Establishment of native vegetation on artificial growth mediums in the Afro-alpine zone, Lesotho

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DECLARATION

I declare that the work presented in this *Magister Scientiae* dissertation is my own work, that it has not been submitted for any degree or examination at any other university, and that all the sources I have used or quoted have been acknowledged by complete reference.

Signature of the student ..……………………………………………………..

Signature of the supervisor ………………………………………………........

Signature of the co-supervisor ………………………………………………........

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ABSTRACT

Mining is an anthropogenic activity that is not only destructive to the environment but creates imbalances between the natural integrity of the environment and human society. Letšeng Diamonds is a kimberlite diamond mining company in the mountain kingdom of Lesotho. Located in the Mokhotlong district, Letšeng Diamond Mine produces post-extraction kimberlite tailings with a sand fraction of 82.7%, clay mineral content of 9.3%, and low organic matter. Such fine material is prone to wind erosion and easily washed away by storm water runoff, necessitating rehabilitation. Vegetation cover is important for soil protection and promotes biodiversity during rehabilitation of mined areas. Native plant species are ideal for such rehabilitation processes through evolutionary adaptations to harsh local growing conditions. The aim of this study was to identify the most suitable species and soil treatment for restoration purposes. Secondary aims included to (1) test the germination response of various native species on different kimberlite and top soil treatments, (2) evaluate the establishment and growth of these selected species, and (3) assess their germination response as part of an experimental seed mix. A rapid germination trial using seeds of seven pioneer plant species acquired from the study area was used to determine the most suited plant species according to predetermined criteria. The ability of *T*. *disticha* to germinate and establish on different kimberlite and top soil treatments was compared. Furthermore, a native plant seed mix was used to determine germination responses of other plant species in the presence of *T*. *disticha* across various treatments. Additionally, the ability of forb species to establish with *T*. *disticha* was compared. The germination trial showed that *T*. *disticha* revealed highest germination ability on various kimberlite treatments. The seedling growth performance results indicated that effective seedling establishment was associated with kimberlite tailing treatments having additional topsoil. Of the nine plant species in the seed mix, only *Dierama robustum*, *Hesperantha schelpeana* and *Sisymbrium turczaninowii* germinated copiously in the presence of *T*. *disticha* seedlings, which suggests that these species can tolerate competition to germinate across various treatments. Addition of topsoil increased the potential of mine tailings to support germination and establishment of plant diversity. Furthermore, the emergence of 18 unsown plant species from 10 families in the trial treatments (most probably due to the soil seed bank and seed dispersal) is a positive indication that plants can naturally colonise kimberlite mine tailings.

Key words: rehabilitation, biodiversity, restoration, kimberlite tailings, species co-existence

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CHAPTER 1: INTRODUCTION

Background

Mining is an activity that involves the extraction of naturally occurring minerals from the earth (Cooke and Johnson, 2002; Tatiya, 2005; Mkpume *et al*., 2015; Arndt *et al*., 2017). The mining industry is a major contributor to economic growth in countries which have rich natural resources (Pegg, 2006; EBRD, 2017; Festin *et al*., 2018). This industry has been beneficial to the development of southern Africa and was introduced in 1867 (Potgieter, 1970).

Depending on the mineralogical characteristics of the site, various approaches are implemented in the mining industry for the extraction of minerals. Two common categories of mining techniques are surface and underground mining (Northey *et al.*, 2013; Mkpume *et al*., 2015; Festin *et al*., 2018). Surface mining entails the acquisition of ore directly from the earth's surface whilst contact is maintained with the surface during removal of topsoil and bedrock, whereas underground mining is practised with subterranean tunnels and the bedrock is kept intact during ore extraction (Altun *et al.*, 2010).

A typical mining cycle consists of different stages based on various activities which take place (Harraz, 2010). In the first stage, potential mining sites are prospected in the search for valuable minerals. The second stage involves exploration, examination and evaluation of the abundance and value of minerals (Ilich, 2018). During the third stage, mineral production is developed and the size and economic value of the targeted mineral is determined to inform stakeholders on profitability (Hudson *et al*., 1999). The fourth stage of the cycle is associated with the recovery and removal of aggregate minerals (Harraz, 2010; Khan *et al*., 2016) which can be categorised into waste (also called overburden), and the mineral bearing material (Johnson, 2010). The fifth and final stage includes the landscape reclamation during the mine closure and entails the restoration of the characteristic natural attributes of the mined areas such as the local biodiversity (Harraz, 2010). During this stage the primary aim is to potentially return the land to a predetermined degree of its former state, however there are multiple environmental components that require rehabilitation to restore a healthy environmental state. Common activities include removing facilities which will not form part of the end-land use and mitigating safety related hazards in the local environment (Hudson *et al*., 1999).

The removal of vast quantities of bedrock and the creation of tailings facilities may result in negative environmental impacts such as elevated heavy metal concentrations and modified soil pH in southern Africa (Pollmann *et al*., 2009). Furthermore, mine closure has not been generally successful leaving unmitigated environmental impacts (Milaras *et al*., 2014).

According to the International Finance Corporation (2014), environmental awareness has increased and as such, governments and companies are implementing environmental policies, standards and procedures for sustainable mining activities which include mine rehabilitation.

Environmental problems

The mining industry positively affects economic growth (Pegg, 2006; EBRD, 2017; Nguyen *et al*., 2017; Festin *et al*., 2018), and human well-being through providing income, jobs and infrastructure development (Mobtaker and Osanloo, 2014; Nguyen *et al*., 2017). Despite its positive effects, mining is an anthropogenic activity that is destructive to the environment and can negatively affect society by creating imbalances between nature and human wellbeing (Biggs *et al*., 2004). For instance, open pit mines can cause a loss of natural habitat and inherently the associated ecosystem goods and services required by rural communities in the vicinity of mining areas (Millennium Ecosystem Assessment, 2005; Mccullough and Van Etten, 2011). According to Mensah (2015), mining activities deplete environmental resources such as arable soil for agriculture, aesthetic value for eco-tourism and vegetation for livestock grazing. Furthermore, mining has direct negative impacts such as pollution which could lead to poor access to clean water and sanitation (Ramani, 2012; Carvalho, 2017). In addition, Schwegler (2006) concluded that mining activities such as coal mining reduces air quality in South Africa. It is therefore necessary for mining practices to transform and become more environmentally orientated through better management of ecological systems, whilst contributing to community socio-economic development (Carvalho, 2017).

Successful rehabilitation of mined areas is generally hampered by a number of limitations, especially the ability of the environment to support original vegetation that occurred in the area (Chamber of Mines of South Africa, 2007; Bell, 2004). These limitations are brought about by factors such as unmanaged waste material disposed of in natural areas causing low soil fertility due to loss of micronutrients, high levels of toxic metals, low soil pH and poor structure with limited water holding capacity (Carvalho *et al.,* 2013; Sheoran *et al*., 2010). However, such limitations which inhibit successful vegetation establishment and survival can be rectified through various soil treatments such as addition of chemical fertilizers, effective seed mixes and organic compost (Carvalho *et al.,* 2013; Meyer, 2017).

Restoration and rehabilitation

Restoration is considered a good practice to achieve conservation objectives in the reclamation phase of the mining cycle (Sheoran *et al*., 2010; Harraz, 2010). Accordingly, mining policies and legislative controls published by the Chamber of Mines of South African in 2007, support advancement of a balance between the four pillars of sustainable development and highlight the importance of environmental protection through restoration and rehabilitation, during which socio-economic development is upheld. According to the Society for Ecological Restoration International (2004), restoration can be defined as a process where damaged ecosystems is repaired to a state equivalent to the pre-existing natural conditions in terms of function and composition of attributes of local landscapes. Haagner (2008) revealed that both restoration and rehabilitation share a similar emphasis on creating pre-existing ecosystems, although occasionally, rehabilitation may aim at repairing damaged ecosystems to reconstruct processes that contribute to ecosystem services and function and not necessarily to pre-existing conditions (Vaughn *et al*., 2010).

According to Vaughn *et al*. (2010), restoration activities are designed to repair damaged ecosystems to restore habitat conditions which occurred prior to disturbance. One such an approach is revegetation of the landscape which entails the re-establishment of natural vegetation (Cooke and Johnson, 2002; Vaughn *et al*., 2010). The Chamber of Mines of South Africa (2007) emphasised the use of native species in rehabilitation and restoration of mined areas. The use of native species is recommended as a substitute for alien species which have largely been introduced for rehabilitation, landscaping and ornamental purposes, and consequently disperse into natural habitats where they become a threat to ecosystems (Rahlao, 2009; Sheoran *et al*., 2010; Mokotjomela *et al*., 2013; Mating, 2018). An example of a study which implemented revegetation practices is Martin *et al*. (2002) who used seeds collected in the wild to limit costs and to achieve revegetation over a large spatial scale.

A second restoration technique involves habitat enhancement through the preparation and development of a habitat to support a desired level of biodiversity (Cooke and Johnson, 2002). This technique was applied in the eastern United States of America, where mined areas were restored to create preferred vegetation structure to accommodate various forms of wildlife that depend on vegetation for their food (Wood *et al.*, 2013). Another approach involves the remediation of habitats through replacing the original habitat which has lost its value and function (Vaughn *et al*., 2010). For example, reclamation of mine land in the United States of America included the creation of prairie grassland, woodland and wetlands that became a hotspot for local biodiversity (Kuter, 2013). Mitigation is a fourth kind of restoration technique, whereby conservation of the protected species and ecosystems on mined areas is achieved through law enforcement (Vaughn *et al*., 2010). The Environmental Act in Australia obliges the Environmental Protection Authority to assess and evaluate potential negative impacts of any mining through rigorous Environmental Impact Assessments to highlight areas with high conservation concern (Kuter, 2013).

Additionally, restoration can be an important scientific undertaking in the mining reclamation phase. In South Africa, there is a greater awareness of environmental pollution and other non-compliant incidents at abandoned mine sites, which has led government to adjust budget requirements, and implement proper rehabilitation and mine closure planning (Van Zyl *et al*., 2012). Furthermore, there is a need for mining companies to align with the goals for sustainable development in order to meet their future business needs (Limpitlaw, 2004). Fourie and Brent (2006) suggest that mine rehabilitation should be planned and implemented in a formal project management approach, and that the ecological impacts should be taken into consideration.

During rehabilitation of mined sites, the importance of native plants and proper soil handling techniques to prevent soil erosion is often overlooked (Javurek, 1999; Van Eeden, 2010; Mhlongo and Amponsah-Dacosta, 2015) as public health and safety threats are more prioritised over environmental problems (Mhlongo and Amponsah-Dacosta, 2015). Soil is important for the establishment of vegetation in disturbed landscapes and provides nutrients and water to support plant growth (Bowen *et al*., 2005). Limited availability of topsoil for rehabilitation purposes and poor properties of mine tailings limit vegetation establishment on rehabilitated landscapes due to high erodibility and metal toxicity (Bacchetta *et al*., 2013). Good growth of vegetation correlates strongly with high quality growth media due to its resistance to nutrient loss (Reid and Naeth, 2002). The traditional rehabilitation methods have been proven to stabilise impaired mining landscapes; however they often do not support sustainable rehabilitation and end-land use (Fourie and Brent, 2006). In most cases the end-land use includes, amongst others, nature conservation, agriculture and forestry (Kodir *et al*., 2017; Wang *et al*., 2017). It is therefore important to plan the rehabilitation of the mined area whilst considering the objectives of end-land use to meet the present and future needs of the site, as well as to resemble, at least to some extent the state in which it used to be.

Context of the study: Letšeng Diamond Mine

Letšeng Diamonds is a kimberlite diamond mining company in the Mountain Kingdom of Lesotho in the Mokhotlong district at 3100 m.a.s.l. The mining sector was established in the late 1950s (Makhetha, 2017). Currently, there are several mines that are burgeoning around the country from small scale artisanal mining to large formal mining projects. The industry has brought positive benefits to Lesotho due to beneficial global diamond prices between the years

2000 to 2011. Nevertheless, there has also been a fluctuation in diamond market price due to global financial crises and recovery. In 1961, four mining sites in Lesotho were established as artisanal mining by licensed local people and Letšeng-la-Terai was one of the areas (Central Bank of Lesotho, 2012). The official prospecting on the Letšeng Diamond kimberlite pipe was initiated in 1968 (International Business Publications, 2008). Subsequently, the diamond sector in Lesotho has come to regard Letšeng as one of the big five diamond mines in the country (Central Bank of Lesotho, 2012).

In 2006, a Lesotho registered company (Pty) Ltd was acquired by Gem Diamonds limited with 70% shares and the Government of Lesotho with the other 30% (Madowe, 2013; Letšeng Diamonds, 2016). The current mine lease area is 1674 hectares which stretches across several valleys. The site spans the watershed between the Matsoku and Khubelu River catchments, which forms part of the Lesotho Highlands Water Project. The main operations comprise open pit mining of kimberlite ore and basalt as a waste rock (Fig. 1) from satellite and main pits (Madowe, 2013). Currently, the Letšeng Diamonds mine is concerned with mineral production and recovery stages as outlined by Writer (2015). The sensitive location and ecosystem imply that if environmental management is not effective, then the mining activities may have negative impacts on the objectives of the Lesotho Highlands Water Project.

Figure 1: Mining pits (A) and a section of a waste rock dump (B) at Letšeng Diamonds.

Problem statement

Tailings are a major by-product of the diamond extraction process at Letšeng Diamonds, cover large areas (~151.71 ha) and can be graded as coarse or fine kimberlite. Coarse tailings are transferred with a conveyor-belt system from processing plants to tailings dam walls, whilst fine material is deposited into tailings storage facilities (dams) (Fig. 2) through a piping system. At Letšeng, these dams are constructed in two natural valley floors. Given that tailings are susceptible to wind erosion and easily washed away by storm water runoff, urgent rehabilitation/stabilisation is needed (Meyer, 2017). Initial rehabilitation trials using non-native species proved neither cost effective nor provided the required vegetation cover (pers. obs.). These shortcomings could be ascribed to poor soil conditions of Kimberlite tailings (which are generally made up of sand (82.7%), silt (7.9%) and clay (9.3%), while the associated soil generally consists of 52.2% sand, 27.9% silt and 16.4% clay), and harsh alpine conditions such as an extremely cold winter season (Ntloko *et al.*, 2017). Kimberlite tailings are predominantly sandy with particle sizes ranging from 0.05-2.00 mm and are therefore characterized by good drainage due to high porosity. However, the high drainage potential results in leaching, which furthermore leads to poor soil fertility levels. It is therefore anticipated that the amelioration of kimberlite tailings with topsoil will improve the structure, water retention, and nutrient availability for plants to establish and grow, and moreover, vegetation will increase mineralization, organic matter and microbial activity in the growth media (Stanton-Kennedy, 2008).

According to literature native plant species are often more beneficial for rehabilitation since they can easily adapt to local growing conditions (Muller, 2014; Winkler *et al*., 2014; Santos *et al*., 2017). This study therefore investigates the establishment of native vegetation on coarse kimberlite tailings ameliorated with topsoil to ultimately identify native species which can potentially form the basis of all future restoration efforts at Letšeng. There is limited knowledge of the applicability and practicality of rehabilitation strategies for mine tailings at high altitudes, especially in the Afro-alpine zone at more than 3000 m in Lesotho. Accordingly, this study was initiated to determine the best practices by testing different soil mixtures for the establishment of a variety of plant species at Letšeng Diamond Mine. High altitude grasses were favoured in the selection process as they generally form tussocks as an adaptation to harsh environmental conditions and furthermore are predominant in the Lesotho highlands (Mucina and Rutherford, 2006). They are therefore considered functionally important in the prevention of soil erosion.

Additionally, this study has been aligned with the rehabilitation and closure objectives of Letšeng Diamonds to optimize post closure delivery of practical ecosystem goods and services through the Lesotho environmental management legal obligations (Letšeng Diamonds, 2016). This study is highly significant as it addresses the establishment of native vegetation on rehabilitation sites to stabilise tailings storage facilities. Moreover, it will provide insights on vital ecosystem goods and services, specifically erosion control, resources for livestock production, and human livelihoods in the area. An in-depth scientific study of potential successful restoration practices of kimberlite tailings in an alpine environment will provide necessary insights that could improve rehabilitation efforts of Letšeng, other diamond mines in Lesotho, and potentially the rest of southern Africa.

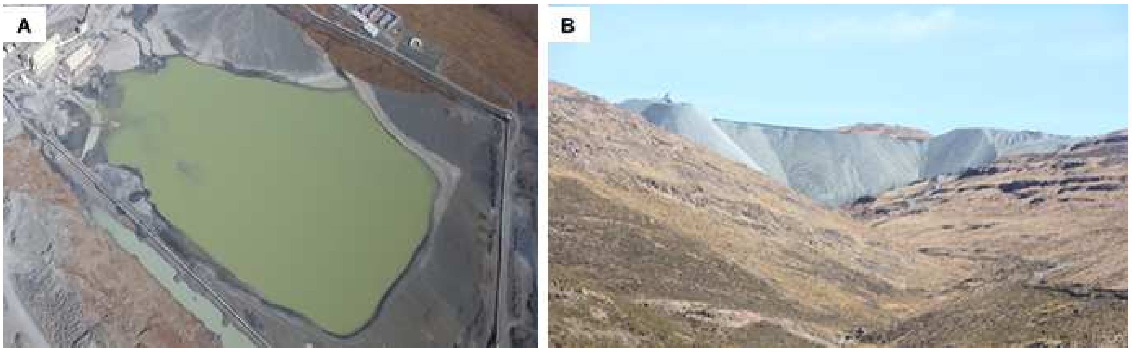


Figure 2: Tailings Storage Facility (dam) with fine kimberlite material (A) and Tailings Storage Facility wall built with coarse kimberlite tailings (B).

Aims

The primary aim of the study was to identify the most suitable species and kimberlite-top soil treatments for rehabilitation purposes. Secondary aims included to (1) test the germination response of various native species on different kimberlite and top soil treatments over two seasons, (2) evaluate the establishment and growth of these selected species, and (3) to assess their germination response as part of an experimental seed mix.

Objectives

Specific objectives of this study were to:

- Determine which species that naturally colonise kimberlite mine tailings at Letšeng have the highest germination numbers on different coarse tailings treatments over a season;
- Quantify whether *T. disticha* establish on coarse tailings treatments after initial high germination rates;
- Select specific coarse tailings treatments that are most beneficial for the growth of *T. disticha* over two seasons;
- Determine whether fine tailings and waste rock are beneficial for the germination of a native seed mix containing *T. disticha*;
- Assess which other species present in the topsoil seedbank enhances the plant diversity across treatments.

Hypothesis

Kimberlite tailings provide an unfavourable soil environment for the germination and establishment of native species (Van Deventer *et al*., 2008; Meyer, 2017). If these tailings are enriched with topsoil, then this artificial soil environment should become beneficial for germination and establishment of both sown and seed bank species.

Thesis layout

This dissertation which encompasses six chapters is in accordance with the guidelines set for a standard dissertation at the North-West University. Cited literature is included as a single list of references at the end of the dissertation.

Chapter 2: Literature Review

An in-depth literature review is provided in this chapter. It provides a backdrop on the establishment of native vegetation on kimberlite tailings, Afro-alpine vegetation of Lesotho and other relevant high-altitude areas in the world, soil management and rehabilitation of mine sites, restoration ecology, biodiversity and rehabilitation management, vegetation monitoring, and invasive plant control.

Chapter 3: Study Area

This chapter describes the study area by presenting a detailed account of the geographical attributes (geology, hydrology, topography, and soils), vegetation, and climatic conditions. The study design, methods, materials and data analyses are presented according to study objectives.

Chapter 4: Results

Survey data related to plant species that naturally colonise kimberlite tailings is presented here. These species are then compared in germination trials to determine which species are most successful on different treatments of topsoil and kimberlite tailings. Plant growth performance of *T. disticha* is investigated across different treatment of topsoil and kimberlite tailings over time. Germination trial results of native species seed mixes are compared over different types of kimberlite tailings (fine or coarse) and waste rock.

Chapter 5: Discussion

This chapter compares the main findings of the study with reference to other studies, with a focus on the germination response of *T. disticha* and its establishment on artificial growth mediums. This chapter also provides findings on the germination ability of different native plant species targeted for use in rehabilitation across different combinations of topsoil and tailings. Findings are integrated and the implications for management are articulated.

Chapter 6: Conclusions

Critical findings from chapter 5 are presented regarding the most suitable species and treatments for the germination and establishment of native species. Recommendations for the use of native plant species in rehabilitation are outlined for future trials and limitations of the study are considered.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

The destruction and fragmentation of habitat threatens biodiversity and is one of the principal reasons for local species extinction (Hanski, 2011; Mullu, 2016). Mining activities often result in degradation of ecosystems, loss of soil structure and functionality, and ultimately loss of biodiversity (Slingenberg *et al*., 2009; Sonter *et al*., 2018). Moreover, soil handling activities such as soil stockpiling usually affect the physical, chemical and biological properties of soil (i.e. soil pH, –structure, aggregate stability and microbial population) (Menta *et al*., 2014; Letheren, 2008; Martinez-Ruiz *et al*., 2007). Such alterations of the top soil increase the probability of unsuccessful rehabilitation at a later stage.

2.2. Mine rehabilitation

Ecological rehabilitation can be used to restore ecosystem function of degraded areas after extractive mining processes (Cummings *et al*., 2005; Rosa *et al*., 2016). Rehabilitation of disturbed mine areas can compensate for the incurred negative impacts by improving the green space of the landscape (Sklenicka and Kašparová, 2008; Wenjun *et al*., 2008). Vegetation cover increases soil stability, enhances cover of organic material and improves ecological functionality of the landscape (Martinez-Ruiz *et al*., 2007; Menta *et al*., 2014).

Various approaches are proposed for the rehabilitation of mine dumps, with the general emphasis being on improving soil conditions (Long, 2010, Vaughn *et al*., 2010). Soil is a key resource that maintains biogeochemical cycles and microorganisms for plant establishment and growth (Hayat *et al*., 2010; Nihorimbere *et al*., 2011; Bhattacharyya, 2015; Lehman *et al*., 2015; Schoonover and Crim, 2015; Li *et al*., 2016; Wang *et al*., 2016). It is therefore important to understand the relationship between soil and plants (Stanton-Kennedy, 2008; Perring *et al*., 2015), and furthermore to determine which factors could inhibit seed germination and plant growth in stressed conditions (Van der Walt *et al*., 2012). Considering that soil particle size influences changes in soil chemical processes such as ion exchange (Stanton-Kennedy, 2008), an important consideration during rehabilitation is the texture of mine tailings as it is the most important medium for vegetation establishment (Passioura, 1991). According to Martinez-Ruiz *et al*. (2007), a suitable substrate improves rehabilitation of natural vegetation.

According to Miles and Tainton (1979), the establishment of vegetation on mine waste, such as kimberlite tailings, is challenging due to a lack of conducive chemical and physical soil conditions for plant growth. A long-term mine reclamation evaluation study in North Dakota has shown that seeded sites yield better vegetation cover than sites left to regenerate on their own (Bohrer *et al*., 2016). Averett *et al*. (2016) concluded that the use of native plant species over non-native species is a better option in high altitude restoration programmes (Adams and Lamoureux, 2005). Furthermore, Novak and Konvicka (2006) stated that rehabilitated land near intact vegetation has an increased advantage to being restored through a process of spontaneous succession, and as a result, those areas may recover faster.

Martinez-Ruiz *et al*. (2007) highlighted the importance of using native plant species over introduced species due to their inherent adaptability to the local environmental conditions. However, it has been shown that successful rehabilitation is greatly dependent on the choice of suitable plant species (O'Dell and Classen, 2009; Tambunan *et al*., 2017). However, Loydi *et al*. (2013) reported that the plant species which produce good ground cover and high biomass could have the potential to dominate and reduce the chance for colonisation by other plant species. In contrast, Hoare (2009) and Carbutt and Edwards (2004) found that tussock grasses of Drakensberg plant communities support species co-existence despite dominating and competing for resources. Protection against harsh weather conditions therefore outweighs competition in these systems (Meyer, 2017).

2.3. Role of vegetation in mine rehabilitation

The re-establishment of vegetation is fundamental to successful mine rehabilitation (Ghose, 2005; Yan *et al*., 2013; Mensah, 2015; Singh and Seema, 2017). Plants stabilise the degraded soil by binding soil particles through their root systems (Ranjan *et al*., 2015; Rossouw, 2016). Furthermore, the canopy cover created by vegetation aids in the reduction and prevention of direct impacts of wind and water erosion (Sheoran *et al*., 2010; Zuazo and Pleguezuelo, 2008; Zhang *et al*., 2014; Li, 2016). As the litter and debris from the re-established vegetation decomposes, it increases soil organic matter content, which in turn helps to enhance biological functionality and different soil nutrient cycles. Additionally, many soil properties such as bulk density, aggregate stability, and water and nutrient retention capacities are improved, inherently enhancing the overall fertility of the degraded land (Sheoran *et al*., 2010; Mensah, 2015). Moreover, the establishment of naturally sustainable ecosystems enhance the aesthetic value of the rehabilitated landscapes (Limpitlaw and Briel, 2014), and also provides water pollution control in natural streams and prevention of dust pollution by particulate matter (Chamber of Mines of South Africa, 2007).

2.4. Rehabilitation with native plant species

Plant community assemblages are primarily influenced by site specific climate, soil, associated and existing plant species, and the type of terrain (Reed *et al*., 2009; Chian *et al*., 2016). When considering which species to use in rehabilitation, it is vital to consider abovementioned ecological aspects, together with local preferences, economy and season. Native species are generally equipped with adaptive traits enabling establishment and survival in unfavourable environmental conditions giving them a competitive edge over non-native species (Stanton-Kennedy, 2008). The use of native species in rehabilitation practices could furthermore improve biodiversity through maintaining native genetic characteristics (Mortlock, 2000; Krauss and He, 2006).

Although knowledge on successful propagation of native vegetation is limited (Marx, 2011), it is known that native seeds has to be collected from local areas to enhance the possibility of a self-sustainable rehabilitation programme (Burke, 2003; Chamber of Mines of South Africa, 2007). Furthermore, a general horticultural knowledge is required to select adequate native vegetation for restoration, especially in high altitude areas (Hansen, 2011). Non-native species provide a well-tested alternative, but have short-term benefits (Burke, 2003). An alternative approach is to utilise non-native species as nurse crops in combination with native species (Burke, 2003; Ren *et al*., 2007). However, non-native species may outcompete locally adapted taxa making the restoration outcomes difficult to predict, especially if the ecosystem loses its resilience (Ewel and Putz, 2004).

2.5. Properties of growth media

2.5.1. Physical properties of growth media

There are four fundamental functions of growth media which are essential for plant growth namely, physical support, moisture, nutrients, and aeration (Nortcliff *et al*., 2006). The basis for selecting a suitable growth medium requires an understanding of physical, chemical and biological properties of the media as it will influence the long-term success of vegetation establishment (Gruda *et al*., 2013).

Water holding capacity is defined as the percentage of pore space that is filled with water after gravitational drainage (Vengadaramana and Thairiyanathan, 2012). A good growth medium holds enough water and has the capability to drain excess water to prevent water logging. Bulk density is a total weight per volume of growth medium (Tokunaga, 2006; Chaudhari *et al*., 2013). A growth medium with adequate bulk density is usually light, and dense enough to physically support plants. Aeration is the percentage of pore space filled with air after excess water is drained from the growth medium (Chaudhari *et al.,* 2013). Well aerated growth media facilitate air circulation and provide sufficient oxygen to plant roots (Gruda *et al*., 2013; Wilkinson, 2014).

Availability of soil nutrients and soil pH are important soil parameters responsible for maintaining growth media productivity (Adams and Lamoureux, 2005). The pH levels of growth media have an effect on nutrient availability to plants. Moreover, it is prudent to understand the Cation Exchange Capacity (CEC) of the growth media as it is a measure of the ability of growth media to hold cations. CEC levels therefore indicate the nutrient storage capacity of growth media. CEC monitoring determines how frequent enrichment should be carried out to maintain soil fertility (Gruda *et al*., 2013; Wilkinson, 2014).

2.5.2. Biological properties of growth media

A good growth medium has the capacity to sustain a high diversity of microorganisms (Tarlera *et al*., 2008; Pasayat and Patel, 2015). These organisms play a role in soil health and may either have a beneficial or pathogenic effect on the vegetation (Kannan *et al*., 2015). Undisturbed soil is characterised by a natural balance where these organisms speed up the process of decomposition and biochemical processes within the growth media, and ultimately improve plant growth and development Gruda *et al*., 2013; (Wilkinson, 2014).

Mine soil is considered to have poor fertility statuses mainly due to poor management practices which is detrimental to soil health (Mushia *et al*., 2016; Vasquesz and Sheley, 2018). However, Stanton-Kennedy (2008) reported that mine soil can be improved through the addition of ameliorants to improve the structure, texture and chemical characteristics potentially making them more suitable for biological processes. However, ameliorating non-soil growth media (such as mine spoil) to achieve optimal plant growth could become expensive when the fertilizer ratio and shortage of certain properties needs to be balanced (Gruda *et al*., 2013).

2.5.3. Soil amelioration

Topsoil is a limited natural resource in the mining industry generally due to initial shallow topsoil or poor soil management practices (Stanton-Kennedy, 2008; Sheoran *et al*., 2010). Additional factors leading to unavailability of topsoil include soil pollution, -contamination, inappropriate storage and wind and water erosion. However, vegetation establishment and growth has been shown to be more effective on growth media containing top soil as it possesses the properties required for plant growth (Medeiros and Drezner, 2012; Gruda *et al*., 2013; Wang *et al*., 2016).

The application of nutrients has been shown to further improve growth media for plants (White and Brown, 2010; Ahmad *et al*., 2016). This is a favoured approach, as Kopittke *et al.* (2016) reported that the establishment of vegetation on unamended growth media results in little or low productivity. As would be expected, deficiencies of essential macro and micronutrients, associated with low pH, are unfavourable for vegetation establishment and growth (Piha *et al.,* 1995). However, Festin *et al.* (2018) stated that low soil pH and the deficiencies of these essential nutrients can be corrected by adding both fertilizers and organic amendments to the soil.

2.6. Relevant regulatory requirements and other mining guidelines

The planning and implementation of mine rehabilitation practices is dependent upon and linked to environmental standards and laws to ensure that the achievement of rehabilitation objectives is reached without harm to the environment and the people (Broemme *et al*., 2015; Kabir *et al*., 2015). Mining in other countries has been characterised by improper rehabilitation planning, implementation and closure (Madalane, 2012), thus resulting in negative environmental and social impacts. These negative impacts require adequate regulatory framework and guidelines in order to be addressed (Kokko *et al*., 2015; Moffet *et al*., 2015). This ultimately becomes a key point for the mining companies to be able to receive a closure certificate by the authorities (Chamber of Mines of South Africa, 2007).

2.6.1. International practice guidelines

International guidelines for mine rehabilitation have been developed and implemented, particularly in more developed countries (Peck, 2005; Blommerde *et al.,* 2015). The International Finance Corporation (IFC) is generally regarded as setting the international benchmark for good mining practices (International Finance Corporation, 2007). Kabir *et al*. (2015) reported that Canada has put in place guidelines and laws for the implementation of mine closure planning. Similarly, South Africa have many guidelines in place, such as the mining and biodiversity standard which is suitable practice guidelines for mining in the Southern African Development Community (SADC) region, emphasising mine closure planning (South African Department of Environmental Affairs *et al.*, 2013).

2.6.2. Letšeng Diamond Mine

Soil in mined areas is usually sparsely vegetated due to unfavourable soil characteristics associated with mine residue deposits (Xia, 2004). At Letšeng Diamond Mine, the environment has been damaged by waste rock dumps, tailings storage facilities, and mining infrastructure.

These destructive activities will increase as production increases. Re-vegetation of mined areas is therefore considered necessary for control of pollution levels and long-term stability of the soil surface.

Letšeng Diamonds strives to align itself with IFC by prioritising biodiversity protection in accordance with the Performance Standard Number 3 (Letšeng Diamonds, 2016). This standard is mainly concerned with pollution control which indirectly relates to rehabilitation of disturbed areas resulting from mining activities (International Finance Corporation, 2007). To protect biodiversity and minimize the impacts on water resources, Letšeng Diamonds implements Performance Standard number 6, which stipulates that protection and conservation of biodiversity, maintenance of ecosystem services and the management of living natural resources are fundamental to sustainable development (International Finance Corporation, 2007). Moreover, this standard is based on the Convention on Biological Diversity and its objectives (International Finance Corporation, 2012), which are relevant to rehabilitation and the protection and sustainable management of living natural resources to maintain the benefits from ecosystem services.

Letšeng Diamonds is co-owned by a London based Gem Diamonds which is listed under the London Stock Exchange. It is subsequently required to carry out its operations and processes in a professional manner in line with globally accepted environmental standards such as ISO14000:2015. The prime purpose of this international standard is the provision of a framework for environmental protection by organizations to enable them to act upon changing environmental conditions in balance with socio-economic needs (ISO, 2015). It is envisaged that a well-planned environmental management system will provide information that will:

- Enhance environmental performance;
- Provide support to accomplish obligations for compliance;
- Share environmental information with interested stakeholders;
- Implement environmentally sound activities and programs;
- Protect the environmental and mitigate adverse impacts;
- Influence products and services design, distribution, disposal and prevention of negative environmental impacts (International Organization of Standardization, 2015).

2.6.3. South African and Lesotho Mining and Environmental legislation

Legal protection of the environment is a fundamental requirement of any environmental law. This can be accomplished through the involvement of various conservation efforts that include rehabilitation of disturbed land. These efforts are practised to achieve sustainable utilization of natural resources. The Constitution of the Republic of South Africa (South Africa, 1996) gives a right to every citizen to live in a clean, healthy and safe environment. Furthermore, the South African National Environment Management Act (NEMA) (South Africa, 1998a) demands the application and implementation of the Mining and Petroleum Resources Development Act (MPRDA) (South Africa, 2002a; Haagner, 2008). The MPRDA requires that the mineral rights be allocated and extended together with opportunities to historically disadvantaged communities, and moreover, it requires that the mining practices should be conducted in a sustainable manner through incorporation of socio-economic and environmental factors.

The MPRDA requires mining companies to alleviate environmental damages related to their mining operations. Furthermore, section 38 (1) of the MPRDA stipulates that the mine area should be restored to its natural or predetermined state or to a land use which conforms to the generally accepted principle of sustainable development. Section 41 of the MPRDA obligates the holder of the prospecting right, mining right or mining permit to make financial provisions for management and rehabilitation of negative environmental impacts. Section 43 (1) of the MPRDA states that the holder of the mining permit will remain liable for any environmental and ecological degradation and management until the Minister issues a certificate to close the operation. NEMA follows the “polluter pays principle” and specifies that whoever was responsible for pollution of the environment is responsible for cleaning the environment both on and beyond the mining lease area. It requires that the environmental aspect and impacts of development together with mitigation measures be considered prior to provision of operation licence.

According to Haagner (2008), the Environmental Conservation Act (South Africa, 1989) provides for the effective protection and controlled utilization of the environment and requires regular reporting from mines on the state of their impacts. Water pollution through contamination of river systems and underground water bodies is regulated under the Conservation of Agricultural Resources Act (CARA) (South Africa, 1983) and the National Water Act (South Africa, 1998b), both requiring that no contamination may flow from mines into the rivers or underground aquifers. Moreover; CARA requires that land with potential for production is maintained, through measures of soil erosion control, protection of vegetation and eradication of invasive plant species. Mining companies are furthermore obliged by the National Environmental Management Air Quality Act (South Africa, 2004) to prevent air pollution. Right of access to information such as the records of private entities under the Promotion of Access to Information Act (South Africa, 2002b) could be disadvantageous to the image of a mining company when they do not comply with environmental standards, as it could result in negative reputational consequences. South Africa has developed mine rehabilitation guidelines that provide a framework for mining companies to be able to deliver a sustainable and legally acceptable end-land use upon completion of their mining operation (Chamber of Mines of South Africa, 2007). The guidelines are designed to be applied in both surface and underground mining, to address the risk of surface and ground water pollution, design the landform and re-vegetation programme that will be acceptable to the needs of the end-land use. However, Fourie and Brent (2006) and Milaras *et al*. (2014) are of the opinion that sustainable mine closure remained a challenge due to inadequate social and environmental management planning and insufficient funding.

The current provisions pertaining to rehabilitation of mine sites in the Lesotho law are not comprehensive and detailed enough to effectively and efficiently regulate the closure and rehabilitation of mine sites. South African regulations are usually applied as good practice by responsible mining companies in Lesotho. In terms of the Lesotho Mines and Minerals Act (Lesotho, 2005), Part VIII, section 58 (1) stipulates that the holder of the mineral right shall in accordance with this Act, or any other applicable law, enforce good mining industry practices and conduct operations in such manner as to preserve the natural environment. Section 58 (4) states that the holder of a mineral right shall ensure that the mineral right area is rehabilitated, and ultimately reclaimed, in a manner acceptable to the commissioner and the authority. Section 58 (5) requires that upon mine closure, the holder of the mineral right shall take measures as required to maintain and restore the top soil of affected areas and otherwise to restore the land sustainability to the condition in which it was prior to the commencement of operation. Section 58 (8) specifies that the holder of a mineral concession shall make adequate on-going financial provision for compliance with his obligations. In addition, research trials will help to provide accurate financial provisions for compliance with obligation to pollution control and rehabilitation. The aim of the Lesotho Environment Act (Lesotho, 2008a), is to provide an environmental law framework for the implementation of environmental management as set out in Part II, section 3 (2) of the Act: ‘Sustainable development is achieved through the sound management of the environment, to reclaim lost ecosystems where possible and reverse the degradation of natural resources and to ensure that appropriate measures are taken to prevent soil erosion.

Relevant specific environmental protection provisions under Part IX of the Act take into account re-forestation and afforestation of hilly and mountainous areas and also conservation of biological diversity. Section 26 (1) specifies that every person has an obligation to prevent pollution of water resources from occurring. Moreover, section 26 (2) declares that where pollution occurs or is likely to occur as a result of activities on land, the person who owns, controls occupies or uses the land in question shall be responsible for taking measures to prevent such pollution from occurring or continuing (Lesotho, 2008b). The key objectives of the Lesotho National Range Resources Management Policy is to rehabilitate and improve the quality of rangeland so as to enhance productivity of livestock and wildlife habitat, to conserve and increase the availability of native plant species for economic, social and cultural utilization, to enhance the aesthetic beauty of the landscape and increase opportunities for sustainable recreation and ecotourism, to develop and implement efficient and effective strategies to avert land and vegetation degradation, and to improve and maintain productivity of rangeland resources at optimum level so as to promote ecosystem balance. One of the strategies is stated as undertaking research to propose appropriate strategies on rangelands management, conservation and rehabilitation of ecosystems (Ministry of Forestry and Land Reclamation, 2014).

Letšeng Diamonds follows a Social and Environmental Management Plan (Letšeng Diamonds, 2016) and implements relevant IFC standards and international treaties where the Government of Lesotho is a signatory. Lesotho adheres to such relevant conventions and protocols such as United Nations Convention on Biological Diversity (UNCBD), United Nations Framework Convention on Climate Change (UNFCCC), Ramsar Convention, and United Nations Convention to Combat Desertification (UNCCD) and Montreal Protocol for the Protection of the Ozone Layer (Ministry of Forestry and Land Reclamation, 2014). Letšeng Diamonds has further developed a register of legal requirements for the operations. This register is checked and discussed with relevant government authorities. Letšeng Diamonds is committed to implement good practice rehabilitation as the lease agreement requires re-establishment of pre-existing conservation values. For example, Letšeng Diamonds maintain and update mine closure plan on an annual basis (Letšeng Diamonds, 2016). Furthermore, the Mine strives for compliance with international standards such as ISO 14001 in its operations (Letšeng Diamonds, 2016).

2.7. Major threats to vegetation

2.7.1. Soil disturbance and pollution

The texture and moisture content of soil can be greatly modified in disturbed sites which could potentially cause alterations in vegetation (Mummey *et al.,* 2002). Soil acidification through pH diminution as a result of chemical contamination can also lead to loss of species (Kumari *et al*., 2010). Contaminants can modify or disturb microorganisms, thus modifying nutrient availability potentially leading to a loss of vegetation. Plant species diversity has been shown to be lower in reclaimed habitat when compared to undisturbed areas (Mummey *et al.,* 2002) However, grass diversity and total cover is less affected by high contaminant concentrations compared to other life forms such as forbs, shrubs and trees (Steinhauser *et al.,* 2009).

Established plants cannot move away from perturbations and will eventually die if their habitat is contaminated by elevated concentrations of heavy metals (Chibuike and Obiora, 2014) as most plants have a low tolerance to metals in the soil (Hodson, 2012). Plants can be affected through direct poisoning, for example, arsenic soil content reduces bryophyte diversity (Steinhauser *et al.,* 2009). Some species are able tolerate elevated metal concentrations in the soil and can colonise polluted mined sites. Some tree roots are not able to develop in contaminated soil layers, subsequently losing anchorage and might be uprooted by the wind when their height and weight increase (Ortega-Larrocea *et al.,* 2010). In general, root exploration is reduced in contaminated areas compared to non-polluted ones.

Adams and Lamoureux (2005) has shown that native perennial species have an advantage in phytoremediation of toxic mine tailings in that their characteristic of slow growth makes them capable to tolerate toxic elements. Siebert *et al*. (2018) reported that some perennial plants have the ability to accumulate high concentrations of metal ions. However, Young (2013) argued that the plant mechanisms for metal tolerances are specific to the metal itself. Consequently, if mine waste contains different metals at toxic levels, it is highly probable that the tolerant species might die becoming inapt for agricultural and pastoral farming practices (Yan, 2013).

2.7.2. Alien and invasive species

Alien invasive species threatens native plant diversity in mining areas (Kumar and Prasad, 2014). Alien plant species have the potential to impact species diversity, native ecosystems and the biological integrity of natural areas (Jeschke *et al*., 2014; Witt *et al*., 2018). A recent study showed that more than 13 000 species have become naturalized outside of their native range as a result of anthropogenic activities (Van Kleunen *et al.,* 2015). It is further reported that invasive plant species can have massive local impacts, reducing native plant diversity, and changing nutrient cycling in the soil (Crowl *et al*., 2008; Pyšek *et al*., 2012). An increase in invasive alien plants in a landscape builds up the fuel loads which could exacerbate the intensity of uncontrolled fires (Mapiye *et al*., 2008).

2.7.3. Overgrazing

Grassland ecosystems around the world have experienced some of the highest rates of destruction and degradation in comparison to any other type of ecosystem (Blair *et al*., 2014). Overgrazing is regarded a serious pressure on the natural environment and a well-known driver of land degradation (Brunner *et al.,* 2008). Poor vegetation cover resulting from overgrazing mitigates water infiltration capacity of the soil, triggers land degradation through soil erosion and the drying up of the land (Papanastasis, 1998; Carmona *et al.,* 2013).

Studies have revealed that overgrazing is a key anthropogenic disturbance on natural grasslands in arid and semiarid ecosystems and plays a pivotal role in shaping the structure and functions of plant communities (Cingolani *et al.,* 2005; Mokotjomela *et al*., 2009). Intensive grazing increases plant mortality and ultimately decrease species richness especially in water and nutrient-limited environments (Fynn and O'Connor, 2000). Overgrazing furthermore reduces the abundance and biomass of palatable species and increases the proportion of unpalatable and grazing-resistant species (Hickman and Hartnett, 2002; Mokotjomela *et al*., 2009). In particular, high levels of soil erosion in the Maloti and Drakensberg mountains have been attributed to overstocking of the domestic livestock that leads to overgrazing (Mokotjomela, 2007; Mokotjomela *et al*., 2009). Other studies have demonstrated that overgrazing can result in grassland degradation (Cooper *et al.,* 2005), although the moderate grazing intensity can promote plant growth and increase species diversity (Sasaki *et al.,* 2008).

2.7.4. Wild fires

Wildfires are uncontrolled and predominantly burn in forests and grasslands. Wildfire has been documented as one of the most wide-spread disturbance agent to impact natural environments (Bowman *et al*., 2009; Kass *et al*., 2011). Wildfires are generally ignited by lightning and falling rocks in mountainous areas. However, sometimes wildfires are started accidently by people being careless with open flames. The negative impacts are recorded at different spatial scales, and they may modify landscape structures (Hochberg *et al*., 1994); increase habitat fragmentation (Cochrane, 2001), and change the species composition of ecosystems (Dıaz-Delgado *et al*., 2004).

CHAPTER 3: METHODS AND MATERIALS

3.1. Study site description

3.1.1. Location

The study was conducted at Letšeng Diamond Mine in the Kingdom of Lesotho (29.0003°S; 28.8619°E). Letšeng Diamond Mine is located in the north eastern parts of Lesotho in the Mokhotlong District (Fig. 3). The mine is situated in the priority conservation area of the Maloti Drakensberg Transfrontier Park and close to uKhahlamba Drakensberg World Heritage Site (Letšeng Diamonds, 2016). The Letšeng Diamond Mine is approximately 3100 meters above sea level, making it the highest diamond mine in the world (Lephatsoe *et al.,* 2014).

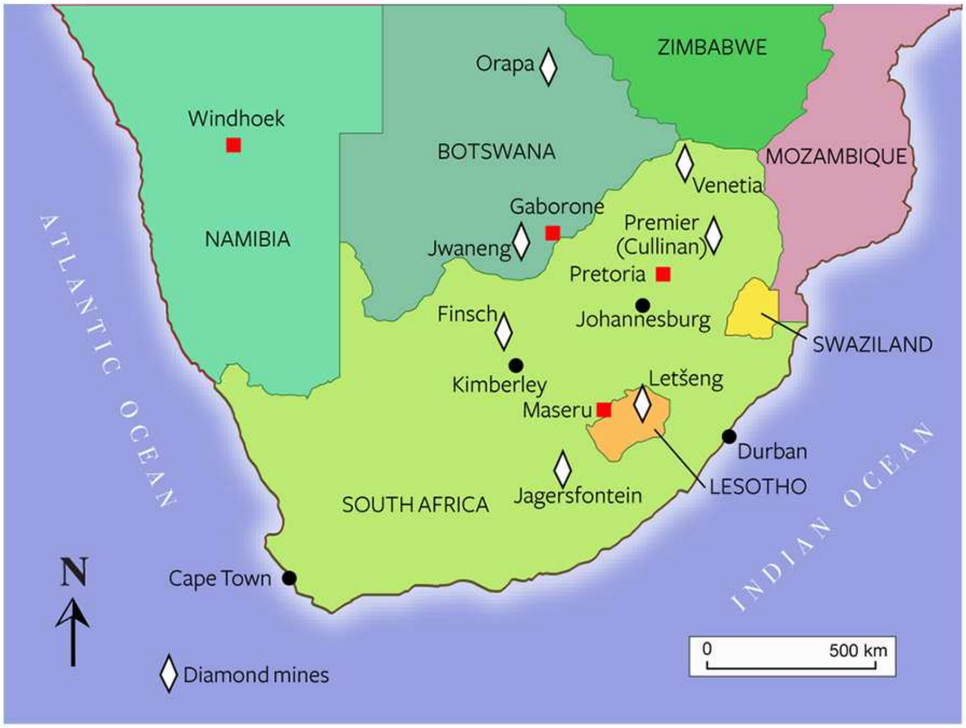


Figure 3: Map indicating the position of Letšeng Diamond Mine in Lesotho (adapted from Shor *et al*., 2015).

3.1.2. Historical land use

The mountain region of Lesotho provides vital ecosystem services to the local people which mainly include pastoral farming and biodiversity (Bawden and Carroll, 1968; Grab and Nüsser, 2001, Mokuku *et al*., 2002). The area is also an important source of water (i.e. catchment) which benefits downstream communities (Letšeng Diamonds, 2016). In the 1960’s there was a considerable number of artisanal mining inhabitants that were diamond diggers and traders that occupied the area (Letšeng Diamonds, 2016).

3.1.3. Current land use

Letšeng Diamond Mine is managed by Gem Diamonds, a British-based global diamond mining company which is a leading worldwide producer of diamonds. The mining method used at Letšeng entails drilling and blasting, loading, and hauling as the main activities (Madowe, 2013; Lephatsoe *et al.,* 2014). The mine lease area has two kimberlite pipes (i.e. the Main Pipe and Satellite Pipe) which cover 17.2 hectares and 5.2 hectares respectively (Lephatsoe *et al.*, 2014; Bowen *et al*., 2009; Fig. 4).

After the treatment process, kimberlite tailings are co-disposed at Patiseng Tailings Storage Facility (TSF) a single compartment valley type storage facility. Coarse residue is transported with a conveyor system to form a cross valley impoundment embankment. The fine residue is pumped as thickened slurry through delivery pipelines and placed in the basin created by the impoundment embankment (Letšeng Diamonds, 2016). Slurry is discharged from the embankment to form a sloping beach and supernatant pool from which water is pumped to the process water dam for reuse in the treatment process. The “old” TSF is no longer in regular use with limited disposal of coarse and fine tailings occurring during breakdowns or maintenance of the conveyance systems. The waste rock dump is a valley fill facility consisting of the Rio Tinto Zinc (RTZ) dump, which occupies the upper valley, and the Qaqa dump, which falls within the Qaqa catchment.

There are other facilities such as a constructed basalt and kimberlite rock fill dam which is primarily a source of raw water for potable use and for make-up in the treatment process. There is also a workshop area which is mainly for management and maintenance of earthmoving equipment, office park, residential areas, and then the remainder is undisturbed landscape.

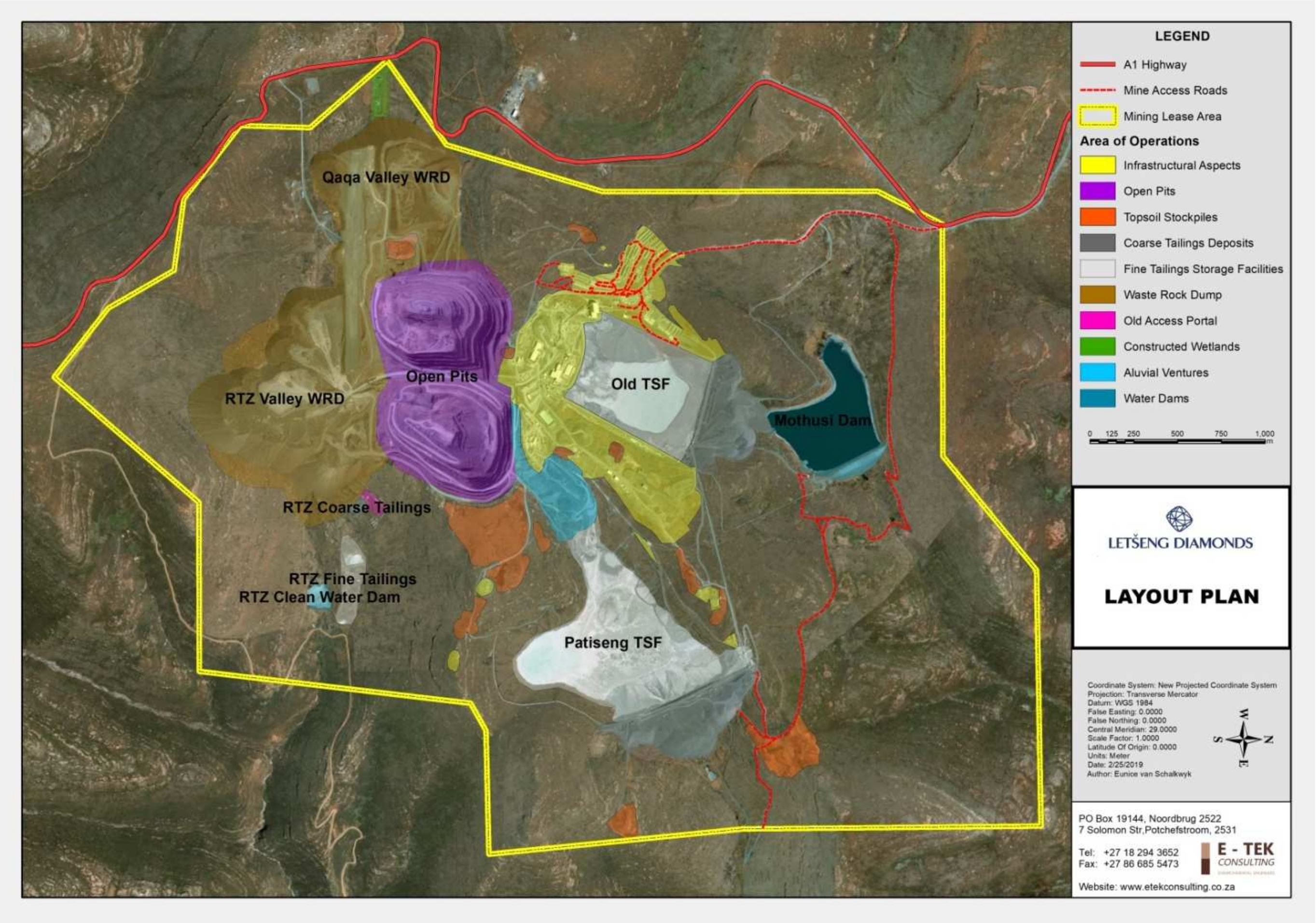


Figure 4: Map of the Letšeng Diamond Mine land uses (adapted from E-Tek Consulting, 2018).

3.1.4. Climate

The mean daily temperature ranges from a minimum of < 0ºC in mid-winter, to a mean daily maximum of >15ºC in midsummer (Letšeng Diamonds, 2016). Snow is common during the winter season which lasts from April to October and temperatures may drop to -20℃ (Lephatsoe *et al.,* 2014). The area holds the record for the lowest temperature ever recorded in Lesotho at -20.4℃ in June 1967 (Mucina and Rutherford, 2006). The study area receives approximately 500–600 mm of rainfall per annum, most of which falls during the summer (Mucina and Rutherford, 2006).

3.1.5. Drainage

The Letšeng Mine lease area straddles the watershed between the Matsoku and the Khubelu drainage basins (Fig. 5). The Mokoalibane, Patiseng and RTZ streams on the eastern aspect drain into the Khubelu River, a tributary of the Senqu River (Gariep Rivier in South Africa). The western extreme of the lease area is drained by a tributary of the Qaqa stream, which flows into the Matsoku River and hence into Malibamats'o River downstream of the Katse Dam.

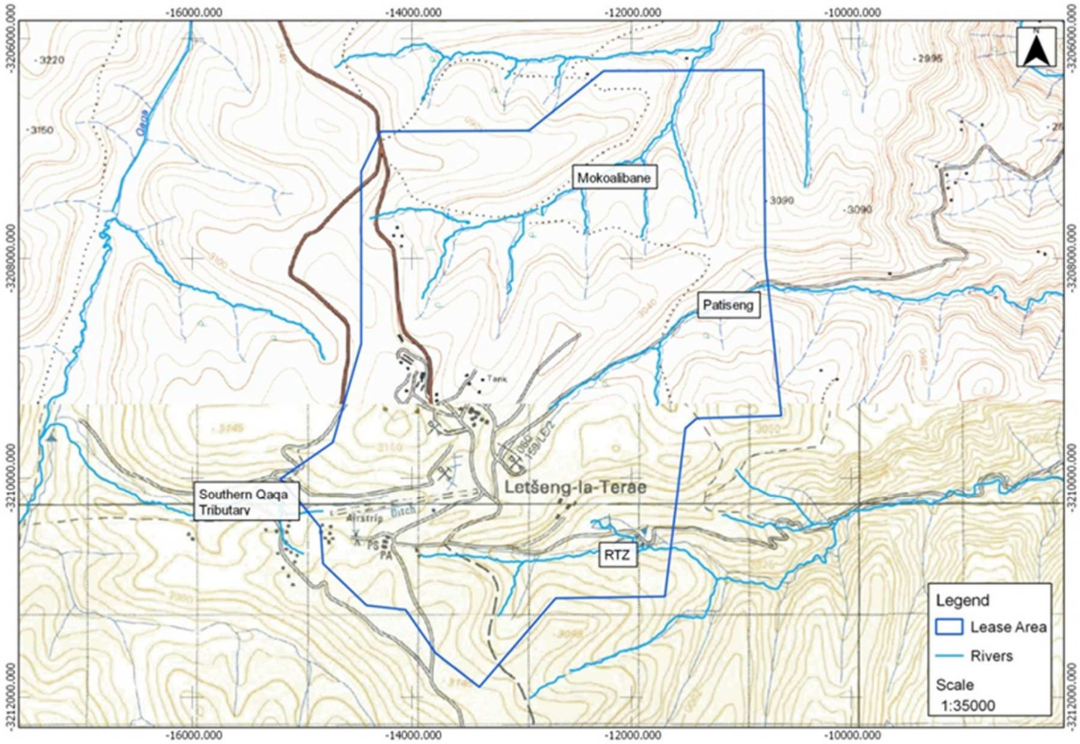


Figure 5: Letšeng Diamond Mine lease area showing the eastern and western drainage streams (adapted from Ross-Gillespie *et al.*, 2018).

3.1.6. Geology and soils

The geology of Lesotho comprises the Karoo Supergroup and lies at the uppermost part of the Karoo basin (Schmitz and Rooyani, 1987; Fig. 6). The Karoo Supergroup varies in age from the Late Carboniferous to Early Permian Dwyka Group to the Middle Jurassic Drakensberg Group (Schmitz and Rooyani, 1987). The Lesotho highlands is dominated by the Drakensberg Group (187–155 Ma) consisting of basaltic lavas referred to as the Lesotho Formation which forms the eastern highlands (Schmitz and Rooyani, 1987). The rocks form a notable range of highly elevated mountains known as the Maloti Mountains in Lesotho (Drakensberg in South Africa). Underlying the basalts is a simple stratification of shale and sandstones belonging to the Beaufort and Stormberg Groups. Dolerite dykes and kimberlite dykes cut through the sediments and lavas (Bloomer and Nixon, 1973; Dempster and Richards, 1973; Bowen *et al.*, 2009).

The host rock for the kimberlite is basalt and the contact between the kimberlite and the lavas is sharp. Kimberlite is a rare ultramafic rock with texture containing distinct crystals embedded in a compact ground mass (Miles and Tainton, 1979). The particle size distribution is usually dominated by sand and gravel with silt and clay contents being very low (Ntloko *et al.*, 2017;

Miles and Tainton, 1979). The soils in this area are Mollisols indicating an udic moisture regime (Office of soil survey, 1979; Nthejane and Ratsele, 2014). The finer soil particles roll down the slopes due to freezing and thawing of the soil material and the soils are shallow with surface rock and rock rubble (Mucina and Rutherford, 2006). These resultant soils from basaltic lavas have even proportions of coarse sand, fine sand, silt, clay and organic matter (Mucina and Rutherford, 2006).

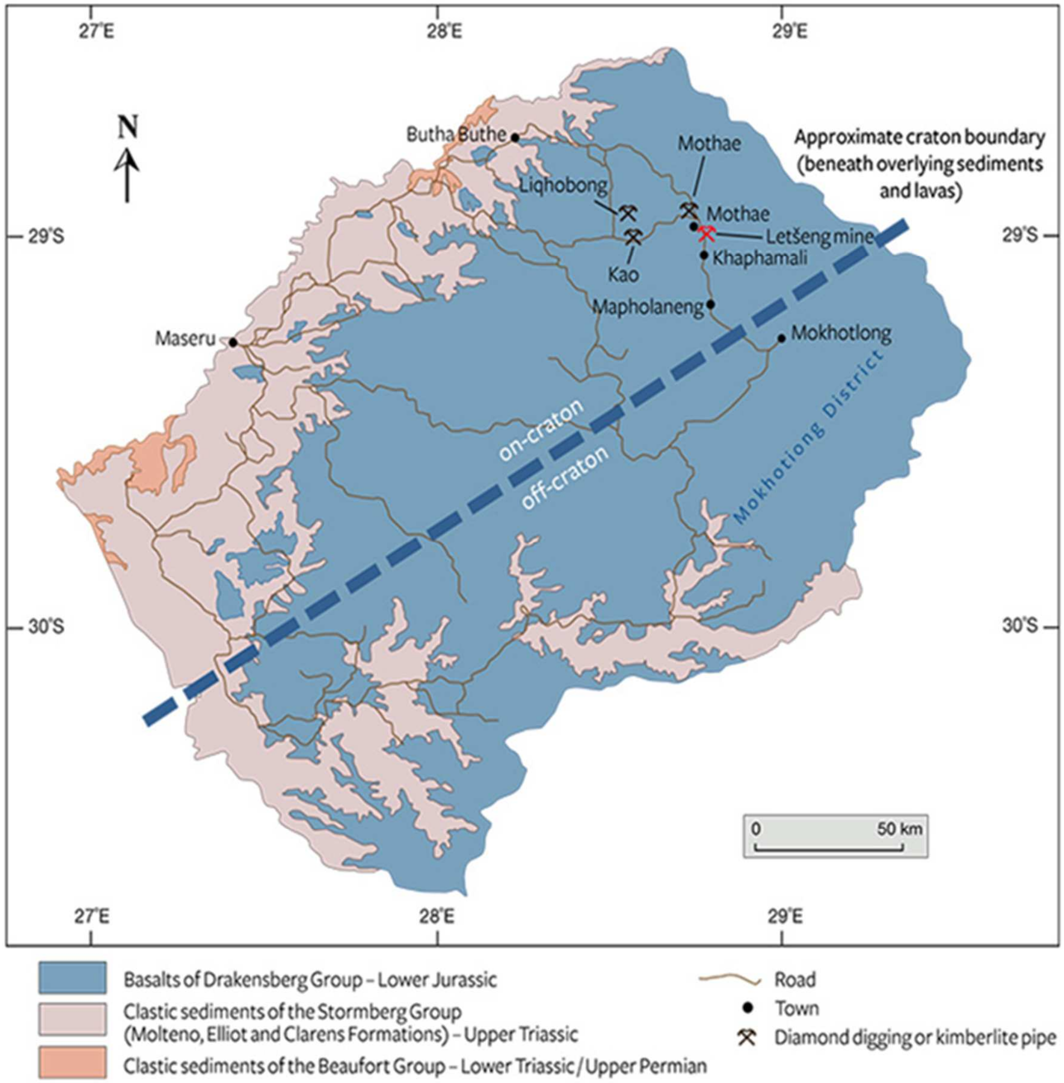


Figure 6: Geological map of Lesotho (adapted from Shor *et al*., 2015).

3.1.7. Vegetation

The historical classification of Lesotho vegetation in the Maloti Mountains includes three grassland types, namely *Festuca* grassland, *Themeda* grassland and scrub (Staples and

Hudson, 1938). According to the contemporary vegetation map (Mucina and Rutherford, 2006; Fig. 7), the study area falls within the Drakensberg Grassland Bioregion, and specifically within the Drakensberg Afro-alpine Heathland and with a portion consisting of Lesotho Highland Basalt Grassland. Vegetation change has occurred over decades, but there are some indications that the vegetation in the study area used to fall within the *Festuca* grassland classification of Staples and Hudson (1938), with the dominant plant species being *Tenaxia disticha* (Nees) N.P.Baker & H.P.Linder*, Festuca caprina* Nees and *F. scabra* Vahl, with the latter being the most palatable for livestock grazing (Chakela, 1999). *Themeda triandra* Forssk. is also a local species although it is rare on the steep southern slopes (Staples and Hudson, 1938; Morris *et al*., 1993). Other co-occurring species are *Agrostis lachnantha* Nees*, Harpochloa falx* (L.f.) Kuntze, *Helichrysum* spp., *Pentaschistis* spp. and *Trifolium burchelianum* Ser.

The wetlands are mostly valley bottom type and mid-slope seeps (Letšeng Diamonds, 2016b). The vegetation outside the mining lease area has been greatly modified by overgrazing (Letšeng Diamonds, 2016). The common wetland plant species include *Cotula paludosa* Hilliard, *Felicia rosulata* Yeo*, F. uliginosa* (J.M.Wood & M.S.Evans) Grau, *Limosella inflata* Hilliard & B.L.Burtt*, Haplocarpha nervosa* (Thunb.) Beauverd*, Ranunculus multifidus* Forssk.*,* and *R. meyeri* Harv. Currently, the fencing of the mining lease area has improved the vegetation cover compared to the adjacent areas which are overgrazed (Letšeng Diamonds, 2016).

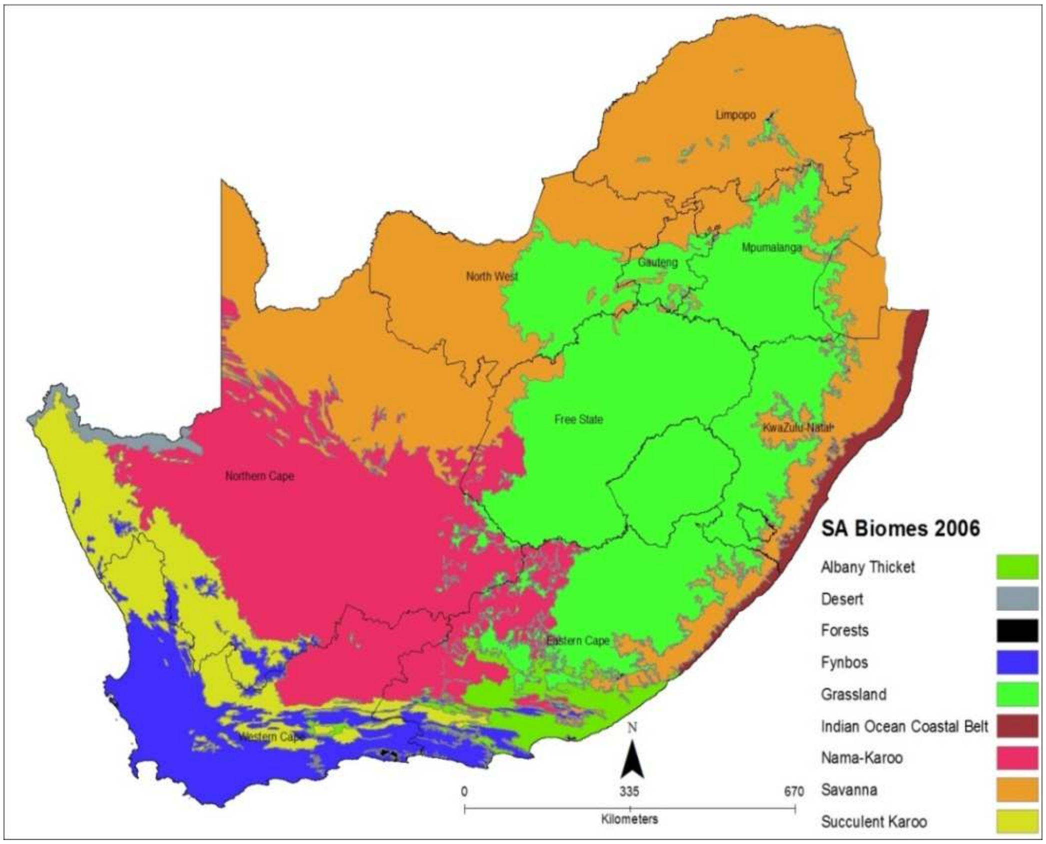


Figure 7: Biomes in South Africa, Lesotho and Eswatini biomes (Mucina and Rutherford, 2006).

3.2. Study design

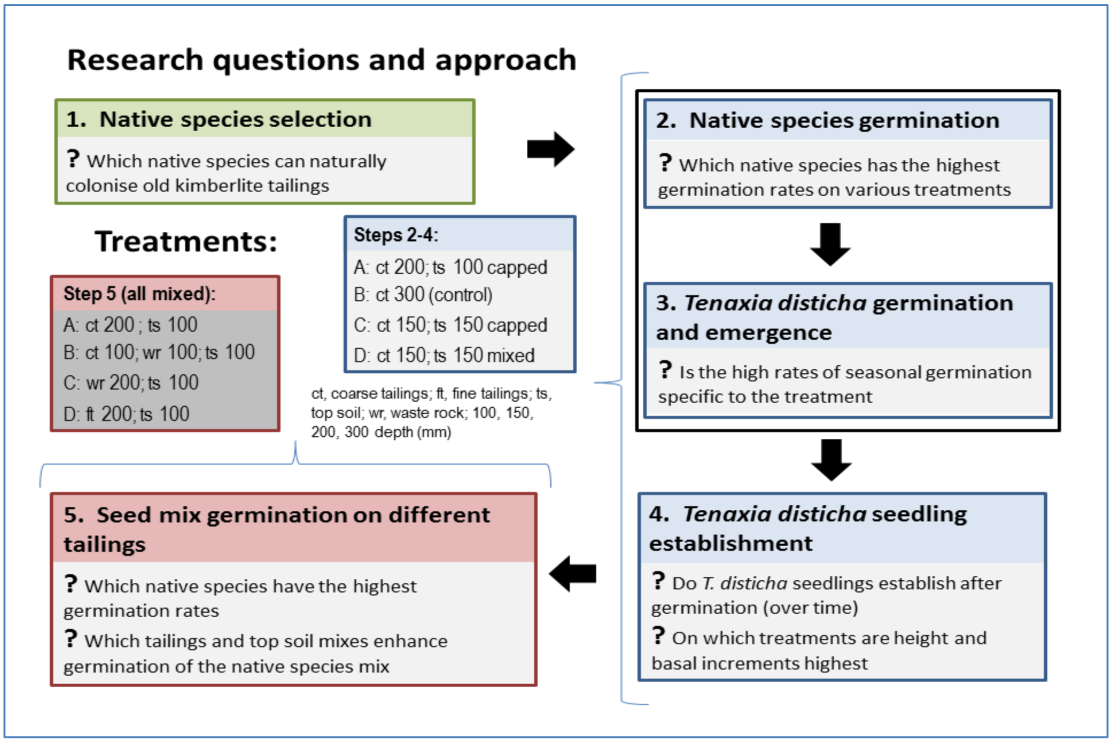


Figure 8: Synopsis of research questions and approach which guided the study.

3.2.1. Choice of suitable plant species

Plant functional traits are considerable measures for successful restoration of degraded land (Giannini *et al*., 2017). Plant functional traits are the physiological, structural, biochemical and morphological characteristics that enables plants to establish and survive in their surrounding environmental conditions (Faucon *et al*., 2017). In this study, the selection of species was based on the native plants with the ability to survive the local environmental conditions, including those of the mine site, and this approach is encouraged by the Chamber of Mines of South Africa (2007).

A reconnaissance survey was carried out in the mine lease area to determine the potential plant species for use in the rehabilitation of course kimberlite tailings (Step 1; Fig. 8), and this approach is supported by Adams and Lamoureux (2005). During the reconnaissance survey, native plant species occurring naturally on disturbed sites were favoured (Fig. 9). A similar approach is supported in O'Dell and Classen (2009); Gallagher and Wagenius (2016); Ranjan *et al*. (2015) and Giannini *et al*. (2017). It means that this would increase the chances for successful rehabilitation.

Figure 9: Natural colonisation by native plant species on disturbed areas covered with coarse kimberlite tailings.

Species chosen for further investigation colonised patches of the mined site. This is a common morphological functional trait typical for high altitude plant species (Isselin-Nondedeu and Spiegelberger, 2014). This morphological adaptation potentially enables these plants to withstand extreme climate conditions such as strong winds and low temperatures, and as such this criterion is widely preferred (Graff and McIntyre, 2014; Hansen, 2011; Adams and Lamoureux, 2005). Hoare (2009) found that tussock grasses in the Drakensberg Mountains allow species to co-exist suggesting that they can facilitate establishment of plant biodiversity during rehabilitation of tailings.

As seeds of native plants are scarce, species exhibiting high seed production were considered. This was expected as an advantage for rehabilitation of larger areas. According to Huxtable *et al*. (2005), seedling recruitment is vital for establishment of native plants, and to ensure recovery on disturbed landscapes. Therefore, local plant species which have ability to regenerate on their own and co-exist with other species were considered during selection (Ranjan *et al*., 2015).

3.2.2. Seed harvesting

Timing of seed harvesting is an important factor for consideration as the phenology of species differ. After suitable species were identified, seeds were harvested within the mine lease area between February and March 2012. Harvesting was carried out manually using hand tools such as sickles, paper bags and plastic bags for collecting the seed. This was similar to the method used by Huxtable *et al*. (2005). The technique of seed harvesting was labour intensive, although it was the only feasible and practical technique as the harvesting sites within mine premises were not accessible by machine but could only be accessed on foot. The advantage for hand harvesting is that seed collectors were able to collect seeds from healthy individuals and avoid seed material of plants with signs of disease (Huxtable *et al*., 2005).

3.2.3. Seed processing

To reduce moisture content, seeds were dried at ambient temperature for 7–14 days by spreading them on paper mats. This drying process was necessary to facilitate separation of seeds and to prevent the growth of fungus, decomposition and ultimately mortality associated with wet seed material (Niaz *et al.,* 2011; Mordecai, 2012). After drying, seeds were separated and sieved to remove husks, stems, soil particles, chuff and any other unwanted materials (Fig. 10). Processed seeds were weighed using an electronic balance scale, placed in clean paper bags, labelled and stored in a seed store at ambient temperature.

Figure 10: Seed processing at Letšeng Diamond Mine seed store.

3.2.4. Seed storage

The facility where seeds were stored (Fig. 11) was well ventilated, dry and kept free from rodents to maintain seed viability and vigour. Climatic conditions at the mine are generally cool throughout the year which is ideal for the maintenance of seed viability during seed storage

(Chala and Bekana, 2017). Cool conditions furthermore enhance the persistence of seed dormancy (Chala and Bekana, 2017).

Figure 11: Seed storage facilities at Letšeng Diamond Mine.

3.2.5. Rapid germination experiment

Successful germination and seedling establishment are crucial in the rehabilitation of disturbed landscapes (Kövendi-Jakö *et al*., 2017). A rapid small-scale observational germination experiment was carried out in January 2012 (Step 2; Fig. 8). The objective of this experiment was to assess the ability of native plants to germinate and produce high numbers of seedlings on kimberlite tailings. Since large numbers of seedlings increase the probability of seedling survival and establishment (Crawley, 1990), the trial species with highest number of seedlings was considered to be ideal for rehabilitation. Kimberlite tailings aggregates (fine tailings, coarse tailings and topsoil) were collected from the Tailings Storage Facility (TSF) and topsoil was collected from a stockpile on the mine premises. Three separate treatments of these growth mediums were prepared and placed in wooden boxes. Each wooden box had a surface area of 1.5 m² (1.23 m x 1.78 m).

Seeds from the selected plant species were sown manually in the boxes and raked into the soil. There was no irrigation for the duration of the experiment. Seedling germination data was collected weekly from the first date of seedling emergence in each treatment until the time when no further seedling emergence was observed.

Results from the germination experiment together with the field observations guided the next phase which entailed the formulation of a more structured experimental research design. High germination and seedling establishment of *Tenaxia disticha* suggested that it was a key native species applicable to be used in the next experiment (Step 3; Fig. 8). The tussock growth form of this grass species is furthermore known to have quick soil binding characteristics, especially in surface soil due to their fibrous root systems (Ranjan *et al*., 2015). From field observations, *T*. *disticha* grew naturally into dense tufts leading to stabilization of the slopes surrounding the mine. Most of the seedlings from other species wilted during the winter. However, *T*. *disticha* seedlings were able to persist during winter conditions and the poor physical and chemical properties of the kimberlite tailings.

3.2.6. Data analysis

Since the rapid germination trial data was not normally distributed, a nonparametric statistical model was applied to select the model species. Trial species with highest number of seedlings were considered be ideal for rehabilitation purposes. A Kruskal-Wallis Analysis of Variance was applied to determine significant differences in the number of seedlings between species. Bonferroni adjustment procedure was furthermore applied to seedling data to distinguish significant differences in means of the seedlings of individual plant species.

3.3. Germination and plant performance experiment

3.3.1. Experimental layout

A subsequent nursery experiment followed the observational experiment to test the validity of the observations made regarding *T*. *disticha* (Steps 3 and 4; Fig. 8). The experiment was designed as a complete block design with split plots, replicated seven times (28 experimental units in total). Rectangular experimental plots covered an area of 3.66 m^2 (length of 3 m and width of 1.22 m (Fig. 12)) and a total volume of 1.098 m^3 (3 m x 1.22 m x depth of 0.30m). Mine waste residue (coarse kimberlite tailings) and topsoil were the two growth media used in the experiment. Treatment combinations were designed as follows:

- Treatment A – 200 mm of coarse kimberlite tailings capped with 100 mm of topsoil;
- Treatment B – 300 mm of coarse tailings only (control);
- Treatment C– 150 mm of coarse kimberlite tailings capped with 150 mm of topsoil;
- Treatment D– 150 mm of coarse kimberlite tailings mixed with 150 mm of topsoil.

Each treatment block and replicate were labelled systematically on a simplified sequence to ensure accuracy.

Experimental Treatments	**Replicate 1**	**Replicate 2**	**Replicate 3**	**Replicate 4**	**Replicate 5**	**Replicate 6**	**Replicate 7**
Treatment A	CT (200 mm) + TS (100 mm)	CT (200mm) + TS (100mm)	CT (200mm) + TS (100mm)	CT (200mm) + TS (100mm)	CT (200mm) + TS (100mm)	CT (200mm) + TS (100mm)	CT (200mm) + TS (100mm)
Treatment B (control)	CT (300 mm) only	CT (300 mm) only	CT (300 mm) only	CT (300 mm) only	CT (300 mm) only	CT (300 mm) only	CT (300 mm) only
Treatment C	CT (150 mm) + TS (150 mm)	CT (150 mm) + TS (150 mm)	CT (150 mm) + TS (150 mm)	CT (150 mm) + TS (150 mm)	CT (150 mm) + TS (150 mm)	CT (150 mm) + TS (150 mm)	CT (150 mm) + TS (150 mm)
Ttreatment D	CT (150 mm) + TS (150 mm) mixed	CT (150 mm) + TS (150 mm) mixed	CT (150 mm) + TS (150 mm) mixed	CT (150 mm) + TS (150 mm) mixed	CT (150 mm) + TS (150 mm) mixed	CT (150 mm) + TS (150 mm) mixed	CT (150 mm) + TS (150 mm) mixed

Figure 12: Germination and plant performance experimental layout for *Tenaxia disticha*. CT = Coarse Tailings, TS = Top soil.

3.3.2. Seed sowing

Seeds were manually sown in January 2013 across all treatments by lightly spreading the seed material over each well prepared plot and raked in. Equal amounts of *T*. *disticha* seeds (2.56 g) were planted in each plot according to the recommended seeding rate of 7g/10m^2 (7 kg/ha) for *T*. *disticha* (E-Tek Consulting, 2013).

3.3.3. Quadrat sampling

Germination and plant performance were assessed using a fixed plot quadrat method following Meyer (2017). A fixed plot quadrat with an area of 1.51 m^2 (0.63 m x 2.40 m) as recommended by Hill *et al*. (2005) was positioned in the centre of each treatment (planting box) taking care to avoid the edge effect (Kotanen, 1997; Lin and Cao, 2009; Ruwanza, 2018). This allowed for representative sampling of each treatment.

3.3.4. Data collection: germination

The collection of seedling count data commenced during the first week of seedling emergence and was recorded on a weekly basis until no new seedlings emerged (Step 3; Fig. 8). Counts were carried out in each fixed plot quadrat throughout all treatments for a period of thirteen weeks between January and April 2013.

3.3.5. Data analysis

To account for pseudo-replication and thus heterogeneity of variance, seed germination data were analysed as the averages of individual treatment replicates using a General Linear Model Analysis of Variance (GLM – ANOVA). Seed germination data of *T*. *disticha* was normally distributed (Fig. 13). GLM-ANOVA with Poison error was applied to the data to determine differences in germination across treatments. Different treatments were specified as the predictor variables, whilst the total average germination was the response variable. One-Way ANOVA was used to compare germination between the weekly germination totals in different treatments compared to the experimental control. Dunnett *post hoc* test was applied to distinguish significantly different means of the seedling germination (i.e. totality and speed) in the treatments compared to the experimental control.

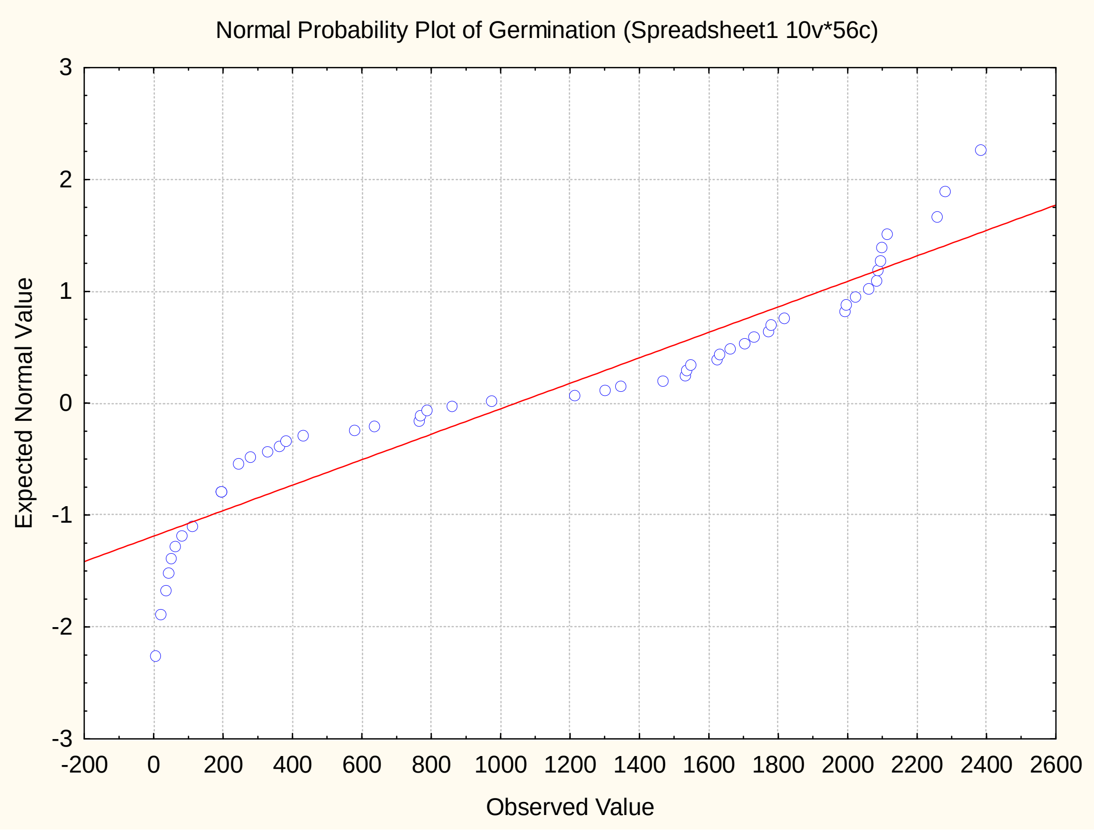


Figure 13: Normal QQ-plot for seed germination of *Tenaxia disticha*.

3.3.6. Data collection: plant performance

The performance of seedlings was further assessed using a functional trait-based approach. Plant functional traits are considered good surrogates for ecosystem function (Díaz and Cabido, 2001). Plant traits related to the successful establishment of plants on degraded soil were considered for this study and included plant height and basal width. An individual plant was defined as a set of leaves and stems growing from the same bunch (Craine *et al*., 1999). Plant growth performance (height and basal width) measurements were taken over a period of twelve months from 2014-2015 (Step 4; Fig. 8). Measurements were carried out in intervals of six months (Period 1: April 2013, Period 2: October 2014 and Period 3: April 2015). Rainfall and temperature data were collected from the weather station at the study site.

3.3.7. Data analysis

To determine seedling growth performance of *T*. *disticha*, height and basal width of surviving seedlings were used as a proxy for seedling success in each treatment. Similar to analysis of germination data, plant performance data were analysed as the averages of individual treatment replicates using a General Linear Model Analysis of Variance (GLM – ANOVA).

Seedling growth performance data were normally distributed (Fig. 14 a & b). The parametric statistical model of analyses was applied to determine the impact of different treatments of seedling growth over three time frames of the experiment. A GLM with a repeated measures design was applied since treatment plots were nested within the three different periods of measurements, and therefore used as predictor variables. The height and basal width of the seedlings in each plot were specified as response variables. A Bonferroni adjustment procedure was furthermore applied to distinguish between significantly different means of the germination and significant interactions between periods of measurements and each of the treatments.

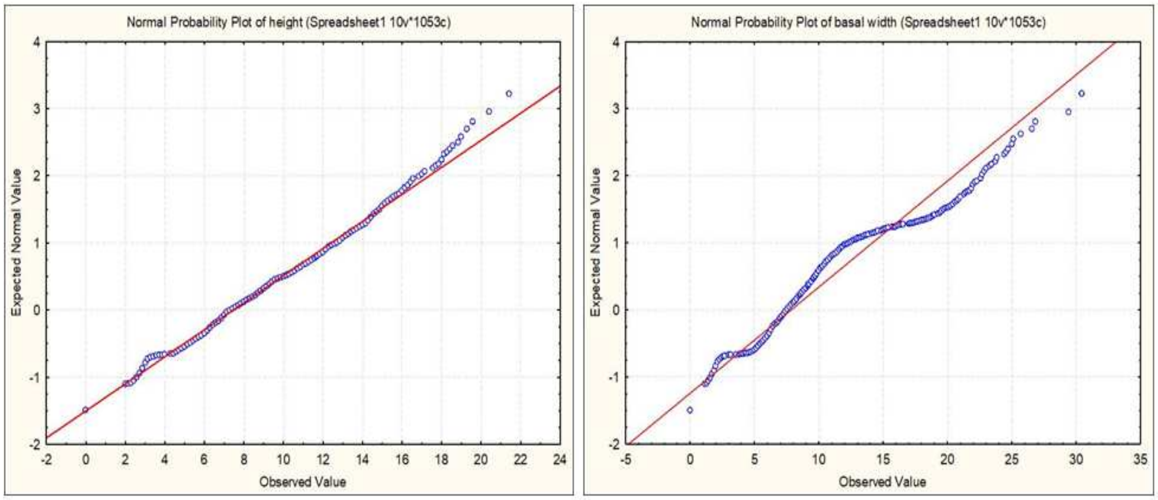


Figure 14: Normal QQ-plots of plant height (a) and basal width (b) for *Tenaxia disticha* seedlings.

3.4. Plant diversity experiment

3.4.1. Experimental layout

Establishment of plant species diversity through a seed mix is associated with increased system diversity as pollinators are attracted to diverse plant species at the different flowering periods (Ghazoul, 2006; Albrecht, 2012). Furthermore, diverse plant communities are more resistant to invasions by diseases, insect and alien species (DiAllesandro *et al*., 2013; Grman *et al*., 2013). As a result, this could enhance the success of species facilitation and rehabilitation.

The experiment was designed as a complete block design with split plots replicated five times and one experimental control per treatment (i.e. a total of 24 experimental units) (Fig. 15). Similar to the *T. disticha* trials, experimental plots were rectangular and 3.66 m² in area and 1.098 m³ in volume. The growth media used in this experiment included mine waste residues (i.e. coarse kimberlite tailings, waste rock (basalt), fine kimberlite tailings) and topsoil. The treatment combinations were designed and filled up with growth media as follows:

- Treatment A– 200 mm of coarse kimberlite tailings mixed with 100 mm of topsoil per replicate;
- Treatment B– 100 mm of coarse kimberlite and 100 mm waste rock (basalt) mixed with 100 mm topsoil per replicate;
- Treatment C– 200 mm of waste rock (basalt) mixed with 100 mm of topsoil per replicate;
- Treatment D– 200 mm of fine kimberlite tailings mixed with 100 mm of topsoil per replicate.

The control for each treatment consisted of coarse kimberlite tailings only. Each of the treatment blocks and replicates were labelled systematically on a simplified sequence to ensure accurate data collection process.

Experimental treatment	**Replicate 1**	**Replicate 2**	**Replicate 3**	**Replicate 4**	**Replicate 5**	**Experimental control (X5)**
Treatment A	CT 200 mm + TS 100 mm (well mixed)	CT 200 mm + TS 100 mm (well mixed)	CT 200 mm + TS 100 mm (well mixed)	CT 200 mm + TS 100 mm (well mixed)	CT 200 mm + TS 100 mm (well mixed)	CT only
Treatment B	CT 100 mm + WR 100 mm + TS 100 mm (well mixed)	CT 100 mm + WR 100 mm + TS 100 mm (well mixed)	CT 100 mm + WR 100 mm + TS 100 mm (well mixed)	CT 100 mm + WR 100 mm + TS 100 mm (well mixed)	CT 100 mm + WR 100 mm + TS 100 mm (well mixed)	CT only
Treatment C	WR 200 mm + TS 100 mm (well mixed)	WR 200 mm + TS 100 mm (well mixed)	WR 200 mm + TS 100 mm (well mixed)	WR 200 mm + TS 100 mm (well mixed)	WR 200 mm + TS 100 mm (well mixed)	CT only
Treatment D	FT 200 mm + TS 100 mm (well mixed)	FT 200 mm + TS 100 mm (well mixed)	FT 200 mm + TS 100 mm (well mixed)	FT 200 mm + TS 100 mm (well mixed)	FT 200 mm + TS 100 mm (well mixed)	CT only

Figure 15: Experimental layout of the plant diversity experiment. CT = Coarse tailings, TS = Top soil, WR = Waste rock, FT = Fine tailings.

3.4.2. Preparation of seed mixture

The seed mix for this trial was made up of pioneer species known for their rapid germination (*Cotula paludosa, Dierama robustum* N.E.Br. and *Selago flanaganii* Rolfe), as well as species which occur naturally on kimberlite tailings (*Harpochloa falx, Hesperantha schelpeana* Hilliard & B.L.Burtt, *Sisymbrium turczaninowii* Sond. and *Tenaxia disticha*). The mixture was further supplemented with species that have a preference for wetter habitat on fine kimberlite tailings (*Carex glomerabilis* V.I.Krecz., *Athrixia fontana* MacOwan and *Kniphofia caulescens* Baker).

The seed mixture therefore comprised of ten native species (Fig. 16 &17; Table 1). Seeds of each species were weighed using an electronic balance and calculated as per the recommended seeding rate of 7g/10m^2 followed at Letšeng Diamond mine (E-Tek Consulting, 2013). The area of each treatment plot (3.66 m^2) was seeded with 2.6 g of each plant species. Each plot was sown with seeds from the 10 native plant species. The seed mixture was prepared by hand mixing and thoroughly shaking all the seeds together in small containers.

Figure 16: Plant diversity seed mixture containing the seeds of ten species typical of natural vegetation at Letšeng.

Table 1: Species composition of the native plant diversity seed mixture.

Scientific name	Common name	Family	Growth form
Athrixia fontana	Sepinare	Asteraceae	Perennial
Carex glomerabilis	Foxtail sedge	Cyperaceae	Perennial
Cotula paludosa	Button weed	Asteraceae	Perennial
Dierama robustum	Harebell	Iridaceae	Perennial
Harpochloa falx	Caterpillar grass	Poaceae	Perennial
Hesperantha schelpeana	-	Iridaceae	Perennial
Kniphofia caulescens	Red hot poker	Asphodelaceae	Perennial
Selago flanaganii	-	Scrophulariaceae	Perennial
Sisymbrium turczaninowii	Russian rocket	Brassicaceae	Annual
Tenaxia disticha	Mountain wire grass	Poaceae	Perennial

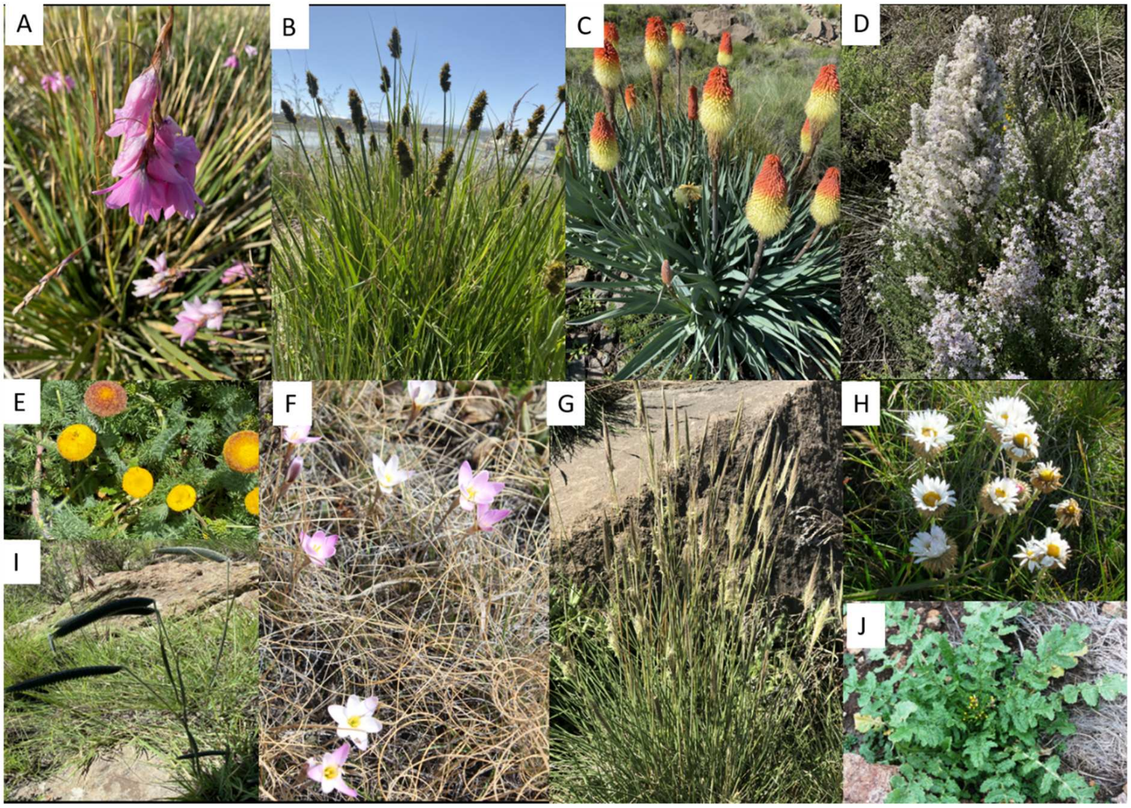


Figure 17: The ten native plant species added to the plant diversity seed mix (*Dierama robustum* (A), *Carex glomerabilis* (B), Kniphofia caulescens (C), *Selago flanaganii* (D), *Cotula paludosa* (E), *Hesperantha schelpeana* (F), *Tenaxia disticha* (G), *Athrixia fontana* (H), *Harpochloa falx* (I) and *Sisymbrium turczaninowii* (J).

3.4.3. Seed sowing

Equal amounts of seed mixture were sown in December 2016. Manual sowing was carried out by lightly spreading the seed mixture over each well prepared plot, followed by raking.

3.4.4. Quadrat sampling

Fixed plots were marked with permanent wooden markers within all the treatment plots. Counts of seedling germination (i.e. emergence) were carried out on a weekly basis from first date of emergence in a fixed quadrat (Meyer, 2017; Chacon and Cavieres, 2008). Seedlings were counted in each fixed plot across all treatments for the full germination period.

3.4.5. Data collection

Counting of seedlings (Step 5; Fig. 8) was aligned with the three periods determined by seasonal conditions (i.e. precipitation and temperature). Seedling counts were initiated upon first week of seedling emergence throughout the first active germination and growth period (season) which was from February to March 2017. The second monitoring period was in winter months from May to June 2017. There was no seedling count carried out during the months of July to October 2017 as it was a cold and dry period with no sign of active plant growth. The third monitoring period of seedling count resumed in November 2017 to April 2018, during the second active growing season. The third monitoring period was carried out within a second full growing season of six months.

3.4.6. Data analysis

Total seedlings were compared across treatments through applying a General Linear Model Analysis of Variance (GLM – ANOVA) to determine which growth medium was more favourable for trial plant species, and to furthermore determine which species were most likely to establish on the kimberlite dumps. Growth medium (i.e. treatment) and plant species were specified as predictor variables, whilst total number of seedlings was considered as the response variable. Where statistically significant results were obtained from the GLM, a Bonferroni adjustment procedure was applied to distinguish significantly different means between the independent groups.

Species composition of each transect and plot within the different treatments were compared using non-metric multidimensional scaling (NMDS) configured in Primer 6 software (Clarke and Gorley, 2006). Frequency data was used to perform ordinations. These analyses were performed using Bray–Curtis similarity. NMDS stress functions indicate a good fit or match between two data points (Clarke and Gorley, 2006). For 2-dimensional ordinations, the stress value increases with decreasing dimensionality and increasing quantity of data. Stress values can be interpreted as follows: (1) a stress value of ≤ 0.05 represents an excellent depiction with no likelihood of misinterpretation, (2) stress values smaller than ≤ 0.1 represents a good ordination, (3) stress values smaller than ≤ 0.2 still provides a useful good ordination, but cross-checks with other techniques are recommended. Stress values that are larger than 0.2 are randomly placed and bear very little relation to the original similarity ranks.

3.5. Biology of *Tenaxia disticha*

Tenaxia disticha (syn. *Merxmuellera disticha* (Nees) Conert) (Fig. 18) is a perennial bunch (tussock) grass in the Poaceae family. Its spikes are arranged alternatively in two vertical rows on opposite sides of an axis (distichous spikelet) and lower glumes (Ellis, 1994). It has wiry leaves and an oblong inflorescence. *Tenaxia disticha* has three forms (typical form, Drakensberg form and Alpine bog form), each with a distinctive leaf anatomy and epidermal structure. However, Ellis (1994) and van Oudtshoorn (2004) substantiated that the distribution of this species is dependent on the form. Different forms are determined by altitude, geology and soils. This species follows the C_3 photosynthetic pathway which is commonly found in high altitude areas (Morris *et al*., 1994; Robinson, 2014). Species that follow the C_3 photosynthetic pathway have competitive advantages over plants that follow the C_4 photosynthetic pathway, when related to harsh environmental conditions in the mountain areas, such as the Maluti Mountains of Lesotho (Morris *et al*., 1994; Robinson, 2014). Germination of grasses occurs over a range of temperatures; however, C_3 grasses tend to germinate better at low temperatures compared to C_4 grasses. *Tenaxia disticha* is able to co-exist with various plant species in different plant communities, however, it has the potential to outcompete other species and dominate (Ellis, 1994; Van Oudtshoorn, 2004). Van Oudtshoorn (2004) argues that at young age, *T*. *disticha* provides good grazing. It has a competitive advantage over other species by remaining partly green in winter and is therefore a good grazing alternative (Zacharias, 1990).

Tussock grasses are generally resilient and able to regrow after defoliation by livestock grazing or fire (Robinson, 2014). The plant composition of the vegetation after rehabilitation depends largely on the objectives set for the rehabilitation programme. Options at such altitude could be to create a plant community which will meet the requirements of the final end-land use such as livestock grazing or a nature reserve that will support native flora and fauna (Bell, 2004). In both cases, *T*. *disticha* is a suitable plant species for early vegetation establishment and erosion control for this study.

Figure 18: ***Tenaxia disticha*** **growing in its natural habitat at Letšeng Diamond Mine.**

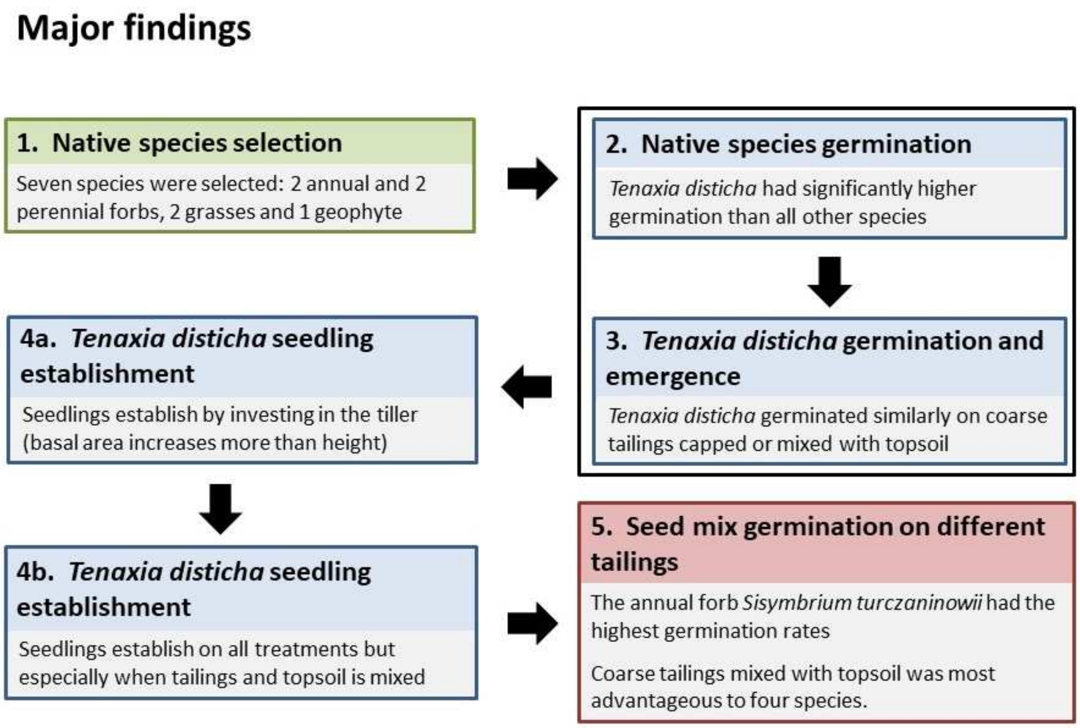
CHAPTER 4: RESULTS

4.1. Native species selection and germination trials

After reconnaissance surveys, seven native species (Table 2) were selected for seed germination trials based on their ability to naturally colonise coarse kimberlite tailings (Step 1; Fig. 8).

Table 2: Selected species that naturally colonise kimberlite tailings at Letšeng Diamond Mine.

Scientific name	**Common name**	**Family**	**Life history**	**Adapted to the site**	**Morphological character**	**Present on tailings**	**Optimum seed harvest**	**Ability to co-exist**
Harpochloa falx	Caterpillar grass	Poaceae	Perennial	Yes	Herbaceous, bunch and spreading with narrow leaves	Yes	Low	Yes
Helichrysum trilineatum	-	Asteraceae	Perennial	Yes	Small bush with multiple stems	Yes	Low	Yes
Hesperantha schelpeana	-	Iridaceae	Perennial	Yes	Herbaceous, small and narrow crown	Yes	High	Yes
Pentzia cooperi	Large Karoo bush	Asteraceae	Perennial	Yes	Small bush with multiple stems	Yes	High	Yes
Senecio asperulus	Ragwort	Asteraceae	Annual	Yes	Herbaceous, broad leaved with broader crown	Yes	Low	Yes
Sisymbrium turczaninowii	Russian rocket	Brassicaceae	Annual	Yes	Herbaceous, broad leaved	Yes	High	Yes
Tenaxia disticha	Mountain wiry grass	Poaceae	Perennial	Yes	Herbaceous, bunch with narrow leaves	Yes	High	Yes



Seven species were selected: 2 annual and 2 perennial forbs, 2 grasses and 1 geophyte

Tenaxia disticha had significantly higher germination than all other species

Tenaxia disticha germinated similarly on coarse tailings capped or mixed with topsoil

Seedlings establish by investing in the tiller (basal area increases more than height)

Seedlings establish on all treatments but especially when tailings and topsoil is mixed

The annual forb *Sisymbrium turczaninowii* had the highest germination rates

Coarse tailings mixed with topsoil was most advantageous to four species.

Figure 19: Flow chart summarizing the selection of native species and germination trails used in this study.

All seven species were subjected to the same soil and tailings conditions and tested for their germination ability on fine and coarse tailings, and waste rock (Step 2; Fig. 19). *Tenaxia disticha* revealed the highest germination ability ($H_{(6\ 126)} = 68.2$; $p < 0.001$; Fig. 20). The only geophyte included in the study, *Hesperantha schelpeana* exhibited the second highest germination ability, followed by the perennial grass *Harpochloa falx* and the forb species *Pentzia cooperi* and *Sisymbrium turczaninowii*. Due to their low germination ability these species were excluded from the next step of the study but were acknowledged for the native plant seed mix used in the final trials.

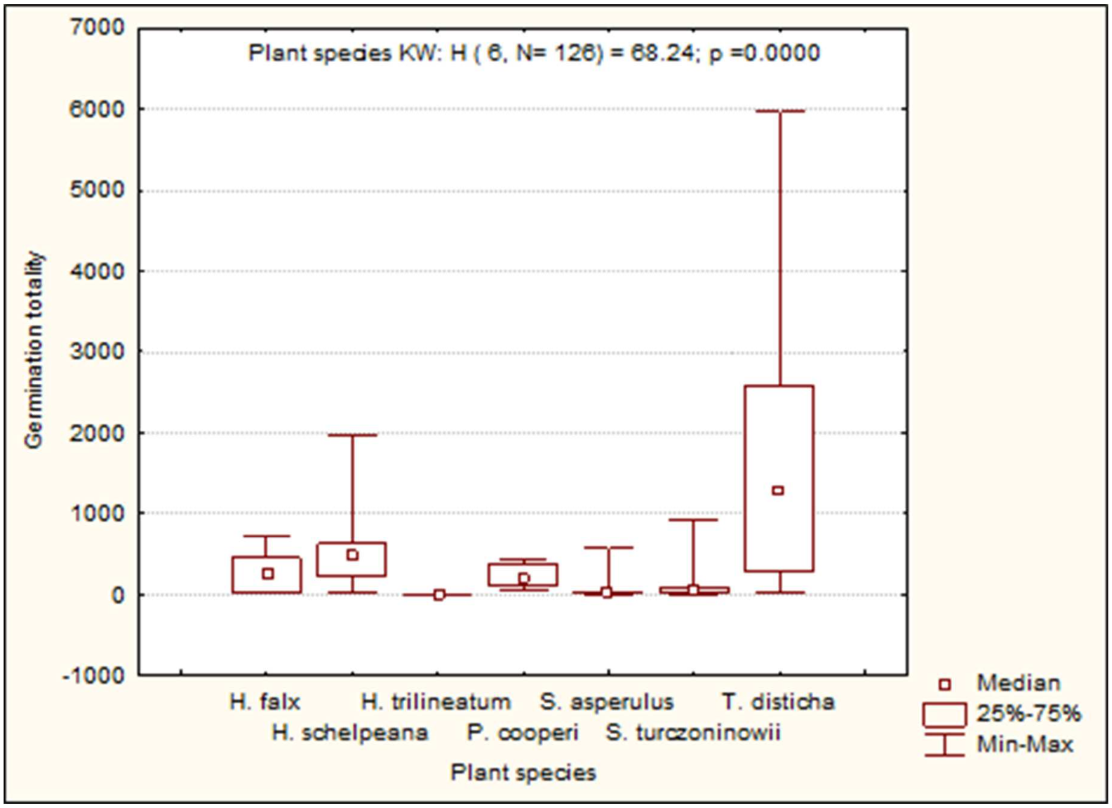


Figure 20: Comparisons of germination ability of native species potentially suitable for rehabilitation trials at Letšeng Diamond Mine, Lesotho. Germination totality refers to the number of seedlings per species after four weeks (at seeding rate 7g/10m^2).

4.2. Seed germination trials of *Tenaxia disticha* on different treatments (Fig.21)

Since *T. disticha* revealed significantly higher germination rates compared to the other species, it was selected as the model species to test the suitability of different topsoil-coarse tailings treatments for seed germination (Step 3; Fig. 19). Germination totality, which refers to the number of seedlings per treatment, was significantly higher in all other treatments when compared to the experimental control (Wald $X^2 = 11323.0$; df = 3; $p < 0.001$; Fig. 22). *Post hoc* tests revealed that treatments A and C which were both capped with topsoil did not differ significantly, although germination totality was greater in these treatments than in treatment D (tailings mixed with topsoil) (Fig. 22).

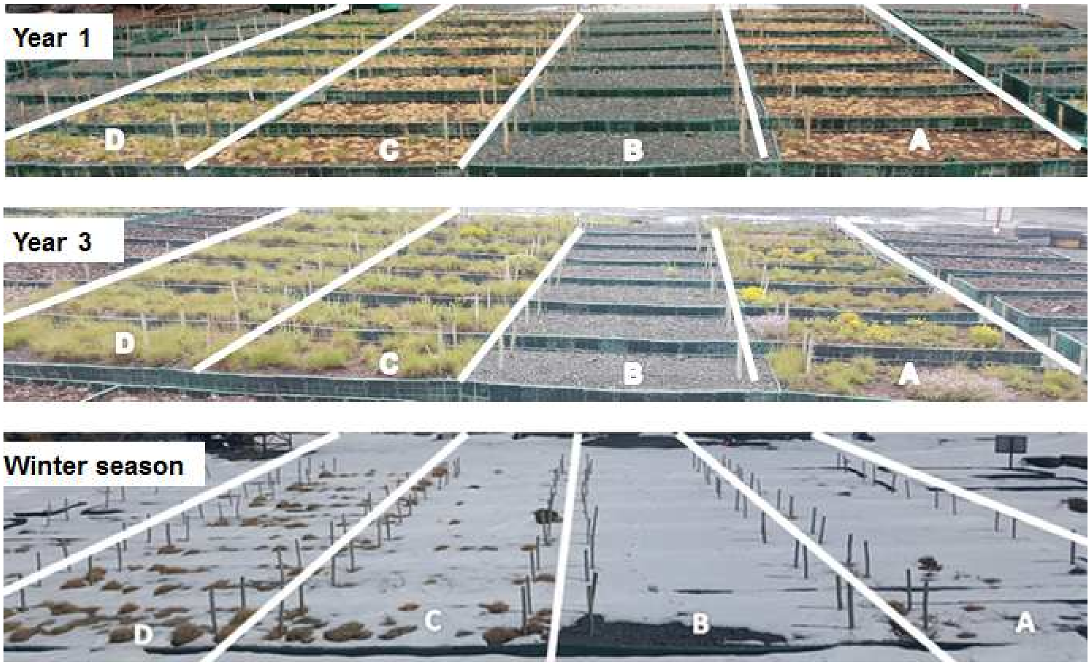


Figure 21: Germination trials of *Tenaxia disticha* on different treatments at the nursery site over a three year period (Year 1-3). The bottom photograph depicts the harsh climate conditions during cold winter months.

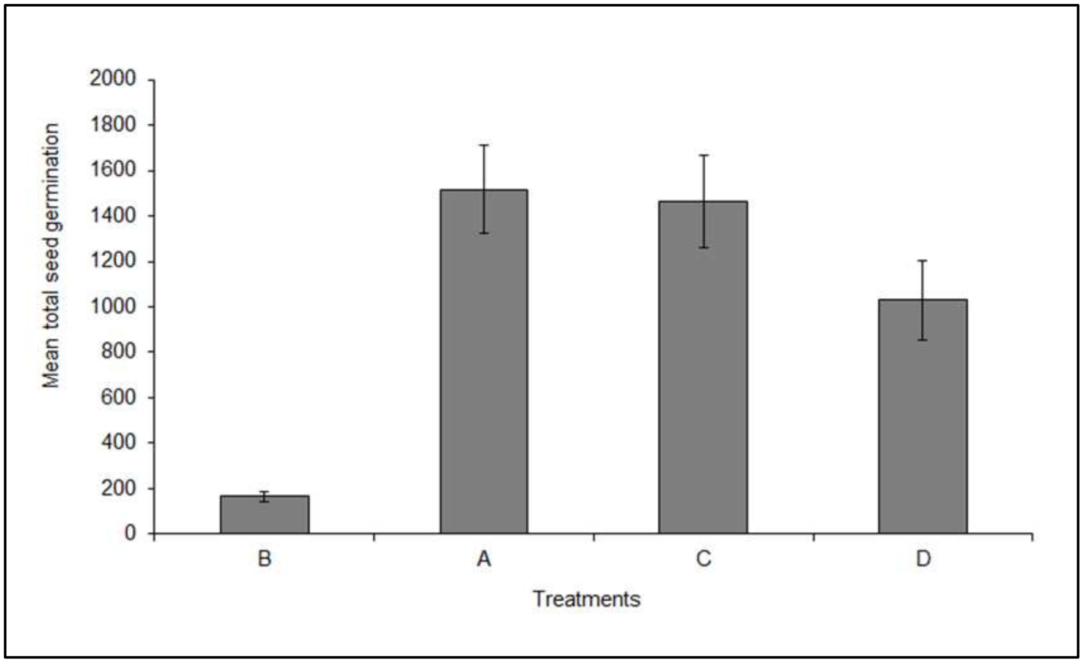


Figure 22: Mean total seed germination of *Tenaxia disticha* across different treatments. Error bars represent the standard error of means. A, 200mm coarse tailings capped with 100mm topsoil; B, 300mm coarse tailings (experimental control); C, 150mm coarse

tailings capped with 150mm topsoil; D, 150mm coarse tailings mixed with 150mm topsoil.

Overall total germination rate of *T*. *disticha* seedlings was not significantly different over the 13 weeks of monitoring across the treatments ($F_{(13,\ 42)} = 2.6$; $p = 0.018$; Fig. 23). However, germination rate in all treatments was significantly higher than in the experimental control ($F_{(3,\ 52)} = 14.4$; $p < 0.001$; Fig. 23). A Dunnett *post hoc* test showed that germination differences between treatments were not significant.

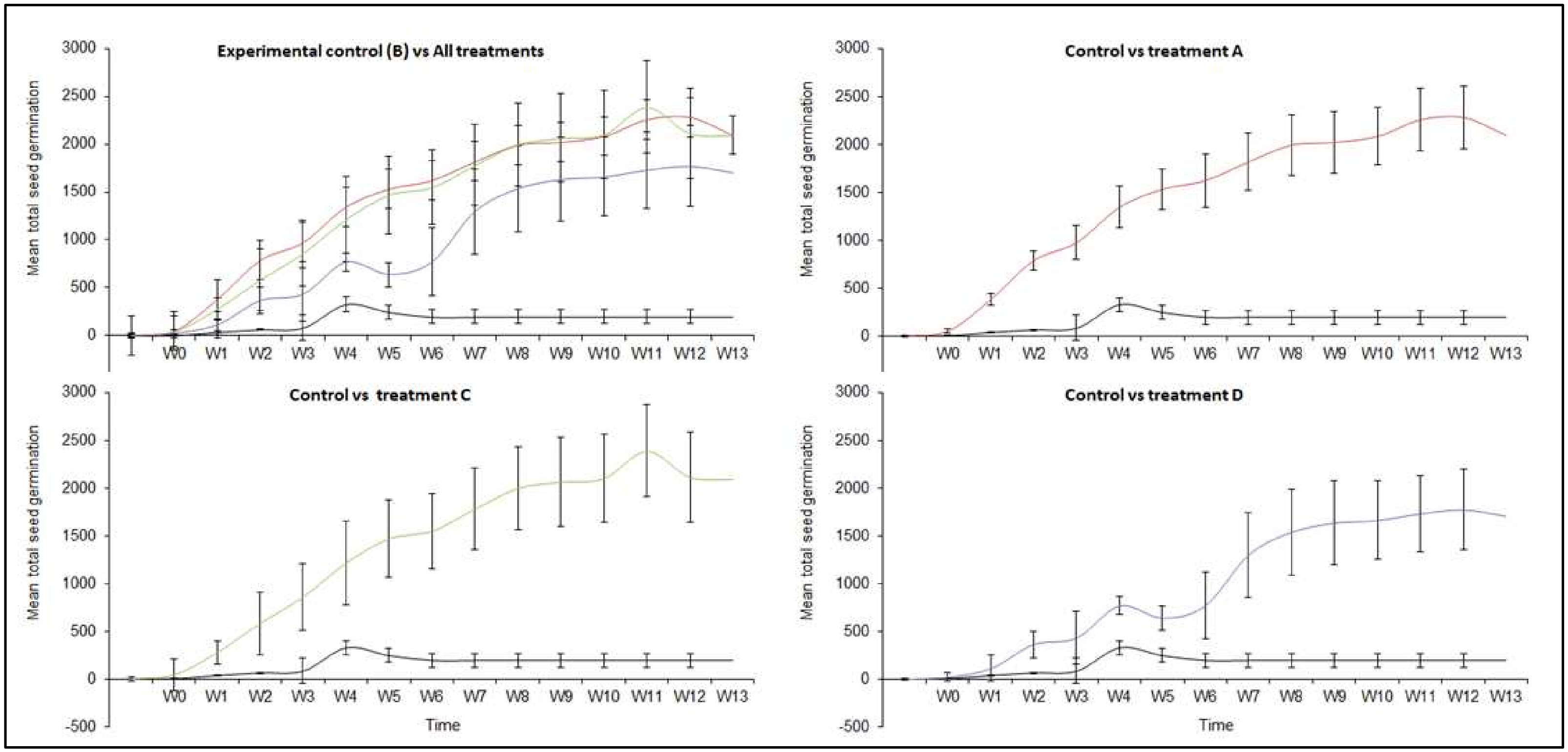


Figure 23: Variation in mean ± SE *Tenaxia disticha* seed germination under different treatments over 13 weeks. Error bars represent the standard error of means. A (red), 200 mm coarse tailings capped with 100 mm topsoil; B (black), 300 mm coarse tailings (experimental control); C (green), 150 mm coarse tailings capped with 150 mm topsoil; D (purple), 150 mm coarse tailings mixed with 150 mm topsoil.

4.3. Seedling growth performance of *Tenaxia disticha*

4.3.1. Seedling height

Germination ability of *T*. *disticha* was largely weighted towards coarse tailings capped with topsoil. After the assessment of germination ability, the plants were allowed to grow for a further 24 months with plant height and basal width measured at the end of three growth periods (Step 4; Fig. 8).

Seedlings were significantly taller in the treatments than the control ($F_{(3,\ 1041)} = 3829.8$; $p < 0.001$; Fig. 24). Bonferroni *post hoc* tests furthermore revealed that seedling height progressively increased across the three treatments (Fig. 24). Seedlings in treatment D were the tallest ($p < 0.001$), followed by treatment C, treatment A and experimental control (B) in decreasing order. Average height showed significant interactions between the treatments and time ($F_{(6,\ 2080)} = 336.6$; $p < 0.001$; Fig. 25). Seedling height therefore varied significantly over time with seedlings in all the treatments growing significantly higher than those in the experimental control ($F_{(2,\ 1041)} = 789.4$; $p < 0.001$; Fig. 25).

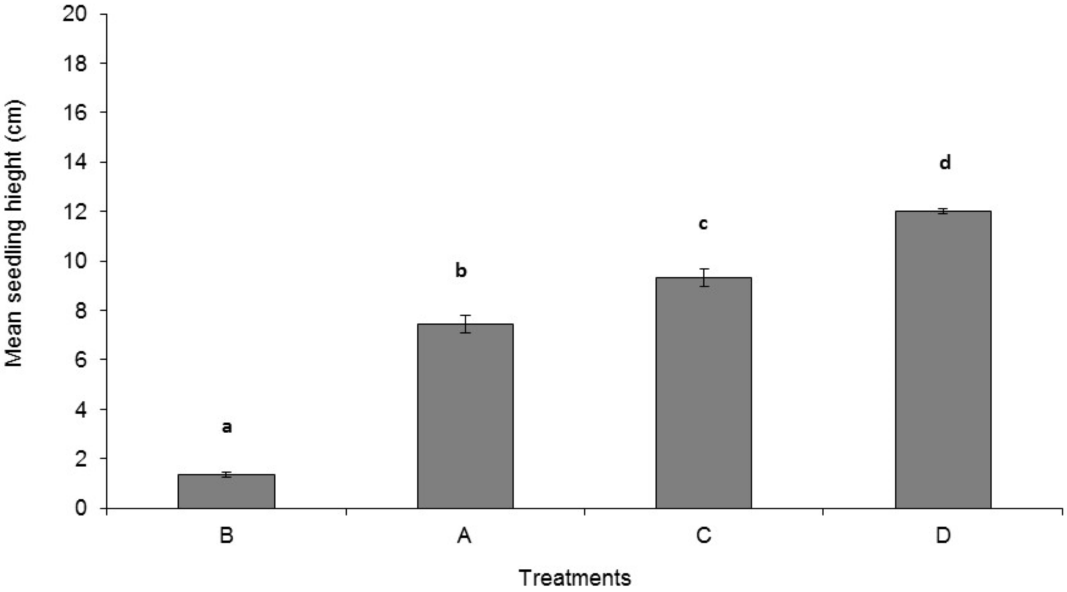


Figure 24: Variation in mean ± SE *Tenaxia disticha* seedling height across treatments. Error bars represent the standard error of means. A, 200 mm coarse tailings capped with 100 mm of topsoil; B, 300 mm coarse tailings (experimental control); C, 150 mm coarse tailings capped with 150 mm of topsoil; D, 150 mm coarse tailings mixed with 150 mm topsoil.

The *post hoc* tests furthermore revealed that the average height of seedlings was the highest during the second sampling period (P2; i.e. treatment A and D) but dropped significantly towards the third sampling period (P3).

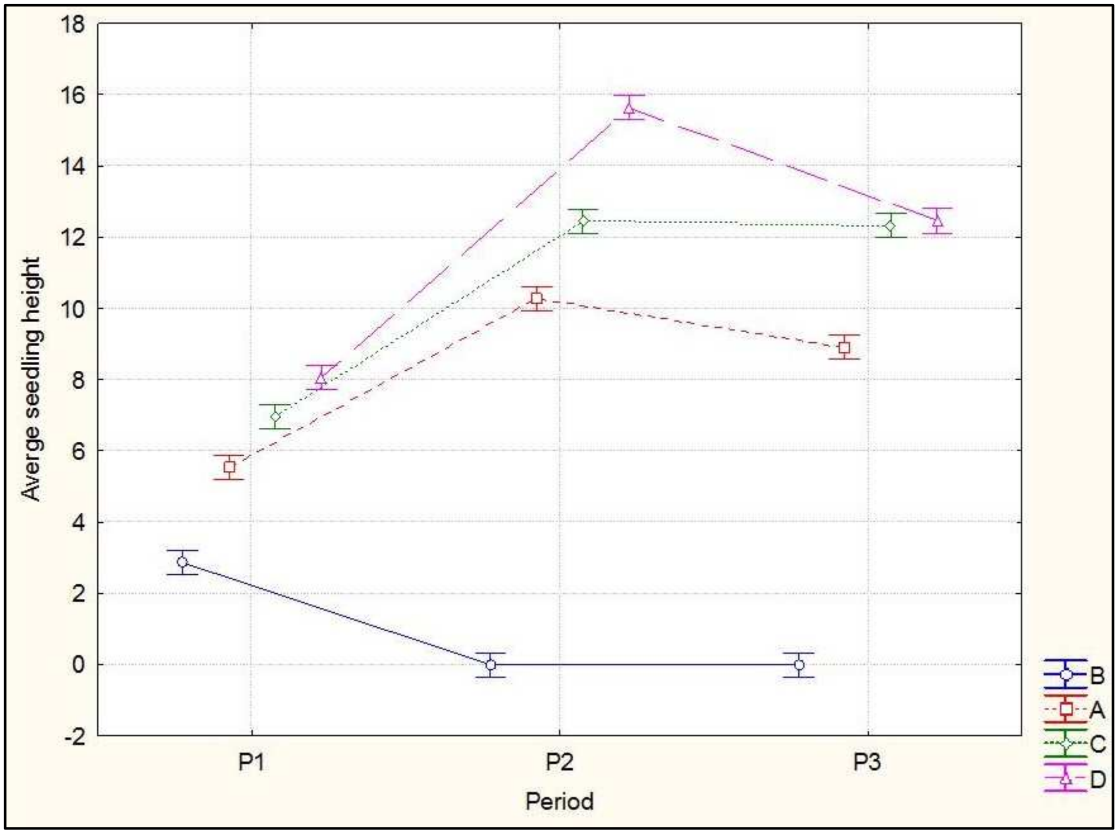


Figure 25: Interactions between time (period) and treatment on the seedling height of *Tenaxia disticha*. Error bars represent the 95% confidence intervals. Treatment: A, 200mm coarse tailings capped with 100mm topsoil; B, 300mm coarse tailings (experimental control); C, 150mm coarse tailings capped with 150mm topsoil; D, 150mm coarse tailings mixed with 150mm topsoil.

4.3.2. Seedling basal width

Average basal width differed significantly across the treatments ($F_{(3, 692)} = 286.8$; $p < 0.001$; Fig. 26). *Post hoc* tests revealed increased seedling basal width with increased complexity of the applied treatment (Fig. 26). Bonferroni *post hoc* tests furthermore revealed that seedling basal width was significantly wider in the treatments, compared to the control with 150 mm coarse tailings mixed with 150 mm topsoil (treatment D) revealing the seedlings with the widest basals (p <0.001; Fig. 26).

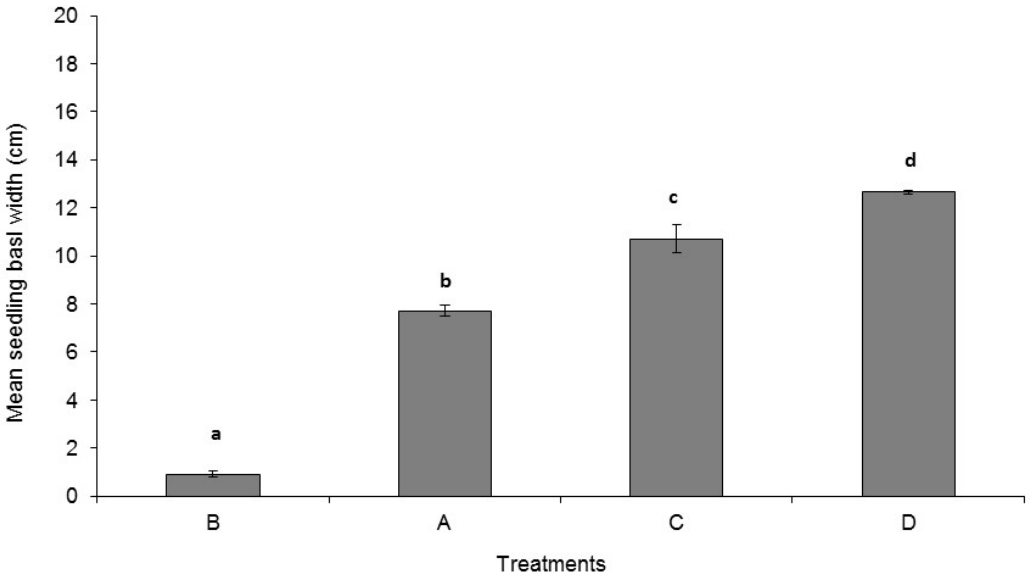


Figure 26: Variation in mean ± SE basal width of *Tenaxia disticha* seedlings across treatments. Error bars represent the standard error of means. A, 200 mm coarse tailings capped with 100 mm topsoil; B, 300 mm coarse tailings (experimental control); C, 150 mm coarse tailings capped with 150 mm topsoil; D, 150 mm coarse tailings mixed with 150 mm topsoil.

Basal width of seedlings revealed significant interactions with sampling time (P1, P2 & P3) ($F_{(2, 1041)} = 4555.0$; $p < 0.001$; Fig. 27).

The *post hoc* test revealed that the average basal width of the seedlings did not differ significantly between the first sampling period (P1) and second sampling period (P2) for all treatments (Fig. 27). However, a significant increase in seedling basal width was revealed during third period of sampling (P3) for all treatments (Fig. 27).

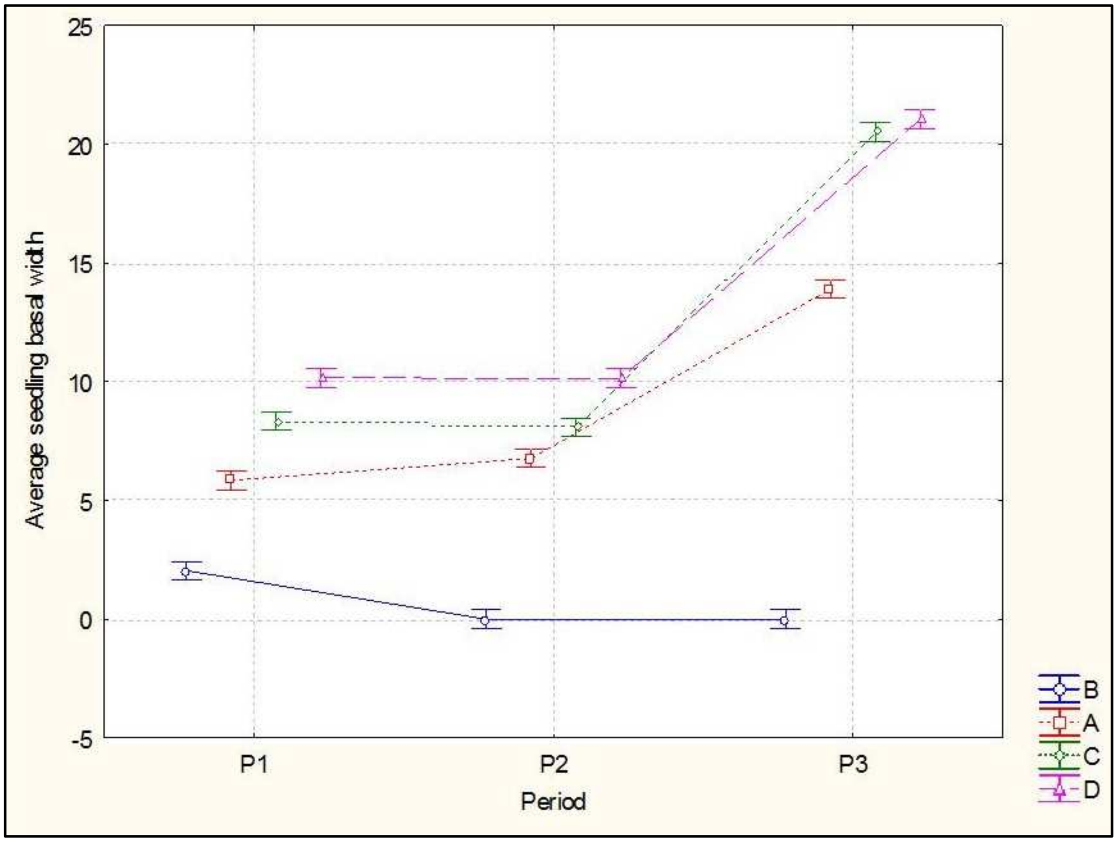


Figure 27: Interactions between time and treatment on *Tenaxia disticha* mean seedling basal width. Error bars represent the 95% confidence intervals. A, 200 mm coarse tailings capped with 100 mm topsoil; B, 300 mm coarse tailings (experimental control); C, 150 mm coarse tailings capped with 150 mm topsoil; D, 150 mm coarse tailings mixed with 150 mm topsoil.

4.4. Germination of plant diversity mixes

4.4.1. Impact of the growth medium on seedling emergence

Up to this point it has been established that four native species have the ability to germinate and grow on kimberlite tailings of which *T. disticha* showed the best results. This species was further tested on topsoil-coarse tailings combinations for germination ability over one year and three months, and seedling establishment was best when topsoil was mixed with coarse tailings. As the study sought to establish high native diversity an indigenous seed mix was sown in five different treatments to test for co-germination patterns.

Generally, growth mediums containing topsoil showed greater numbers of seedlings from the seed mix in comparison with the control ($F_{(4, 1070)} = 14.1$; $p < 0.001$; Fig. 28). The *post hoc* test revealed that three different treatments (i.e. A, B and C) were highly favourable for seedling germination and had greater numbers of seedlings than the experimental control and treatment D. The control and treatment D did not differ significantly in terms of the number of seedlings.

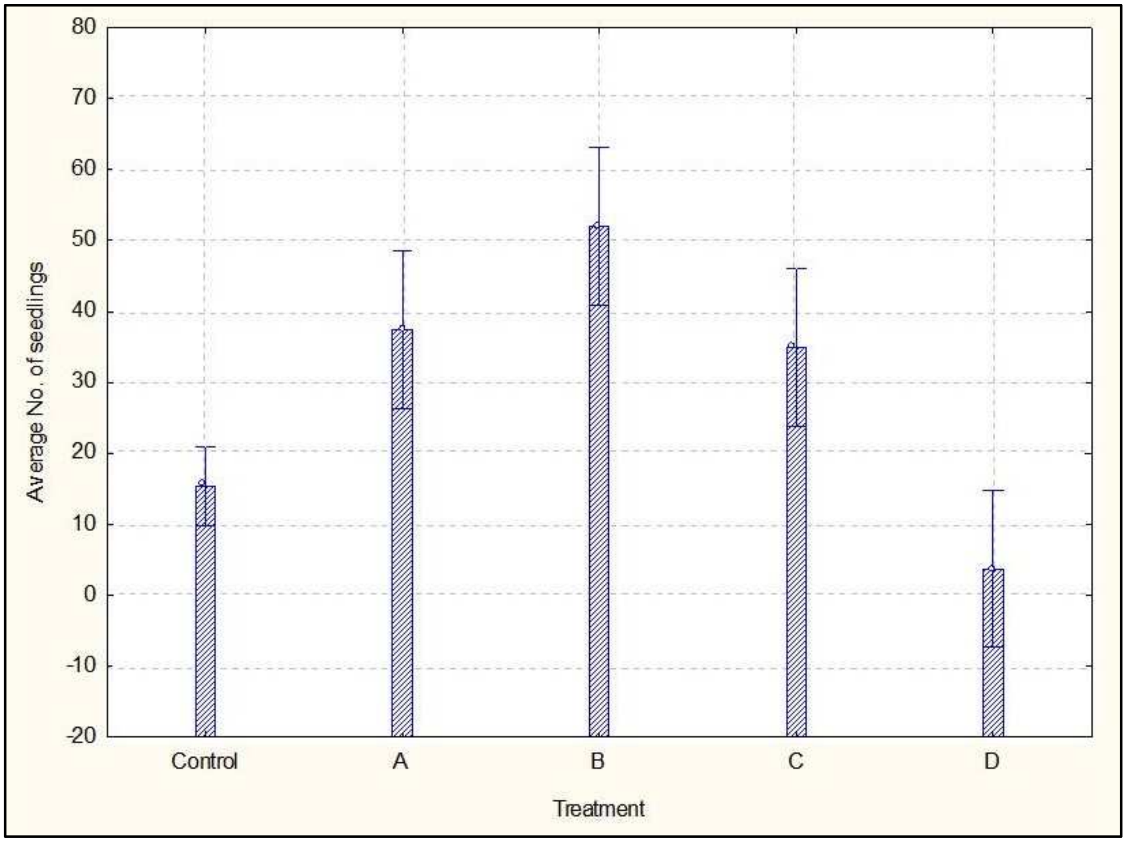


Figure 28: Average number of seedlings per treatment of all plant species in the seed mix that emerged from each growth medium after 12 months of germination trials. Experimental control: course tailings 300 mm; A, 200 mm coarse tailings mixed with 100 mm topsoil; B, 100 mm coarse tailings, 100 mm waste rock mixed with 100 mm topsoil; C, 200 mm waste rock mixed with 100 mm topsoil; D, 200 mm of fine kimberlite tailings mixed with 100 mm of topsoil.

4.4.2. Comparing seedling emergence

Other native species revealing high germination included the geophytes *Dierama robustum* and *Hesperantha schelpeana*, and the annual forb *Sisymbrium turczaninowii* ($F_{(8, 1070)} = 78.2$; $p < 0.001$; Fig. 29).

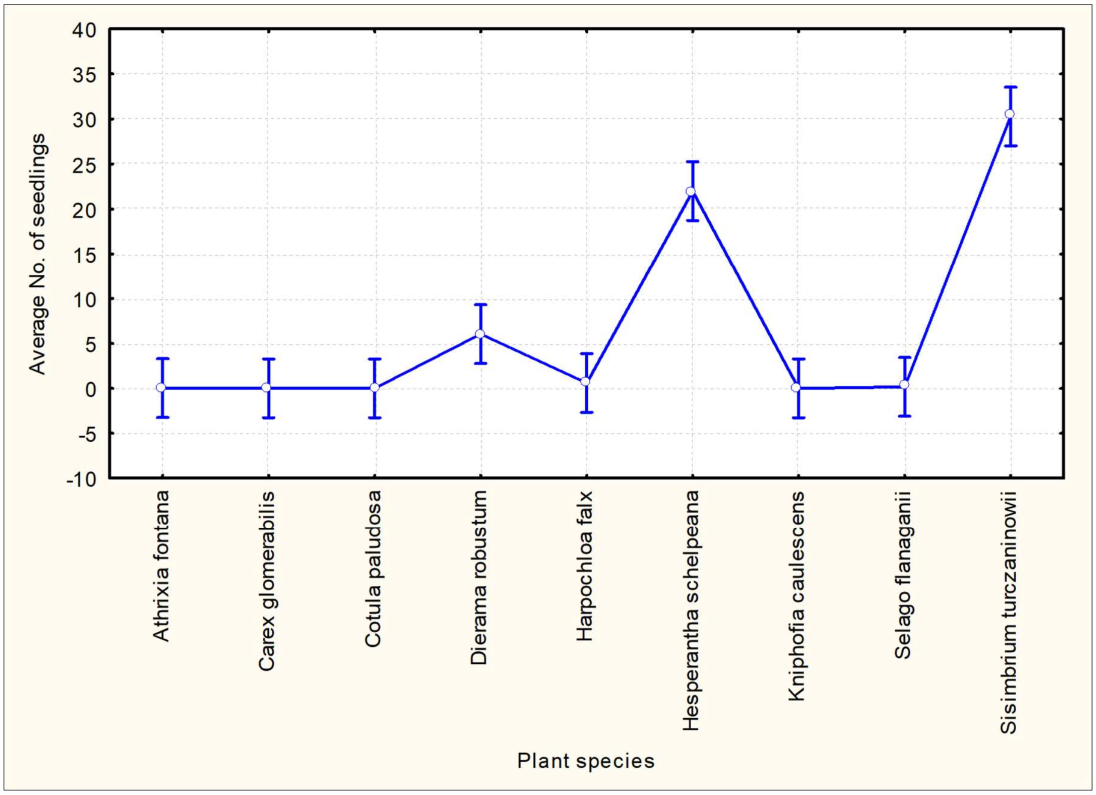


Figure 29: Mean number of seedlings per plant species (excluding *T. disticha*) across all treatments.

There were significant two-way interactions between plant species and treatment media ($F_{(36, 1070)} = 10.2$; $p < 0.001$; Fig 30). Treatments A, B and C favoured high seedling numbers for all germinated species. Furthermore, *Tenaxia disticha* germinated successfully in all these treatments, with the exception of fine tailings (treatment D), where the germination of *Sisymbrium turczaninowii* was favoured.

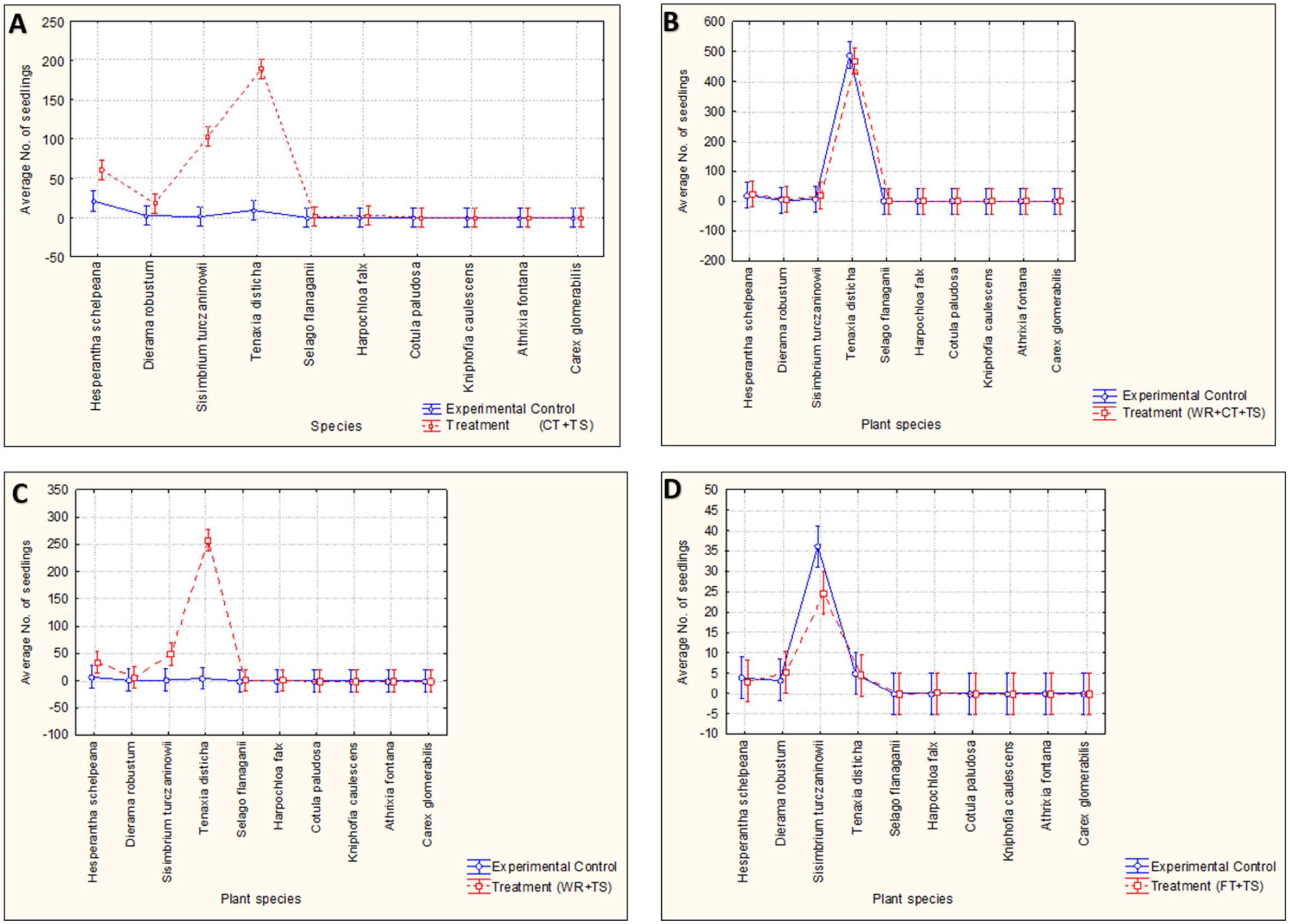


Figure 30: Relative average number of seedlings per plant species in each treatment (A–D). The experimental control comprised the coarse kimberlite tailings

4.5. Spontaneous plant species

Spontaneous recruitment of species present in the seed bank was observed during the seed germination trials. A total of eighteen plant species from ten families were recorded across the treatments (Table 3). Eleven of these were perennials, whilst the remaining seven species were annuals (Table 3). These species contributed considerably to the diversity on the treatments. The controls, which lacked topsoil, were not colonised suggesting that most of the spontaneous germination of seed originated from the topsoil in the treatment mixes. Although only presence/absence data was recorded, it is evident that treatments A to C were much more suitable for seed bank regeneration than treatment D containing fine kimberlite tailings. Treatments with additional topsoil had the highest numbers of unsown plant species which is a clear indication that these extra species come from the topsoil (Table 3).

Table 3: Unsown species that germinated from the seedbank on different growth mediums. √ = present in the treatment plot A, B, C and D

Plant species	Family	Common name	Plant growth form	Experimental treatment							
				A	A: No topsoil	B	B: No topsoil	C	C: No topsoil	D	D: No topsoil
Agrostis lachnantha	Poaceae	-	Perennial	√		√		√		√	√
Bupleurum mundii	Apiaceae	Thorow wax	Annual	√		√	√	√			
Chrysocoma ciliata	Asteraceae	Bitter karoo	Perennial	√		√		√		√	
Euphorbia natalensis	Euphorbiaceae	-	Perennial					√			
Festuca caprina	Poaceae	Goat-beard grass	Perennial	√				√	√		
Gazania krebsiana	Asteraceae	Terracotta gazania	Perennial			√		√			
Glumicalyx montanus	Scrophulariaceae	-	Perennial			√		√			
Helictotrichon longifolium	Poaceae	Alpine oat grass	Perennial	√		√		√		√	
Lotononis eriantha	Fabaceae	Russet lotononis	Perennial	√		√		√		√	
Oxalis obliquifolia	Oxalidaceae	Oblique leaved sorrel	Annual	√		√				√	
Pentaschistis airoides	Poaceae	Common annual pentaschistis	Perennial	√		√		√			
Poa annua	Poaceae	Annual blue grass	Annual	√		√		√			
Ranunculus multifidus	Ranunculaceae	Wild buttercup	Annual	√		√				√	
Rumex lanceolatus	Polygonaceae	Common dock	Perennial	√		√	√	√			
Senecio asperulus	Asteraceae	-	Annual	√		√	√	√			
Senecio caloneotes	Asteraceae	-	Annual	√		√	√	√		√	
Senecio inaequidens	Asteraceae	Narrow-leaved ragwort	Annual	√		√	√	√	√	√	√
Silene burchellii	Caryophyllaceae	Gunpowder plant	Perennial					√			
Total number of individual plants				**14**	**0**	**15**	**5**	**16**	**2**	**8**	**2**

Nonmetric multidimensional scaling (NMDS) ordinations of between treatment resemblances in 2017 revealed limited species overlap across the treatments in a two-dimensional space (Fig. 31). However, species assemblages of the coarse tailings, coarse tailings with waste rock and waste rock treatments were similar. In 2018, similar patterns were revealed with fine tailings-topsoil mix and the control plots scattered towards the left hand side of the ordination and the coarse tailings, waste rock treatments and a combination thereof clustering towards the right (Figure 32).

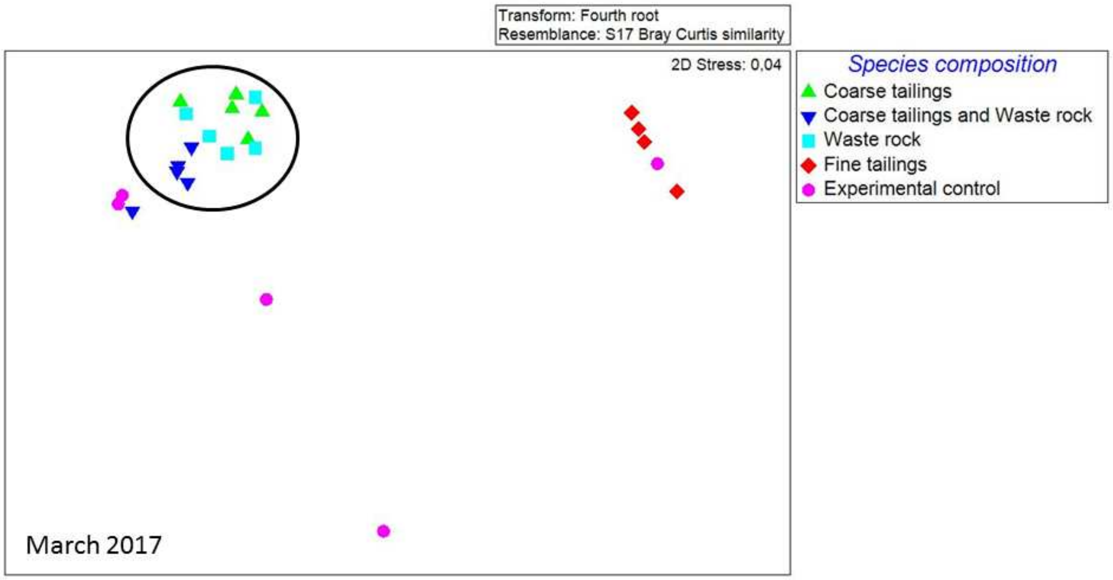


Figure 31: Nonmetric multidimensional scaling (NMDS) ordination plot of between treatment resemblances in March 2017.

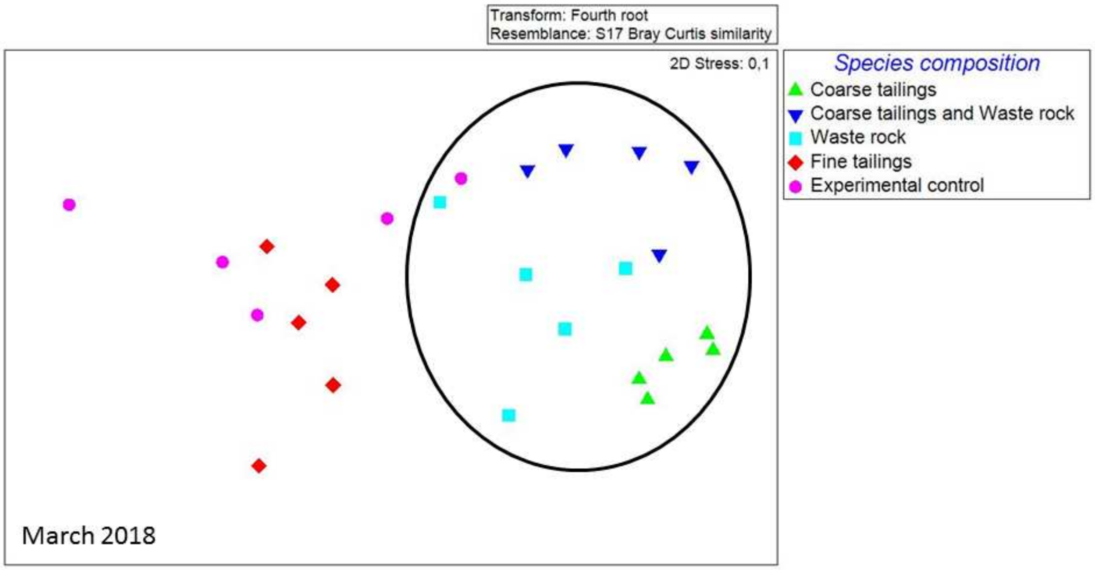


Figure 32: Nonmetric multidimensional scaling (NMDS) ordination plot of between treatment resemblances in March 2018.

CHAPTER 5: DISCUSSION

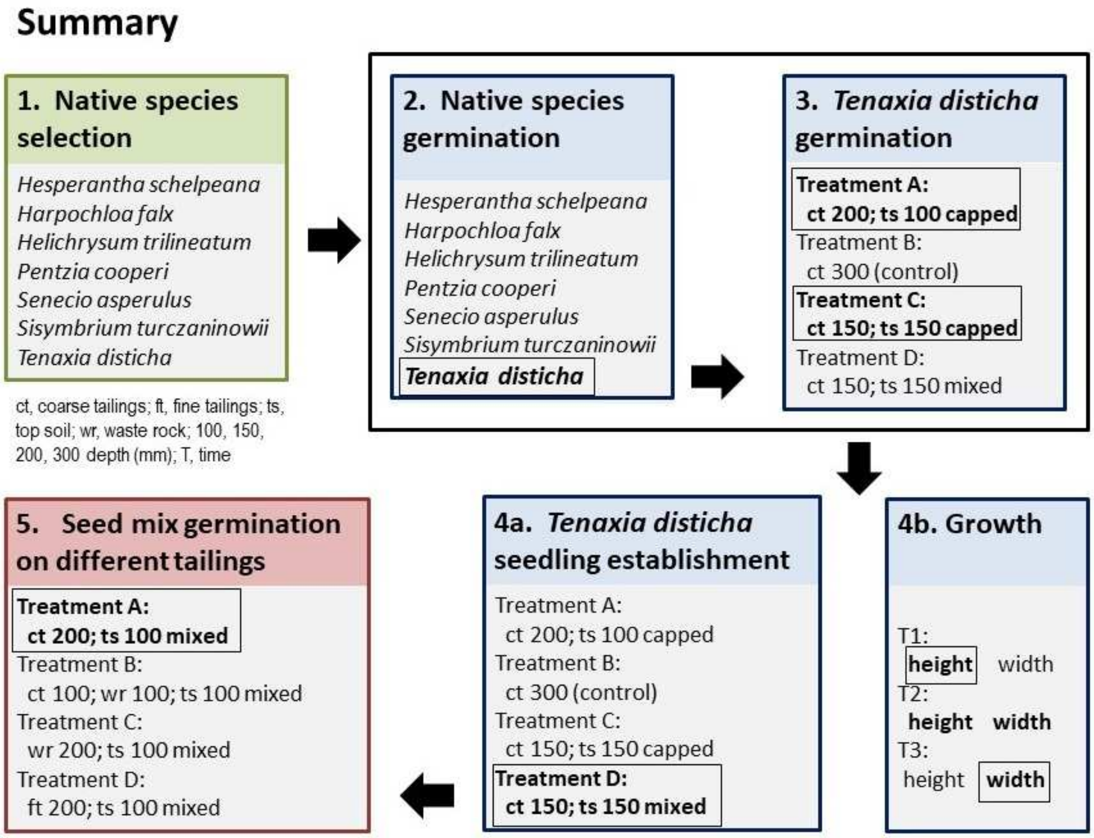


Figure 33: Summary of the research approach and subsequent major findings to meet the objectives of the study.

5.1. Germination of native species on tailings

Considering that the conditions of kimberlite tailings in this mining setting is fixed and that additional amelioration is not possible due to the isolated nature of the mine (Meyer, 2017), the study had to determine (as a main objective), given the current environmental conditions, which native species have the highest germination rates on various treatments (Step 1; Fig. 33). This is considered the most cost-effective approach for rehabilitation (Graiss *et al*., 2008; Van Eeden, 2010). *Tenaxia disticha* revealed the best germination results (Step 2; Fig. 33). These findings are advantageous given that grasses are often considered the most reliable and valuable species for initial rehabilitation on mine tailings (Granger and O'Connor, 2015). However, the value of the other species should not be disregarded, as there are several factors which might have impacted negatively on the ability of these species to germinate at levels comparable to *T. disticha*. Further amelioration efforts are anticipated to improve germination rates of these species necessitating further research. According to Van Rensburg *et al*. (2004) and Claassens *et al*. (2005) it is critical to improve mine tailings material to create a medium that supports plant growth and better grass establishment (Power *et al*., 1981).

There are several factors that affect seed germination, such as storage conditions, which directly influence seed dormancy (Wang, 2005; Sayuti, 2013). Some seeds might have been exposed to fungal attack and insect infestations due to poor storage conditions (Brown, 1943a). Post-sowing environmental conditions for seed germination might not have been ideal for specific species, including oxygen for seed respiration, and optimum temperature for metabolic processes (Brown, 1943a; Yilmaz and Aksoy, 2007), or moisture and soil nutrients to support development shoots after the endosperm reserves are expended (Olivia *et al*., 2013; Muller, 2014; Moraes *et al*., 2017).

After it was established which species germinated most successfully in the different treatments, a second objective was to determine whether high rates of seasonal germination of *T. disticha* was specific to any treatment (Step 3; Fig. 33). Germination ability was at higher levels on tailings capped with topsoil compared to tailings and topsoil mixes. Observed lower germination in treatment D might have been due to destruction of soil structure during the mixing of topsoil with coarse kimberlite tailings, thereby creating non-conducive conditions recommended for seed germination (Opande *et al*., 2017). In addition, the soil in treatment D might have lost its water holding capacity as stone granules of the kimberlite increased soil porosity and drainage (Osman, 2018). Seedlings of some species might also have perished after not receiving the required amounts of moisture, nutrients and oxygen after germination. The poor germination ability in experimental control (treatment B) compared to other treatments was expected due to poor conditions on kimberlite tailings, and a similar finding was reported by a previous study at the same site (Meyer, 2017). Consistently, the study of Bengao and Cababat (2014) also found that germination of seeds in kimberlites can be poor in the absence of topsoil.

Seed planting depth also influences germination success (Muller, 2014; Tang *et al*., 2016). Germination was comparatively higher in all topsoil treatments than the experimental control. The role of topsoil in seed germination is to create suitable habitat (Opande, 2017), which allows the absorption of moisture into the seed to stimulate germination (Shaban, 2013). Water is essential for initiating seed physiological processes through enzyme activation and breakdown, translocation of nutrients and oxygen, and use of reserve storage material (Brown, 1943b). However, other studies have reported that excess moisture can lead to seed rot, fungal attack and consequently lower seed germination (Saatkamp *et al*., 2014). Also, deeper soil improves seed germination through increased water infiltration and nutrient cycling (Bowen *et al*., 2005). Consequently, topsoil capping of course kimberlite tailings in treatments

A and C may have accounted for higher seedling germination. Nevertheless, variation of soil depth in this study did not influence seed germination. This finding concurs with a study reported by Dalling *et al*. (1995) where the effect of soil depth on seedling emergence was tested for treatments with 2.5mm, 5mm, 10mm and 20mm topsoil depth, but no difference in germination rates was recorded. The observed trends at Letšeng should rather be ascribed to the presence or absence of tailings within topsoil.

5.2. Seedling growth performance of *Tenaxia disticha*

The growth in height of *T*. *disticha* across treatments was stimulated by the addition of topsoil (Step 4; Fig. 33) which plays an important role in the growth of plants (Harwood *et al*., 1999; Mensah, 2015). Consistently, at Saraji mine in Australia, Harwood *et al*. (1999) found better grass establishment and survival on the plots with topsoil. Topsoil provides habitat conditions enhancing moisture for seedlings to effectively start the process of photosynthesis (Zlatev and Lidon, 2005; Wang *et al*., 2017; Crouse, 2018). Furthermore, topsoil contains essential soil microbes for decomposition and facilitation of nutrient uptake (Claassens *et al*., 2005; Koorem *et al*., 2014). The outcome at Letšeng is also in agreement with Bowen *et al*. (2002), in a study carried out in south-central Wyoming, where they assessed the effects of different topsoil replacement depths on plant community cover and production and found the dominance of cool season grasses on deeper soils. Similarly, Redente *et al*. (1997) confirmed that deeper soils were favoured by cool season grasses. Similarly, *T*. *disticha* preferred topsoil of 150 mm compared to 100 mm on tailings in the cool alpine zone of Lesotho (Fig. 33 (step 4a)).

It seems that during early seedling growth (P1), *T. disticha* invested energy in height for competition for light on treatments with high germination ability (Falster and Westoby, 2003). During the first two periods of growth monitoring, increasing height was observed for *T*. *disticha*, but in the third period it decreased, likely as a result of hostile (i.e. windy and cold) alpine environmental conditions that limit photosynthesis and growth during the cool season (Haase *et al*., 1999). Another factor is that if grasses are not defoliated, they may become moribund (Tainton, 2000; Cowling *et al*., 2004; SANBI, 2014). Thus by the third period with no defoliation it is most likely that the grass increased its tuft size in order to develop new leaves that can photosynthesize.

Following the same pattern observed for height, basal width increased with additional topsoil in the treatments which may play a similar role as explained above (Fig. 33 (step 4b)). However, the basal growth of *T*. *disticha* was substantial during the third monitoring period which may suggest that over time, the plants invested most of their resources in the development of the secondary root system and the formation of tillers (Robinson, 2014). The secondary roots also increase transport of moisture and nutrients (Craine *et al*., 2002). It has been shown that formation of tussocks may be an adaptation to hostile (i.e. windy and shallow soils) environmental conditions of the alpine zone where plants may require stronger hold on the ground (Monteiro, 2012). This outcome is supported by Perez-Hargnindeguy *et al*. (2013), Chacon and Cavieres (2008) and Callaghan *et al.* (1992), in that clonal growth in plants promote survival mechanism through increased access of the surrounding resources especially where the conditions are unfavourable. In rehabilitation it provides a surety for long-term plant survival under hostile conditions. *Tenaxia disticha* is a long-lived grass species and falls in the category of species known to have low seed dispersal potential (Chacon and Cavieres, 2008; Perez-Hargnindeguy *et al*., 2013). Therefore, the tussock growth trait is an advantageous trait that could compensate for its low seed dispersal in alpine conditions.

Treatment D was the most beneficial for *T*. *disticha* seedling establishment, because the lower germination rate on mixed versus capped with topsoil resulted in lower competition for resources due to low seedling densities. Subsequently, the plants on these treatments have performed better (fewer seedlings to share resources). Thickness of a capped topsoil layer may lead to rehabilitation failure when it is thicker, as plants cannot reach the moisture in the underlying material (Limpitlaw *et al*., 2005). Therefore, topsoil-tailings mixes allow for roots to reach deeper and penetrate the underlying tailings material. The important physical properties of soils that affect root growth include soil structure (Bengough and Mullins, 1990; Dexter, 2004), and consequently, the mixing of the tailings with topsoil in this study, made it easier for the roots to penetrate the tailings with low resistance and allowed effective access of the resources for seedling growth.

5.3. Germination of plant diversity mixes

Rehabilitation can either be done passively whereby the landscape is left to recover without any active intervention, or actively through direct intervention measures to facilitate achievement of the desired attribute of the environment. While choice of species for certain environmental settings is crucial during vegetation restoration (Long, 2010), knowledge of ecological behaviour of a species such as competition and coexistence ability is important since it may influence achievement of the desired state of the vegetation (Hobbs and Norton 1996; Orrock and Christopher, 2010).

According to Orrock and Christopher (2010), seeds may either increase their germination rate or delay it in response to competition with other seeds. For example, use of species that display high coexistence ability can accommodate other species and consequently facilitate the attainment of the ecological maturity of the patch being rehabilitated (Long, 2010). Establishment of plant diversity using native plants seeds is recommended as a reliable approach in rehabilitation because of the pre-adaptation of the plant species to prevailing environmental conditions (Adams and Lamoureux, 2005; Hansen, 2011). Similarly, a test of *T*. *disticha* showed species' ability to coexist and facilitate establishment of other species during rehabilitation. This was confirmed by the finding that out of nine sown species, three species (*Dierama robustum, Hesperantha schelpeana* and *Sisymbrium turczaninowii)* together with *T*. *disticha*, can be used for co-enhancement of plant diversity during rehabilitation of kimberlite tailings in Letšeng Diamond Mine. More species translate to more functional traits in the system and more ecosystem services (Díaz and Cabido, 2001).

The findings of this study correlate with that of Meyer (2017) which have been included in the current rehabilitation plan at Letšeng Diamond Mine. Meyer (2017) has reported various successes with *T*. *disticha* as one of the key species in the establishment of vegetation cover due to its resilience to local conditions. It has been reported by Sayuti (2013) that generally, the South African montane plant species such as *Dierama robustum* survive better if sown on the topsoil. Furthermore, *T*. *disticha* has already been earmarked for use on-site for large scale rehabilitation trials at Letšeng Diamond Mine as a key species for stabilization of the slopes and to facilitate the two geophytes and the annual forb which also exhibited high germination ability (E-Tek Consulting, 2016).

The six species sown as part of the biodiversity mix which did not germinate are therefore considered unable to colonise kimberlite tailings under current rehabilitation practices. *Athrixia fontana*, *Carex glomerabilis*, *Cotula paludosa* and *Kniphofia caulescens and Selago flanaganii* did not germinate; most probably due to the absence of typical habitat of moist to wet soil conditions of the Drakensberg Mountains (Killick, 1978). Moreover, Mating (2018) stated that *Harpochloa falx* naturally prefers a rocky and shallow soil habitat which also suggests a failure for it to germinate. It has been reported by Xu *et al*. (2014) that habitat has a substantial effect on germination. Comparatively, the three species (*Dierama robustum, Hesperantha schelpeana* and *Sisymbrium turczaninowii)* that have displayed higher germination also had the advantage of larger seed size (Xu *et al*., 2014; Kumar *et al*., 2017), which increases persistence of seedlings and increase their resistance to various environmental hazards. This outcome is in accordance with a study on effects of seed size on germination which was conducted for high altitude plants in northern Spain and found that the large seeds have higher germination rate than the smaller seeds (Vera, 1997). There are many reasons for the prolonged seed dormancy as discussed earlier (Finch-Savage and Leubner, 2006; Liu *et al*., 2013). Further research is required to improve knowledge of the germination of the native seed mix after sowing.

Treatment D performed poorly most probably due to high clay content that is commonly reported in the fine kimberlite tailings (Leeper and Uren, 1993; Morkel, 2006). High clay content in the soil increase water holding capacity even though most of water may not be available to plants and thus poor performance in seed germination (Leeper and Uren, 1993; Charman and Murphy, 1998; Morkel, 2006). Because of limited porosity and ventilation (Leeper and Uren, 1993; Charman and Murphy, 1998), it is possible that seeds' metabolic processes requiring oxygen could not be initiated to break seed dormancy to allow germination. According to Hoare (2009), growth mediums with low levels of nutrients (Ntloko *et al*., 2017) provide limited opportunities for any plant species to germinate and establish. Similarly, germination on "tailings only" controls was highly unsuccessful compared to tailings-top soil mixes (no capping).

5.4. Spontaneous germination of plant species

The emergence of 18 unsown plant species in the trial treatments, with a total of 11 perennial and seven annual species, could largely be ascribed to the natural seed bank associated with the stockpiled topsoil (Zhang *et al*., 2001), as native species have long-term persistent seed banks (Holmes, 2001). It is possible that these species could also have reached the treatments through wind dispersal from neighbouring vegetation especially in the alpine environment (Tackenberg and Stöcklin, 2009). The harsh alpine conditions such as strong winds, shallow soils with less moisture retention capacity and winter thermal stress from snowfall are limiting for plant life (Brink, 1964; Wipf *et al*., 2009), therefore tussock grasses provide a buffering effect of stable soil environment for the other herbaceous species, and through their canopy shelter that has a nurse effect for seed germination and establishment (Hoare, 2009; Maestre *et al*., 2003). This confirms the report by Hoare (2009) which noted that montane plant communities made up of grasses and forbs usually support high numbers of coexisting species.

It has been argued that in order for restoration efforts to achieve greater diversity and community maturity, the species that display high coexistence are important (Hobbs and Norton 1996; Young, *et al*., 2005; Long, 2010). The ability of plant species to share resources, while avoiding direct competition, can facilitate a rapid attainment of the natural ecological maturity of the desired plant community of the rehabilitation programme (Long, 2010; Kodir *et al*., 2017). Therefore, observed integration of new plant species during the first and second year of monitoring suggest that *T*. *disticha* can accommodate and thus coexist with other species, and that the growth mediums used during the trials can support a variety of species to facilitate rapid restoration of the local biodiversity on kimberlite tailings at Letšeng Diamond Mine. Arrival of new plant species either through the topsoil seed bank or seed dispersal encourages development of plant community structure, diversity and habitat functionality which is mostly targeted by rehabilitation plans (Drake, 1991; Young *et al*., 2005; Vaughn *et al*., 2010).

CHAPTER 6: STUDY CONCLUSIONS AND RECOMMENDATIONS

6.1. Germination of native species on tailings

The first objective of this study was to determine which native plant species have the highest germination rate on various treatments in order to select a model plant species that can be used in the rehabilitation of kimberlite tailings at Letšeng Diamond Mine, Lesotho. The results showed that out of seven indigenous trial plant species which naturally colonise kimberlite tailings, *T*. *disticha* had the highest germination ability on various kimberlite treatments. This species can therefore tolerate a wide range of growth mediums and this makes it the most suitable species for vegetation restoration on the kimberlite tailings at the Letšeng site.

The second objective of this study was to determine whether high rates of seasonal germination of *T. disticha* were specific to any treatment. Generally, the germination results indicated that the treatments with addition of topsoil performed better. This suggests that the germination ability of native plants from Letšeng is strongly dependent on the addition of topsoil for rehabilitation of kimberlite tailings. Additional topsoil in such conditions can provide physical support for germinating seeds, aeration, improved water infiltration for moisture and movement of necessary nutrients (Bowen *et al*., 2005; Wilkinson *et al*., 2014). This finding is consistent with the initial expectations of the study because the kimberlite tailings reportedly have poor chemical and physical conditions generally unsuitable for seed germination (Wilkinson *et al*., 2014; Bengao and Cababat, 2014; Meyer, 2017). Amelioration of kimberlite tailings creates conducive conditions for seed germination and as a scarce resource holds important implications for the rehabilitation process at the study site. For example, given that soil is a limited resource in alpine areas, the findings of this study emphasises the importance to develop and implement effective management of topsoil during mine operations.

6.2. Seedling growth performance of *Tenaxia disticha*

The study also set out to determine if the *T*. *disticha* seedlings establish after germination using the seedling height and basal width as surrogate measures of growth. The results indicated that seedling growth performance, and thus establishment, was associated with kimberlite tailing treatments having additional topsoil which promotes plant rooting and the accessibility of water and the availability of nutrients (Power *et al*., 1981; Bowen *et al*., 2005; Jat *et al*., 2018). It is speculated that increased height of seedlings promotes access to sunlight which is essential for photosynthesis especially in early stages of plant growth (Fiorucci and Fankhauser, 2017) while the growth displayed by the seedling basal width pointed to the potential adaptation of *T*. *disticha* to windy and shallow soil conditions of the high altitude areas in the study site. In conjunction, raw tailings material resulted in poor germination ability and demonstrated that *T*. *disticha* requires topsoil to have effective germination and establishment. Therefore, it is concluded that amelioration of coarse kimberlite tailings with topsoil provides best growth mediums and can encourage establishment of *T*. *disticha* during the large scale rehabilitation in Letšeng Diamond Mine. Furthermore, although initial germination studies indicated a preference for tailings capped with topsoil, the longer term study of establishment indicated that topsoil-kimberlite tailings mixes were more conducive to plant growth.

6.3. Germination of plant diversity mixes

Having established that *T*. *disticha* can be used as model plant species in rehabilitation of kimberlite tailings mixed with topsoil, the study also determined which other native species display high germination ability. The final objective was to determine whether *T*. *disticha* can germinate in a native species mix. This is important for rapid achievement of desired ecological maturity and biodiversity value of the tailings facilities (Long, 2010). The results showed that *Dierama robustum, Hesperantha schelpeana* and *Sisymbrium turczaninowii* can germinate copiously in the presence of *T*. *disticha* seeds*,* which suggests that these species can tolerate the underground interspecific seed competition to germinate across various treatments. It is concluded that these three species (*Dierama robustum, Hesperantha schelpeana* and *Sisymbrium turczaninowii)*, together with *T*. *disticha*, can be used for establishment of biodiversity during rehabilitation of mine tailings in Letšeng Diamond Mine.

The species which did not germinate include *Athrixia fontana*, *Carex glomerabilis*, *Cotula paludosa*, *Harpochloa falx*, *Kniphofia caulescens* and *Selago flanaganii* . However, *A. fontana*, *C. glomerabilis*, *C. paludosa* and *K. caulescens* were expected to germinate better on fine kimberlite tailings, because among other properties, it has high clay content which is suitable for wetland plants. If this is a result of seed dormancy, investigations should be conducted to perhaps test for the best scarification techniques in breaking this dormancy. Furthermore, Mating (2018) stated that there is limited information with regards to germination of some Lesotho native grass species. For example, the planting requirements for *Harpochloa falx* such as soil pH, temperature and planting depth were not identified. These species are valuable as they produce seed in abundance on the mining property and demonstrate the necessary functional traits required for kimberlite rehabilitation. The best topsoil tailing mixes were found to commonly have topsoil and coarse tailings, whereas fine tailings reduced the germination ability of these species considerably.

The results in this study indicated that the addition of topsoil increases the potential of artificial growth mediums to support establishment of plant diversity. This is also supported by Bowen *et al*. (2005) who reported that the depth of topsoil has an influence on plant species diversity and other attributes such as biomass, plant cover, plant nutrients and water infiltration rate. It is concluded that establishment of plant diversity requires the use of topsoil in order to overcome physical limitations of artificial growth mediums. This technique of amelioration of mine waste with topsoil is important in situations where the artificial growth mediums do not support plant biodiversity. The choice of suitable plant species is highly effective in consideration of plant functional traits that enable the plants to survive the conditions of tailings. Long (2010), in a study of species co-existence, has shown that species diversity is dependent on number of factors such as environmental conditions and species traits. Therefore, it is essential to consider plant functional traits of species of the vegetation type around the rehabilitation site, and also the local environmental conditions.

6.4. Spontaneous plant species

The emergence of large numbers of unsown plant species in the trial treatments could be ascribed to the soil seed bank associated with the topsoil. Seed banks can therefore facilitate a rapid attainment of a desired plant community that will contribute to the ecological maturity on tailings (Long, 2010; Kodir *et al*., 2017). This observation supports the assertion by Long (2010) that in order for active restoration efforts to achieve greater diversity and community maturity, the species that display high coexistence are important. This assertion is true for *T*. *disticha* as it accommodates other species in the seed bank and does not displace it through competition or suppress it with allelopathy. The results of the study revealed that knowledge of different conditions in the treatments, and similarly in any habitat patch targeted for rehabilitation, are important in determination of rehabilitation success. Above all, these findings stress the importance of effective topsoil management to protect the valuable species diversity contained as propagules within the soil seed bank. Alpine environments usually have poor reproductive output for many plant species thereby pointing out that seed limitation is an obstacle to rehabilitation success. Hence, soil seed banks can make an important positive contribution.

6.5. Study limitations

Mine dump rehabilitation is a global environmental conservation obligation for reclaiming the damaged environment. Consequently, E-Tek Consulting was commissioned by Letšeng Diamonds to develop the rehabilitation program for the Letšeng Diamond Mine, Lesotho. Industries (i.e. E-Tek Consulting) are often engaged in large scale application of science and this sometimes leads to flaws in scientific experimental design requirements. To achieve the vegetation rehabilitation, the company's rehabilitation trials determined seeding rate as seed weight per area, instead of number of seeds per area (E-Tek Consulting, 2013). For example, Letšeng Diamonds considered seed weighing approach as cost effective to apply for large scale vegetation rehabilitation instead of counting individual seeds which is labour intensive and time consuming. Therefore, this approach did not allow calculations of seed germination proportions in this study.

Other studies have shown that seed germination and establishment do not always lead to plant community development (Wang and Smith, 2002). Weather conditions could also have affected the experimental results for discerning more detail about the pioneer species used in the trials. For instance, knowledge of the plant species relationships with the local environmental conditions and determination of physiological thresholds for different species would guide effective environmental amelioration patterns. Further studies of the seed banks would shed light on the vulnerability of the disturbed study site (i.e. mine dumps) to invasive alien species (i.e. biodiversity threat) as well as understanding of their movement pathways such as roads and rivers.

6.6. Recommendations

6.6.1. Working towards legal compliance

Compliance of Letšeng Mine for rehabilitation of the environment is carried out through implementation of the Social and Environmental Management Plan (SEMP) which ensures mining processes comply with all relevant Lesotho legislation requirements as well as alignment with Good International Industry Practice as embodied in the IFC Performance Standards and guideline documents (International Finance Corporation, 2007; Letšeng Diamonds, 2016). Therefore, Letšeng Diamonds planned and developed a Rehabilitation and Closure approach aligned with safe and sustainable end land use as outlined in the SEMP (Letšeng Diamonds, 2016). This plan has taken into consideration closure criteria for all the features that will be remaining at closure of the mine in order to minimise the long-term risk to the environment and public health.

The on-site rehabilitation trials (i.e. vegetating different tailings) were launched to ensure that the selected closure criteria are achievable and environmentally sustainable (E-Tek Consulting, 2016). Among others, the objectives of the trials were to determine the optimal growth mediums which can support natural vegetation; testing the growth performance of native grasses, forbs and dwarf shrubs to be established on these disturbed areas; and the determination of preferred seed mixtures, application rates and seeding techniques to obtain the required ecological diversity of tailings at Letšeng Diamonds.

6.6.2. Letšeng Diamond Mine operations and soil management

Rehabilitation of surface mine tailings commonly entails the establishment of vegetation (Bell, 2004). The results of this study indicated that topsoil is an essential constituent for successful rehabilitation of kimberlite mine tailings at Letšeng Diamond Mine. For example, the initial germination studies indicated a preference for tailings capped with topsoil. This study recommends *Tenaxia disticha* as the most suitable species for effective early vegetation restoration on kimberlite tailings due to its tolerance to a wide range of growth mediums and ability to accommodate other plant species. Furthermore, the study strongly recommends the investigation of germination ability of other potential species before they could be included in the seed mix to optimise the rehabilitation process.

Similarly, the longer term study on establishment indicated that the most preferred treatment of the tailings for successful plant growth must constitute the topsoil being mixed with (raked into) coarse tailings, in contrast to being capped by topsoil. Therefore, this study recommends that Letšeng Diamond Mine must prioritise the extraction and management of topsoil resulting from the mining operations, because this enhances rehabilitation success of vegetation cover. For example, the topsoil stripping and stockpiling during the mining process must avoid long periods of topsoil storage as this may compromise the soil structure and soil health (Mansfeld, 2006). An appropriate standard operating procedure should be developed and guided by in-depth soil science expertise. Moreover, the study found that soil-seed bank played an important role by contributing new plant species (spontaneous recruitment) for rehabilitation success. Other studies (e.g. Kodir *et al*., 2017) have shown that seed banks help to rapidly achieve the desired vegetation communities and ecological succession.

6.6.3. Plant diversity as target of vegetation rehabilitation

During rehabilitation, plant diversity could be an indicator of successful restoration of the vegetation component (Wood *et al*., 2015). In an attempt to expedite achievement of the plant diversity on-site, a native seed mix was prepared and tested for germination and coexistence in order to establish a plant community with a richer diversity of plant species. The results for plant diversity mixes indicated that other native species were able to germinate abundantly and establish in the presence of *T. disticha*. This study is able to provide a list of locally occurring native species which can be used in the establishment of diversity during rehabilitation of kimberlite mine tailings at Letšeng Diamond Mine. However, some of the species (*Athrixia fontana*, *Carex glomerabilis*, *Cotula paludosa*, *Harpochloa falx*, *Kniphofia caulescens* and *Selago flanaganii*) did not germinate on all tailing mixes, and therefore, further germination studies are required to explore their specific micro-habitat requirements. It is further recommended that Letšeng Diamond Mine should consider 7g/10m^2 of seed per plant species as a minimum requirement for rehabilitation of its artificial growth mediums with native vegetation.

6.6.4. Successful rehabilitation

Some of the main findings of this study are actively being incorporated into the rehabilitation program at Letšeng Diamond Mine, particularly in the stabilization of some of the slopes around the premises (Fig. 34 & 35) through the application of the recommended growth medium mixes and vegetation strategies. Successful stabilization thus far is based on the application of the minimum topsoil depth (100 mm). This application has been sufficient to promote plant establishment and growth on the kimberlite tailings slopes, and furthermore allows the completion of the full plant life cycle in a reasonable short period of time (<2 years). Additionally, the successfully rehabilitated slopes are self-seeding, and lot of spontaneous species have been recorded which are probably from the soil seed bank, or from water and wind dispersal. It is recommended to continue carrying out fixed photo point monitoring for visual assessment of vegetation cover and change.

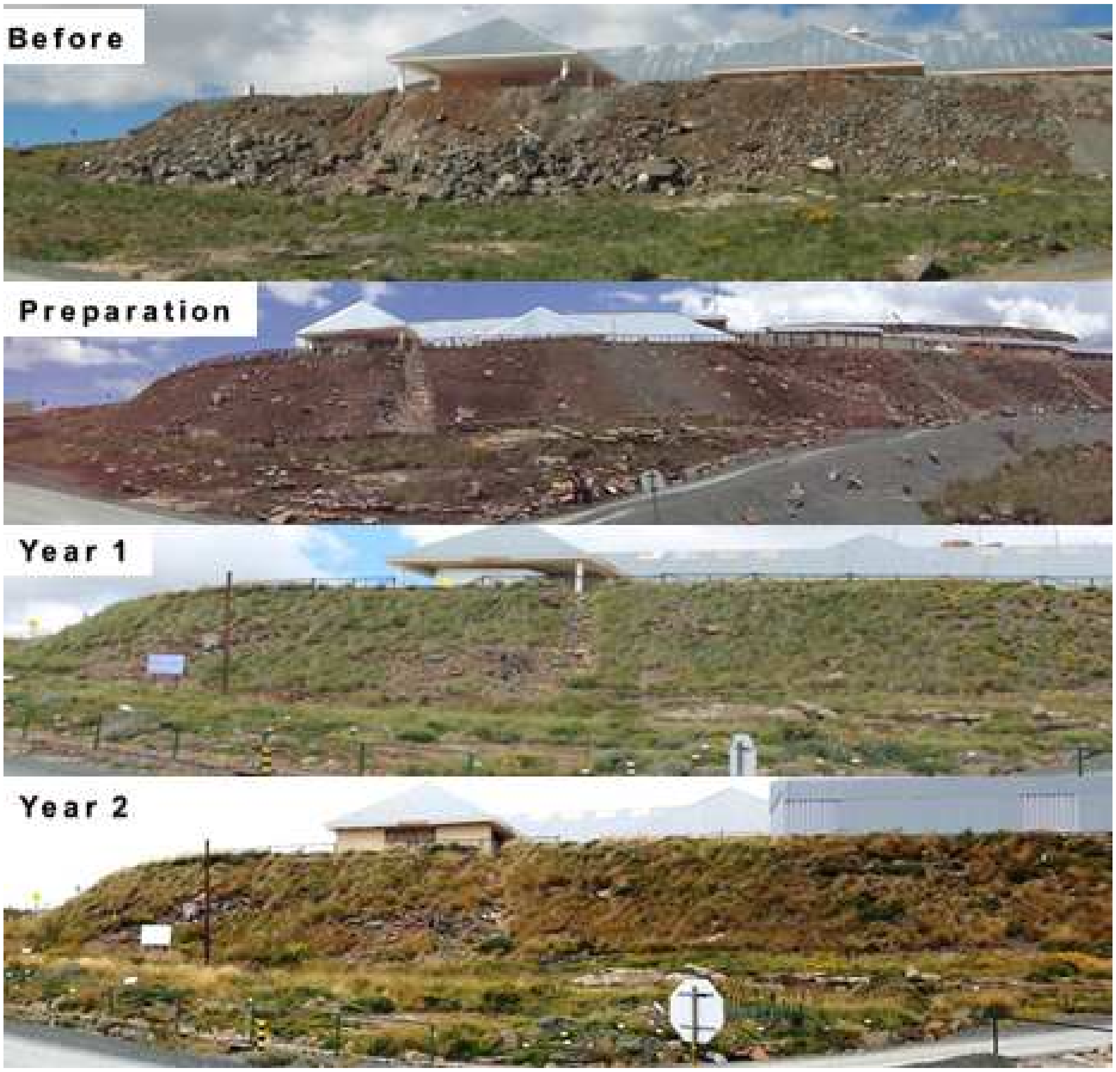


Figure 34: Vegetation cover established on a waste rock slope through raking of the topsoil.

Figure 35: Establishment of vegetation on a waste rock dump and coarse tailings slope. A considerable proportion of the vegetative cover is made up by spontaneous plant species present in the soil seedbank.

6.6.5. Implications of the study findings to the mining life cycle

Mine rehabilitation should ideally be initiated and maintained throughout the mine’s life cycle in order to achieve continuity in the mine rehabilitation plan (Sánchez *et al*., 2014). This study is relevant to all stages of the mine cycle in that it can be used to influence Letšeng Diamond Mine’s Health, Safety and Environmental policy, rehabilitation planning and objectives (see, Table 4 below).

Table 4: The importance of incorporating rehabilitation planning in a mining life cycle.

Mining stage	Associated environmental and biodiversity (e.g. vegetation) impacts:	How do the study results influence this mining stage?
1. Prospecting	Exploration for geological history and theories of mineral occurrence. Mineral occurrences are confirmed by digging of reconnaissance pits, trenches and excavation of gravel for treatment, screening and recovery of minerals. These operations cause environmental damage through vehicle tracks, oil spillages, soil compaction, disturbance of soil profiles and destructing biodiversity (Mansfeld, 2006).	Demarcation of the targeted area for mining should allow concurrent selection of topsoil and key species for rehabilitation planning and should include rescue of threatened species. The study has also shown that there is a need to investigate other potential species for expediting vegetation restoration.
2. Exploration, examination and evaluation	Requires description of quality and quantity of the mineral resources deposit.	The study did not evaluate the cost for rehabilitation. However, the results could help estimate the cost for rehabilitation, for example, by providing the estimates of volume of topsoil (e.g. essential component for vegetation restoration) required for successful restoration of the local biodiversity. This study therefore shows the importance of also describing the quality and quantity of topsoil at sites considered for future mining activities.

3. Development of mineral production	To determine the potential for mineral profitability and scale of production in order to make informed business decisions.	Mineral resources planning should include an optimal soil conservation plan and biodiversity management as part of the main business plan. This could save budget for implementation of the topsoil and biodiversity management measures for rehabilitation, as it would prevent unnecessary losses of topsoil and plant propagules.
4. Recovery of the minerals	Recovery of the minerals involves a series of processes such as removal of waste rock and processing of ore to extract the minerals. The operational activities include dumping of waste rock in the surrounding environment, building of infrastructure, and other land disturbance activities. These activities usually result in direct loss of topsoil and vegetation. Additionally, other impacts are introduction of alien invasive species which are commonly brought by employees and builders' materials and equipment.	Mining operations should institute sound soil stripping and stockpiling plan in order to efficiently harvest and store the topsoil as a source of seed bank and resource for successful rehabilitation. This can be achieved by developing operational protocol guidelines for areas with valuable plant species that are source of seed for native plants for use in rehabilitation. Moreover, a protocol is required for seed collection of native plants, genetic resources conservation and use in rehabilitation.
5. Mine closure	It involves cessation of production and the removal of all unnecessary infrastructure facilities and services and also implementation	The proposed end-land use for Letšeng Diamond Mine is a Managed Resource Area; its overall goal is working towards achieving pre-mining land use of the site, which were mainly the community grazing land and a

	of rehabilitation actions to ensure the area is secure and stable.	biodiversity conservation area. The results of the study provide as guideline to achieve this goal and provides tested approaches to initiate rehabilitation on kimberlite tailings that will receive only a very thin topsoil layer during rehabilitation.

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