	-28.15174104	16.84494501	61.65	P. modesta
SG016S	-28.15174104	16.84494501	61.65	P. modesta
SG016S	-28.15174104	16.84494501	61.65	Amellus sp.
SG016S	-28.15174104	16.84494501	61.65	Trachyandra sp.
SSR67S	-28.14897199	16.87244503	62.37	
SSR68S	-28.14510902	16.86748101	77.51	Trachyandra sp.
SSR68S	-28.14510902	16.86748101	77.51	J. albata
SSR68S	-28.14510902	16.86748101	77.51	J. albata
SSR69S	-28.13788299	16.86685497	72.22	B. arenosus
SSR70S	-28.149002	16.87943403	46.99	Perennial plant
SSR70S	-28.149002	16.87943403	46.99	Perennial plant
SSR70S	-28.149002	16.87943403	46.99	Perennial plant

SSR70S	-28.149002	16.87943403	46.99	Perennial plant
SSR70S	-28.149002	16.87943403	46.99	Perennial plant
SSR70S	-28.149002	16.87943403	46.99	Perennial plant
SSR70S	-28.149002	16.87943403	46.99	New grass
SSR70S	-28.149002	16.87943403	46.99	Perennial plant
SSR71S	-28.16373303	16.88281696	86.16	S. obtusa
SSR72S	-28.14037601	16.87011897	64.29	
SSR73S	-28.13772599	16.86897299	69.82	
SSR74S	-28.144458	16.87944098	50.35	S.ciliata
SSR75S	-28.14909101	16.87072598	68.38	T. polycephala
SSR75S	-28.14909101	16.87072598	68.38	S. obtusa
SSR76S	-28.15646298	16.86994404	80.4	S.ciliata

Appendix 3. A map of the study area showing different plant species encountered in the field at Sendelingsdrif mine.