

Forb and soil microbe diversity patterns of ultramafic tailings facilities at Phalaborwa

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(Photo: <https://www.google.co.za/search?q=palabora+mining+company>)

Keep your eyes on the stars, and your feet on the ground.

-Theodore Roosevelt

Declaration

I declare that the work presented in this Masters 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.



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Abstract

Palabora Mining Company (PMC) in the Limpopo Province has exploited unique ultramafic rock formations in the Phalaborwa Igneous Complex. Subsequently, mining activities has created 'mountains' of processed materials (tailings and dumps). Efficient reclamation approaches have stabilized the degraded landscape and improved the ecosystem functionality of these facilities. However, successful rehabilitation of copper mine tailings requires an in depth understanding of the biotic and abiotic factors most limiting to vegetation establishment and growth. Knowledge of the factors that promote effective rehabilitation is important, as it allows mine management to make informative decisions to address rehabilitation shortcomings by means of appropriate mitigation measures. Therefore, to achieve sustained rehabilitation success, knowledge of aboveground and belowground factors form a crucial link in assessing rehabilitation progress on post-mining sites. The objectives of this study were therefore to determine the effect of different post rehabilitation ages, aspects and topographic positions on; i) soil microbial biomass and community structure, ii) species composition, diversity, biomass and cover of the herbaceous layer, and iii) physical and chemical soil properties of tailings facilities.

The herbaceous layer of two of the PMC tailings facilities, namely the Rock Dump (RD) and Tailings Dam (TD), were sampled by means of the fixed quadrat method. Quadrats were placed in a stratified manner to sample the different age levels, aspects and topographic positions of both the facilities. A total of 174 quadrats were sampled, and the herbaceous plant richness, abundance, cover and biomass was documented for each quadrat. Soil sampling was conducted simultaneously to vegetation sampling. A total of 91 soil, and soil microbial, samples were collected and analysed. PRIMER 6, PAST and STATISTICA 11 were used for data analyses, which included Non-metric Multidimensional Scaling (NMDS) ordinations based on the Bray-Curtis index, One-way Analysis of Similarities (ANOSIM), Similarity Percentage Analysis (SIMPER), One-way Analysis of Variance (ANOVA) and Tukey's post-hoc HSD for unequal N.

Results indicated high levels of vegetation cover on the oldest and intermediate post rehabilitation ages on the RD and TD respectively, while the intermediate age on the RD and youngest age on the TD had the highest biomass. Regarding aspect and topography, the RD and TD reacted similarly, with cover highest on the slope positions on the eastern aspects, and biomass highest on the terrace positions on the western aspects. Terrace positions revealed the highest species richness and diversity, especially on the eastern aspect of the RD and southern aspect of the TD. Highest species richness and diversity was

recorded for the oldest age on the RD and youngest age on the TD. Benchmark vegetation results indicated that all tested vegetation indices of natural Mopaneveld were significantly higher than both the RD and TD.

Slope positions of eastern aspects on the oldest post rehabilitation ages maintained the highest microbial biomass; however, precarious patterns of microbial community structure were identified. Highly variable physical and chemical soil properties were noticeable on both the RD and TD. Best performing soils were found on the oldest soils on slopes with an eastern aspect on the RD and the oldest soils on terraces of the western aspect on the TD.

This study revealed that different post rehabilitation ages, aspects and topographic positions do not affect floristic composition to such an extent that a significant dissimilarity could be identified across the RD and TD. Most of the tested vegetation variables, although with erratic occurrence of significant differences, were recorded between terrace and slope topographic positions, eastern and western aspects, and oldest and youngest post rehabilitation ages of the RD and TD. Overall, enhanced species richness, diversity, physical and chemical soil and soil microbial properties were revealed under combined conditions of slope positions on the RD and terrace positions on the TD on the eastern aspects of the oldest post rehabilitation ages.

This study provides valuable information regarding patterns of herbaceous species diversity, microbial community structures and physical and chemical soil characteristics on copper mine tailings and serves as benchmark for long-term monitoring of biotic and abiotic environmental factors.

Keywords: Abiotic; biotic; copper mining; herbaceous layer; long-term; Mopaneveld; Palabora Mining Company; rehabilitation; success; tailings facilities; ultramafic.

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Chapter 1 – Introduction

1.1 Background

Mining has been, and very much still is, an important aspect in the modern day life, and human kind wouldn't be able to advance to where we are today without it (Hossner & Shahandeh, 2006). With the growth of the global mining industry, metals have been mined and exploited, and will continue on this trend, for many generations to come (Hossner & Shahandeh, 2006). Iron, lead, zinc and copper are on high demand and have been mined extensively in regions all over the world. Massive volumes of waste rock and tailings are produced and deposited on the landscape surface due to mining practises. The once pristine natural landscape in mining areas becomes transformed and the waste rock dumps and tailings can be very unstable causing land degradation and sources of pollution.

South Africa was a world leader in mining (Harris, 2003), and mining strongly dominated the country's economy (Fourie & Brent, 2006). The country is famous for its abundance of mineral resources, which accounts for a significant proportion of the world's production and reserves. Hence, South Africa's landscapes, biodiversity and ecosystem functionality are continuously altered by mining (Lubke *et al.*, 1996; Bell *et al.*, 2001). In many countries land degradation through mining activities is of major concern, and it is of no exception also the case in South Africa (Hoffman & Meadows, 2002).

In the case of Palabora Mining Company (PMC) in the Limpopo Province, semi-arid Mopaneveld savanna has been converted to 'mountains' of processed materials (tailings and dumps). PMC is a copper mine, smelter and refinery complex, and has been operational since 1956. It is South Africa's only producer of refined copper, producing approximately 80 000 tonnes per year (Kapusta, 2004). The mine owes its origin to a unique ultramafic rock formation in the region known as the Phalaborwa Igneous Complex (PIC), which consists of pegmatoidal pyroxenite cores, and is the only alkaline complex that is intensively mined for a large selection of raw minerals, which includes copper, phosphate, uranium, thorium, zirconium, iron, titanium and limestone (Frick, 1986).

Extraction of these minerals leads to the transformation of the landscape. Such an altered mining environment harbours site specific biodiversity, which maintains the functionality of the man-made system, and provides a platform for monitoring of disturbed sites that are prone to rapid degradation due to climate or land-use change after mine closure (Fourie & Brent, 2006). These changes affect the soil-plant associations, which require monitoring to

identify when mitigation measures are required. Arid and semi-arid zones are plagued by long-lasting droughts, and long-term stability is therefore of critical importance (Mendez *et al.*, 2008). Mendez *et al.* (2008) mentioned that efforts to revegetate mine tailings fail due to various soil parameters such as inappropriate soil pH values, low acid-neutralizing potential, high metal concentrations and low microbial activity. Constant monitoring is therefore a requirement to identify these problematic issues as they arise.

Vegetation establishment and stabilisation is what first spring to mind for an effective way to rehabilitate mine discard facilities. Considering structural and floristic vegetation characteristics as an indicator in the analysis of environmental quality is highly recommended, as vegetation is a component of ecosystems which displays the effects of other environmental conditions and historical factors in an easily measurable manner (Sango *et al.*, 2006). However, these investigations/methods fall short in accommodating more integrated and diverse rehabilitation goals or struggle to stay up to date with new environmental legislation developments (Baillie, 2006). The current legislation forces mining companies to plan rehabilitation, using exploration data, before the official mining process initiates (Fourie & Brent, 2006). These authors put emphasis on physical, chemical and biological data of the geology and ore of the mining site, and must be used to develop an Environmental Management Plan (EMP). By having an EMP in place to set goals, it would not only simplify long-term monitoring, but ultimately lead to more successful rehabilitation practises (Fourie & Brent, 2006).

The only reliable way to truly understand and measure change in an ecosystem and to broaden the understanding of the basic structure and function of that specific ecosystem is through long term monitoring (Wong, 2003). The necessities for long term, large scale programmes aimed at rehabilitating or restoring ecosystem structure, composition, and function plays a crucial part in management decision-making. Forming robust success criteria for rehabilitation, and the ability to demonstrate progress in recuperating or ameliorating ecological processes, is perceived as a vital link to obtaining rehabilitation goals (SER Primer, 2004). Lacking the sufficient monitoring criteria to prove that rehabilitation is improving or successful, mines will not be considered for closure under the provisions of the Minerals and Petroleum Resources Development Act (Cawood, 2004).

To ensure the most successful rehabilitation of copper mine tailings, in depth understanding of the factors that is most limiting to vegetation growth is required, thus enabling management to make informed decisions regarding amendments and optimally use it to ensure more successful rehabilitation results in the long-term (Kramer *et al.*, 2000). The

majority of vegetative studies on tailings largely reflect structure, diversity and productivity of above-ground factors (Chabrierie *et al.*, 2003), but to a lesser extent considers the crucially important link between soil microorganisms and vegetation characteristics (Wolters, 2001). However, the need to consider the essential and inevitable interaction between aboveground and belowground factors has become an increasingly important aspect in assessing rehabilitation progress on post-mining sites (Chabrierie *et al.*, 2003; Claassens *et al.*, 2011). While the rehabilitation of mined land has been greatly improved over the years, the monitoring of the success or failure after rehabilitation has been neglected (Haagner, 2008).

The enormity of the environmental impact of mine tailings disposal sites is becoming more unmanageable as mining technology improves, which leads to 'faster' mining processes (Mendez & Maier, 2008). This results in mining sites not being reclaimed and which generally remain unvegetated for tens or hundreds of years. Limiting factors for natural revegetation of mine tailings includes insufficient or excessive concentrations of metals (Mendez & Maier, 2008). Further, and possibly the most important factor, is that tailings facilities are comprised of insufficient or no organic matter or macronutrients. This leads to tailings lacking a normal soil structure and support a severely stressed heterotrophic microbial community (Mendez & Maier, 2008). Mining substrates derived from deep in the earth, or from wastes produced by processing minerals, present extreme challenges to the colonization of plants and the establishment of a self-sustaining ecosystem when compared to normal soils (Cooke & Johnson, 2002).

Due to tailings material lacking soil structure, such facilities remain unstable and unprotected against eolian dispersion, water and wind erosion, which in turn has the potential to pollute surrounding environmentally sensitive areas (Mendez & Maier, 2008). Tailings covered with vegetation produces higher levels of heterotrophic microbial community activity, and in turn can lead to better plant growth and contribute to metal stabilization (Mendez & Maier, 2008).

In the past, the emphasis of mine rehabilitation in South Africa was more on the establishment of a healthy vegetation cover to prevent and minimize erosion, but rehabilitation focuses more on the establishment of productive grasslands and the restoration/creation of plant diversity or habitats (Rethman, 2000). In other words, tailings facilities are now considered as part of the landscape and rehabilitation should be done by keeping the surrounding land-use in mind, not only to ensure more successful rehabilitation, but also more success regarding the aesthetic value (Zhang *et al.*, 2011). With the development of better integrated and calculated rehabilitation programs, in depth decisions can be made that includes environmental impact assessments and post mining land use or

closure plans (Rethman, 2000). This in turn leads to a change in attitude towards rehabilitation and predominantly biodiversity.

Conventionally, physical and chemical soil analyses and vegetation-based aboveground indicators have formed the basis of rehabilitation criteria and management decision making. However, these methods do not include the soil microbial functions and structure of the soil which are the foundation of terrestrial ecosystems (Pascual *et al.*, 2000). Numerous mine rehabilitation studies have shown that a strong association exists between the establishment of a stable vegetation and microbial community and structure (Mendez *et al.*, 2008).

However, years need to elapse to successfully measure significant changes of chemical and physical soil properties, because these parameters change very slowly (Pascual *et al.*, 2000). On the contrary, soil microbial properties are responsive to miniscule changes that occur in the soil and provides instant and precise information on transmutations in soil quality (Pascual *et al.*, 2000). The reason for the previously mentioned is that soil microbial activity directly influences ecosystem fertility and stability. Recently the importance of microbial communities has been recognised and it plays important roles in the formation of soil structure and establishing biogeochemical cycles (Tate & Rogers, 2002; De Deyn *et al.*, 2003). The function and structure of these communities is an accurate assessment of the degree of degradation and success of rehabilitation practises. The degradation of soils leads to the loss of natural vegetation cover and soil quality, and ultimately erosion (wind, water and soil) (Pimentel, 2006).

1.2 Rationale

Ecosystem disturbance may be defined as an event or series of events that alters the organism – habitat relationships in time and space (Sarma, 2005). Degraded landscape reclamation has increased exponentially during the past decade, however a scarcity of data exist on the long-term effects on plant conservation (Holl, 2002). While large improvements have been made in the rehabilitation of mine ecosystems, the management information systems that monitor the successes and failures of rehabilitation have not necessarily kept up (Aronson *et al.*, 2007). In South Africa, a widely used and almost generic guideline for mine site rehabilitation monitoring has been in practice for many years and has remained largely unchanged. These guidelines consists of rapid assessments of species richness and average basal cover, regardless of the nature of the species or how the importance of existing vegetation cover is interpreted (Ruiz-Jaen & Aide, 2005; Herrick *et al.*, 2006). However, these investigation methods are inadequate to accommodate more diverse rehabilitation goals and without adequate monitoring criteria to justifiably prove rehabilitation success or failure, mines will not be in consideration for closure under the provisions of the Mineral and Petroleum Development Act, Act no. 28 of 2002. Attaining long term ecosystem stability is a formidable challenge facing rehabilitation managers.

Successful rehabilitation of copper mine tailings requires an in depth understanding of the biotic and abiotic factors most limiting to vegetation establishment and growth so that management can make studied and informative decisions to address mine tailings rehabilitation shortcomings (Kramer *et al.*, 2000). Therefore, to achieve higher rehabilitation success, aboveground and belowground factors form a crucial link in assessing rehabilitation progress on post-mining sites (Wolters, 2001; Chabrierie *et al.*, 2003; Claassens *et al.*, 2011).

This study will provide valuable information regarding herbaceous species richness and cover of copper tailings facilities by taking into account the physical and chemical soil characteristics, soil microbial biomass and microbial community structures of different post rehabilitation ages, aspects and topographic positions (slopes and terraces).

1.3 Research aims and objectives

1.3.1 General aims

The primary aim is to describe the herbaceous plant composition and diversity, soil physical and chemical conditions, and soil microbe composition and structure of copper mine dumps in the Mopaneveld Bioregion, and congruently link the derived patterns to a chronosequence and to the aspect and topography. Relationships between vegetation, soil and soil microbial data will indicate optimum conditions to promote functionality and plant species diversity on copper mine dumps. The floristic data from the copper mine dumps will be compared to benchmark data from surrounding Mopaneveld analogues. These reference sites provide comparatively higher diversity values to estimate the rehab deficit. Overall the findings will provide suggestions to enhance functionality and to improve the sustainability of the rehabilitation program. The sampled data will also serve as a benchmark for long-term monitoring.

1.3.2 Objectives

The objectives of the study are to determine the effect of different post rehabilitation ages, aspects and topographic positions on:

- i. soil microbial biomass and community structure;
 - ii. species composition, richness, diversity, density, biomass and cover of the herbaceous layer; and
 - iii. physical and chemical soil properties
- of tailings facilities.

1.4 Thesis structure

Chapter 2: Literature review – An in-depth review is given of existing literature entailing environmental impact of mining in South Africa, the soil environment (physical and chemical properties) the role of soil microbes in the rehabilitation process and how vegetation is effected by certain abiotic factors.

Chapter 3: Study area – A detailed account of the study area is presented in this chapter, including locality, climate, geology, natural vegetation, revegetation of the tailings facilities, and site management history.

Chapter 4: Materials and methods – The chapter outlines the basis for the selection of the monitoring techniques and details the methods that was used to acquire floristic, soil and soil microbial data. Data preparation and analytical procedures is comprehensively described.

Chapter 5: Results and Discussion separate– Herbaceous species diversity. This chapter describes the herbaceous species composition, vegetation cover, biomass and herbaceous species diversity patterns of different post rehabilitation ages, aspects and topographic positions (terraces and slopes) on the Rock Dump (RD) and Tailings Dam (TD). An additional outcome is the benchmarking of the RD and TD against surrounding natural Mopaneveld.

Chapter 6: Results and Discussion separate– Microbial biomass and community structure. Microbial biomass and community structure of different post rehabilitation ages, aspects and topography sites on the RD and TD is described.

Chapter 7: Results and Discussion combined – Soil characteristics. Physical and chemical soil characteristics of the RD and TD are described and compared across post rehabilitation ages, aspects and topographic positions.

- Chapter 5 and Chapter 6 results and discussion will be discussed separately, while Chapter 7's results and discussion were combined.

Chapter 8: Conclusion

References: Full reference list of all chapters are given at the end of each chapter.

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Chapter 2 – Literature review

2.1 Mining impacts in South Africa

South Africa is ranked second worldwide as having a wide variety of major mineral commodities that is being produced with 55 different minerals mined (Harris, 2003; Gauteng Department of Agriculture 2008). Fairbanks *et al.* (2000), Cooke and Johnson (2002) and Guerra *et al.* (2010) reported that between 170 000 ha and 200 000 ha of South Africa's land surface is directly affected by mining activities, and increases every year with 'faster' mining technology and new leases being granted (Mendez & Maier, 2008). Even though mining is of great economic importance, from employment to economic growth, it is unfortunately accompanied by disturbance and destruction of terrestrial ecosystems (Milton, 2001).

The South African mining sector forms the backbone of the Limpopo Province's economy making it one of the main contributors to economic growth (Limpopo State of the Environment Report, 2004). In the Limpopo Province, there are roughly 234 different mines which constitutes 24 % of the gross domestic product (GDP) (Limpopo State of the Environment Report, 2004). It is a well-known that a lot of waste material is generated during mining operations. Fertile, cultivated land is transformed into wasteland, as mining activities produce colossal volumes of solid wastes, which is deposited at the surface and occupy vast areas of land (Li, 2006). Rehabilitation of degraded land has become one of the pressing needs to be addressed for social and economic development to be healthy and sustainable (Laurence, 2006; Li, 2006). Mined land, in particular, is legally required to be rehabilitated and the industry has the opportunity to manage such rehabilitation according to codes of best practice.

2.2 Mine waste disposal facilities

2.2.1 Waste rock dumps

In principle, mining production waste can be separated into two categories, namely waste rock, produced once the ore body has been uncovered and mine tailings which is generated during ore processing (Eriksson & Destouni, 1997). The initial waste products of mining activities, which is produced in large quantities, is composed of barren rock and ores that cannot be economically extracted, and have to be disposed, usually in the surrounding environment (Dinelli & Lombini, 1996). The waste produced by mining activities through crushing and grinding methods increases the metal release rate into the environment (Dinelli & Lombini, 1996). These extracted concentrates of metals make elements environmentally labile through ordinary biogeochemical pathways to sinks such as sediments, soils or

biomass (Dinelli & Lombini, 1996). Therefore, the high metal concentrations of waste rock dumps eventually become a source of metal pollution. Other factors such as pH levels, water holding capacity and slopes, to name a few factors that influence the rate of pollution, should be taken into account in the evaluation of environmental surroundings of waste rock dumps (Dinelli & Lombini, 1996). Not only these factors, but many others, greatly influence the capability of vegetation establishment on these limiting environments and ultimately complicate the rehabilitation process (Dinelli & Lombini, 1996; Mendez *et al.*, 2008). Unlike tailings, the texture of waste rock dumps is quite heterogeneous with particle size distribution alternating from fine sand to large boulders (Eriksson & Destouni, 1997).

2.2.2 Tailings

Since the 1960's a progressive increase in the production of metals and minerals have been witnessed and mine waste (tailings) facilities now cover vast areas of South Africa (Cooke & Johnson, 2002; Weiersbye *et al.*, 2006). Among a range of processes, the mining of metals and minerals include two main activities, namely primary (extraction) and secondary (milling, processing, refining and waste disposal) stages (Cooke & Johnson, 2002). Mine soils or mine tailings are pedogenically young soils due to the fact that it develops from mine dump material which is generated by anthropogenic activities (Vogel & Kasper, 2002). Mine tailings or mill tailings are a mixture of water and finely milled leftover rock or waste product that are discarded after the completion of the metalliferous ore extraction process (Blight, 1989; Fitton, 2007). Waste productions and disposal of the waste is in most forms of mining the primary cause of long-term and extensive disturbance to natural land (Cooke & Johnson, 2002). Mine 'soil' (tailings) properties differs vastly from natural soil in such a way that it present a completely different set of limitations to vegetation development (Kramer *et al.*, 2000; Vogel & Kasper, 2002). The tailings medium that remain after beneficial mineral extraction is completed, is in general uniformly fine in particle size (<0.1 mm) and lacks structure (Cooke & Johnson, 2002; Haagner, 2008). Coupled with the above mentioned lack of soil structure and uniform particle size the tailings possess minimal amounts of clay particles, organic matter and macronutrients, but high concentrations of often toxic metals (Vogel & Kasper, 2002). These attributes will ultimately lead to a growth medium with low water infiltration rates and directly influence the cation exchange capacity negatively (Kramer *et al.*, 2000; Cooke & Johnson, 2002; Vogel & Kasper, 2002; Haagner, 2008). The list of environmental hindrance is considerable, and also include physical crust formation and compaction due to the uniform texture and poor structure that is associated with inadequate aeration in tailings soils (Haagner, 2008).

2.3 Factors limiting rehabilitation success

Areas disturbed by mining practices are highly susceptible to erosion not only due to a lack of vegetation cover but also steep slopes and fine, dispersed particles as growth medium (Limpitlaw *et al.*, 1997). Plants help to stabilise slopes, support soil physical and chemical properties and contribute to microbial resources (Moynahan *et al.*, 2002). Limpitlaw *et al.* (1997) further explains that it is compulsory for rehabilitation projects to focus on revegetating tailings facilities using plant species that will not only decrease erosion, but also provide vegetative diversity.

The substrate properties of copper mine tailings have profound effects upon vegetation growth (Kramer *et al.*, 2000). The physical, chemical and biological environment of the growth medium influences vegetation establishment, productivity and regeneration (Kramer *et al.*, 2000). Heavy metal concentrations and/or semi-arid environments are proven to have serious limitations on plant productivity (Medina & Azcón, 2010). Poor soil structure, low water-holding capacity, lack of organic matter and nutrient deficiency usually characterise semi-arid and/or contaminated soils (Medina & Azcón, 2010).

Iglesia *et al.* (2006) mentioned that long-term revegetation success on copper tailings has been limited and that some of the failures on these mine tailings can be explained due to lack of knowledge of the presence and activity of microbial communities. In recent times the role of soil microbes has been identified to exert profound effects on vegetation composition (De Deyn *et al.*, 2003). However, vegetation cover on mine tailings is a necessity to help control several environmental problems related to mine tailings (Kramer *et al.*, 2000). On the other hand, Kramer *et al.* (2000) mentioned that the revegetation of copper mine tailings pose quite a challenge due to high levels of acidity, which is the result of the oxidation of metallic sulphides.

2.4 Soil environment: Physical, chemical and biological properties

2.4.1 Importance of soil

Rehabilitation of mined land to a stable state that is also compatible with the surrounding landscape is a main focus for a closure plan (Limpitlaw *et al.*, 1997). Before this can be achieved, a thorough comprehension of the physical and chemical nature of mine soils is required, ordinarily due to the fact that mine soils are, generally, inhospitable to vegetation (Limpitlaw *et al.*, 1997).

Soil forms the basis of life on earth and sustains environmental quality on different scales, however if the quality of the soil ecosystems degrade it will lead to a significant decrease in the soil's ability to maintain sufficient resources for plant communities (Claassens, 2007). For ecosystems to survive, soil is needed as a vital living system to sustain, maintain and enhance plant and animal productivity, water and air quality, and plant and animal health (Doran & Zeiss, 2000). Degradation of soil health and quality due to anthropogenic influences is of great ecological concern. As far as natural resources go, soil is the most significant and performs multifunctional roles (Young & Crawford, 2004; János, 2012). Some of the more important functions are listed by János (2012):

- reactor and transformer system;
- medium for biomass production;
- major natural storage of heat, water, and plant nutrients;
- natural filter and detoxifying system;
- high capacity buffer medium; and
- significant gene-reservoir of the biosphere, an important element of biodiversity.

One of the vital factors influencing the success of rehabilitation of land disturbed by mining is soil quality (Carter & Macewan, 1996; Zhu *et al.*, 2009). János (2012) defines soil quality as “a sensible and dynamically changing property which responds to the use of soil and represents the soil state”. The quality of soil is determined by the physical, chemical and biological state of the soil (Carrasco *et al.*, 2010; János, 2012). Additionally, a sound knowledge of physical and chemical soil properties is necessary to determine the effects from anthropogenic activities (Khalil *et al.*, 2013). One of the most consequential elements of soil quality is the appropriate management and rational utilisation of soil, which incorporates the importance of correct land use and environmental protection (János, 2012). Knowledge about all the processes taking place in the soil environment forms part of the important matter of sustainable development and poses quite a challenge attempting to improve degraded systems (János, 2012). Linking ecosystem function to ecosystem biodiversity is a significant challenge and trying to do so in soils is an even greater task (Fitter *et al.*, 2005). Many soil organisms do not have an explanatory role within carbon and nitrogen cycles that occur in soils, but microbial, plant and animal diversity and abundance in soil appears to have various influences on ecosystem function (Fitter *et al.*, 2005).

2.4.2 Ultramafic soil properties

The formation of ultramafic soils is due to weathering of ultramafic rocks (igneous or metamorphic rocks that consists of approximately 70 % mafic minerals) (Brady *et al.*, 2005).

The weathering of ultramafic rocks results in the formation of unique soil conditions, which is often characterised by toxic soil conditions (Rajakaruna & Bohm, 1999). Similarly, Brady *et al.* (2005) states that the colonization of polluted areas such as mine soil is challenging for plants because they must develop tolerance to toxic levels of heavy metals, as well as adapt to a suite of other edaphic restrictions, such as low nutrients or drought conditions (Nagy & Proctor, 1997).

'Serpentine soil' is a globally used term, but it is in fact a misnomer, because in no way is it the exclusive mineral in ultramafic soils (Brady *et al.*, 2005; Boneschans *et al.*, 2015). The distribution of 'serpentine' or ultramafic outcrops is witnessed all around the world and have unique features that sets it apart from adjacent areas (Whittaker, 1953; Brady *et al.*, 2005; Abou-Shanab *et al.*, 2007). According to various sources (Proctor, 1971; Bonifacio *et al.*, 1997; Moser *et al.*, 2005; Kierczak *et al.*, 2007) the most unique feature of ultramafic soils is the higher magnesium to calcium (Mg>Ca) ratio, and higher iron (Fe), chromium (Cr), nickel (Ni) and cobalt (Co) concentrations. In addition calcium (Ca), sodium (Na), potassium (K), phosphorus (P) and aluminium (Al) are present, but in extremely low quantities (Moser *et al.*, 2005; Kierczak *et al.*, 2007).

Further, and more applicable to this study, is that ultramafic zones are also associated with unique vegetation, due to the distinctive chemical composition of these soils (Brady *et al.*, 2005; Moser *et al.*, 2005). Although variation may occur between sites, Brady *et al.* (2005) and Proctor (1971) acknowledged three shared traits of serpentine zones specifically: i) reduced vegetation productivity, ii) high endemism rates, and iii) vegetation types distinct from bordering non-serpentine areas.

2.4.3 Role of microbial communities in soil

The physical and chemical properties of soil ensure growing conditions and functionality of all living organisms, however these properties change slowly and long periods are required for environmental changes to be observed (János, 2012). On the other hand, soil microbial properties possess an increased susceptibility to environmental change and therefore reveal changes quickly and continuously (Mummey *et al.*, 2002; János, 2012). Soil microbial parameters are suitable for use as the earliest indicators of soil quality (Zelles, 1999). Objective measurements of the ecosystem status are needed to manage or even reverse degradation effectively (Harris, 2003). Harris (2003) has also shown that by measuring characteristics of microbial communities in soil, the quality of that soil can then be determined. These measured characteristics enable management practices to define the

state of degradation in which it finds itself in terms of restoring the ecosystem structure and function. The occurrence of drastic disturbance will cause significant alteration to both the structure and biomass of the soil microbial community (Mummey *et al.*, 2002; Wahl *et al.*, 2012). Extreme environments put tremendous pressure and limitations on soil resilience, soil biodiversity and soil health and are therefore more sensitive to disturbance. With that being said, Moynahan *et al.* (2002) mentioned that the activities of microbial communities are fundamental components of ecosystem function, as they provide essential links between biological, physical and geochemical systems. Plant ecology and restoration studies indicate the importance of soil microbial communities which ensure more successful plant establishment, community development and growth (Hamilton & Frank, 2001; Moynahan *et al.*, 2002). The microbial community develops in response to organic carbon exudates and products from plants, which in turn promotes vegetation growth through mobilizing nutrients, transforming soil organic matter and producing growth-promoting substances (Moynahan *et al.*, 2002).

Microbes play a vital role in vegetation root development and growth. It directly affects the aggregation of root-adhering soil (RAS), which make up the surrounding and immediate physical environment (soil) in which roots find the necessary oxygen, water, and nutrients for uptake and eventually growth (Papli & Laing, 2006). Regardless of the correlations that have been observed linking microbial diversity and successful revegetation efforts of mine tailings facilities, bacterial activity of the mine tailings microbial communities had not been comprehensively studied (Mendez *et al.*, 2008). Mine tailings reveal high levels of metals such as Arsenic (As), Copper (Cu), Iron (Fe), Manganese (Mn), Nickel (Ni), Lead (Pb), Cadmium (Cd) and low quantities of nutrients and organic matter which leads to tailings that are often devoid of vegetation (Mendez *et al.*, 2008). Carbon (C), nitrogen (N) and sulphur (S) nutrient cycle movements in the soil system is mainly driven by microbes (Papli & Laing, 2006).

In the rehabilitation context, total organic carbon, microbial biomass and microbial community structure is greatly affected by heavy metal contamination (Moynahan *et al.*, 2002). High metal concentrations reduce the ability of the microbial community to metabolize a variety of carbon resources (Moynahan *et al.*, 2002). Active soil microbial populations frequently secrete polysaccharides that form a layer around soil particles in their immediate environment, to ensure sufficient lubrication and space between them. The result is increased soil stability and porosity. Soil may be unable to support plant life if an absence of sufficient biological components occurs, even if ample soil physical and chemical fertility is present. Therefore, an in depth understanding of soil ecosystems, including their physical,

chemical and biological characteristics, each of which is crucial to plant productivity, is necessary (Carter & Macewan, 1996; Claassens, 2007). The previously mentioned characteristics are necessary to ensure that rehabilitated mine soils are capable of supporting plant growth in order to achieve long-term rehabilitation goals (Carter & Macewan, 1996; Claassens, 2007).

Although the importance of a well-established microbial community for the restoration of mine tailings has been acknowledged, only a few studies concerning mining areas and the effect they have on the environment in South Africa have been conducted (Wahl *et al.*, 2012). There remains is a scarcity of information available regarding microbial community structure in reclaimed metal-contaminated sites and about the impact of restoration practices on these communities (Potthoff *et al.*, 2006).

Different methods can be applied to study microbial communities. The analysis of phospholipid fatty acids (PLFAs) is a biomarker method that can be used to characterise specific structural changes in a certain microbial community and estimate the viable microbial biomass (Willers *et al.*, 2015a; Willers *et al.*, 2015b). Determining the viable biomass of a microbial community provides an estimate of the amount of active microorganisms in a particular environment and, therefore, the capability for metabolic transformations in that environment (Vestal & White, 1989).

Microorganisms change the lipid composition of their membranes in reaction to several environmental conditions such as temperature changes and chemical stress (Malik *et al.*, 2008). In addition, different microbial groups have unique signature lipid biomarkers (Table 2.1). Therefore, any changes to the structure of the microbial community or to the lipid composition of their membranes, will translate to a variation in the signature lipid profile of the microbial community. PLFAs is a good indicator of living organisms because it degrades rapidly upon cell death and a further advantage is that changes in PLFA patterns under environmental stress conditions are a suitable biomarker tool to describe the community structure (Willers *et al.*, 2015a; Willers *et al.*, 2015b). PLFAs provide a sensitive measure of change at community levels, as it accounts for a much larger portion of the soil microbial community than culturing techniques would (Carrasco *et al.*, 2010).

Most cells have phospholipids in their membranes containing ester-linked fatty acids. These fatty acids sustain the membrane fluidity to ensure that the transport of nutrients can occur (Vestal & White, 1989). Since the total lipids of a cell can be quantitatively extracted, a quantitative and qualitative analysis of the phospholipid fraction for fatty acids will reveal the

presence and abundance of certain types of microbes under natural conditions, giving an indication of the microbes present at a particular moment (Vestal & White, 1989). Furthermore the PLFA technique offers the opportunity to gain insight into the metabolic state of the microbial community. This is done by studying the ratios of certain fatty acids that forms in a response to a given environmental stress, consequently generating characteristic PLFA stress signatures (Willers *et al.*, 2015b).

Table 2.1: Major phospholipid fatty acid (PLFA) groups associated with the membranes of various microorganisms (Table from Claassens, 2007)

PLFA Structure Group	Fatty Acids	General Classification
Normal saturated	14:0, 15:0, 16:0, 17:0, 18:0, 20:0, 21:0, 22:0, 23:0, 24:0	A general microbial biomarker found in both the prokaryotic and eukaryotic (polyenoic fatty acids) kingdoms; a relative increase has been shown to correlate with decreased diversity.
Monounsaturated	14:l ω 5c, 15:1, 16:1 ω 9c, 16:l ω 7c, 16:l ω 7t, 16:l ω 5c, 17:l ω 8, cy17:0, 17:1, 18:3 ω 6, 18:3 ω 3, 18:l ω 9c, 18:l ω 7c, 18:l ω 7t, 18:l ω 5c, 19:l ω 12c, 19:l ω 12, cy19:0, 20:l ω 9c, 20:l ω 9t, 22:l ω 9c, 22:l ω 9t	Indicative of predominantly Gram-negative bacteria, which is fast-growing, utilise many carbon sources and adapt quickly to a variety of environments; may also be found in the cell membranes of obligate anaerobes such as sulphate or iron-reducing bacteria; an increase in the amount and type of carbon sources has been shown to increase this marker.
Terminally-branched saturated	i14:0, i15:0, a15:0, i16:0, i17:0, a17:0, i18:0	Common to Gram-positive bacteria, including <i>Arthrobacter</i> and <i>Bacillus</i> spp. Many of these types of bacteria can be spore formers and can exist in environments that are lower in overall organic carbon content.
Mid-chain branched saturated	i10Me15:0, a10Me15:0, br15:0a, 10Me15:0, br16:0a, br16:0b, br16:0c, 10Me16:0, 11Me16:0, 12Me16:0, br17:0, 2Me17:0, 10Me17:0, 12Me18:0	Primarily indicative of Actinomycete type bacteria in surface soils. It has been hypothesised that since these bacteria grow hyphae they are able to better survive in, harsh environments due to their ability to span interstitial spaces to collect water and-nutrient sources
Polyunsaturated	18:2 ω 6, 18:3 ω 3, 20:2 ω 6, 20:5 ω 3	Representative of fungi and other micro-eukaryotic organisms; this marker too shows significant differences due to land-use.

2.5 Topography

2.5.1 Aspect and slope

Topography, as an abiotic environmental factor, can have influences on plant diversity, abundance and distribution (Fattahi & Ildoromi, 2011; Zeng *et al.*, 2014), which is directly applicable to tailings facilities due to their shape and height. The main topographic factors affecting vegetation diversity and distribution patterns through ecological gradients include elevation, and slope position, aspect and angle (Palmer, 1992; Wang *et al.*, 2002; Zeng *et al.*, 2014). The occurrence of different species along an ecological gradient can be explained by the availability of resources such as water, sunlight, heat and soil nutrients, which leads to the development of micro-climatic conditions (Fattahi & Ildoromi, 2011; Zeng *et al.*, 2014). For instance, Rech *et al.* (2001) found that in the northern hemisphere plant species composition and productivity, soil weathering and erosion are generally enhanced on cooler, moister slopes. Furthermore, differences in soil properties is also evident between north and south facing slopes (Rech *et al.*, 2001).

Environmental factors such as topography influences vegetation diversity and distribution more in arid areas than humid areas (Zeng *et al.*, 2014) and would therefore be more significant to investigate in arid regions where the effect is more pronounced. Slope and aspect greatly determine the total amount of solar radiation that the surface receives (Bennie *et al.*, 2008). Auslander *et al.* (2003) reports that in the Northern Hemisphere, north facing slopes can get as much as six times less solar radiation than south facing slopes. Thus, in the Southern Hemisphere the north facing slopes contains more species adapted to warm and xeric conditions with a more versatile micro-climate. The two opposite slopes significantly differs in terms of radiation and temperature, and influences the biology of organism at all levels (Auslander *et al.*, 2003). The principle component of the surface energy balance is solar radiation. It influences ecologically critical factors of the microclimate, such as surface temperature, evaporation and soil moisture content (Bennie *et al.*, 2008). Further, and more importantly, solar radiation is responsible for the vegetation's exposure to photosynthetically active wavelengths, and therefore the spatial variation in slope and aspect will define species distribution, vegetation patterns and ecosystem processes in a wide variety of environments (Bennie *et al.*, 2008).

2.6 Age of tailings

A sequence of related soils that differ in their degree of profile development because of differences in their age is known as soil chronosequences (Silvertown *et al.*, 2002; Walker *et al.*, 2010). According to Huggett (1998), soil chronosequences are naturally related suites of

soils which developed under similar circumstances of vegetation, topography and climate. It has been found that 40 year old vegetated tailings offer a unique variety of plant communities of incrementing biotic diversity. In addition, it provides an opportunity to investigate successional measures as plants colonize these anthropogenic generated ecosystems (John *et al.*, 2002). John *et al.* (2002) goes further in saying that by vegetating tailings the assumption can be made that a dense cover of plant material will lead to soil formation, and in return it will decrease erosion, dust and leaching of various metals and acids. Considering successional theory, it is assumed, and has been shown, that older plots reveal the highest plant species diversity (Greenslade & Majer, 1993). Greenslade and Majer (1993) found that high diversity of soil fauna showed a correlation with high plant diversity, high vegetation biomass and large quantities of organic matter.

As functionally significant decomposing groups in the soil structure, soil fauna community composition undergoes changes as a specific habitat develops (Greenslade & Majer, 1993). Different ages of reclamation sites need to be analysed to more accurately understand how soil microbial communities change and reorganize (Mummey *et al.*, 2002). Huggett (1998) and Mummey *et al.* (2002) stated that rapid change of the biotic and abiotic components of arid soils occur over time, which indicates the importance of examining the biotic and abiotic components at different time scales to fully elucidate these relationships. Greenslade and Majer (1993) stated that soil properties of degraded mine sites approaches that of natural undisturbed conditions only 10 to 13 years after rehabilitation. As time progresses an exponential or linear increase or decrease in soil properties is witnessed (Huggett, 1998).

2.7 Plant diversity

The latest attentiveness in rehabilitation of mine tailings in arid and semi-arid areas focuses on revegetation (Mendez *et al.*, 2008). A well-defined and regularly used approach to determine plant diversity is by measuring species richness which reveals most of an area's specific biodiversity, although not every single species in even a single ecosystem will ever be identified or counted (Bengtsson, 1998).

Biodiversity is not just the number and variety of organisms found in a specific geographic region but it forms part of a more complex combination of biological variability across different scales from species to ecosystems and landscapes (Walker, 1992). According to Walker (1992), the best approach for conserving biodiversity is not to focus on species alone but to conserve and maintain the integrity of ecosystem functions. Therefore, the correct habitat and the management of the specific service and function that habitat has to offer, has a greater ability to assure successful survival of different plant species. The unforgiving habitat of mine tailings consists of completely altered soil characteristics and topography, and can therefore not provide the necessary resources to maintain high species diversity which is required to colonize all the available niches to sustain the ecosystem function (Walker, 1992).

In the past, ecologists concentrated on interspecific competition as one of the most important aspects that structured plant communities (Bever *et al.*, 2001). However, interactions between plants are most likely to be facilitated by numerous soil organisms (Bever *et al.*, 2001). More emphasis has been placed on incorporating a greater diversity of indigenous species in revegetation projects (Rethman, 2000). This is based on evidence suggesting that a greater plant diversity of local indigenous species will increase the stability of the vegetation (Rethman, 2000).

Total soil organic carbon, soil temperature and water content can be affected by plant diversity and vegetation cover and thus has the potential to affect microbial community composition and function (Potthoff *et al.*, 2006; Carrasco *et al.*, 2010). Zelles *et al.* (1995) also found that a permanent vegetation cover leads to increased organic carbon content, and induces change in microbial community structure and higher microbial biomass.

2.8 Concluding summary

South Africa has been built on the back of a flourishing mining economy. For nearly 150 years, mining has been the driving force behind the economy (Promethium Carbon, 2016). While there is great economic benefits, the negative impact of mining cannot be overlooked as the single most destructive impact of mining is on the environment. It is required by law that mines are held responsible for rehabilitation of the environments which they alter (Swart, 2003).

Therefore, from a mine tailings rehabilitation point of view it is critical to firstly reduce the mining impact on the environment as far as possible and secondly to rehabilitate the disturbed areas. Tailings facilities' 'soil' properties differ vastly from natural soil in such a way that it presents a completely different set of limitations to vegetation development. High metal concentrations coupled with the lack of soil structure, uniform particle size, minimal amounts of organic matter and macro-nutrients, and often high concentrations of toxic metals ultimately lead to an unfavourable growth medium.

Vegetation establishment, and specifically greater species diversity on mine tailings, is the most important but also most difficult objective to achieve as part of the rehabilitation process. However, interactions between plants are most likely to be facilitated by numerous soil organisms. Rehabilitation practises in recent times started to place more emphasis, not only on the revegetation of mine tailings, but also on belowground physical and chemical soil characteristics and soil microbial structures. One of the vital factors influencing the success of rehabilitation of land disturbed by mining is soil quality. The physical and chemical properties of soil ensure growing conditions and functionality of all living organisms. However, these properties change slowly and long periods are required for environmental changes to be observed. On the other hand, soil microbial properties possess an increased susceptibility to environmental change and therefore reveal changes quickly and continuously, and are suitable parameters for use as the earliest indicators of soil quality.

Another equally important element in the rehabilitation process is the abiotic factors and how it affects the biotic components. Different topographic positions (slopes and terraces), the age of tailings since rehabilitation (chronosequence) and aspect (East, South and West) all play a significant role in the amount of solar radiation a particular slope receives, temperature fluctuations, recovery time since rehabilitation and soil erosion.

Indicated in this summary of selected aspects is the importance of the combination of biotic and abiotic factors with the primary focus on the effects of different post rehabilitation ages,

aspects and topographic positions on the herbaceous species diversity, soil physical and chemical characteristics and soil microbial community structures of mine tailings facilities. All of which will be addressed in the results chapters of this dissertation.

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Chapter 3 – Study area

3.1. Locality

Palabora Mining Company (PMC) is situated in the north-eastern part of the Limpopo Province, South Africa, neighbouring the town of Phalaborwa (Figure 3.1), which itself is located 550 km northeast of Johannesburg, and adjacent to the Kruger National Park (24°00'02.69" S, 31°10'59.26" E). PMC operates the country's largest copper mine and form part of the Rio Tinto world group of mines (Moukodi, 2008). Mining commenced in 1956 making it South Africa's only producer of refined copper and producing approximately 80 000 tons per year (Lennox, 2011). Production began as a large-scale opencast mine in 1966. During the 1960's to 1980's PMC produced nearly 3 million tons of their primary product, copper (Lennox, 2011). By-products produced and dumped at disposal sites include magnetite, nickel sulphate, anode slimes, sulphuric acid and vermiculite (Lennox, 2011).

This study was conducted on two rehabilitated disposal sites consisting of waste rock (Figure 3.2) and tailings (Figure 3.3). The PMC tailing facilities cover a total area of approximately 816 ha with the rock dump making up 291 ha and the tailings dam 395 ha, respectively. The study area is surrounded by natural vegetation which is connected to the Kruger National Park on the eastern side and Ba-Phalaborwa Local Municipality to the north, south and west.

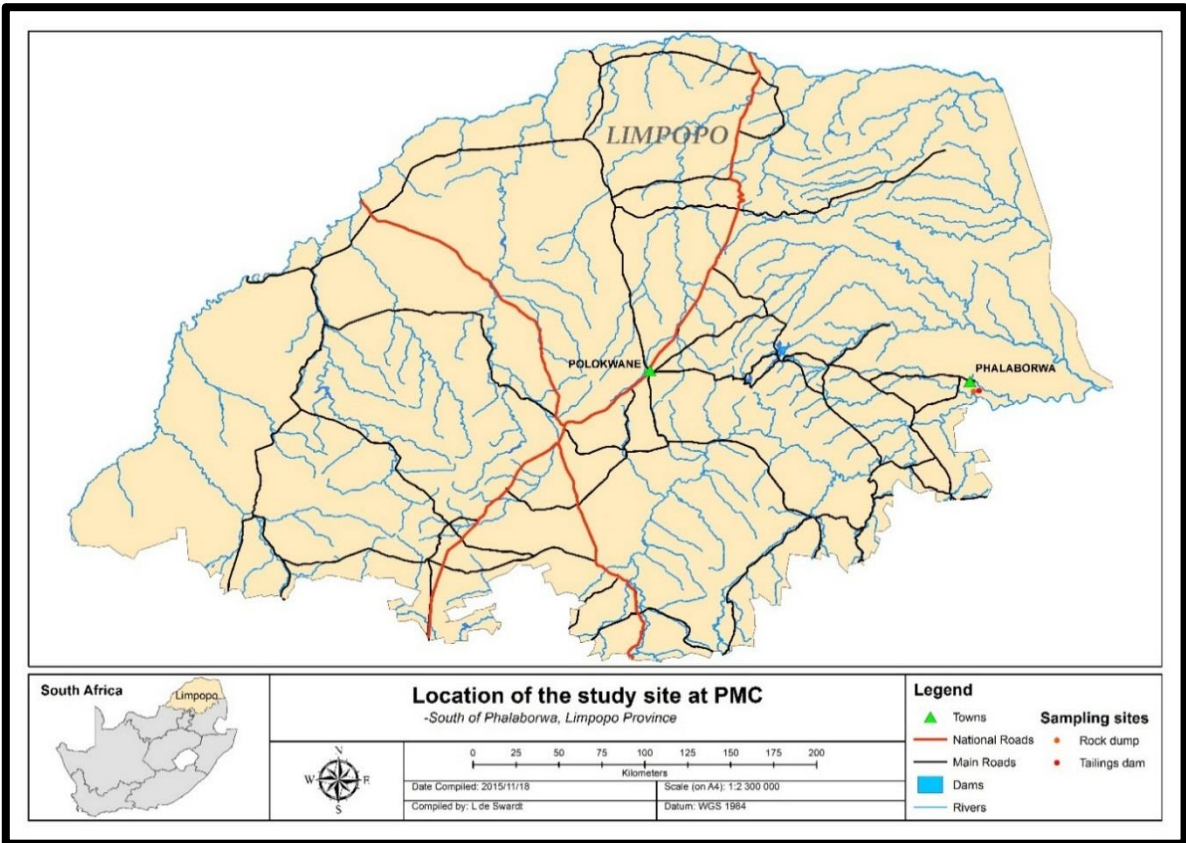


Figure 3.1: Location of the study sites at PMC south of Phalaborwa in the Limpopo Province.



Figure 3.2: Rock Dump with sampling plots indicated by red dots.



Figure 3.3: Tailings Dam with sampling plots indicated by red dots.

3.2. Climate

3.2.1 Rainfall

The study area is located in a summer rainfall region, with moderately cold, generally frost free, but very dry winters, and extremely hot and humid summers (Schulze, 1994). Most of the rainfall emanates during spring and summer (October to April) thunderstorms (Mucina & Rutherford, 2006) (Figure 3.4). The study area lies in the 400-600 mm isohyet and has a mean annual precipitation of 501 mm (Vegter, 2003; Mucina & Rutherford, 2006) with monthly variation (Figure 3.4 and 3.5). However, over the last 10 years (2003 - 2013), which includes the study period in 2013, the average annual rainfall was 415 mm (South African Weather Services, 2014) (Figure 3.5). The study area can therefore be considered as semi-arid.

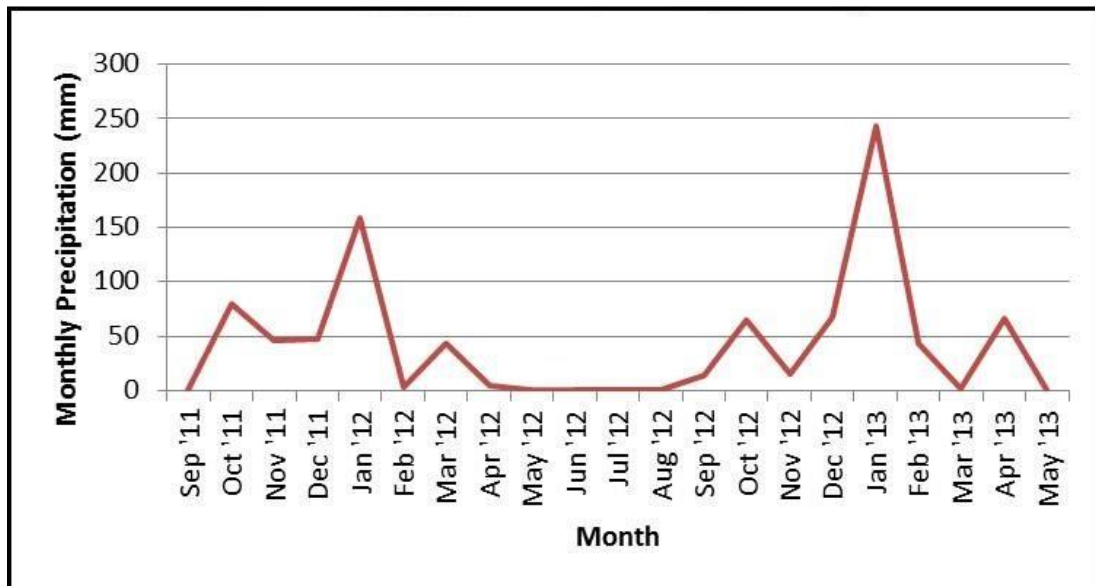


Figure 3.4: Monthly precipitation leading up to and including the sampling of the tailings facilities at PMC during February-March 2013. Data was obtained from the Phalaborwa weather station (South African Weather Services, 2014) which is situated approximately 6 km to the north of the study sites.

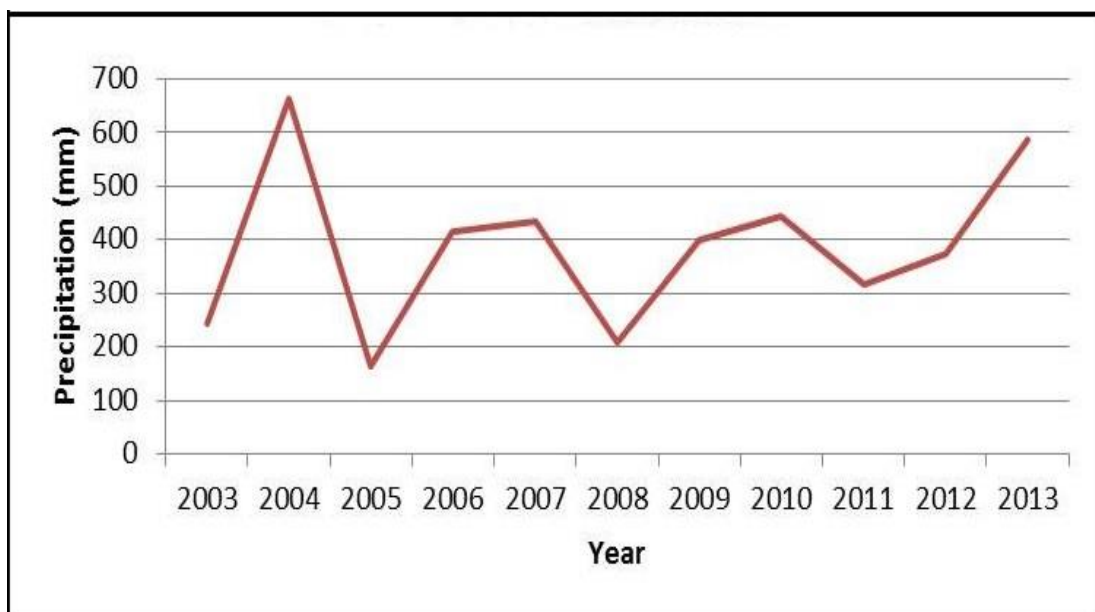


Figure 3.5: Long term yearly precipitation recorded at the Phalaborwa weather station (South African Weather Services, 2013).

3.2.2 Temperature

The mean monthly maximum and minimum temperatures for Phalaborwa were measured at 33.9°C and 6.5°C for January and July respectively (South African Weather Services, 2014) (Figure 3.6). The mean annual temperature was 22.5°C, with an average minimum temperature of 15.9°C and an average maximum of 29.1°C (South African Weather Services, 2014) (Figure 3.6). During the study period, from mid-February to mid-March 2013,

not only was the mean minimum temperature higher (20.9°C) than the long-term mean (15.9°C), but the mean maximum temperature also showed an increase (31.7°C) compared to the long-term mean of 29.1°C (South African Weather Services, 2014) (Figure 3.6).

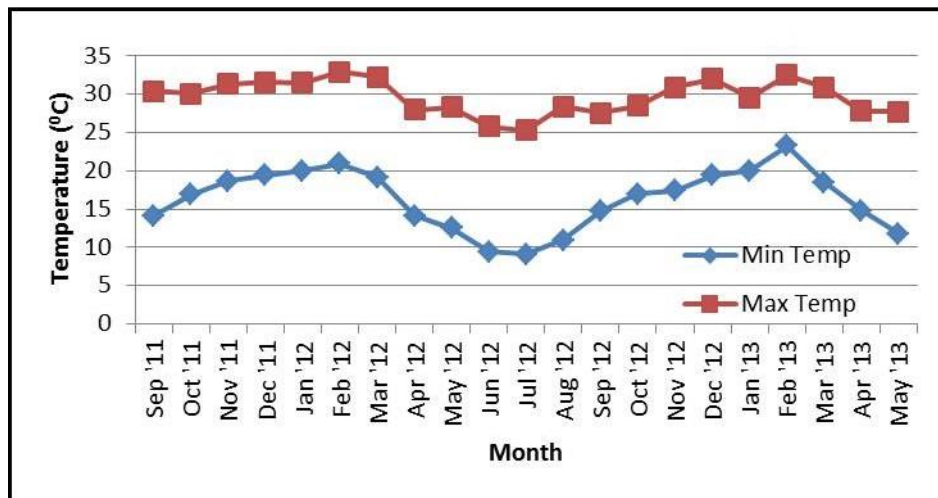


Figure 3.6: Mean monthly minimum and maximum temperatures leading up to and including the sampling of the tailings facilities at PMC during February-March 2013. Data was obtained from the Phalaborwa weather station (South African Weather Services, 2014) which is situated approximately 6 km to the north of the study sites.

3.3. Geology

The study site shares its geology with the larger unique ultramafic rock formation known as the Phalaborwa Igneous Complex (PIC) underlying the Letaba district, alongside the western periphery of the Kruger National Park (KNP) (Frick, 1986). Some two billion years ago, a series of violent volcanic eruptions, which took place over a period of millions of years, gave rise to a rich body of minerals that became known as the PIC. The PIC is unique due to the fact that it is the only alkaline complex that is intensively mined for a large selection of raw minerals which includes copper, phosphate, uranium, thorium, zirconium, iron, titanium and limestone (Frick, 1986). The parent material primarily consists of granite and gneiss (Gertenbach, 1983). Soils that originate from ultramafic rocks are broadly dispersed on earth, and are generally indicative of (a) low plant nutrient levels such as nitrogen (N), phosphorus (P), potassium (K); (b) elevated concentrations of toxic elements such as nickel (Ni), cobalt (Co), copper (Cu), chromium (Cr); (c) higher magnesium to calcium (Mg>Ca) ratios (Vithanage *et al.*, 2014)

The tailings at PMC therefore originate from copper mining in the PIC, which consists of pegmatoidal pyroxenite cores (Van der Merwe & Killick, 1979). The outer layer has zones of serpentine pegmatoid, while the central parts enclose foskorite (olivine/serpentine-

magnetite-apatite-calcite rock) (Van der Merwe & Killick, 1979). A banded carbonatite (calcite/ magnetite/apatite) intrusion is host to the copper (Cu) mineralisation.

Gertenbach (1983) explains that secluded plugs of syenite, which originated from the PIC, penetrated into the granite to form syenite inselbergs in the landscape surrounding PMC. A unique ore body outcropping at a small saddleback hill, later to be called Loolekop, contained a unique variety of minerals, namely copper, phosphates, magnetite, uranium, zirconium, nickel, gold, silver, platinum and palladium. Two other volcanic pipes nearby contained vermiculite and phosphate. The reason for this significant occurrence is that the syenite inselbergs contain a blend of orthoclase and extents of quartz, and weathering has different effects on the coarse-grained, easily weathered granite than on the massive and more resilient syenite (Frick, 1986). Therefore these slow-weathering syenite inselbergs protrude from the landscape.

3.4. Vegetation

3.4.1 Natural vegetation

PMC harbours a wide diversity of fauna and flora due to its close proximity to the Kruger National Park and responsible management requires constant monitoring of the natural environment and the living organisms within it (Surmon, 2006a). The greater Phalaborwa is part of the dryer northern sub-region, and is situated in the Savanna Biome. The vegetation is classified as Phalaborwa-Timbavati Mopaneveld of the Mopane Bioregion (Mucina & Rutherford, 2006). This vegetation type is relatively tolerant to low rainfall, and hot and humid temperatures that is characteristic of semi-arid regions (Surmon, 2006a; South African Weather Services, 2013). In semi-arid regions the vegetation growth and recovery is restricted by aridity and nutrient-poor soils (Milton, 2001).

A substantial area of natural vegetation has been lost in the active part of the mining area. Vegetation in the immediate vicinity of the mine pit and tailings include tree species typical of semi-arid Lowveld such as *Colophospermum mopane*, *Combretum apiculatum*, *C. imberbe*, *Sclerocarya birrea*, *Senegalia nigrescens* and *Vachellia tortilis* (Surmon, 2006a). Various grass species occur in natural areas, but the sward is dominated by *Digitaria eriantha* and *Themeda triandra*. Patches with high grazing pressure are dominated by wiry grasses such as *Aristida congesta*, *Eragrostis trichophora*, *Perotis patens* and *Schmidtia pappophoroides* (Mucina & Rutherford, 2006).

3.4.2 Revegetation

In 1998 PMC became one of the first mining companies in South Africa to comply with the requirements of the ISO 14001 environmental management system. Success rate of revegetation of the TD and RD at PMC has been high (Surmon, 2006b). Primarily the main purpose of revegetation of the tailings facilities was to ensure sufficient plant cover that would in turn diminish wind and water erosion, where after the established vegetation could also advance the aesthetic aspects of the mined areas to ultimately prepare for mine closure (Surmon, 2006c).

The waste rock dump ranges in height from 148 to 163 m, and is capped with a 250 to 300 mm mixture of soil and fine vermiculite waste material, which is also mined at the same site. Vermiculite is proven to be a satisfactory growth medium where top soil was absent (produced by PMC's vermiculite production facility) (Surmon, 2006c; Sustainable Development Report, 2010). The vermiculite is a good candidate as amendment for chemical stabilization of contaminated soils, due to the fact that it significantly reduces the uptake of metal pollutants in plants. As the vermiculite contact time with polluted soil increases, its effectiveness increases (Malandrino *et al.*, 2011). Subsequently, the tailings facilities walls have also been capped with this material. The capped areas were then fertilized and seeded with the grasses *Anthephora pubescens*, *Chloris gayana*, *Cynodon dactylon*, *Cenchrus ciliaris*, *Digitaria eriantha*, *Eragrostis tef* and *Panicum maximum*. According to Surmon (2006c), many tree species had also been planted in the rehabilitation areas which include *Bolusanthus speciosus*, *Combretum apiculatum*, *C. imberbe* and *Dodonaea angustifolia*. Unfortunately, the survival rate of these trees were unsatisfactory due to many trees having been pulled out by wild animals such as elephants and baboons (Surmon, 2006c). A scarcity of substantial historic records exist regarding the rehabilitation processes on both the RD and TD, specifically the species combinations and fertilizer mixtures that was used to seed the tailings facilities (Surmon, 2006a; Surmon, 2006b; Surmon, 2006c; Lennox, 2011).

Once the grass had germinated on the dumps, it was carefully monitored and maintained in order to achieve a satisfactory, self-sustaining cover on the tailings facilities. The parameters that were taken into account during the rehabilitation process were species composition, number of species, vigour and basal cover (Surmon, 2006c). These helped to determine whether the revegetation programme worked and whether any changes were required to improve it. To date, PMC has rehabilitated an area of approximately 360 ha (Surmon, 2006c). The current practises being performed by PMC are to ensure that the mined areas are being well managed and monitored with respect to environmental control. Surmon

(2006c) stated that natural plant succession will slowly result in the colonisation of the rehabilitated areas by natural vegetation from the protected surrounding environments.

3.5. Site management history

All mines eventually close, and with no exception it is also the case for PMC. PMC's initial closure plan was developed during the late 1980's. Ever since then the plan was constantly renewed and updated as new technologies, knowledge and legislation came to light (Surmon, 2006b). The last full update of the closure plan took place in 2005, although a revision took place in 2010 with a shift in closure objectives towards sustainability (Surmon, 2006b).

Industrial processes used at PMC are relatively inert, with low acid rock drainage potential, and another beneficial factor is the calcitic nature of the ore and waste rock which neutralizes any formation of acid rock drainage from residual sulphides (Moukodi, 2008). According to the mine closure fact sheet (Surmon, 2006b), the potential liabilities lie in the areas of physical safety of human and wildlife and the management of saline surface and sub-surface water (Surmon, 2006b). The saline groundwater will continue to be pumped for a period of 10-20 years from around the tailings dams until the seepage ceases.

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Chapter 4 – Materials and methods

4.1 Methods of investigation

The current state of plant diversity in a rehabilitation process and the link between above and below ground properties can only be determined by means of a synthesis of different approaches. This study therefore comprised extensive field sampling and analytical procedures. The methodological approach conforms to general guidelines of the South African Environmental Observation Network (SAEON) (SAEON 2013).

The field procedure incorporates three components. The first involved the stratification of PMC tailings facilities which comprises two dumps, namely a rock dump and tailings dam. Each of the two dumps was stratified according to topography (slopes or terraces), aspect (east, south or west), and post rehabilitation age (chronosequence). The second component entailed vegetation sampling to describe the floristic characteristics of the herbaceous layer. The third involved the collection of soil samples for physical and chemical analysis, and soil microbe samples for microbial biomass and community structure analysis.

4.2 Experimental Design

The study sites were stratified according to different units of topography, aspect and post rehabilitation age (Figures 4.1 & 4.2). This was necessary to ensure adequate sample size (number of plots) for each variable.

Three post rehabilitation ages were sampled on the rock dump (28, 32 and 42 years) and four post rehabilitation ages were chosen for sampling on the tailings dam (20, 24, 30 and 32 years). Although the tailings dam had eight age levels, only every second level was sampled. Rehabilitation levels (ages) of mine tailings provide unique and rare opportunities to investigate the development of ecosystems through succession beginning at 'point zero' (Picaud & Petit, 2007). Soil and vegetation characteristics will be affected by the amount of time that has elapsed after the establishment of each level, mainly due to post rehabilitation exposure time to resources, soil processes and environmental factors (John *et al.*, 2002).

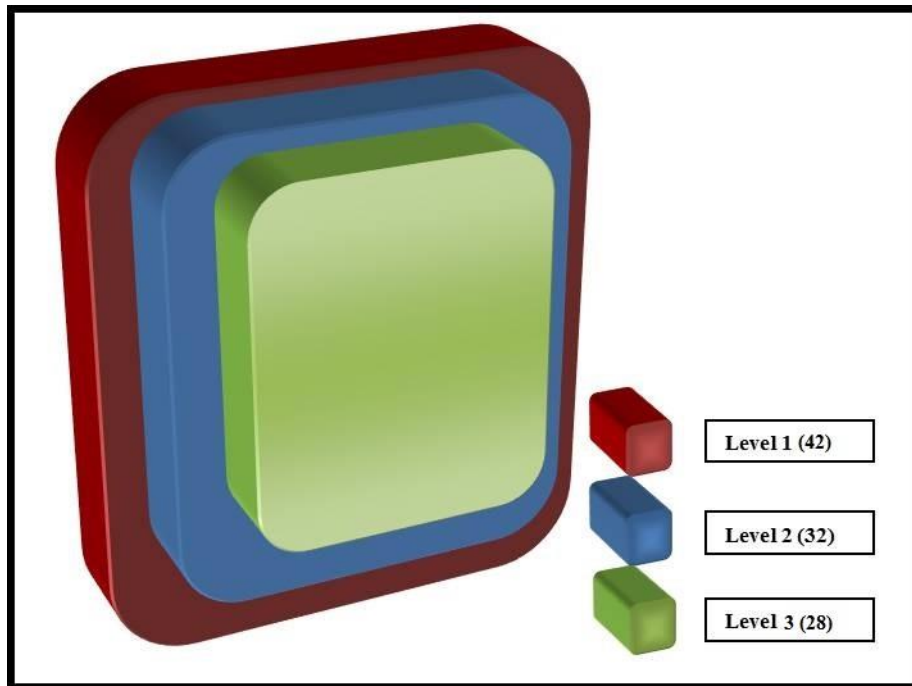


Figure 4.1: Schematic representation of the rock dump's age level stratification. Years are given in brackets.

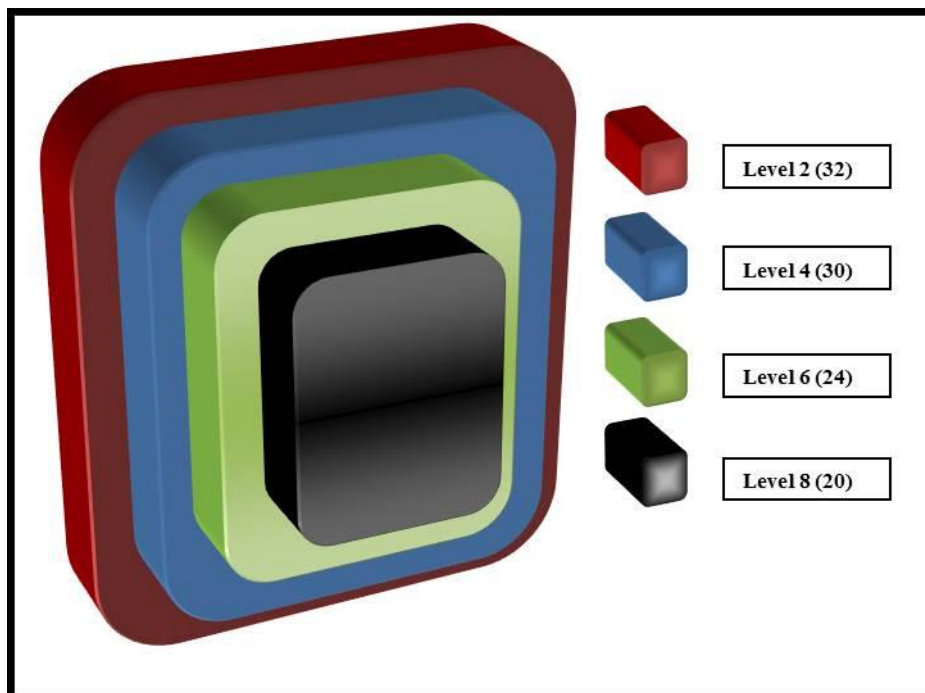


Figure 4.2: Schematic representation of the tailings dam age level stratification. Years are given in brackets.

The second stratification unit involved topography which included different aspects (Fig. 4.3) and slopes and/or terraces (Fig. 4.4). To measure the relevance and impact of these topographical factors, vegetation characteristics and soil properties of slopes have to be measured (Fattahi & Ildoromi, 2011). Eastern, southern and western aspects were surveyed

to gather data on vegetation characteristics and soil properties. The northern aspect of both facilities could not be sampled, because in the case of the tailings dam (Fig. 3.3, Chapter 3) another tailings dam made up the northern aspect, and in the case of the rock dump (Fig. 3.2, Chapter 3) the northern face had been extensively excavated.

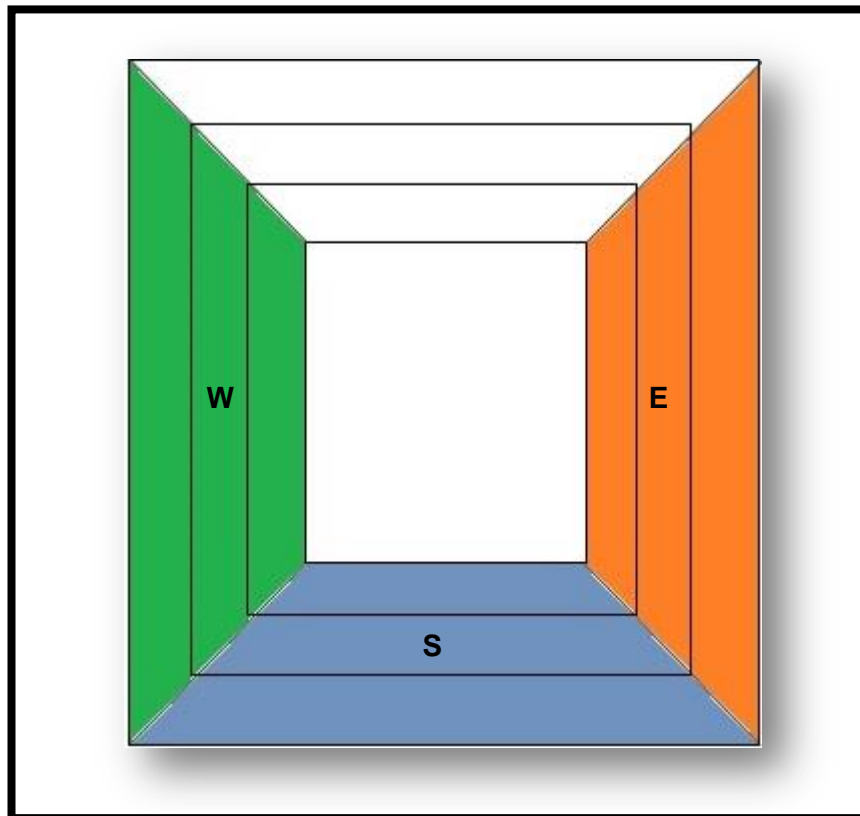


Figure 4.3: Schematic representation of the aspects sampled on the tailings facilities (East, South, West) stratification (Amended from Haagner, 2008).

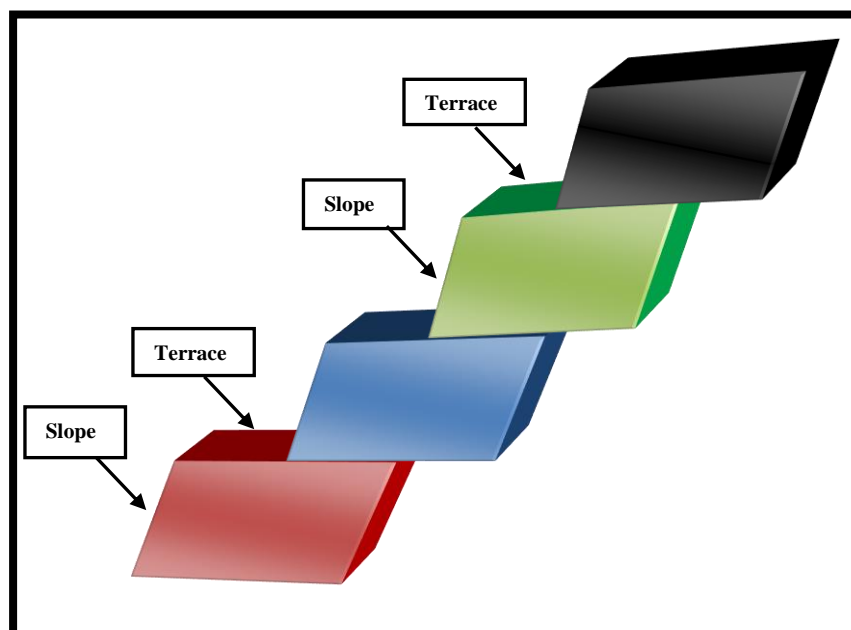


Figure 4.4: Schematic representation of the slope and terrace stratification on the tailings facilities.

4.3 Sampling design

4.3.1 Vegetation sampling

The herbaceous layer was sampled during the peak growing season, from February to March 2013 by means of the fixed 1 x 1 m quadrat method (Hill *et al.*, 2005). A total of 174 quadrats were sampled; namely, 85 on the rock dump and 89 on the tailings dam (Table 4.1). The quadrats were positioned to adequately sample the aspect, and slope and terrace of each individual age level (Tables 4.2 & 4.3). Sampling was repeated five times respectively on the eastern, southern and western aspects of the rock dump (Fig. 4.5).

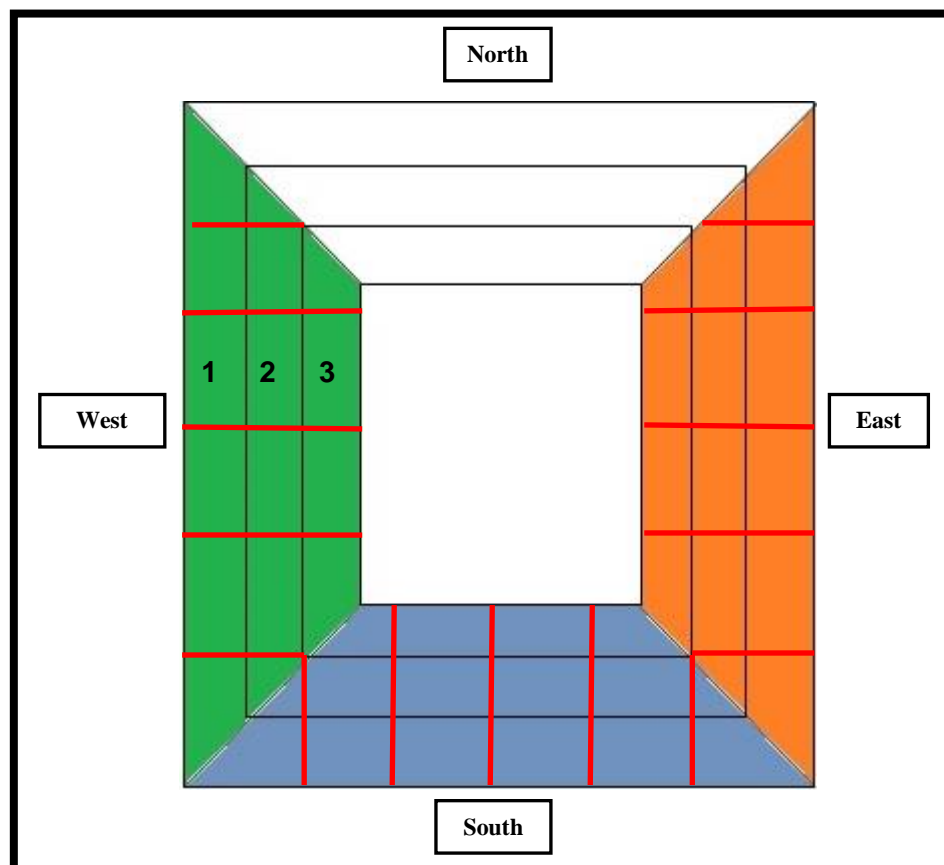


Figure 4.5: Schematic representation of the vegetation sampling design. Red lines depict the five repetitions per aspect while the numbers indicate the different rehabilitation levels or different ages.

4.3.2 Tailings dam

The tailings dam had two short and one long aspect, and therefore three replicates were sampled on the western and southern aspects, whereas six were sampled on the eastern aspect. Sections of the first level had been lost to additional dumping in the past, and therefore level two was chosen as the starting point, and from here upward every second level was sampled.

Table 4.1: Tailings facility levels, ages and sampling plots.

Tailings facility	Level	Rehabilitation age (years)	Altitudinal (m) range per level	Number of sample plots
Rock Dump	1	42	387-440	37
	2	32	440-458	34
	3	28	458-470	14
				Total = 85
Tailings Dam	2	32	382-392	20
	4	30	392-397	25
	6	24	397-402	22
	8	20	402-407	22
				Total = 89

Table 4.2: Tailings facilities aspects and sample plots.

Facility	Aspect	Number of sample plots
Rock Dump	East	24
	South	36
	West	25
Tailings Dam	East	45
	South	20
	West	24

Table 4.3: Tailings facilities topographic position and sample plots.

Facility	Topography	Number of sample plots
Rock Dump	Slope	45
	Terrace	40
Tailings Dam	Slope	43
	Terrace	46

4.3.3 Rock dump

The RD had two long and one short aspect and on all three aspects five replicates were sampled. The RD consisted of three different age levels, the youngest age level terrace could not be sampled due to management safety measures regarding reactive metals. The southern aspect comprised of large terraced areas and more replicate samples were taken here (Table 4.2).

Each quadrat's location was uploaded to a mobile Geographical Positioning System (GPS) for mapping purposes (Appendix D). The following data was recorded within each individual 1m² quadrat (Figure 4.6):

- All the species of forbs and grasses (herbaceous vegetation) were identified up to species level;
- Alive and rooted individuals of individual species were counted (total counts);
- Percentage cover of grass, forbs, rock, bare soil and dead plant material (debris) were visually estimated for each 1m² quadrat;
- Biomass was collected by dropping a 100 cm² disk randomly within the marked quadrat (Figure 4.7). This step was repeated three times to ensure more accurate biomass values. All the rooted, living plant material within the disk were harvested using secateurs and air dried for two weeks. The dry material was weighed and converted to kilograms per hectare (kg/ha).



Figure 4.6: Quadrats of 25x25 cm (set of four) was used to accurately sample the 1 x 1 m plots.



Figure 4.7: A 100 cm² disk was randomly thrown into each quadrat to sample biomass.

4.3.4 Soil sampling

Soil sampling was conducted simultaneously to vegetation sampling. A total of 91 soil and soil microbial samples were collected, 45 samples on the RD and 46 samples on the TD site. The soil and soil microbial samples were collected in the same quadrats used for vegetation sampling. The only difference was that only three repetitions were taken on each aspect due to budget limitations. A soil auger could not be used due to the rocky substrate therefore a spade had to be used to acquire approximately 1 kg composite of soil from five positions in each plot for the soil analysis. In addition, 200 g of soil was sampled for soil microbial analysis. Only the first 10 cm of the top soil layer was sampled due to the rocky nature of the rock dump and the effective topsoil layer of the tailings dam of roughly 15 cm deep. The separate soil and microbe samples were stored in clearly marked zip lock bags.

Soil microbial samples were stored and transported to the laboratory in cooler boxes with ice at approximately 4°C to preserve the biological properties. At the laboratory it was stored at -80°C. After 24 h, the samples were freeze dried, mixed thoroughly, homogenized and passed through a 2 mm mesh sieve before being analysed (Drenovsky *et al.*, 2004).

4.4 Analysis

4.4.1 Physical and chemical analysis of the soil samples

A range of physical and chemical properties of the soil samples were tested and quantified (Table 4.4).

Peech (1965) described a 1:2 (v/v) water extraction technique to determine the water-soluble basic cation fraction [Ca (calcium), Mg (magnesium), K (potassium) and Na (sodium)]. Extractable and exchangeable micro-elements [Fe (iron), Mn (manganese), Cu (copper), Zn (zinc) and B (boron)] were determined using the 0.02M (NH₄)₂ EDTA.H₂O method (Black, 1965). The quantification process was conducted through atomic absorption spectrometry with a Spectrometer AA-250 (Varian, Australia) with acetylene-air to determine the basic cations (Ramirez-Munoz, 1968). Exchangeable cation concentration was determined using the 1 M NH₄-Acetate extraction method at a pH of 7 (Black, 1965). The replaced cations were analysed with the spectrometer.

Table 4.4: Physical and chemical properties tested for 91 soil samples.

Physical & Chemical Properties				
Macro-elements	Micro-elements	Nutrient status	Exchangeable cations	Particle size
Ca (mmol/L)	Fe (µmol/L)	Ca (mg/kg)	Ca (cmol+)/kg	>2 mm (%)
Mg (mmol/L)	Mn (µmol/L)	Mg (mg/kg)	Mg (cmol+)/kg	Sand (% <2 mm)
K (mmol/L)	Cu (µmol/L)	K (mg/kg)	K (cmol+)/kg	Silt (% <2 mm)
Na (mmol/L)	Zn (µmol/L)	Na (mg/kg)	Na (cmol+)/kg	Clay (% <2 mm)
PO ₄ (mmol/L)	B (µmol/L)	P (mg/kg)	CEC (cmol+)/kg	
SO ₄ (mmol/L)		pH(H ₂ O)	S-Value (cmol+)/kg	
NO ₃ (mmol/L)		EC (mS/m)	Base saturation (%)	
NH ₄ (mmol/L)		Organic % C		
Cl (mmol/L)				
HCO ₃ (mmol/L)				

The following equation explains how exchangeable-ion status of soil samples were used to determine the percentage base saturation, which specifies the content of exchangeable bases as a percentage of the cation exchange capacity (CEC) measured at pH 7.0 or 8.2:

$$\text{Bsat} = \frac{\text{Xb}}{\text{CEC}} \times 100\%$$

Bsat = Base saturation

Xb = sum of exchangeable bases (Ca, Mg, K and Na)

CEC = Cation Exchange Capacity

The anions (Cl (chloride), NO₃ (nitrate), PO₄ (phosphate) and SO₄ (sulphate)) were quantified by means of ion chromatography (Metrohm 761 Compact IC, Switzerland). Concentrations of ammonium (NH₄) were measured using the ammonia-selective electrode technique (Banwart *et al.*, 1972). Boron (B) concentration was assessed spectrophotometrically at a wavelength of 420 nm (John *et al.*, 1975). The soil's Electrical Conductivity (EC) and the pH value were calculated by means of 1:2 extract with a calibrated pH/conductivity meter (Radiometer PHM 80, Copenhagen). Method for measuring the EC, which indicates the total amount of soluble salts in the soil, was quantified by saturated extraction. The soil pH (H₂O/KCl) was determined with a 1:2.5 extraction method.

The quantification of P (phosphorus) concentrations was also done using a P-Bray 1 analysis described by Bray and Kurtz (1945). The procedure entails adding P-Bray 1 solution to each soil sample, after that it was filtrated and the P concentration measured using an Auto Analyser (OI Analytical, Texas, USA).

The calculation of particle size distribution (sand, silt and clay) fractions of the soil samples were done by sieving the soil samples and then treating it with hydrogen peroxide 2(HO) while heated for 4 hours (hydro-method). Samples were left to cool after which Calgon is added and the soil suspension tested for particle size with a Thermo Scientific ERTCO® Soil Hydrometer, ASTM 152H (Cole-Parmer, Illinois) (ASTM 1985). Organic carbon (C) was also determined conforming to the Walkley-Black technique (Walkley & Black, 1934).

4.4.2 Soil microbial community structure analysis

4.4.2.1 Phospholipid fatty acid (PLFA) analysis

The total viable microbial biomass and the microbial community structure were assessed. The microbial biomass was quantified by the total extractable PLFAs and the microbial community structure was determined by groups of signature lipid biomarkers (McKinley *et al.*, 2005). This method was used to detect differences in the microbial community structure (Zelles, 1999) from the soils sampled on both the rock dump and tailings dam.

Glassware used in PLFA analysis was washed with phosphate-free soap and rinsed with tap water, distilled water and finally nano-pure water. The glassware was then baked in a muffle furnace for 4 hours at 450 °C. For extraction of lipids, 5 g soil was weighed off from the

freeze-dried samples. Lipids were extracted with a single-phase chloroform-methanol-phosphate buffer system, in a ratio of 1:2:0.8 (v:v:v) (5 ml: 10 ml: 4 ml), using a modified Bligh and Dyer (1959) method as cited by McKinley *et al.* (2005). Nano-pure water (5 ml) and chloroform (5 ml) were then added to each sample and centrifuged to separate the two phases. The chloroform phase (containing the lipids) was then extracted, reduced by evaporation and stored at -20 °C until lipid fractionation.

Silicic acid column chromatography were used to fractionate the total lipid extract (dissolved in chloroform) into neutral lipids, glycolipids and polar lipids using chloroform (5 ml), acetone (5 ml) and methanol (5 ml), respectively. The polar lipids (including phospholipids) were isolated in methanol and transesterified into fatty acid methyl esters (FAMES) using alkaline methanolysis (McKinley *et al.*, 2005).

The FAMES were dissolved in hexane (100 µl) and analysed by capillary gas chromatography with flame ionisation detection on an Agilent 7890A gas chromatograph, using a 60 m SPB-1 column. The injector and detector temperature was maintained at 270 °C and 290 °C, respectively. Hydrogen was the carrier gas used and sample injection (1 µl of each sample was injected) was split less. Gas flow was at a constant pressure of 300 kPa. Column temperature was programmed to start at 60 °C for 2 minutes, ramped at a rate of 10 °C/minute to 150 °C, and then increased at 3 °C/minute to 320 °C. Methyl nonadecanolate (19:0) was used as the internal standard in the procedure. Definitive peak identification was made for representative samples by gas chromatography / mass spectrometry using an Agilent 6890 series II gas chromatography interfaced with an Agilent 5973 mass selective detector under the same column and temperature programme described previously. Mass spectra were determined by electron impact at 70 eV (McKinley *et al.*, 2005).

A:BωC represents the format of fatty acid nomenclature. Fatty acids are designated in terms of the total number of carbon atoms (“A”) and the number of double bonds (“B”) followed by the position of the first double bond from the aliphatic (methyl) end (“C”) (Frostegard *et al.*, 1996). The prefixes “c” and “t” indicate *cis* and *trans* geometry, respectively. The prefixes “a” and “i” refer to the anteiso- and iso-branching, respectively, whereas “br” refers to an unknown branch position. “OH” refer to the hydroxyl group and “Me” refer to the methyl group. The cyclopropyl fatty acids are represented by “cy”. For example, 10Me indicates a methyl group on the 10th carbon atom from the carboxyl end (Zelles, 1999).

To analyse the results obtained during PLFA analysis, microbial biomass and the ratio of fungal to bacterial biomass were calculated. The PLFA markers used for these calculations are indicated in Table 4.5.

Table 4.5: Phospholipid fatty acid (PLFA) markers for biomass calculated

Properties	PLFA markers used
Bacterial biomass¹	Sum of 15:0, i15:0, a15:0, i16:0, 16:1 ω 9, 16:1 ω 7t, 17:0, i17:0, a17:0, cy17:0, 18:1 ω 7, & cyc19:0
Fungal biomass¹	18:2 ω 6
F/B ratio	Fungal biomass / Bacterial biomass

¹Frostegard et al. (1996)

4.5 Data preparation

Specific analyses involved first creating abundance matrices (Excel spreadsheets) of data for all sites. These matrices consisted of quantitative floristic (each species with individual counts), biomass and cover percentage data for each of the different post rehabilitation ages, aspects and topographic sites on the RD and TD. Also included in the data matrices were all physical and chemical soil parameters and soil microbial data. Data were then formatted to be imported into Paleontological Statistics (PAST) (Hammer *et al.*, 2001), PRIMER 6 (2012) and STATISTICA version 11 (2012). Unknown plant species collected during vegetation sampling was sent to the Pretoria National Herbarium (PRE) of the South African National Biodiversity Institute (SANBI) for identification.

4.6 Statistical analysis

Non-metric Multi-Dimensional Scaling (NMDS) analyses were done which represents a matrix of sampling plots and their associated herbaceous vegetation species within a visual dimensional space, illustrating clustering of plots on the basis of a similar floristic composition or the lack of similar floristic composition.

Pair-wise R-values reported in the ANOSIM output indicated how floristically distinct the different post rehabilitation ages, aspects and topographic positions of RD and TD were on a scale from 0 (indistinguishable) to 1 (high separation) based on the Bray-Curtis index (Venn *et al.*, 2014). Similarity percentage analysis (SIMPER) was used to identify the

species contributing most strongly to the floristic compositional differences between the different post rehabilitation ages, aspects and topographic positions on the RD and TD.

One-way breakdown ANOVA was performed in combination with post-hoc pair-wise comparisons of treatments with Tukey's Honest Significant Difference (HSD) test to statistically determine whether

- total species (S) i.e. the mean number of species per 1m²;
- total individuals (N) i.e. mean total individuals per plot;
- Margalef Species Richness (d) where $d = (S-1) / \text{Log } N$;
- Pielou's Evenness (J');
- Shannon-Wiener Diversity (H') where $H' = -\sum (p_i \cdot \ln p_i)$;
- Simpson's Diversity (D) with the formula $1 - \sum (N_i \cdot (N_i - 1) / N \cdot (N - 1))$;
- Cover percentage variables (%); and
- Biomass (Kg/ha)

varied significantly between the different post rehabilitation ages, aspects and topographic sites on the RD and TD ($p < 0.05$).

Hierarchical Linear Model (HLM) analysis were performed on the dataset using a two-way ANOVA with a random effects model (McMahon & Diez, 2007) in SPSS software to test for overall significant differences between different topographic variables. The index values were chosen as response variables to determine if these values differed between the Rock Dump (RD), Tailings Dam (TD) and control Mopaneveld. Sampling points of the same slope and terrace position were considered dependent variables for statistical analyses. Effect sizes (Cohen's d) were calculated to express practical significance between sampling points where residual variance as well as transect variance were taken into account in the calculation of the effect size (Ellis & Steyn, 2003). The effect sizes were interpreted as follows: small effect: $d=0.2$, (b) medium effect: $d=0.5$ and (c) large effect: $d=0.8$.

Data of soil physical and chemical characteristics, microbial biomass and PLFA composition of samples were also subjected to analysis of variance (ANOVA), followed by Tukey's Honest Significant Difference (HSD) test to determine significant differences between the various treatments ($p < 0.05$).

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Chapter 5 – Herbaceous species diversity

5.1 Background

The results of Chapter 5 is aimed at reporting on herbaceous species composition, vegetation cover percentage, biomass, herbaceous species diversity patterns and benchmarking against natural Mopaneveld of different post rehabilitation ages, aspects and topographic positions (terraces and slopes) on the Rock Dump (RD) and Tailings Dam (TD).

The objectives of this results chapter were to test (Figure 5.1):

- (i) how the herbaceous species composition of each tailings facility differs in terms of
 - Post rehabilitation age
 - Aspect
 - Topographic position
- (ii) how the vegetation cover and biomass of each tailings facility differs in terms of
 - Post rehabilitation age
 - Aspect
 - Topographic position
- (iii) how the herbaceous species diversity of each tailings facility differs in terms of
 - Post rehabilitation age
 - Aspect
- (iv) how the herbaceous species diversity of each tailings facility compare with natural Mopaneveld in terms of
 - Topographic position

Mopaneveld data from the neighbouring Cleveland Nature Reserve was obtained from Van Staden (2016). Inselberg and plains plot data from this study (87 quadrats) was used as benchmark to compare with the terraces and slopes on the RD and TD.

Research questions and presentation of results

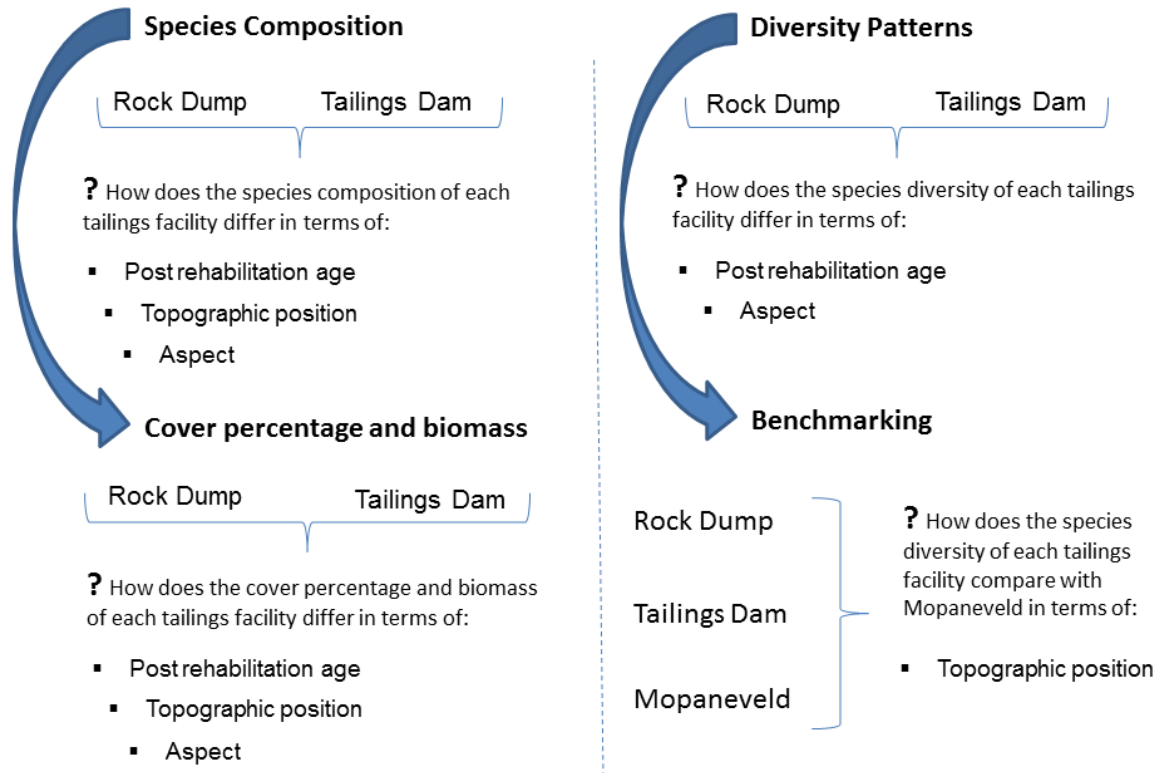


Figure 5.1: Research questions and the approach followed in this chapter to assess the response of species composition and diversity to selected spatial and temporal variation on PMC tailings facilities.

5.2 Species composition

Altogether 94 plant species were identified for the tailings facilities across 174 quadrats, namely 75 species were found on the RD of which 29 species did not occur on the TD, while the TD comprised of 65 species of which 19 were not recorded on the RD. Of the 94 recorded species, 45 were shared between the facilities. Overall, the different post rehabilitation ages, aspects and topographic positions on the RD and TD are not well separated floristically, with all R-values close to 0 (Tables 5.1 & 5.2).

The NMDS analysis represents the matrix of sampling plots and their associated herbaceous vegetation within a visual dimensional space, illustrating clustering of plots on the basis of similar floristic composition or the lack of similar floristic composition (Figures 5.1 & 5.2). The plant species that contributed most to the average similarities between the different post rehabilitation ages, aspects and topographic positions on the RD and TD are listed in Appendix A. The cut-off point was taken at 60 % cumulative percentage, and in each case approximately 5-6 species were responsible for the 60 % contribution.

5.2.1 Rock dump

5.2.1.1 Post rehabilitation age

The NMDS results showed little to no clear separation of the floristic composition between the different post rehabilitation ages on the RD (Figure 5.2a; NMDS stress value = 0.18). ANOSIM analysis of pairwise comparison consequently indicated that the species composition of the youngest age level (28 years) did not differ from the intermediate age level (32 years) (R value = 0.005107) or the oldest age (42 years) (R value = -0.09482). The same similarity was also determined for the intermediate age level (32 years) and the oldest age level (42 years) (R value = 0.004801) (Table 5.1).

Further, SIMPER analysis results correspondingly indicated subtle differences (Appendix A; Table A1). Between the different post rehabilitation ages on the RD a total of nine species was responsible for minute variations – seven grass species (Poaceae) and two forb species (Asteraceae and Fabaceae) of which six were perennials and three were annuals. Simper analysis of the data between 28 and 32 years vary based on small changes in the average abundance of key grass species *Aristida congesta*, *Cenchrus ciliaris*, *Enneapogon cencroides*, *Heteropogon contortus* and *Stipagrostis hirtigluma*, and key forb species *Tephrosia purpurea*. Between 28 and 42 years the key grass species comprised of *Aristida adscensionis*, *Cenchrus ciliaris*, *Enneapogon cencroides* and *Pennisetum setaceum* and the key forb species *Tephrosia purpurea* and *Tridax procumbens*. Between 32 and 42 years the key grass species responsible for differences were *Aristida adscensionis*, *A. congesta*, *Cenchrus ciliaris*, *Enneapogon cencroides*, *Heteropogon contortus* and *Stipagrostis hirtigluma*, but no forb species played a role on the two youngest age levels (Appendix A; Table A1). Small variations in the relationships of these species to each other differentiate the different post rehabilitation ages on the RD.

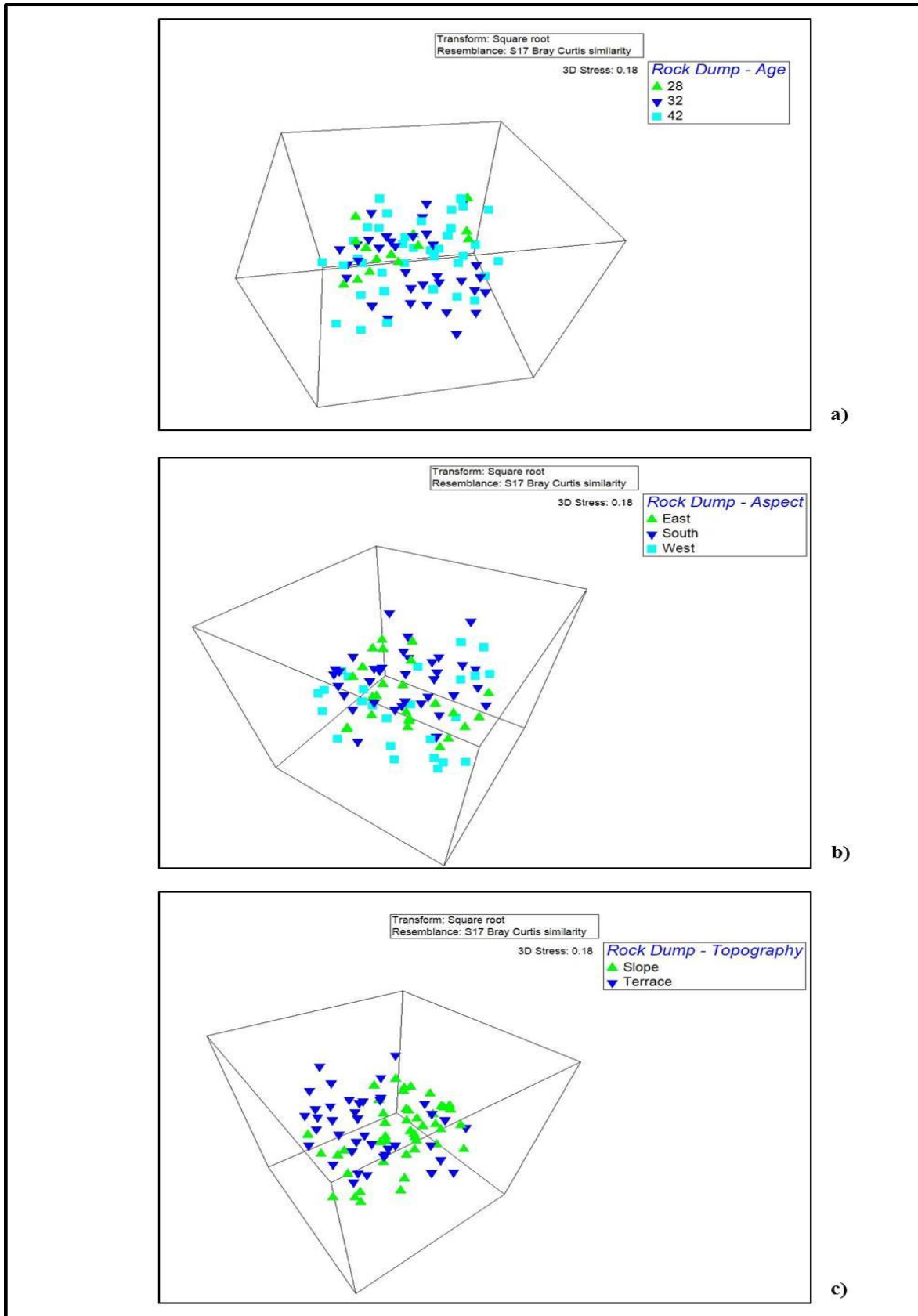


Figure 5.2: Nonmetric multidimensional scaling (NMDS) ordination diagram of herbaceous vegetation abundances of the different (a) post rehabilitation ages; (b) aspects; and (c) topographic positions on the Rock Dump

5.2.1.2 Aspect

The NMDS results again showed little separation of the floristic composition between the different aspects on the RD (Figure 5.2b; NMDS stress value = 0.18). ANOSIM analysis indicated that the eastern aspect did not differ from the southern aspect (R value = 0.0309) or from the western aspect (R value = 0.0203) and also no clear differentiation between the southern and western aspect was supported (R value = 0.0032) (Table 5.1).

SIMPER analysis revealed small variations in species composition between the different aspects (Appendix A; Table A2). Between the different aspects on the RD a total of ten species was responsible for small variations – seven grass species (Poaceae) and three forb species (Asteraceae and Fabaceae) of which six were perennials and four were annuals. The Simper analysis of the data between the eastern and southern aspect varied based on minor changes in the average abundance of key grass species *Aristida adscensionis*, *Aristida congesta*, *Cenchrus ciliaris*, *Enneapogon cencroides*, *Pennisetum setaceum* and *Stipagrostis hirtigluma* and key forb species *Tephrosia uniflora* and *Tridax procumbens*. Between the eastern and western aspects the key grass species included; *Aristida congesta*, *Cenchrus ciliaris*, *Enneapogon cencroides*, *Heteropogon contortus* and *Stipagrostis hirtigluma*. Between the southern and western aspects the key grass species were as follows *Aristida adscensionis*, *Aristida congesta*, *Cenchrus ciliaris*, *Enneapogon cencroides* and *Stipagrostis hirtigluma* (Appendix A; Table A2).

5.2.1.3 Topographic position

Once again the NMDS results indicated little separation of quadrats based on floristic composition between the different topographic positions on the RD (Figure 5.2c; NMDS stress value = 0.18). ANOSIM analysis showed that the terrace position did not differ from the slope position (R value = 0.0001) (Table 5.1).

Between the different topographic positions the SIMPER analysis once again showed small variations in species composition (Appendix A; Table A3). Between the different topographic positions on the RD a total of seven grass species (Poaceae) were responsible for the small variations of which four were perennials and three were annuals. The Simper analysis of the data between the terraces and slopes varied based on minor changes in the average abundance of the key grass species *Aristida adscensionis*, *Aristida congesta*, *Cenchrus ciliaris*, *Enneapogon cencroides*, *Heteropogon contortus*, *Pennisetum setaceum* and *Stipagrostis hirtigluma* (Appendix A; Table A3).

5.2.2 Tailings dam

5.2.2.1 Post rehabilitation age

On the TD the NMDS also revealed unconvincing separation of quadrats according to different post rehabilitation ages (Figure 5.3a; NMDS stress value = 0.16). Although most of the tested factors did not separate well, 30 and 32 years post rehabilitation age on the TD were separated with R-values closer to 1 (Table 5.2). ANOSIM analysis of pairwise comparison indicated that the youngest age level (20 years) did not differ from the intermediate age levels (24 years) (R value = 0.0032) or the older ages of 30 years (R value = 0.0004) or 32 years (R value = 0.0006) (Table 5.2). Further the two intermediate levels of 24 years and 30 years displayed similar species composition (R = 0.0016). The intermediate age level of 24 years did not differ compositionally from the oldest age level (32 years) (R value = 0.0003). Last of all the intermediate age level of 30 years compared to the oldest level (32 years) revealed stronger species composition separation (R value = 0.685) (Table 5.2).

Further the SIMPER analysis results subsequently indicated subtle differences between the different post rehabilitation ages on the TD (Appendix A; Table A4). Between the different post rehabilitation ages on the TD a total of eight species was responsible for small variations – five grass species (Poaceae) and three forb species (Asteraceae and Fabaceae), of which four were perennials and four were annuals. Simper analysis of the data between 20 and 24 years varied based on small changes in the average abundance of key grass species *Aristida scabrivalvis*, *Cenchrus ciliaris* and *Enneapogon cencroides*, and key forb species *Sesbania bispinosa* and *Tephrosia purpurea*. Between 20 and 30 years age levels the grass species responsible for slight differences in composition were; *Aristida scabrivalvis*, *Cenchrus ciliaris*, *Enneapogon cencroides* and *Stipagrostis hirtigluma*; and key forb species *Sesbania bispinosa* and *Tephrosia purpurea*. Between 20 years and 32 years the key grass species were *Aristida scabrivalvis*, *Cenchrus ciliaris*, *Enneapogon cencroides* and *Stipagrostis hirtigluma*, and the key forb species *Indigostrum costatum* and *Sesbania bispinosa*. Between 24 years and 30 years the key grass species *Aristida scabrivalvis*, *Cenchrus ciliaris* and *Stipagrostis hirtigluma* and the key forb species *Sesbania bispinosa* and *Tephrosia purpurea*. Finally between 30 years and 32 years the key grass species responsible for compositional differences, mainly based on abundances, were *Aristida scabrivalvis*, *Cenchrus ciliaris* and *Stipagrostis hirtigluma* and the key forb species *Sesbania bispinosa* and *Tephrosia purpurea*.

5.2.2.2 Aspect

The NMDS results again showed little separation of the floristic composition between the different aspects on the TD (Figure 5.3b; NMDS stress value = 0.16). ANOSIM analysis indicated that the eastern aspect did differ from the southern aspect (R value = 0.7378) with R-values approaching 1, but showed unclear separation from the Western aspect (R value = 0.3491). Southern and western aspects showed little separation (R value = 0.1224) (Table 5.2).

SIMPER analysis revealed small variations in species composition between the different aspects on the TD (Appendix A; Table A5). Between the different aspects on the TD a total of seven species were responsible for small variations – four grass species (Poaceae) and three forb species (Asteraceae and Fabaceae) of which three were perennials and four annuals. The Simper analysis of the data between the eastern and southern aspect showed variation in composition based on changes in the average abundance of key grass species *Aristida scabrivalvis*, *Cenchrus ciliaris*, *Enneapogon cencroides* and *Stipagrostis hirtigluma* and the key forb species *Sesbania bispinosa* and *Tephrosia purpurea*. Slight variation between the eastern and western aspects was due to the key grass species *Cenchrus ciliaris*, *Stipagrostis hirtigluma* and key forbs species *Indigastrium costatum*, *Sesbania bispinosa* and *Tephrosia purpurea*. Between the southern and western aspect the following key grass species contributed *Aristida scabrivalvis*, *Cenchrus ciliaris* and *Enneapogon cencroides*, and the key forb species *Indigastrium costatum*, *Sesbania bispinosa* and *Tephrosia purpurea*.

5.2.2.3 Topographic position

Once again the NMDS results indicated little separation of the floristic composition between the different topographic positions on the TD (Figure 5.3c; NMDS stress value = 0.16). ANOSIM analysis showed that the terrace position did not differ from the slope position (R value = 0.04009) (Table 5.2).

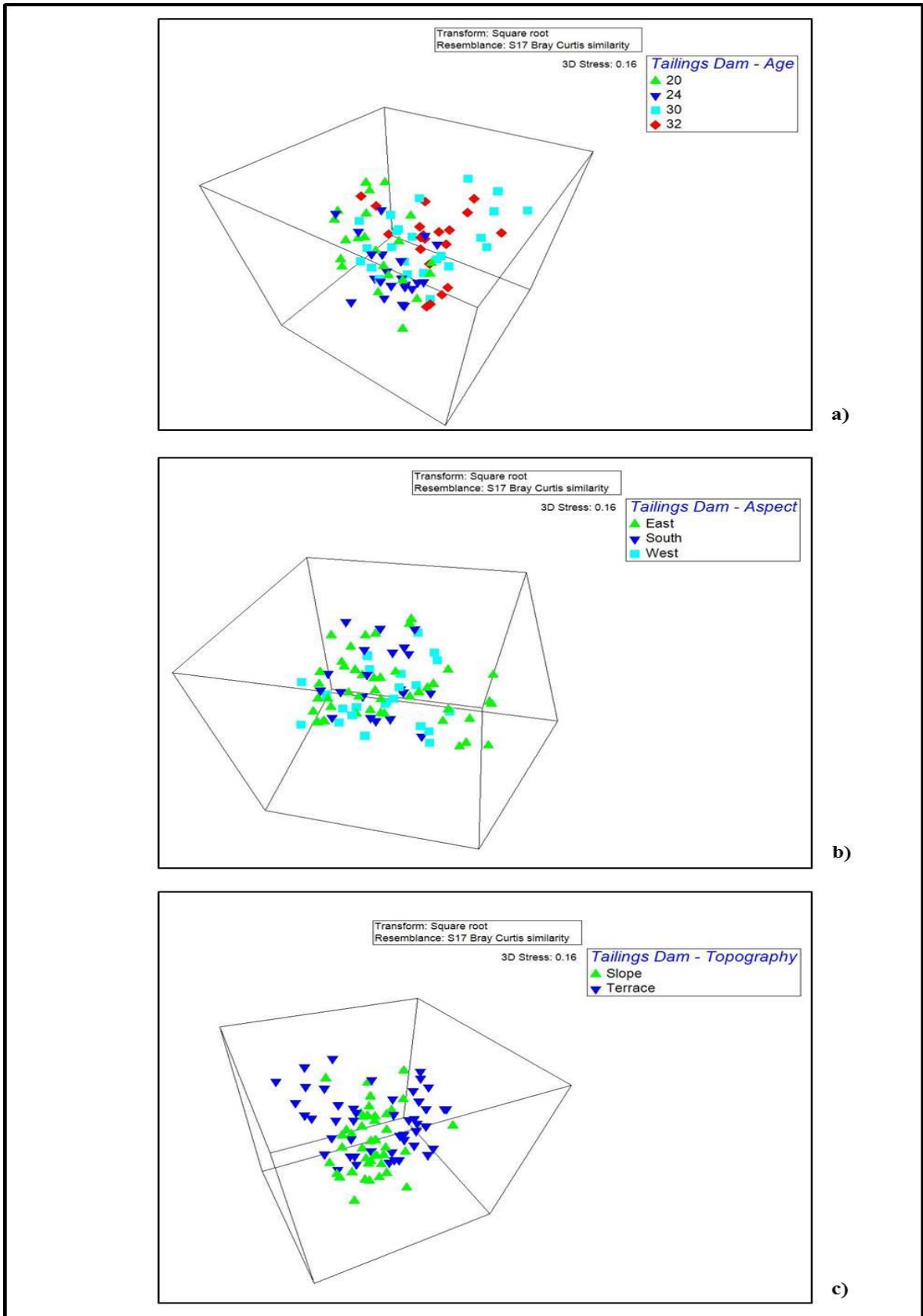


Figure 5.3: Nonmetric multidimensional scaling (NMDS) ordination diagram of herbaceous vegetation abundances of the different (a) post rehabilitation ages; (b) aspects; and (c) topographic positions on the Tailings Dam.

Between the different topographic positions the SIMPER analysis again showed small variations in species composition (Appendix A; Table A6). Between the different topographic positions on the TD a total of four grass species (Poaceae) and three forb species (Asteraceae and Fabaceae) was responsible for the small variations of which three were perennials and three were annuals. The Simper analysis of the data between the terraces and slopes varied based on minor changes in the average abundance of the key grass species *Aristida scabrivalvis*, *Cenchrus ciliaris* and *Stipagrostis hirtigluma*, and key forb species *Indigostrum costatum*, *Sesbania bispinosa* and *Tephrosia purpurea* (Appendix A; Table A6).

Table 5.1: Overall and profile comparison of floristic similarities between different post rehabilitation ages, aspect and topographic positions on the Rock Dump (ANOSIM).

Rock Dump	
Age	R
Overall model (All ages)	-0.01592
28 vs 32	0.005107
28 vs 42	-0.09482
32 vs 42	0.004801
Aspect	R
Overall model (All aspects)	0.08671
East vs South	0.0309
East vs West	0.0203
South vs West	0.0032
Topography	R
Overall model (Slopes & Terraces)	0.1384
Slopes vs Terrace	0.0001

Table 5.2: Overall and profile comparison of floristic similarities between different post rehabilitation ages, aspect and topographic positions on the Tailings Dam (ANOSIM). R-values marked with * indicate significant differences in species composition ($p < 0.05$).

Tailings Dam	
Age	R
Overall model (All ages)	0.1334
20 vs 24	0.0032
20 vs 30	0.0004
20 vs 32	0.0006
24 vs 30	0.0016
24 vs 32	0.0003
30 vs 32	*0.685
Aspect	R
Overall model (All aspects)	-0.003556
East vs South	*0.7378
East vs West	0.3491
South vs West	0.1224
Topography	R
Overall model (Slopes & Terraces)	0.04009
Slopes vs Terrace	0.04009

5.3 Cover percentage

5.3.1 Rock Dump

Cover percentages of the different post rehabilitation ages, aspects and topographic positions on the RD is displayed by Figure 5.4. The results revealed a small number of cover variables that showed significant differences ($p < 0.05$) between the different post rehabilitation ages, aspects and topographic positions on the RD (Figure 5.4). The only significant differences were seen for rock cover (Figure 5.4a) at the different rehabilitation ages and bare soil and debris cover at the different aspects (Figure 5.4b).

Rock cover was significantly higher at 28 years with 23.5 %, while the older ages had 10 % less with 13.2 % and 11.7 % respectively ($p < 0.05$) (Figure 5.3a). Bare soil on the southern and western aspects were significantly more with 43.5 % and 46.8 % respectively, as well as for debris cover with the eastern aspect revealing a significantly higher percentage with 20.5 % compared to South and West with 11.7 % and 12.5 %, respectively ($p < 0.05$) (Figure 5.3b).

Despite the few significant differences that were noted, herbaceous vegetation (forbs and grass) cover as a percentage of the total cover variables was less than 30 % for grass and less than 10 % for forbs (Figure 5.4). Bare soil as a percentage of the total cover variables revealed distinctively higher values of more than 40% across the different post rehabilitation ages, aspects and topographic positions (Figure 5.4). The percentage cover of variables on the topographic positions did not show much variation, although slightly higher forb, grass and debris cover was noted on the slopes, and higher bare soil and rock cover on the terraces (Figure 5.4c). Overall, the older post rehabilitation ages (32 and 42 years), eastern aspect and the slopes of the RD revealed higher herbaceous vegetation and debris cover and lower bare soil and rock cover (Figure 5.4a, b, c).

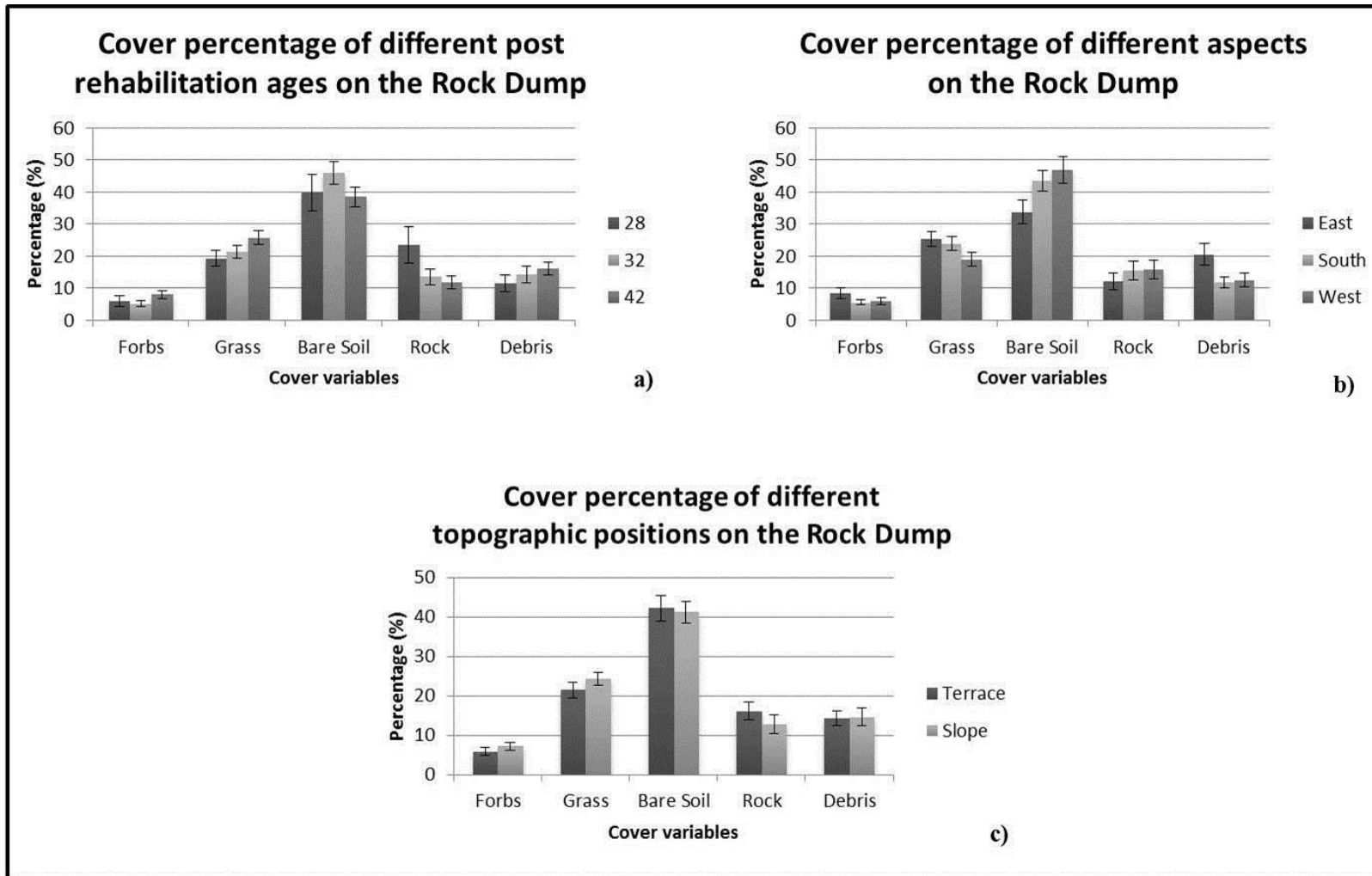


Figure 5.4: Mean cover percentage of forbs, grass, bare soil, rock and debris of the different a) post rehabilitation ages; b) aspects and c) topographic positions on the Rock Dump.

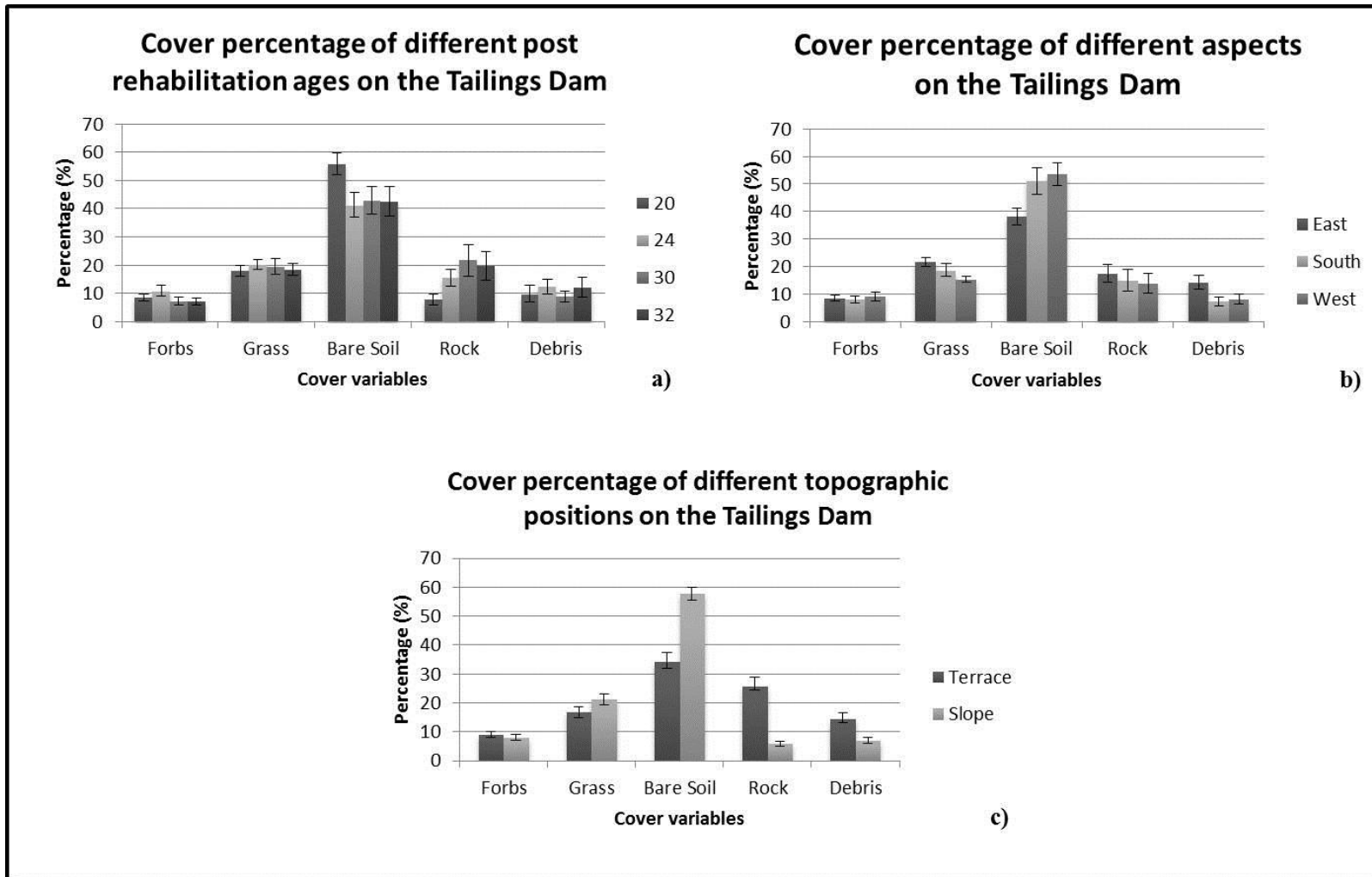


Figure 5.5: Mean cover percentage of forbs, grass, bare soil, rock and debris of the different topographic positions on the Tailings Dam.

5.3.2 Tailings Dam

Cover percentages of the different post rehabilitation ages, aspects and topographic positions on the TD is displayed by Figure 5.5. Somewhat more of the different cover variables were significantly different on the TD than was found for the RD (Figure 5.4a, b, c). The noticeable significant differences occurred between the different post rehabilitation ages for bare soil and rock cover, between the different aspects for grass, bare soil and debris cover, and between the different topographic positions for bare soil, rock and debris cover ($p < 0.05$).

Bare soil revealed significantly higher values (Figure 5.5a) at the youngest post rehabilitation age (20 years) at 56 %, while the older ages showed just over 40 % bare soil ($p < 0.05$). The opposite is witnessed for rock cover as the youngest age showed significantly lower values with 7.7 %, while the older post rehabilitation ages indicated 2 to 3 times more ($p < 0.05$) (Figure 5.5a).

Grass (21.7 %) and debris (14.3 %) cover was significantly higher on the eastern aspect ($p < 0.05$) than both the southern and western aspects (Figure 5.5b). Bare soil cover (Figure 5.5b) indicated significantly higher values on the western aspect with 53.5 % than the eastern aspect with 38.1 % ($p < 0.05$).

Between the different topographic positions, highly significant differences occurred for bare soil, rock and debris cover ($p < 0.001$) (Figure 5.5c). Rock and debris cover were significantly higher on the terraces with 25.6 % and 14.3 % respectively, compared to the slopes with 5.9 % and 7.1 % respectively. On the other hand, bare soil cover was significantly lower on the terraces with percentage values of 34.3% compared to 57.7 % for the slopes.

Herbaceous vegetation (forb and grass) cover as a percentage of the total cover variables was less than 20 % for grass and less than 10 % for forbs (Figure 5.5). Bare soil cover was distinctly higher with a mean value of 45 % across the different post rehabilitation ages, aspects and topographic positions on the TD (Figure 5.5a, b, c). In the case of the TD, the terraces seemed to fare better in terms of the different cover variables tested. The TD cover results revealed no clear trend with regard to age, aspect or topographic position as was the case for the RD. On both RD and TD herbaceous vegetation cover is low and contributes only approximately 30% of the total cover variables tested (Figure 5.4 & 5.5).

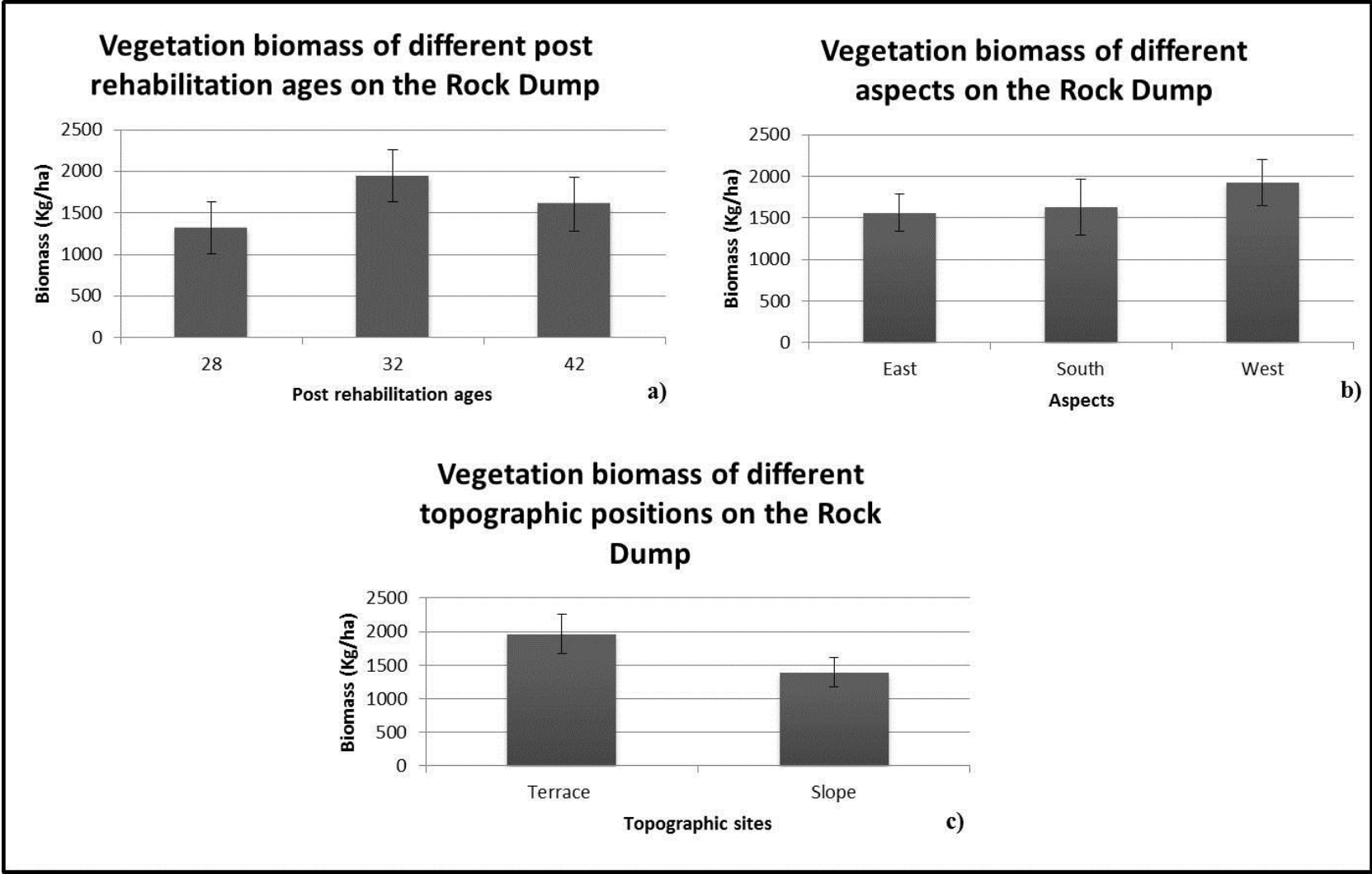


Figure 5.6: Mean herbaceous vegetation biomass (kg/ha) of the different a) post rehabilitation ages, b) aspects and c) topographic positions on the Rock Dump.

5.4 Biomass

5.4.1 Rock Dump

No significant differences were found for herbaceous biomass between the different post rehabilitation ages, aspects and topographic positions on the RD ($p > 0.05$) (Figure 5.6).

The 32 year old post rehabilitation age on the RD showed the highest mean biomass at 1948 kg/ha followed by the oldest age level (42 years) at 1608 kg/ha and the lowest biomass value was found at the youngest age level (28 years) with 1316 kg/ha (Figure 5.6a). Against expectations, the western aspect showed the highest biomass at 1924 kg/ha, followed by the southern aspect at 1629 kg/ha and the lowest biomass value on the eastern aspect with 1562 kg/ha (Figure 5.6b). Further, the terrace positions held higher biomass than the slopes with values of 1964 kg/ha and 1395 kg/ha, respectively (Figure 5.6c). This does not conform to the earlier mentioned results of the cover percentages, as the slope positions on the RD yielded higher herbaceous vegetation cover (Figure 5.6c).

5.4.2 Tailings Dam

As in the case of the RD, no significant differences were found for herbaceous vegetation biomass between the different post rehabilitation ages, aspects and topographic positions on the TD ($p > 0.05$) (Figure 5.7).

The youngest (20 years) and 30 year old post rehabilitation age revealed the highest mean biomass with 1552 kg/ha and 1252 kg/ha respectively (Figure 5.7a). The lowest mean biomass was found on the oldest post rehabilitation age (32 years) at 1003 kg/ha. As was seen earlier on the RD, the western aspect also revealed the highest biomass value with 1539 kg/ha, but the TD results indicated that the southern aspect had the lowest biomass with less than one ton per hectare at 862 kg/ha (Figure 5.7b). The same trend of the different topographic positions at RD is repeated for TD, as the terraces also showed higher biomass with 1296 kg/ha and slopes with 1198 kg/ha (Figure 5.7c).

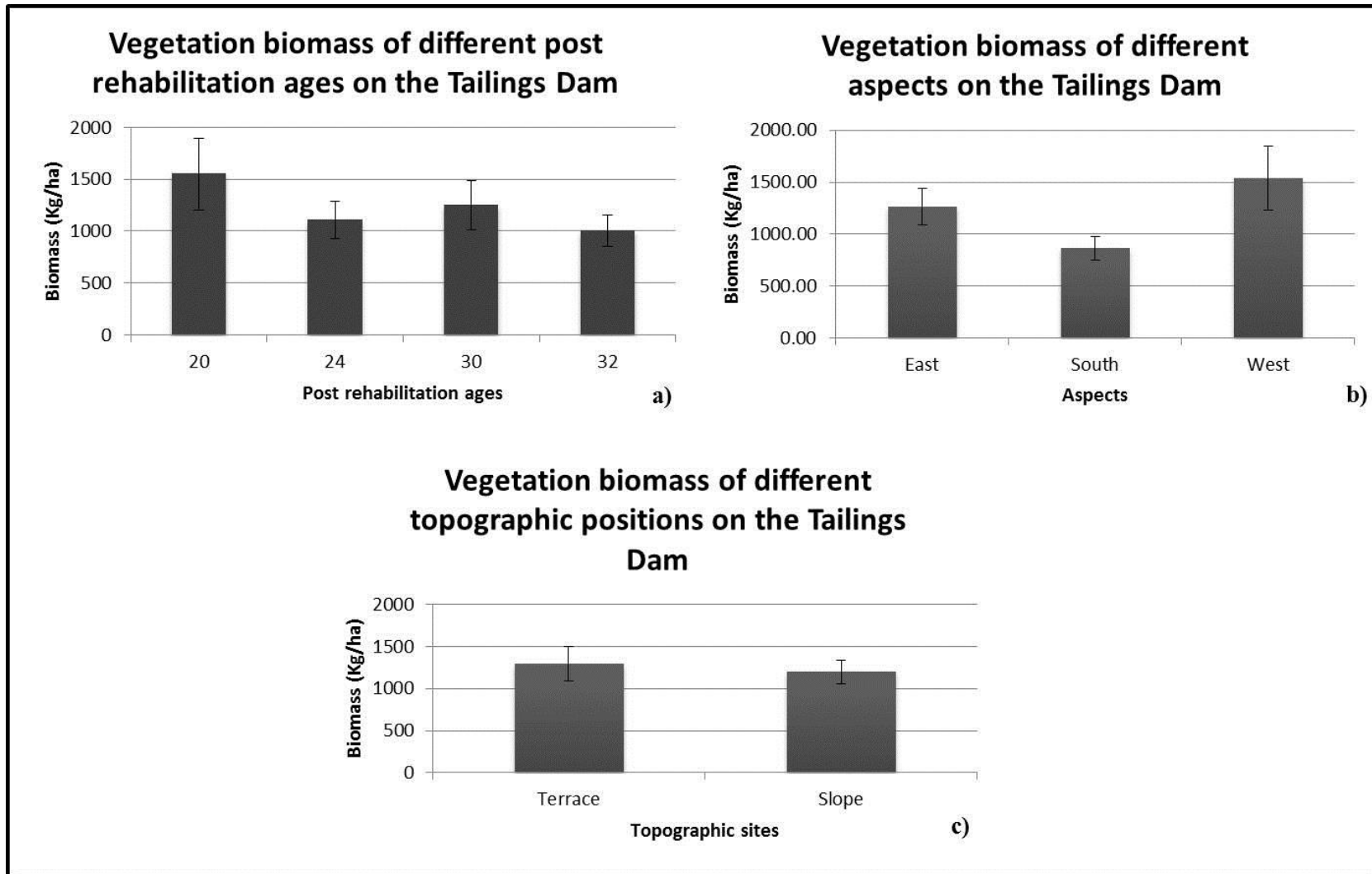


Figure 5.7: Mean herbaceous vegetation biomass (kg/ha) of the different a) post rehabilitation ages, b) aspects and c) topographic positions on the Tailings Dam.

5.5 Herbaceous plant diversity patterns

5.5.1 Rock Dump post rehabilitation ages

When considering significant variation for the vegetation diversity indices between the different ages on the RD, only the total individuals (or vegetation density) revealed a significant difference, with the youngest age level (28 years) showing significantly lower individuals (38.93) per quadrat than the mid age level (32 years) with 61.83 ($p < 0.05$) (Table 5.3). Although no further significance was seen for the rest of the tested vegetation diversity indexes, a decreasing trend becomes evident for species richness on younger levels of the RD.

Table 5.3: Comparison of mean diversity index values between different post rehabilitation ages on the Rock Dump.

	Rock Dump Age		
	28	32	42
Sample size (n)	14	34	37
Total species	5.93±0.366 a	6.32±0.427 a	6.50±0.450 a
Total individuals	38.93±5.68 a	61.83±5.14 b	53.56±6.52 ab
Margalef species richness	1.437±0.127 a	1.368±0.097 a	1.439±0.100 a
Pielou's evenness	0.731±0.036 a	0.667±0.030 a	0.689±0.029 a
Shannon-Wiener diversity index	1.298±0.093 a	1.198±0.074 a	1.249±0.076 a
Simpson diversity index	0.662±0.040 a	0.603±0.034 a	0.620±0.033 a

¹Mean diversity index values ± Standard Error of Mean (SEM).

²Statistically significant differences are indicated by alphabetic letters. The same letters indicate no significant differences, while different letters indicate significant differences.

As shown in Table 5.3, a significant age effect was observed only for total individuals per 1m² which increased steadily with significantly more individuals on the mid age level (32 years) than on the youngest post rehabilitation age (20 years) ($p < 0.05$). Highest Margalef Species Richness (d) was found on the oldest post rehabilitation age (42 years) as well as plant species richness (S). It should be noted that Margalef Species Richness at 28 years was almost identical to the oldest age with the mid age level (32 years) being the lowest ($p > 0.05$). Pielou's evenness (J'), Shannon-Wiener diversity (H') and Simpson's diversity (D) revealed the same trend where the highest diversity values were seen on the youngest post rehabilitation age (28 years) and the lowest values on the mid age level (32 years), leaving the oldest post rehabilitation age (42 years) with the mid-level diversity values ($p > 0.05$) (Table 5.3). Overall a clear tendency of highest species diversity on the youngest post rehabilitation age with a slight decrease at the mid age level, and with time after 32 years an increase in species diversity is witnessed. Mean herbaceous species richness per quadrat was lowest on the youngest level and highest on the oldest level (Table 5.3).

5.5.2 Rock Dump aspects

No significant differences for diversity are recorded between the different aspects (East, South and West) on the RD ($p > 0.05$) (Table 5.4). The southern aspect has the highest plant species richness (S) and West the lowest, while the latter aspect revealed the highest number of individuals per quadrat and East the lowest. Another clear trend comes to light with Margalef species richness (d), Pielou's evenness (J'), Shannon-Wiener diversity (H') and Simpson's diversity (D) all indicating the highest diversity values on the eastern aspect of the RD, while the southern aspect showed a slight decrease in diversity and the western aspect the lowest values (Table 5.4).

Table 5.4: Comparison of mean diversity index values between different aspects on the Rock Dump.

	Rock Dump Aspect		
	East	South	West
Sample size (n)	24	36	25
Total species	6.41±0.466 a	6.68±0.409 a	5.84±0.467 a
Total individuals	41.99±6.29 a	57.48±5.58 a	62.36±6.35 a
Margalef species richness	1.536±0.111 a	1.449±0.097 a	1.246±0.109 a
Pielou's evenness	0.719±0.033 a	0.665±0.029 a	0.682±0.033 a
Shannon-Wiener diversity index	1.329±0.084 a	1.217±0.074 a	1.169±0.083 a
Simpson diversity index	0.660±0.037 a	0.600±0.032 a	0.604±0.037 a

¹Mean diversity index values ± Standard Error of Mean (SEM).

²Statistically significant differences are indicated by alphabetic letters. The same letters indicate no significant differences while different letters indicate significant differences.

5.5.3 Tailings Dam post rehabilitation ages

The entire set of diversity indices tested significantly different between the post rehabilitation ages on the TD (Table 5.5), most of the mentioned significance occurred between ages 20 – 24 years and 24 – 32 years.

Table 5.5: Comparison of mean diversity index values between different post rehabilitation ages on the Tailings Dam.

	Tailings Dam Age			
	20	24	30	32
Sample size (n)	22	22	25	20
Total species	8.49±0.377 a	6.17±0.494 b	6.77±0.570 ab	7.31±0.652 ab
Total individuals	71.82±5.23 a	79.21±8.28 ac	64.38±6.82 ab	46.25±4.03 b
Margalef species richness	1.786±0.084 a	1.232±0.109 b	1.414±0.128 ab	1.648±0.160 ab
Pielou's evenness	0.708±0.019 ab	0.614±0.033 a	0.667±0.039 ab	0.753±0.035 b
Shannon-Wiener div. index	1.469±0.051 a	1.119±0.095 b	1.263±0.111 ab	1.492±0.113 a
Simpson diversity index	0.694±0.018 a	0.556±0.035 b	0.616±0.049 ab	0.702±0.044 a

¹Mean diversity index values ± Standard Error of Mean (SEM).

²Statistically significant differences are indicated by alphabetic letters. The same letters indicate no significant differences, while different letters indicate significant differences.

Total plant species per quadrat was significantly higher at the youngest post rehabilitation age (20 years) compared to the 24 years that revealed the lowest number of species ($p < 0.05$). Total individuals were found to be significantly lower at 32 years ($p < 0.05$). Margalef species richness (d) was significantly higher on 20 years than the intermediate age level (24 years) ($p < 0.05$). Further Pielou's evenness (J'), Shannon-Wiener diversity (H') and Simpson's diversity (D) all had significantly higher values on the oldest post rehabilitation age (32 years). The 24 year age level showed the lowest diversity values on the TD ($p < 0.05$) (Table 5.5). An interesting trend comes to light here as was seen between the different post rehabilitation ages on the RD. As seen in Table 5.5 the youngest age level (20 years), although not of higher magnitude, corresponded relatively well with that of the oldest age level (32 years) in terms of diversity. The age level of 24 years indicated a sharp decrease in diversity with the lowest values for all the tested vegetation diversity indices, except for the total individuals that was the highest. After the initial decrease in diversity from 20 years to 24 years, an increase is noticed at 30 years and goes on to where it is significantly higher at the oldest post rehabilitation age (32 years) ($p < 0.05$) (Table 5.5).

5.5.4 Tailings Dam aspects

The results for the different vegetation diversity indices tested between the different aspects on the TD indicated no significant differences ($p > 0.05$) (Table 5.6). The TD do not show the same trend found on the RD regarding herbaceous species diversity on different aspects. As mentioned previously the highest species diversity was found on the eastern aspect on the RD (Table 5.4). On the TD the southern aspect revealed increased diversity showing the highest values for Margalef species richness (d), Pielou's evenness (J'), Shannon-Wiener

diversity (H') and Simpson's diversity (D) followed by the eastern aspect and the western aspect showing the lowest diversity.

Table 5.6: Differences in vegetation diversity index values between different aspects on the Tailings Dam.

	Tailings Dam Aspect		
	East	South	West
Sample size (n)	45	20	24
Total species	7.26±0.340 a	8.00±0.561 a	6.29±0.457 a
Total individuals	65.83±4.36 a	64.79±6.09 a	65.63±5.75 a
Margalef species richness	1.534±0.078 a	1.702±0.132 a	1.323±0.105 a
Pielou's evenness	0.668±0.021 a	0.694±0.033 a	0.694±0.028 a
Shannon-Wiener div. index	1.313±0.062 a	1.430±0.100 a	1.264±0.083 a
Simpson diversity index	0.637±0.025 a	0.663±0.040 a	0.625±0.033 a

¹Mean diversity index values ± Standard Error of Mean (SEM).

²Statistically significant differences are indicated by alphabetic letters. The same letters indicate no significant differences, while different letters indicate significant differences.

5.6 Benchmarking the Rock Dump and Tailings Dam against Mopaneveld

5.6.1 Species richness (total species) and Margalef species richness

Total species and Margalef species richness indicated similar trends and will therefore be discussed together. Generally, for all tested species diversity indices, terraces demonstrated the highest values across all three study sites (Figure 5.8 a-f & Table 5.8).

5.6.1.1 Terraces

Comparisons of total species (S) and Margalef species richness (d) between different topographic positions revealed that the number of species was significantly higher in the Mopaneveld (MV) than both the RD and TD ($p < 0.05$) (Figure 5.8a and 5.8e). But, there were no significant differences in the total species and Margalef species richness between the RD and TD ($p > 0.05$).

5.6.1.2 Slopes

The total number of species revealed significant differences between all the different slope positions ($p < 0.05$) (Figure 5.3b), with MV showing significantly higher total species values than both RD and TD. Further, the slopes on the RD revealed significantly lower species richness than the TD slopes ($p < 0.05$) (Figure 5.3b). Regarding Margalef species richness, MV slopes revealed significantly higher values than both RD and TD ($p < 0.05$), although no

significant species richness differences were noted between the RD and TD ($p > 0.05$). The same trend prevails as for the RD with higher species richness on the TD slopes (Figure 5.3f and Table 5.8).

5.6.2 Total individuals

5.6.2.1 Terraces

The RD showed significantly higher total individuals than the MV ($p < 0.05$) (Figure 5.3c). However, there were no significant differences in the total number of individuals between MV and TD ($p > 0.05$) (Figure 5.3c). There seems to be a reversed relationship between total species (S) and total individuals (N), as MV showed the highest total species richness, but the lowest amount of total individuals. The opposite is true for RD (Figure 5.3c Table 5.8).

5.6.2.2 Slopes

The TD had the highest mean total individuals on the slopes (Figure 5.3d and Table 5.8). Both MV and RD had significantly lower total individuals than TD ($p < 0.05$) (Figure 5.3d). The same trend is witnessed where MV with the highest total species, once again had the lowest total individuals (Figure 5.3d; Table 5.8).

Table 5.7: Effect sizes of Hierarchical Linear Modelling (HLM) analysis for comparisons between different topographic variables in terms of mean plant diversity index values. Control MV Slope = Mopaneveld Koppies (Natural); Control MV Terrace = Mopaneveld Plains (Natural); RD Slope = Rock Dump Slope; RD Terrace = Rock Dump Terrace; TD Slope = Tailings Dam Slope; TD Terrace = Tailings Dam Terrace. Significance codes: * = small effect at $d \geq 0.2$; ** = medium effect at $d \geq 0.5$; * = large effect at $d \geq 0.8$.**

Topographic positions		Total Species	Total Individuals	Margalef Species Richness	Pielou's evenness	Shannon-Wiener diversity index	Simpson Diversity Index
Control (MV) Slope analogue	RD Slope	1.12***	0.21*	1.05***	0.70**	0.91***	0.76**
	TD Slope	1.43***	0.42*	1.25***	0.43*	0.81***	0.50**
Control (MV) Terrace analogue	RD Terrace	0.67**	0.85***	0.94***	0.85***	0.76**	0.70**
	TD Terrace	1.50***	0.06	1.26***	0.40*	0.78**	0.48*
RD Slope	TD Slope	0.45*	0.64**	0.11	0.15	0.15	0.06
RD Terrace	TD Terrace	0.07	0.36*	0.01	0.03	0.03	0.02

Table 5.8: Hierarchical Linear Modelling (HLM) analysis for differences in diversity index values between different topographic positions (slope & terrace) positions.

	Control (Mopaneveld)		Rock Dump		Tailings Dam	
	Slope	Terrace	Slope	Terrace	Slope	Terrace
Sample size (n)	44	43	45	40	43	46
Total species	7.90 ± 0.63 a	10.53 ± 0.65 a	5.67 ± 0.42 b	7.68 ± 0.45 b	6.57 ± 0.44 c	7.53 ± 0.41 b
Total individuals	31.30 ± 8.32 a	65.37 ± 8.54 a	39.04 ± 5.55 a	81.15 ± 5.88 b	63.07 ± 5.74 b	67.70 ± 5.43 ab
Margalef species richness	1.99 ± 0.14 a	2.36 ± 0.14 a	1.34 ± 0.09 b	1.58 ± 0.09 b	1.43 ± 0.09 b	1.61 ± 0.09 b
Pielou's evenness	0.80 ± 0.03 a	0.74 ± 0.03 a	0.69 ± 0.02 b	0.67 ± 0.02 b	0.68 ± 0.02 b	0.68 ± 0.02 b
Shannon-Wiener div. index	1.59 ± 0.09 a	1.69 ± 0.10 a	1.19 ± 0.07 b	1.29 ± 0.07 b	1.29 ± 0.07 b	1.37 ± 0.07 b
Simpson diversity index	0.74 ± 0.04 a	0.73 ± 0.04 a	0.61 ± 0.03 b	0.63 ± 0.03 b	0.63 ± 0.03 b	0.65 ± 0.03 b

¹Mean diversity index values ± Standard Error of Mean (SEM).

²Statistically significant differences are indicated by alphabetic letters. The same letters indicate no significant differences while different letters indicate significant differences.

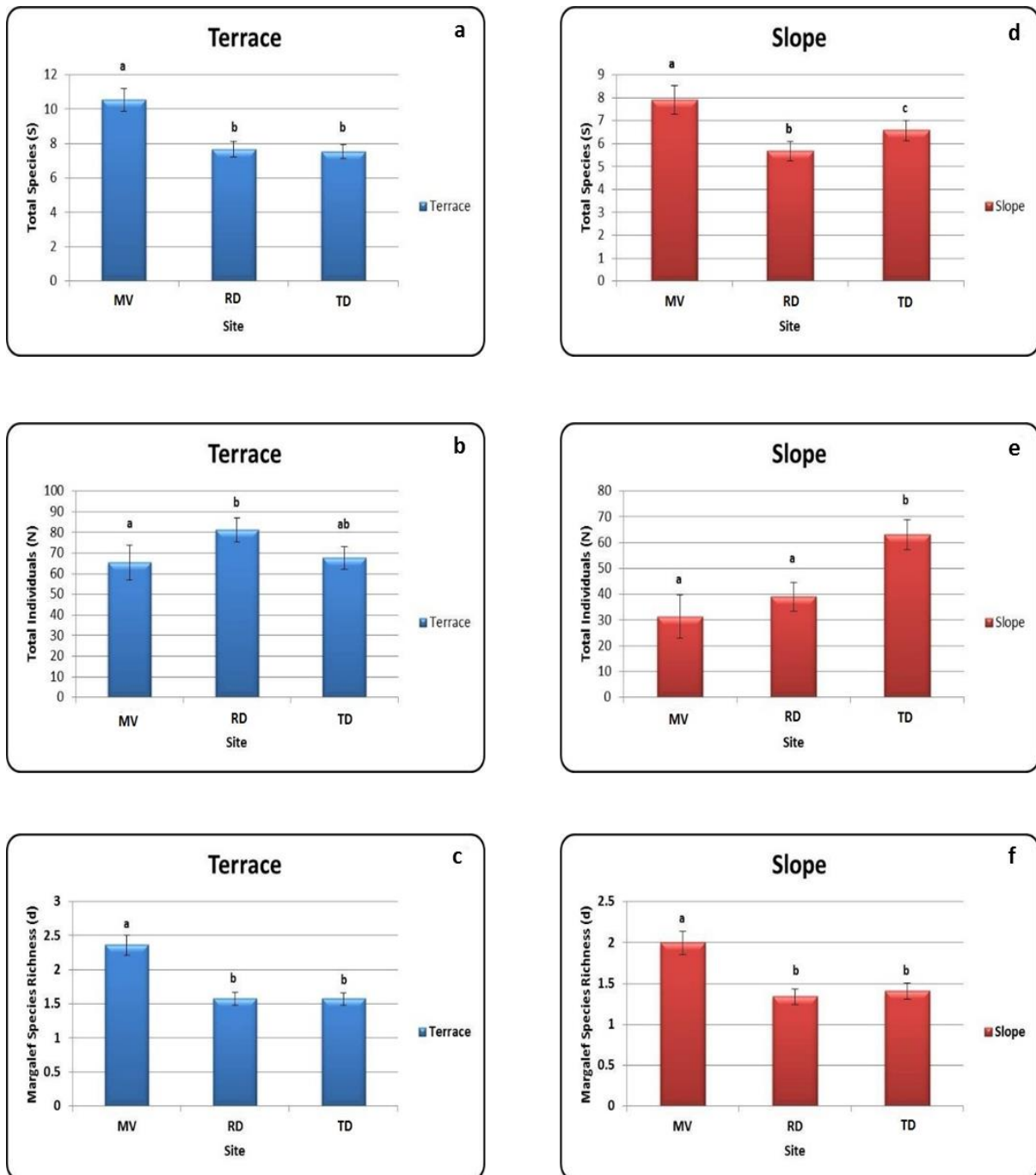


Figure 5.8 (a-f): Mean total species (S), Total individuals (N) and Margalef species richness (d) measures across the different treatments of topography on the control site, rock dump and tailings facility. Statistical significant differences are indicated by alphabetic letters. Different letters indicate significant differences between sites while the same letters indicate no significant differences. Vertical bars denote standard error values (Table 5.8) with 0.95 confidence intervals. Site abbreviations of Fig 5.8 – (MV = Mopaneveld (natural area); RD = Rock Dump; TD = Tailings Dam).

5.6.3 Pielou’s Evenness, Shannon-Wiener Diversity and Simpson’s Diversity

Pielou’s evenness, Shannon-Wiener diversity index and Simpson’s diversity index, which is all an indication of heterogeneity, responded similarly to the species richness measures

between the terrace and slope positions, and will therefore be discussed together (Figure 5.9a-f).

5.6.3.1 Terraces

The only significant differences were witnessed between the MV terraces and both the RD and TD terraces ($p < 0.05$) (Figure 5.9a-c; Table 5.8). Between all three diversity indices the MV terraces revealed the highest diversity values, followed by the TD and the RD terraces showing low evenness values (Figure 5.9a, b, c). RD terraces were primarily dominated by *Enneapogon cencroides*, *Cenchrus ciliaris* and *Aristida congesta*. TD terraces were dominated by *Tephrosia purpurea* and *Cenchrus ciliaris*.

5.6.3.2 Slopes

Again Pielou's evenness, Shannon-Wiener diversity index and Simpson's diversity index reacted in a similar way to the species richness measures (Figure 5.9d-f), with the MV slope analogues indicating significantly higher variation in species diversity and evenness than both the RD and TD slope positions ($p < 0.05$) (Figure 5.9d-f; Table 5.8). The RD and TD had low mean evenness. RD slopes were primarily dominated by *Enneapogon cencroides*, *Cenchrus ciliaris* and *Aristida congesta*. TD slopes were dominated by *Tephrosia purpurea* and *Cenchrus ciliaris*. No significant differences were displayed between the RD and TD slopes for all three heterogeneity indices ($p > 0.05$). The same trend is witnessed with the RD again showing the lowest values, except for evenness where the TD had the lowest.

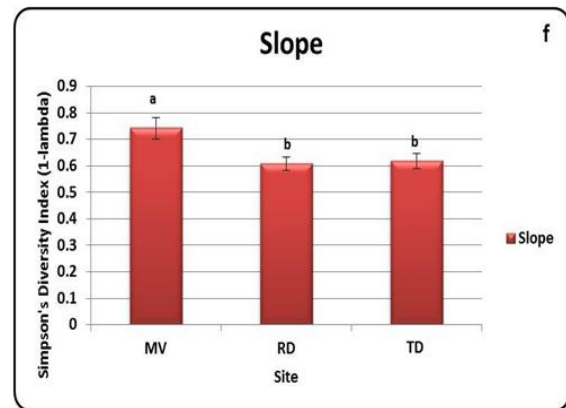
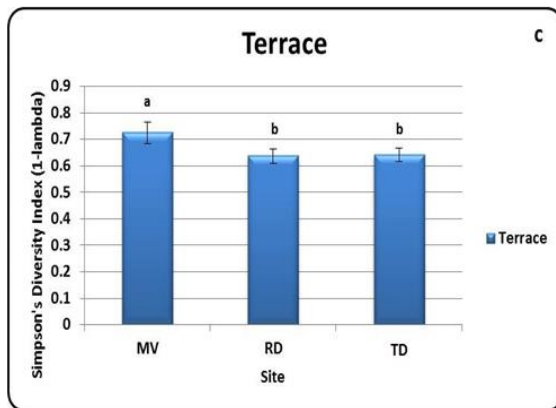
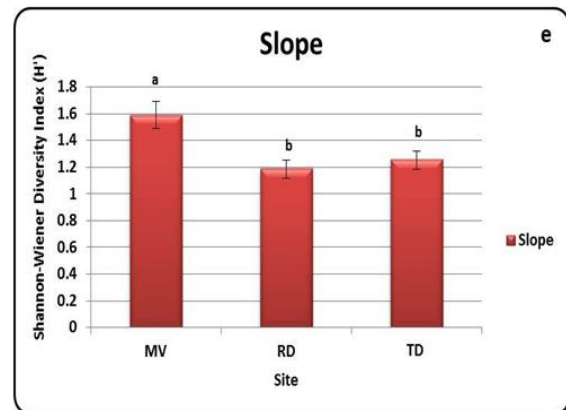
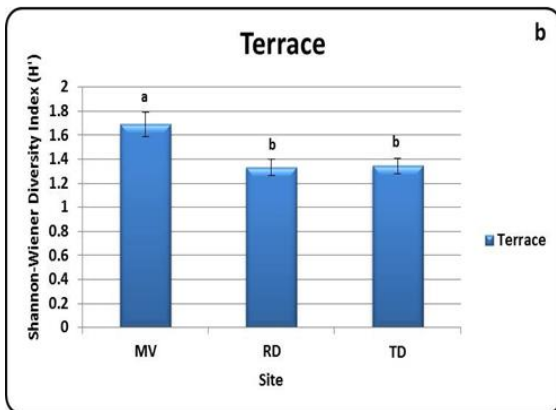
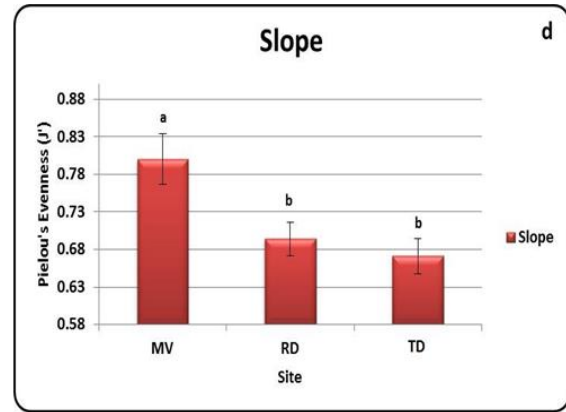
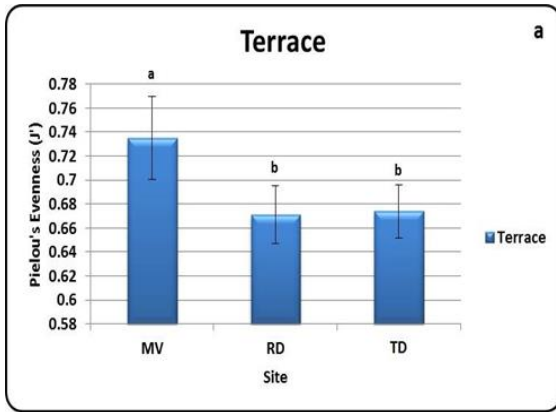


Figure 5.9 (a-f): Pielou's evenness (J'), Shannon-Wiener Diversity (H') and Simpson's Diversity ($1-\lambda$) measures across the different treatments of topography on the control site, rock dump and tailings facility. Statistical significant differences are indicated by alphabetic letters. Different letters indicate significant differences between sites while the same letters indicate no significant differences. Vertical bars denote standard error values (Table 5.8) with 0.95 confidence intervals. Site abbreviations of Fig 5.9 – (MV = Mopane veld (natural area); RD = Rock Dump; TD = Tailings Dam).

5.7 Discussion

No substantial historic records could be found regarding the history of rehabilitation processes on both the RD and TD of PMC. The first and foremost area of concern in terms of rehabilitation, and final closure, is what is known and what had been done historically (Coaltech, 2007). There are also gaps in the available data even with specifics, such as the precise seed combinations and the specific fertilizer mixtures used on each of the two tailings facilities (RD and TD).

It is vital that all actions regarding the rehabilitation process be documented and records stored for future accessibility and use (Coaltech, 2007). Hence, without proper documentation the results of this study could not be compared to previously sampled or analysed benchmark data of the facilities. Consequently the results obtained for the different topographic terrace and slope positions had to be benchmarked against natural areas in the nearby vicinity, to form a basis concerning herbaceous species diversity on a rehabilitated man-made ecosystem.

Biodiversity directly reflects ecosystem function and resilience to stress or change in the environment, and further it is considered fundamental to successful rehabilitation (Cousins & Lindborg, 2004). Any restoration process has the main goal to create sustainable vegetation communities representative of the species diversity of the surrounding natural undisturbed areas (Jefferson, 2004; Courtney *et al.*, 2009). In areas severely disturbed by mining, whether it's tailings dams or waste rock dumps, the establishment of vegetation can be particularly challenging, and resemble the natural process of primary succession due to extremely harsh growing environments (Yan *et al.*, 2013). Natural areas (with organic matter rich A horizons) show soil and vegetation development that is more affiliated to secondary succession, since natural undisturbed topsoil has organic matter, nutrient accumulation and possesses a seed bank from the original or previous vegetation (Wali, 1999). This is not the case for tailings facilities.

However, depending on local site conditions, vegetation succession and the development of an extensive vegetation cover on such dilapidated land can take decades or even centuries to complete by natural processes (Dobson *et al.*, 1997; Bradshaw, 2000; Kirmer *et al.*, 2012; Yan *et al.*, 2013). Further and equally important in the rehabilitation process and planning is the design of waste rock dumps and tailings dam facilities, especially slope angle, which in turn should minimise erosion if satisfactory vegetation richness and cover is established.

5.7.1 Herbaceous vegetation dominance of different post rehabilitation ages, aspects and topographic positions on the RD and TD.

It is evident from the NMDS results, and the Simper analysis supports the finding, that different post rehabilitation ages, aspects and topographic position does not affect floristic composition to such an extent that a significant dissimilarity across the RD and TD could be identified. Slight variations in composition between post rehabilitation ages, aspects and topographic positions on the RD and TD were the result of changes in abundances and not due to variations in floristics. The grass species *Aristida adscensionis*, *Aristida congesta*, *Cenchrus ciliaris*, *Enneapogon cencroides*, *Heteropogon contortus*, *Pennisetum setaceum* and *Stipagrostis hirtigluma* and key forb species *Tephrosia purpurea*, *Tephrosia uniflora* (Fabaceae) and *Tridax procumbens* (Asteraceae) contributed the most to the differences between assemblages on the RD. The dominance of grasses, although non-significant, on the RD reflects the tolerance advantage and colonizing ability of grasses in hostile tailings environments (Ekka & Behera, 2011; Ssenku *et al.*, 2014). The capacity of grass species to tolerate drought, low soil nutrients and climatic stress contribute to their success in colonizing mine soils (Ekka & Behera, 2011).

On the TD, grass species such as *Aristida scabrivalvis*, *Cenchrus ciliaris*, *Enneapogon cencroides*, *Heteropogon contortus* and *Stipagrostis hirtigluma*, and the forbs *Indigostrum costatum*, *Sesbania bispinosa* and *Tephrosia purpurea* (all Fabaceae) were accountable for the differences between assemblages. Grass species on the TD were much less dominant than on the RD. Forb species belonging to the Fabaceae are the most diverse and widespread group of plants that have the capacity to host nitrogen-fixing bacteria (Al-Fredan, 2011). Nitrogen deficiency is one of the most important factors limiting vegetation growth during rehabilitation of mine tailings and, although a self-sustaining ecosystems depend on several major elements, the accumulation and effective cycling of nitrogen is particularly important because it is most easily lost from ecosystems (Piha *et al.*, 1995). The continuous occurrence of a specific set of dominant species on the different post rehabilitation ages, aspects and topographic positions of the RD and TD indicate their excellent adaptive ability to utilise tailings soils (Borpujari, 2008).

5.7.2 Herbaceous vegetation cover and biomass of different post rehabilitation ages, aspects and topographic position on the RD and TD

Commonly, vegetation cover is defined as the vertical projection of the crown or shoot area of vegetation to the ground surface expressed as a percentage of the reference area (Purevdorj *et al.*, 1998). In arid and semi-arid areas the estimation of vegetation cover is an

important factor, and may help to indicate vulnerability to soil degradation (limited plant cover and low biomass) (Purevdorj *et al.*, 1998; Chabrilat, 2006). Furthermore, vegetation cover not only reduces, but to some extent even prevents, the distribution of pollutants through wind and water erosion, and improves the aesthetic value of the specific site (Tordoff *et al.*, 2000; Vangronsveld *et al.*, 2009; Zornoza *et al.*, 2012).

As the results indicated none of the different post rehabilitation ages, aspects or topographic position on the RD revealed vegetation cover percentages of more than 30 %, even lower on the TD with less than 20 % cover. The role of vegetation cover in soil erosion control is well known. Numerous authors acknowledged this by confirming that with a vegetation cover of more than 30 % soil erosion rates are greatly reduced (Thornes, 2004; Gimeno-Garcia *et al.*, 2007; Moreno-de las Heras *et al.*, 2009; Shrestha *et al.*, 2010), and particularly confirmed the drastic reduction of soil loss with a 30 % vegetation cover on slopes of mining reclamation sites. Thornes (2004), Gimeno-Garcia *et al.* (2007) and Moreno-de las Heras *et al.* (2009) further concluded that a 50 % cover of herbaceous vegetation is ideal on man-made slopes in practice as a conservative target for site stabilisation. Emphasis should be set on the fact that cover percentage were not converted to biomass. In addition, basal cover of grasses is often a better indicator of biomass (Guevara *et al.*, 2002) and the system's ability to withstand erosion (Gutierrez & Hernandez, 1996). As most slopes were characterised by high cover, but low basal cover, the effects of a fire could be detrimental to the stability of the slopes in a high rainfall year (Evans *et al.*, 1999).

It could be expected that there would be an inversely correlated link between vegetation diversity and biomass. Results portrayed this, as there was no clear trend concerning biomass production and vegetation diversity. Nevertheless, using multiple species variables, for instance biomass, assists in better understanding the mechanics and details of community structure and diversity patterns (Guo & Rundel, 1997). Several important reasons come to light for using biomass/productivity as a complementary way of measuring vegetation communities. It was not necessarily the case that the study sites with the highest biomass, meant that the highest species diversity also occurred there. RD (28 years) had the highest species diversity with the lowest biomass, while RD (32 years) had the highest biomass with the lowest species diversity. The same could be seen on the TD, as the oldest post rehabilitation age had the highest species diversity with the lowest biomass. This can most likely be attributed to the humpback model, due to large *Cenchrus ciliaris* and *Pennisetum setaceum* tufts dominating patches (Van Coller & Siebert, 2015). Similar trends were observed for the different aspects on both the RD and TD. Western aspects had the highest biomass with the lowest species richness and diversity, while eastern aspects had

the lowest biomass and highest species richness and diversity. The contrary was true for the different topographic positions as the terraces were characterised by the highest biomass and species richness and diversity. When species diversity decrease biomass increase as less species dominate and outcompete other species; this conforms to the conclusions of Van Coller and Siebert (2015), that higher species diversity is characterised by decreased biomass in the herbaceous layer.

5.7.3 Post rehabilitation age effect on herbaceous vegetation diversity

In general it was to be expected that under harsh environmental conditions species diversity may be low, due to the fact that only a few species which are particularly adapted, could withstand or thrive above others (Martínez-Ruiz *et al.*, 2001; Makineci *et al.*, 2011). Tailings facilities are not known for rich and diverse plant species composition (Conesa *et al.*, 2006). Martín-Moreno *et al.* (2013) goes further in saying that mine tailings has been proven to be unstable, and even more so in arid and semi-arid climates. Although the species richness was low at the study sites, this study found a surprisingly high number of different herbaceous plant species growing on the RD and TD. Based on the survey results 94 species were recorded on the study sites compared to the 138 from natural areas.

On the RD the results indicated high initial herbaceous species richness (Margalef species richness) on the youngest age (28 years), a decrease on the mid-age level (32 years) and then recovery to the highest species richness on the oldest post rehabilitation age (42 years). Quite a few indirect succession studies revealed the same pattern on power plant waste dumps, rehabilitated nickel and copper mine tailings, plot age of a reclaimed coal mine, as well as abandoned agricultural land (John *et al.*, 2002; Wissuwa *et al.*, 2012). However, total species (S) did not follow the same trend as it had the lowest species count at the youngest age (28 years) and increased with time to the highest at the oldest age (42 years). This might be expected, because as time since rehabilitation increases there is a greater chance of new species colonising the RD (Alday *et al.*, 2010). Therefore, the continuous rise in species richness with time on the RD was reflective of a progressive succession and restoration process (Ssenku *et al.*, 2014).

However, herbaceous species diversity (Shannon Wiener diversity and Simpson diversity) indices showed the highest diversity at the youngest age (28 years), a decrease on the mid-age level (32 years) and a slight recovery of intermediate diversity on the oldest post rehabilitation age (42 years). On the youngest age level the process of reseeding and fertilizing had been done more recently and causes higher species diversity. After the initial fertilising and seeding the species richness decreases at the mid age level (32 years) and

with time species richness increases as is evident from the results. One of the reasons for higher species richness on the oldest age level is that the 'lowest'/older slope is in close proximity to the Kruger National Park and it is known that many species colonize slopes of tailings facilities from the bottom up (Ssenku *et al.*, 2014), while the 'higher'/younger level is further removed from seed sources (i.e. surrounding veld) than the older levels (Weiersbye *et al.*, 2006). A sort of filtering effect takes place, by means of the increase in altitude, which causes the colonizing of the lower/older slopes first (Ssenku *et al.*, 2014). Another significant aspect is the important role that animals play in terms of seed dispersal. A lot of animal movement were noticed on the lower age level on the RD, which included buffalo, elephant, kudu, waterbuck and lion (personal observation).

On the TD the same trend is witnessed where higher species richness (total species and Margalef species richness) occurs on the youngest age level (20 years), while the mid age levels (24 and 30 years) shows a decrease resulting in the lowest and intermediate plant species richness. With time an increase in richness is noticed on the oldest age level (32 years). With time, mine tailings select for a specific assemblage of plant species, distinct from the surrounding vegetation (Wu, 1990), which then enhances richness as habitats become colonised. The only trend consistent with the RD regarding herbaceous species diversity (Shannon-Wiener and Simpson diversity indices) is that the intermediate age levels revealed the lowest diversity values. On the TD, the highest species diversity occurred on the oldest post rehabilitation age (32 years). Despite the species diversity decrease at the intermediate age of 24 years, it showed that as the age of the TD increased the diversity index also increased, which conforms to the findings of Borpujari (2008). Borpujari (2008) further found that younger post rehabilitation ages revealed similar species diversity index values and that older ages were more closely related to each other. In contradiction with Borpujari (2008), this study found that the youngest and oldest post rehabilitation age were closely paired in terms of species diversity and the intermediate age levels closer related to each other.

Due to the active nature of the TD, which includes a large number of vehicle and people movement, lower species richness and diversity was expected. Despite the fact that the TD is cloistered by mining activities compared to the RD, higher species richness and diversity is witnessed.

5.7.4 Orientation (aspects) effect on herbaceous vegetation diversity

Due to the southerly latitude of the study area, the inclination of the sun, the abiotic characteristics such as temperature, moisture relations and solar radiation differ distinctly

between different aspects (Bennie *et al.*, 2006; Kawule, 2007). Hence, the vegetation associated with these different aspects was directly affected by the above mentioned variations and is reflected in the species assemblages (Pykälä *et al.*, 2005; Bennie *et al.*, 2006).

A similar and anticipated trend of herbaceous species richness (total species and Margalef species richness) and diversity (Shannon-Wiener and Simpson diversity indices) occurs on both the RD and TD as a result of the three different aspects. The eastern and southern aspects revealed the highest species diversity, which can be explained on the basis that southern and eastern aspects are, in terms of microclimate, cooler and moister. The occurrence of higher species diversity can be explained by the availability of more resources such as water, sunlight, heat and soil nutrients which leads into the development of micro-climatic conditions (Fattahi & Ildoromi, 2011; Zeng *et al.*, 2014). At the same time the western aspect revealed the lowest species diversity on both the RD and TD. This observation can be attributed to maximum air temperature occurring during the afternoon, at the time of day when the direct solar radiation loading is at its highest peak on west facing slopes (McCune & Keon 2002; Bennie *et al.*, 2006). Only highly specialised and tolerant species can survive these conditions. On the western aspect of the RD species such as *Aristida congesta*, *Cenchrus ciliaris*, *Enneapogon cencroides*, *Heteropogon contortus*, *Stipagrostis hirtigluma* and *Tephrosia purpurea* were prevalent. The species dominating the western aspect on the TD included *Cenchrus ciliaris* and *Tephrosia purpurea*, together with the riparian species *Indigastrium costatum* and *Sesbania bispinosa*.

5.7.5 Topographic position effect on herbaceous vegetation diversity

A predefined reference site plays an important role in investigating rehabilitation successes and failures and is dependent on measuring ecosystem change in relation to values obtained from these reference sites, also known as benchmark or analogue sites (Herrick *et al.*, 2006). It is the first benchmarked study done of herbaceous species richness and diversity on the tailings facilities at PMC. Consequently the importance of the benchmarked results indicated the extent to which the diversity on the tailings facilities compares to that of natural Mopaneveld after more than 30 years post rehabilitation.

According to the results, all the tested herbaceous species diversity indices revealed similar trends with the natural benchmark areas of Mopaneveld, namely the plains compared to terraces and the inselbergs to slopes of the RD and TD. Mopaneveld showed significantly higher plant species diversity. The species diversity of the herbaceous layer of the study

sites was low in relation to natural areas due to harsh environmental conditions (Mapaure *et al.*, 2011).

In general, the results indicate strong effects of topographic position (terrace or slope) on plant species diversity in the study area (Zeng *et al.*, 2014). The higher plant species richness (total species and Margalef species richness) and diversity (Shannon-Wiener diversity and Simpson diversity) on the terrace position of both the RD and TD conforms to the findings of Rossouw *et al.* (2009) and Weiersbye *et al.* (2006), who found the greatest number of species on the flat parts (in this case terrace positions). It can be suspected that more species were originally planted on the terraces with its flat surface in comparison to the 36° slope angles at PMC, but no data is available to confirm this. Steep slopes are more subject to water runoff and erosion which limits seed capture and vegetation establishment (Felleson, 1999; Rossouw *et al.*, 2009; Fattahi & Ildoromi, 2011). Further, Riaza *et al.* (2012) and Martín-Moreno *et al.* (2013) found that plants colonized the flatter, lower parts better as the water availability is higher because small ponds dry up slowly on flat surfaces. Riaza *et al.* (2012) and Martín-Moreno *et al.* (2013) goes further in saying that the contrary is observed on slopes as the material on slopes of mine tailings is susceptible and dominated by water runoff and washing during rainy periods, which in turn severely limits natural plant colonization on steep slopes.

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Chapter 6 – Microbial biomass and community structure

6.1 Phospholipid Fatty Acid (PLFA) analysis

The viable microbial biomass, microbial community structure (concentrations of major PLFA structural groups – mol%) and the fungal to bacterial ratios derived from PLFA data for the different post rehabilitation ages, aspects and topography for both the Rock Dump (RD) and Tailings Dam (TD) treatments are summarized in Tables 6.1 to 6.6, and Figures 6.1a-f.

6.1.1 Soil microbial biomass of different post rehabilitation ages

6.1.1.1 Rock Dump

The viable microbial biomass was determined by means of phospholipid fatty acid (PLFA) analysis and was calculated as the sum of all signature biomarker lipids present in the samples (Figure 6.1a). The microbial biomass for the different post rehabilitation ages of 28, 32 and 42 years on the RD were calculated at 4890.04, 4590.92 and 6429.37 pmol per gram soil dry weight, respectively (Figure 6.1a and Table 6.1). The oldest post rehabilitation age (42 years) showed significantly higher soil microbial biomass than both 28 and 32 year post rehabilitation ages ($p < 0.05$). The youngest level revealed the lowest microbial biomass.

Table 6.1: Viable microbial biomass and phospholipid fatty acid (PLFA) structural group averages (\pm standard error) for different post rehabilitation ages on the Rock Dump. The same letters indicate no significant differences while those with different letters indicate significant differences at $p < 0.05$ (Tukey's HSD). Key: NSats = normal saturated fatty acids; MBSats = mid-chain branched saturated fatty acids; TBSats = terminally-branched saturated fatty acids; Bmonos = branched monounsaturated fatty acids; Monos = monounsaturated fatty acids; Polys = polyunsaturated fatty acids.

	Rock Dump – Age		
	28	32	42
Viable microbial biomass (pmol.g⁻¹) soil dry weight	4890.04 \pm 811.3 a	4590.92 \pm 402.14 a	6429.37 \pm 490.98 b
PLFA groups (mol %)			
NSats	25.03 \pm 1.204 a	37.16 \pm 6.231 a	34.89 \pm 5.009 a
MBSats	13.30 \pm 0.989 a	16.32 \pm 3.526 a	12.97 \pm 1.872 a
TBSats	16.88 \pm 1.707 a	17.50 \pm 0.875 a	30.07 \pm 4.17 b
Bmonos	0	0	1.035 \pm 0.58
Monos	40.260 \pm 0.911 a	44.690 \pm 7.964 a	51.22 \pm 7.782 a
Polys	1.822 \pm 0.482 a	0.594 \pm 0.116 b	0.791 \pm 0.153 b
PLFA Ratio			
Fungal / Bacterial	0.01	0.01	0.01

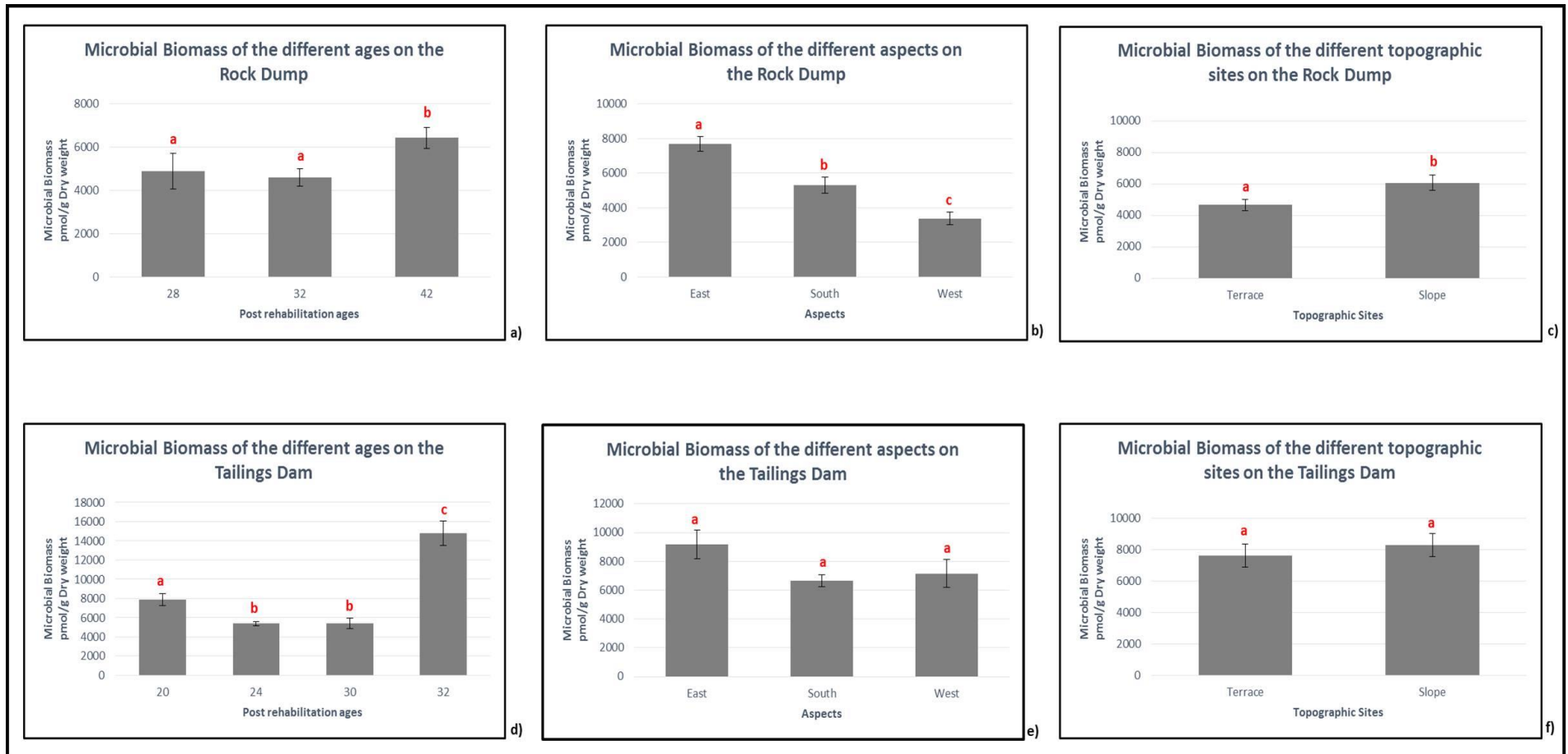


Figure 6.1: Microbial biomass for different post rehabilitation ages, aspects and topographic sites on the Rock Dump (a-c) and Tailings Dam (d-f).

6.1.1.2 Tailings Dam

The microbial biomass on the TD for the different post rehabilitation ages of 20, 24, 30 and 32 years were 7856.63, 5375.30, 5394.41 and 14806.37 pmol per gram soil dry weight respectively (Figure 6.1d and Table 6.2). Significant differences in soil microbial biomass can be seen between the four different ages on the TD ($p < 0.05$). The oldest post rehabilitation age (32 years) showed significantly higher microbial biomass values than all of the younger ages. Although the microbial biomass at the youngest post rehabilitation age (20 years) were also significantly higher than 24 and 30 years, the oldest age level revealed almost twice the amount. The microbial biomass follows the same trend noticed on the RD, as the youngest post rehabilitation age showed high values followed by a sharp decline at the intermediate age levels, after which, it increases to the highest values at the oldest post rehabilitation age.

Table 6.2: Viable microbial biomass and phospholipid fatty acid (PLFA) structural group averages (\pm standard error) for different post rehabilitation ages on the Tailings Dam. Statistical significant differences are indicated by alphabetic letters ($p < 0.05$). The same letters indicate no significant differences while those with different letters indicate significant differences at $p < 0.05$ (Tukey's HSD). Key: NSats = normal saturated fatty acids; MBSats = mid-chain branched saturated fatty acids; TBSats = terminally-branched saturated fatty acids; Bmonos = branched monounsaturated fatty acids; Monos = monounsaturated fatty acids; Polys = polyunsaturated fatty acids.

	Tailings Dam – Age			
	20	24	30	32
Viable microbial biomass (pmol.g⁻¹) soil dry weight	7856.63 \pm 623.66 a	5375.30 \pm 229.11 b	5394.41 \pm 520.67 b	14806.37 \pm 1277.04 c
PLFA groups (mol %)				
NSats	26.27 \pm 2.211 a	51.76 \pm 10.43 b	52.52 \pm 12.35 b	23.79 \pm 0.225 a
MBSats	8.197 \pm 0.475 a	22.54 \pm 5.02 b	24.93 \pm 5.365 b	5.995 \pm 0.436 a
TBSats	20.83 \pm 0.502 a	32.51 \pm 7.195 a	32.97 \pm 10.77 a	20.59 \pm 0.447 a
Bmonos	0	0	0	0
Monos	41.05 \pm 2.716 a	66.39 \pm 14.67 a	57.66 \pm 18.49 a	46.80 \pm 0.688 a
Polys	0.858 \pm 0.246 a	2.077 \pm 0.41 b	2.053 \pm 0.36 b	0.579 \pm 0.035 a
PLFA Ratio Fungal / Bacterial	0.01	0.01	0.01	0.01

6.1.2 Soil microbial biomass of different aspects

6.1.2.1 Rock Dump

Significant differences in microbial biomass can be seen between all the aspects of the Rock Dump ($p < 0.001$) (Figure 6.1b and Table 6.3). The eastern aspect revealed the highest microbial biomass and the western aspect the lowest. It differed with 4300 pmol per gram soil dry weight between western and eastern aspects (Figure 6.1b).

Table 6.3: Viable microbial biomass and phospholipid fatty acid (PLFA) structural group averages (\pm standard error) for different aspects on the Rock Dump. The same letters indicate no significant differences while those with different letters indicate significant differences at $p < 0.05$ (Tukey's HSD). Key: NSats = normal saturated fatty acids; MBSats = mid-chain branched saturated fatty acids; TBSats = terminally-branched saturated fatty acids; Bmonos = branched monounsaturated fatty acids; Monos = monounsaturated fatty acids; Polys = polyunsaturated fatty acids.

	Rock Dump – Aspect		
	East	South	West
Viable microbial biomass (pmol.g⁻¹) soil dry weight	7674.49 \pm 422.73 a	5291.63 \pm 464.82 b	3374.97 \pm 372.92 c
PLFA groups (mol %)			
NSats	44.08 \pm 6.976 a	24.30 \pm 1.048 b	38.61 \pm 8.498 ab
MBSats	15.66 \pm 2.598 a	10.24 \pm 0.630 a	19.20 \pm 4.818 a
TBSats	31.67 \pm 6.114 a	19.12 \pm 0.928 b	22.56 \pm 1.340 b
Bmonos	1.510 \pm 0.833	0	0
Monos	51.70 \pm 11.84 a	38.24 \pm 1.535 a	53.74 \pm 10.36 a
Polys	1.418 \pm 0.202 a	0.373 \pm 0.039 b	1.134 \pm 0.334 a
PLFA Ratio			
Fungal / Bacterial	0.01	0.01	0.01

6.1.2.2 Tailings Dam

Microbial biomass between the different aspects on the TD did not show significant differences, with $p = 0.093$ ($p > 0.05$). However, the same trend found on the RD is noticed as the eastern aspect also has the highest biomass with 9187.68 pmol per gram soil dry weight (Figure 6.1e and Table 6.4). Overall, the different aspects on the TD revealed considerably higher microbial biomass values compared to the different aspects on the RD (Table 6.3 & 6.4).

Table 6.4: Viable microbial biomass and phospholipid fatty acid (PLFA) structural group averages (\pm standard error) for different aspects on the Tailings Dam. The same letters indicate no significant differences while those with different letters indicate significant differences at $p < 0.05$ (Tukey's HSD). Key: NSats = normal saturated fatty acids; MBSats = mid-chain branched saturated fatty acids; TBSats = terminally-branched saturated fatty acids; Bmonos = branched monounsaturated fatty acids; Monos = monounsaturated fatty acids; Polys = polyunsaturated fatty acids.

	Tailings Dam – Aspect		
	East	South	West
Viable microbial biomass (pmol.g-1) soil dry weight	9187.68 \pm 993.40 a	6657.11 \pm 397.97 a	7162.74 \pm 953.26 a
PLFA groups (mol %)			
NSats	41.31 \pm 7.033 a	30.59 \pm 5.831 a	43.69 \pm 9.292 a
MBSats	15.33 \pm 3.106 a	17.71 \pm 4.973 a	15.19 \pm 3.449 a
TBSats	26.35 \pm 5.798 a	29.22 \pm 6.274 a	26.23 \pm 4.962 a
Bmonos	0	0	0
Monos	48.68 \pm 10.03 a	54.82 \pm 10.05 a	53.32 \pm 6.174 a
Polys	1.790 \pm 0.282 a	0.835 \pm 0.149 a	1.404 \pm 0.357 a
PLFA Ratio			
Fungal / Bacterial	0.01	0.01	0.01

6.1.3 Soil microbial biomass of different topographic positions

6.1.3.1 Rock Dump

The viable microbial biomass of the different topographic positions (terrace and slope) on the RD differed significantly ($p=0.001$) (Figure 6.1c and Figure 6.5). The slopes showed significantly higher microbial biomass at 6065.79 (pmol.g-1) soil dry weight than the terraces at 4652.50 (pmol.g-1) soil dry weight.

Table 6.5: Viable microbial biomass and phospholipid fatty acid (PLFA) structural group averages (\pm standard error) for the two different topographic sites (Terrace & Slope) on the Rock Dump. The same letters indicate no significant differences while those with different letters indicate significant differences at $p < 0.05$ (Tukey's HSD). Key: NSats = normal saturated fatty acids; MBSats = mid-chain branched saturated fatty acids; TBSats = terminally-branched saturated fatty acids; Bmonos = branched monounsaturated fatty acids; Monos = monounsaturated fatty acids; Polys = polyunsaturated fatty acids.

	Rock Dump – Topography	
	Terrace	Slope
Viable microbial biomass (pmol.g-1) soil dry weight	4652.5 \pm 343.4 a	6065.79 \pm 479.46 b
PLFA groups (mol %)		
NSats	24.19 \pm 1.065 a	45.24 \pm 6.52 b
MBSats	11.05 \pm 0.628 a	18.18 \pm 3.352 b
TBSats	18.98 \pm 1.029 a	26.6 \pm 3.776 b
Bmonos	0	0.906 \pm 0.509
Monos	38.12 \pm 1.290 a	56.13 \pm 9.441 b
Polys	0.856 \pm 0.192 a	0.932 \pm 0.152 a
PLFA Ratio		
Fungal / Bacterial	0.01	0.01

6.1.3.2 Tailings Dam

No significant difference in microbial biomass were witnessed between the different topographic positions on the TD ($p > 0.05$) (Figure 6.1f and Figure 6.6). Although no significant differences occurred the slopes did reveal higher microbial biomass than the terraces and overall the topographic sites on the TD revealed much higher microbial biomass values in comparison with the RD topographic sites.

Table 6.6: Viable microbial biomass and phospholipid fatty acid (PLFA) structural group averages (\pm standard error) for the two different topographic sites (Terrace & Slope) on the Tailings Dam. The same letters indicate no significant differences while those with different letters indicate significant differences at $p < 0.05$ (Tukey's HSD). Key: NSats = normal saturated fatty acids; MBSats = mid-chain branched saturated fatty acids; TBSats = terminally-branched saturated fatty acids; Bmonos = branched monounsaturated fatty acids; Monos = monounsaturated fatty acids; Polys = polyunsaturated fatty acids.

	Tailings Dam – Topography	
	Terrace	Slope
Viable microbial biomass (pmol.g⁻¹) soil dry weight	7619.11 \pm 739.07 a	8276.00 \pm 745.27 a
PLFA groups (mol %)		
NSats	31.85 \pm 6.522 a	46.83 \pm 5.893 a
MBSats	11.88 \pm 2.793 a	19.89 \pm 3.075 a
TBSats	26.69 \pm 5.199 a	27.37 \pm 4.301 a
Bmonos	0	0
Monos	57.23 \pm 8.455 a	49.42 \pm 9.064 a
Polys	0.759 \pm 0.143 a	2.113 \pm 0.280 b
PLFA Ratio Fungal / Bacterial	0.01	0.01

6.2 Microbial Community Structure

6.2.1 Post rehabilitation age – Rock dump and Tailings dam

The microbial community structure based on the mol% fraction of the various PLFA groups for the RD and TD between the different post rehabilitation ages, aspects and topographic sites are displayed in Figure 6.2a and Figure 6.3a.

Monounsaturated fatty acids (Monos) are indicative of gram-negative bacteria and terminally branched saturated fatty acids (TBSats) of gram-positive bacteria (McKinley *et al.*, 2005; Claassens, 2007). On the RD, gram-negative and gram-positive bacteria showed an increase from 28 to 42 years post rehabilitation age (Table 6.1), although only the gram-positive bacteria were significantly higher at the oldest post rehabilitation age. Between the different ages on the TD both gram-negative and gram-positive bacteria increased from the youngest age (20 years) up to 30 years, and showed a decrease at the oldest age (32 years) (Table 6.2). Gram-positive bacteria are considered to be K-strategists and represent a more established community than the Gram-negative bacteria, which are considered to be R-

strategists (Potgieter, 2012). Mid-chain branched saturated fatty acids (MBSats), primarily indicative of Actinomycete type bacteria, is able to better survive in harsh environments due to their ability to span interstitial spaces to collect water and nutrient sources (Claassens, 2003). MBSats increased from the youngest age (28 years) to where it was the highest at the mid age level (32 years) and showed a decrease to the lowest value at the oldest age level (42 years) on the RD. MBSats between the different post rehabilitation ages on the TD followed the same trend as Monos and TBSats, with significantly lower MBSats recorded on the youngest and oldest ages and the highest on the mid age levels (Table 6.2).

A decrease in polyunsaturated fatty acids (Polys) (indicative of fungi) was witnessed for older ages on the RD as the youngest rehabilitation age (28 years) showed significantly higher polyunsaturated fatty acids. On the TD a significant increase in Polys was observed as highest for 24 and 30 years post rehabilitation age, after which it showed a significant decrease to the lowest value at the oldest age level. Normal saturated fatty acids (NSats) occur in all organisms (Zelles, 1999), and no significant differences were found between the different ages on the RD, although increased NSats can be seen on the older ages suggesting an increase in life forms. Significant differences were witnessed between the different post rehabilitation ages on the TD. Mid age levels of 24 and 30 years revealed significantly higher NSats than both the youngest (20 years) and oldest (32 years) post rehabilitation ages.

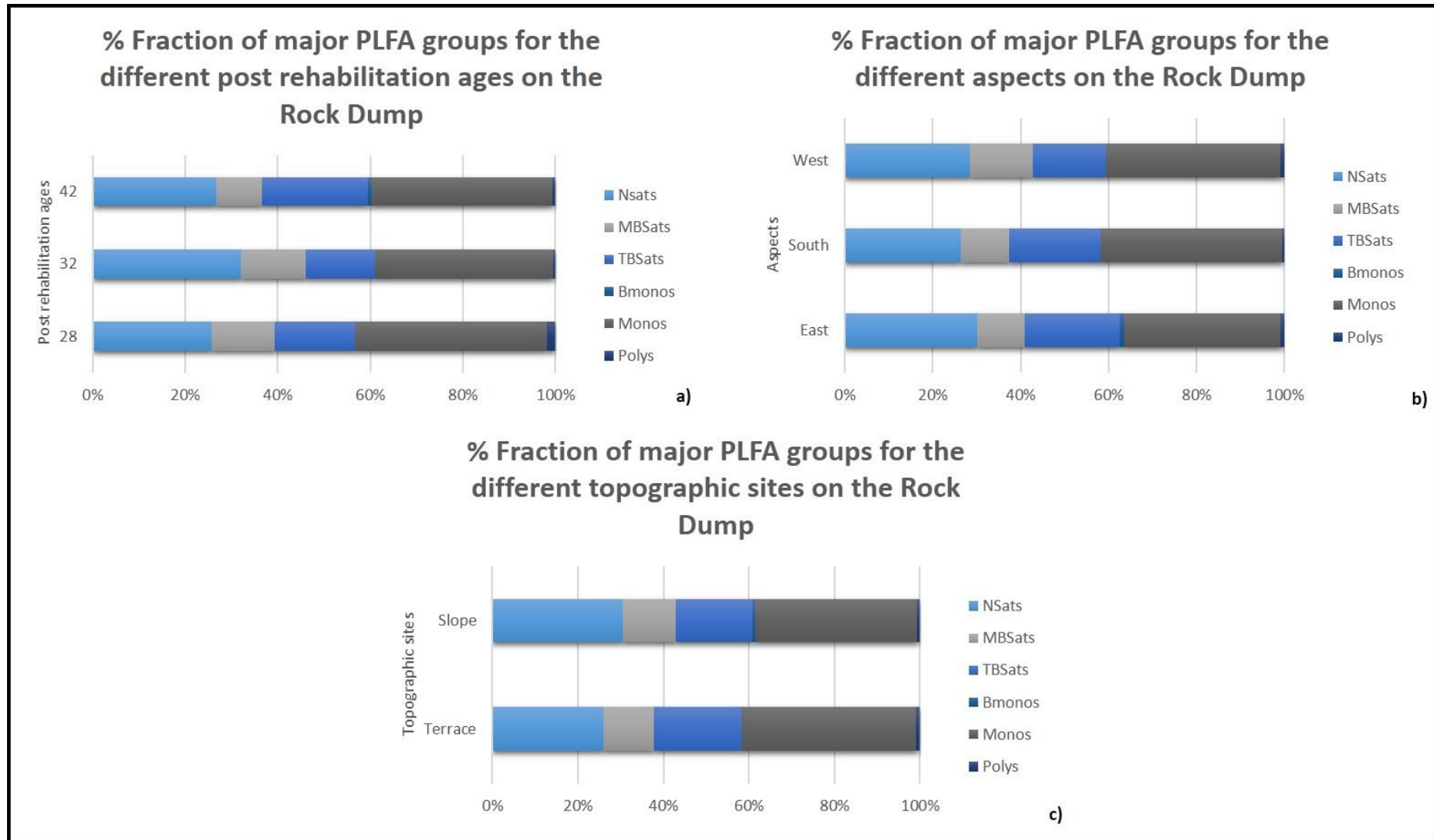


Figure 6.2: Microbial community structure based on the mol% fraction of the major phospholipid fatty acid groups of the different (a) post rehabilitation ages, (b) aspects and (c) topographic positions (slopes and terraces) on the Rock Dump.

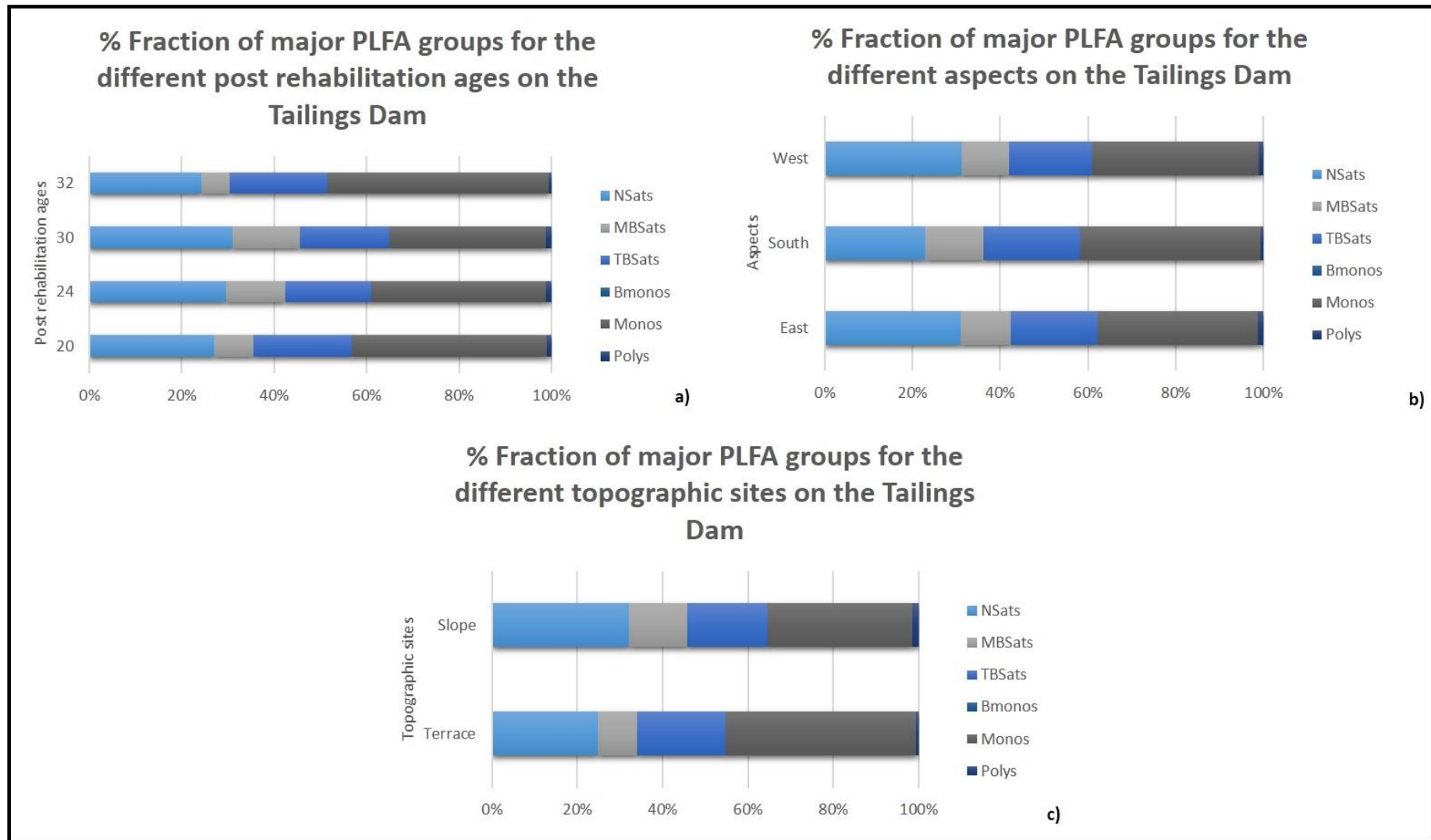


Figure 6.3: Microbial community structure based on the mol% fraction of the major phospholipid fatty acid groups of the different (a) post rehabilitation ages, (b) aspects and (c) topographic positions (slopes and terraces) on the Tailings Dam.

6.2.2 Aspect – Rock dump and Tailings dam

The results of the microbial community structure based on the mol% fraction of the various PLFA groups for the RD and TD between the different aspects are displayed in Table 6.3 and 6.4, and Figure 6.2b and 6.3b.

Significant differences ($p < 0.05$) between the different aspects (East, South, West) is observed for NSats ($p=0.031$), TBSats ($p=0.009$) and Polys ($p=0.001$) on the RD, while no significant differences were witnessed for any of the tested microbial community structures on the TD (Table 6.3 & 6.4). All of the above mentioned microbial structure groups were significantly higher on the eastern aspect of the RD while the southern aspect revealed significantly lower values. The same trend was not observed between the different aspects on the TD as only Polys were highest on the eastern aspect. The tendency on the TD shifted more towards the southern aspect showing increased MBSats, TBSats and Monos (Table 6.4). NSats revealed increased values on the eastern and western aspects.

6.2.3 Topographic position – Rock dump and Tailings dam

The results of the microbial community structure based on the mol% fraction of the various PLFA groups for the RD and TD between the different topographic positions are displayed in Table 6.5 and 6.6, and Figure 6.2c and 6.3c.

Highly significant differences ($p < 0.005$) are witnessed between the slopes and terraces of the RD (Table 6.5). The slope positions showed significantly higher values for NSats ($p < 0.001$), MBSats ($p=0.001$), TBSats ($p=0.032$), Bmonos ($p < 0.001$) and Monos ($p < 0.001$) in relation to the terraces. Although no significant difference was noticed for Polys the slopes did show higher soil fungi content (Figure 6.2c and Table 6.5).

The TD topographic positions showed only significant differences for the Polys ($p < 0.001$) (Table 6.6). The slopes revealed significantly higher fungi content. Granting no further significant differences was witnessed, it should be noted that all the tested microbial structural groups were higher on the slopes (Figure 6.3c and Table 6.6).

6.3 Discussion

Mining activities lead to harsh soil conditions and stressors that alter the biochemical activities of soil microorganisms (Kujur & Patel, 2012). Analysis of PLFAs is a reliable manner in which the viable microbial community can be quantified and the method provides useful information on the changes in soil microbial properties (Claassens *et al.*, 2011; Kujur & Patel, 2012).

The investigation into the microbial biomass of post-mining sites of different ages at the RD and TD of PMC indicated a relationship based on post rehabilitation ages of the different facilities (Figure 6.1 & Figure 6.2). For both the RD and TD the oldest post rehabilitation ages revealed the highest microbial biomass and the intermediate post rehabilitation age levels the lowest, all of which varied within different ranges (4890.04 – 6429.37 pmol per gram soil dry weight for the RD and 7856.63 – 14806.37 pmol per gram soil dry weight for the TD). These results are in agreement with the findings of Claassens *et al.* (2011), who found markedly varied microbial biomass between rehabilitation sites of different ages.

Microbial biomass can be attributed to the amounts of soil organic carbon (SOC) resources that are available in the soil (Feketeova *et al.*, 2015), which should improve with the rehabilitation age of the site (Frouz & Kalčík, 2006) (Chapter 7; Table 7.1 and 7.4). SOC is an essential component of soil quality and plays a vital role in the maintenance of microbial activity. Over the post rehabilitation period from 28 to 42 years on the RD and from 20 to 32 years on the TD the SOC in the soil rose from 0.13% to 0.44% and from 0.31% to 0.68%, respectively.

Nayak *et al.* (2011) and Kujur & Patel. (2012) found that on different mine spoils SOC, microbial biomass fluctuations and soil microbial diversity were all closely related and have large effect on one another. This is an important driver of the development process, since it will provide a crucial resource for soil microbes and micro fauna. Both of these play an important role in both soil structure and nutrient cycling (Wardle *et al.*, 2004).

As the results indicated, the highest SOC content and consequently the highest microbial biomass was found on the eastern and southern aspects of the RD (Chapter 7; Table 7.2). This can be explained due to the fact that eastern aspects and to some extent southern aspects have a cooler and moister climate and are usually characterised by higher SOC content (Sidari *et al.*, 2008). Dorji *et al.* (2014) found that SOC can be influenced by biotic variables such as microbial and plant species, as well as environmental variables such as moisture availability, temperature and soil texture. Moisture (precipitation), solar radiation and temperature are factors of significance influencing vegetation growth, the production of litter and SOC mineralization

(Jobbagy & Jackson, 2000). Jobbagy and Jackson (2000) goes further in saying that moisture (precipitation) causes an increase in SOC, but it decreases with higher temperature due to higher decomposition of organic matter. This is in agreement with the findings of this study that the warmer and dryer western aspects of the RD reflected the least amount of SOC content and microbial biomass. The eastern aspect on the TD also showed the highest microbial biomass, which supports the trend that eastern aspects have an ideal micro-climate and is therefore characterized by higher SOC content.

Regarding the southern and western aspects the same tendency, as was the case on the RD, is not evident on the TD. On the TD the southern aspect revealed the lowest amount of microbial biomass. A possible reason for the higher amount of microbial biomass on the western aspect could be due to the fact that the TD is positioned at a slight angle (see Figure 3.3 in Chapter 3), which could have an influence on the amount of mid-day sun this particular aspect receives. Not being orientated perpendicular to the warm sun setting in the west might have a temperature influence. Further the total amount of SOC carbon content support this finding, since the highest values were recorded for the western aspect (Chapter 7; Table 7.5).

Between the different topographic positions on the RD and TD, microbial biomass and community structure on the slope positions revealed higher overall values. As mentioned earlier SOC plays an essential role in regulating microbial activity. The slope positions on the RD had significantly higher SOC and in return higher microbial biomass (Nayak *et al.*, 2011; Kujur & Patel, 2012) (Chapter 7; Table 7.3). Conversely the TD terrace position had the highest SOC but the lowest microbial biomass. However, factors inherent to a site such as topographic position significantly effects the spatial distribution of soil moisture, SOC and soil nutrients, which in turn affect the microbial activity (Florinsky *et al.*, 2004; Swallow *et al.*, 2009). Literature regarding the effect of topography on microbial community structure and biomass is often contradicting. Bergstrom *et al.* (1998) and Decker *et al.* (1999) found that microbial activity depend on slope topographic positions, while Ulrich and Wirth (1999) observed that soil bacteria decreased downslope, and that topography does not influence some microbial bacteria structures.

The RD and TD was characterised by elevated levels of monounsaturated fatty acids, which is considered indicative of Gram-negative bacteria. Many Gram-negative microorganisms are considered r strategists and the elevated levels of Gram-negative bacteria on the RD and TD's post rehabilitation ages, aspects and topographic positions could possibly be the response of these r strategists to the presence of excessive nutrients (Claassens, 2003) (Chapter 7; Table 7.1-7.6).

6.4 References

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Chapter 7 – Soil characteristics

7.1 Rock Dump soil

7.1.1 Post rehabilitation age

The macro-elements (mmol/l) and micro-elements ($\mu\text{mol/l}$) reported here provides a good indication of the available nutrients for plant absorption, as it was derived by means of a 1:2 water extraction method (Peech, 1965).

None of the macro-elements Ca, Mg, K and Na (Table 7.1) differed significantly between the three post rehabilitation ages (Tukey's HSD test – $p > 0.05$) on the Rock Dump (RD). Even though no significant differences were noted, Ca, Mg, K and Na values were at the highest concentrations at 32 years, and at the lowest at 28 years post rehabilitation age (Table 7.1). These macro-elements showed an increase at 32 years and over time decreased at 42 years. These macro-elements serve as a good source of plant nutrients (Singh & Agrawal, 2008), and from all alkali metals found in soils, Ca, Mg, K and Na is the most important in plant nutrition (Jakovljevic *et al.*, 2003). As seen in Table 7.1, the SO_4 concentrations were significantly ($p < 0.05$) elevated for the 32 year post rehabilitation age having the highest value (0.289 mmol/l). Although NO_3 and Cl did not show significant differences, values for NO_3 increased as time progressed as the 42 year post rehabilitation age had the highest concentration (0.086 mmol/l) ($p > 0.05$), while the highest concentration Cl was at 32 years. NH_4 concentration was significantly lower at 28 years than both 32 and 42 years ($p < 0.05$). The essential micro-elements or trace elements, which are most likely responsible for deficiency complications in plants, are Fe, Mn, Cu, Zn and B (Herselman, 2007).

It is also important to keep in mind that there could be elevated concentrations of Cu and sulphides due to the fact that Rio Tinto Palabora Mining Company is a copper mine. Copper's mobility is related to soil pH, and increases as the pH decreases (Kabata-Pendias, 2001; Herselman, 2007). Although studies show a relationship between Cu and pH, the opposite was witnessed between the different ages of the RD as the Cu concentration decreases as the pH decreases (Table 7.1).

The micro-element concentrations of the elements Fe, Mn and Cu revealed significant differences between the three post rehabilitation ages (Tukey's HSD test – $p < 0.05$). Again the same trend was evident, as the concentrations increased over time, showing the lowest values at 28 years and the highest at 42 years post rehabilitation ages (Table 7.1). The highest micro-element concentrations on the oldest age (42 years) can be attributed to the effect of weathering and leaching over time (Chadwick *et al.*, 1999; Yimer *et al.*, 2006). No significant differences were evident for Zn and B, although the B concentration also increases over time.

The electrical conductivity (EC) did not reveal any significant differences between the three different ages, although the lowest conductivity was recorded for the youngest rehabilitation age (28 years), increased at 32 years to the highest value (0.201 mS/cm), and then decreased at 42 years. EC is the ability of an aqueous solution to conduct an electric current and is correlated to the presence of ions in solution, and, therefore, is often used as an indication or measure of the total salt content of the soil. While no significant differences were witnessed between the different rehabilitation ages on the RD (Tukey's HSD test – $p > 0.05$) (Table 7.1), after 32 years there was an decreasing trend in EC, owing to leaching of soluble ions (Zornoza *et al.*, 2010), to a value slightly higher than that of the 28 years post rehabilitation age.

Table 7.1: Soil physical and chemical characteristics of the three different post rehabilitation ages on the Rock Dump.

Properties	Rock Dump – Age		
	28	32	42
Sample size (n)	18	18	9
Macro-elements (mmol/ℓ)			
Ca	0.345±0.025 a	0.504±0.060 a	0.443±0.024 a
Mg	0.189±0.017 a	0.249±0.030 a	0.203±0.008 a
K	0.227±0.015 a	0.296±0.028 a	0.262±0.011 a
Na	0.081±0.007 a	0.171±0.057 a	0.096±0.009 a
PO ₄	0.005±0.000 a	0.005±0.0001 a	0.008±0.0007 b
SO ₄	0.024±0.002 a	0.289±0.099 b	0.049±0.006 a
NO ₃	0.054±0.008 a	0.070±0.007 a	0.086±0.011 a
NH ₄	0.017±0.002 a	0.024±0.002 b	0.022±0.001 b
Cl	0.039±0.007 a	0.046±0.004 a	0.043±0.005 a
HCO ₃	1.253±0.090 a	1.307±0.070 a	1.446±0.060 a
Micro-elements (μmol/ ℓ)			
Fe	3.505±0.666 a	5.795±0.828 ab	7.941±1.257 b
Mn	0.075±0.018 a	0.095±0.026 a	0.223±0.034 b
Cu	0.209±0.083 a	1.407±0.244 b	2.004±0.245 b
Zn	0.017±0.003 a	0.011±0.001 a	0.017±0.003 a
B	3.795±0.869 a	4.313±0.610 a	5.839±0.629 a
Nutrient status (mg/kg)			
Ca	1965.13±158.20 a	2646.97±165.21 b	3008.48±167.71 b
Mg	668.43±16.36 a	529.79±42.44 a	553.31±24.62 a
K	102.13±3.871 a	105.11±6.37 a	122.79±6.51 a
Na	3.367±0.564 a	8.157±2.245 a	6.343±0.808 a
P	12.096±3.232 a	17.485±2.554 a	11.745±2.143 a
Exchangeable cations (cmol(+)/kg)			
Ca	9.806±0.789 a	13.209±0.824 b	15.012±0.837 b
Mg	5.090±0.135 a	4.360±0.349 a	4.554±0.203 a
K	0.262±0.010 a	0.270±0.016 a	0.315±0.0167 a
Na	0.146±0.002 a	0.035±0.010 a	0.028±0.004 a
Chemical properties			
pH	7.678±0.043 a	7.901±0.034 b	7.912±0.050 b
pH(H ₂ O)	8.402±0.051 a	8.255±0.066 ab	8.060±0.062 b
pH(KCl)	7.723±0.025 a	7.518±0.047 b	7.385±0.041 b
EC(mS/cm)	0.140±0.009 a	0.201±0.023 a	0.169±0.007 a
P-Bray I (ppm)	4.816±0.566 a	5.501±0.313 ab	6.822±0.478 b
Organic Carbon (%)	0.132±0.018 a	0.336±0.041 b	0.443±0.044 b
CEC (cmol(+)/kg)	13.22±0.414 a	15.48±0.724 ab	16.95±0.659 b
S-value	15.17±0.808 a	17.87±0.804 ab	19.91±0.930 b
Base saturation (%)	113.92±2.824 a	115.99±1.816 a	116.53±2.099 a
Soil texture			
Sand > 2mm (%)	19.54±1.844 a	16.73±0.960 ab	14.80±1.207 b
Sand < 2mm (%)	93.89±0.532 a	89.05±1.097 a	87.89±1.122 a
Silt (%)	5.061±0.662 a	7.760±1.058 a	9.013±0.941 a
Clay (%)	1.045±0.256 a	3.188±0.204 b	3.092±0.377 b

¹ All values ±SEM represent results obtained from sample size (n=85).

² Statistical significant differences are indicated by alphabetic letters (p < 0.05). The same letters indicate no significant differences while those with different letters indicate significant difference at p<0.05 (Tukey's HSD).

³ EC – electrical conductivity; ppm – parts per million; CEC – cation exchange capacity.

Organic carbon (%) showed significantly higher percentage values for both 32 and 42 years post rehabilitation age (0.336 and 0.443, respectively) than at 28 years (0.132). Organic carbon being

lowest in the most recent rehabilitated site (28 years), significantly lower than the 32 and 42 year old post rehabilitation ages, indicates a reduction in the variability of the observed organic carbon values following disturbance at the initial stage. This trend of increasing organic carbon with age of tailings spoil finds similarity with other reports (Rai *et al.*, 2011; Biswas *et al.*, 2013; Malakar *et al.*, 2015). This increase of organic carbon was probably due to the accumulation of litter/debris and its decomposition which occurs with increasing age of the RD (Table 7.1) (Biswas *et al.*, 2013; Malakar *et al.*, 2015). Sheoran *et al.* (2010) and Malakar *et al.* (2015) reported that organic carbon content greater than 0.75% indicates good fertility whereas < 0.4 % as of low quality. Müller & Höper (2004), and Pasayat and Patel (2015), also found that soils with higher clay content can store more organic C which is in accordance with the results in this study (Table 7.1 and Figure 7.1). Organic matter not only provides a food resource for microorganisms that supports the decaying process and helps nutrient recycling, but also acts as a reservoir of essential macro-elements (Johnson *et al.*, 1994).

Cation Exchange Capacity (CEC) can be explained as the amount of exchange positions that is available on a specific soil particular for cations to absorb to, in other words it is a measure of the soil's capacity to absorb and release metals (Herselman, 2007). CEC refers to the ability of soil to maintain positively charged nutrients and is hence a respectable indicator of nutrient retention capacity and soil fertility (Roy *et al.*, 2012). Ersahin *et al.* (2006) stated that soil texture (particle size distribution) and organic carbon content affects the overall CEC and is highly dependent on both these physical and chemical properties. The lower CEC at 28 years post rehabilitation age could be linked to the lower organic C percentage and higher CEC values for both 32 and 42 years to the significantly higher organic C. In general, CEC increases with increasing pH (Kabata-Pendias, 2001; Herselman, 2007; Roy *et al.*, 2012), which was also evident in this study. At the youngest rehabilitation age, soil pH and CEC was 7.678 and 13.22 respectively, at 32 years pH and CEC was 7.901 and 15.48, and at 42 years was 7.912 and 16.95 (Table 7.1). The CEC and pH were both significantly lower at the youngest rehabilitation age.

Base saturation, although not significantly different across the different rehabilitation ages, were high. All three ages revealed more than 100% saturation (Table 7.1). The high base saturation could be ascribed to soil pH being above pH 7.2, resulting in the cation saturation adding up to more than 100% (Yimer *et al.*, 2006). Soils found at PMC are generally shallow and eutrophic with a high clay content (Kendall, 2012). These eutrophic soils have a high base saturation status which means reasonable fertility and have a decent supply of plant nutrients (Kendall, 2012).

The pH of the soil is considered to be the primary soil property that controls chemical and biological processes in the soil environment (Alexander, 1999; De Beer, 2005; Herselman, 2007).

Moukodi (2008) reported no sign of acid mine drainage at PMC with the results indicating an increase in alkalinity over the years. This study supports these findings as the soil pH increased from 7.678 at 28 years to 7.901 at 32 years, and 7.912 at 42 years (Table 7.1). Soil pH at 28 years was significantly lower than both 32 and 42 years. Buffering that is mainly responsible for alkalinity in soils include the increasing presence of the base anion, bicarbonate (HCO_3) (Merry, 2004). HCO_3 did not reveal any significant differences between the different RD ages, however, highly elevated HCO_3 concentrations were witnessed as the values ranged from 1.253 mmol/l (28 years), 1.307 mmol/l (32 years) to 1.446 mmol/l (42 years) (Table 7.1). This could be a possible link to the alkalinity state and high soil pH values found on the RD.

Soil particle size distribution and the way particles are aggregated significantly influences the processes that occur in the soil environments. Soil textural composition (% sand, silt and clay) effects water retention properties, potential for erosion, organic matter characteristics and the soil's ability to store plant nutrients (Kettler *et al.*, 2001). Although not significantly different ($p=0.067$) (Figure 7.1), all three post rehabilitation ages were dominated by sand, ranging from 93.89 % at 28 years to 89.05 % at 32 years, and 87.89 % at 42 years. The sand particle percentage decreases as the RD level becomes older, which subsequently means that silt and clay percentages have increased due to leaching. Jha and Singh (1991) also found that coarse fragments decreased with the age of mine tailings and that silt particles increased with age. While it is true for the increase in silt and clay percentage, only clay showed significant differences ($p<0.001$), revealing significantly less clay at 28 years than both 32 and 42 years (Table 7.1 & Figure 7.1).

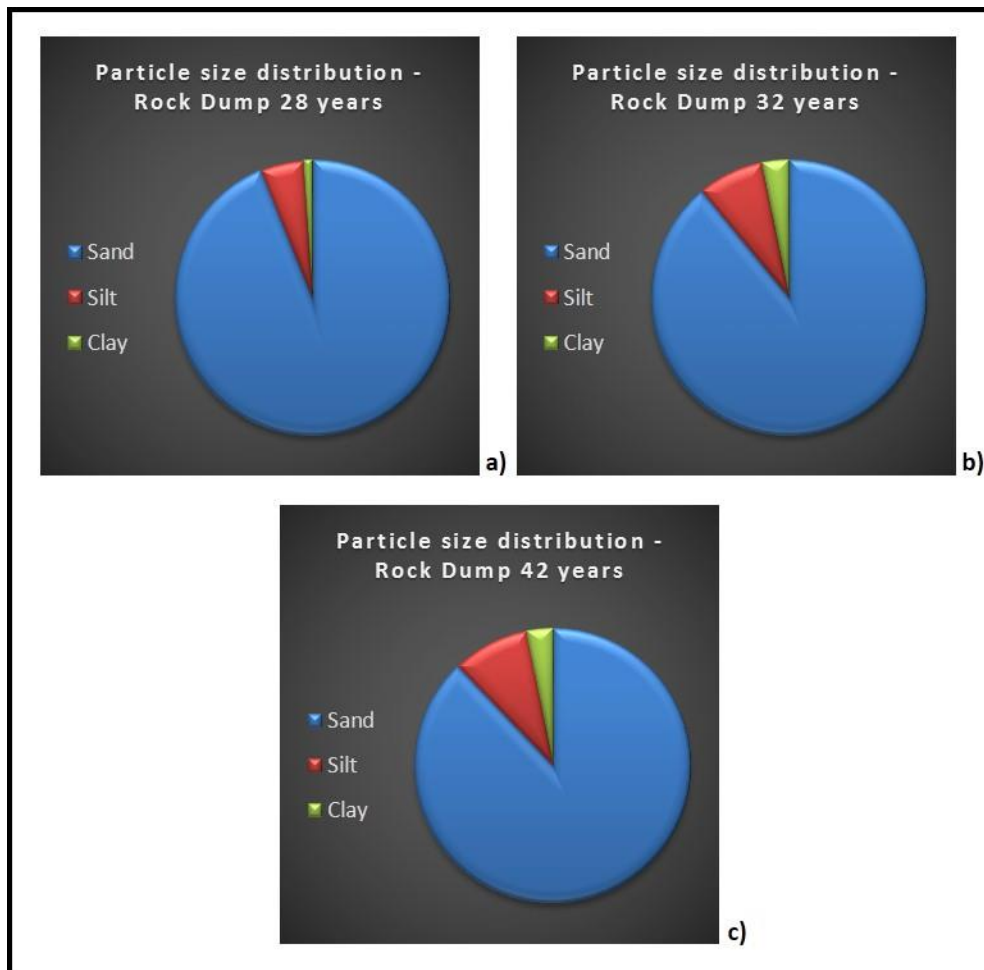


Figure 7.1: Soil particle size distribution of the different rehabilitation ages on the rock dump. Sand, silt and clay percentage at a – 28 years; b - 32 years; and c - 42 years.

This trend was expected, as finer material is washed down to the older rehabilitation ages leaving the large, coarser textured sand at the top (Yimer, 2007). Moukodi (2008) stated that the RD is composed of coarse material and that particle size differs in certain areas however areas with high sulphates had been noticed and assumed that finer particles are present there. These findings correspond to this study as the highest clay percentage together with elevated sulphate concentrations (SO_4) occurred at 32 years post rehabilitation age (Table 7.1). Clay minerals are the product of weathered rock, and due to clay having permanently negatively charged, large surface areas it effects both the physical and chemical properties of soil (Herselman, 2007).

7.1.2 Aspect

The results revealed significant effects of different aspects on some soil physical and chemical characteristics, and available nutrients of the RD (Table 7.2). Soil pH was found to be significantly higher on the southern aspect compared to the other aspects with 7.93, followed by eastern and western with 7.878 and 7.763, respectively. None of the macro-elements, except HCO_3 , showed

any significant differences between the different aspects on the RD (Table 7.2). It is commonly documented that at a soil pH of 6.5 the nutrient availability for plants is at a maximum and metal toxicity at a minimum (Harris *et al.*, 1998; Wong, 2003; Freitas *et al.*, 2004). The higher pH values might again be linked to elevated concentrations of HCO_3^- , as the different aspects revealed elevated and significantly different levels of HCO_3^- at the various aspects, the western aspect had a significantly lower amount of 1.164 than both eastern and southern at 1.415 and 1.447 respectively.

As mentioned for the post rehabilitation ages, some of the micro-nutrients that are essential for plant growth and that are most likely to cause insufficiency complications are Fe, Mn, Cu, Zn and B. The availability of these micro-nutrients in the soil is due to constant weathering of minerals mixed with primary minerals (Sheoran *et al.*, 2010). Only Mn and Zn showed significant differences between the different aspects on the RD (Tukey's HSD test – $p < 0.05$) (Table 7.2). The western aspect had significantly higher concentrations of Mn at $0.228 \mu\text{mol}/\ell$ than both eastern and southern aspects with values of $0.126 \mu\text{mol}/\ell$ and $0.103 \mu\text{mol}/\ell$, respectively.

Table 7.2: Soil physical and chemical characteristics of the three aspects (east, south and west) on the Rock Dump.

Properties	Rock Dump – Aspect		
	East	South	West
Sample size (n)	15	15	15
Macro-elements (mmol/l)			
Ca	0.404±0.030 a	0.459±0.031 a	0.484±0.078 a
Mg	0.218±0.008 a	0.224±0.012 a	0.214±0.042 a
K	0.260±0.018 a	0.287±0.021 a	0.255±0.028 a
Na	0.095±0.007 a	0.124±0.012 a	0.153±0.081 a
PO ₄	0.006±0.000 a	0.007±0.001 a	0.007±0.001 a
SO ₄	0.042±0.005 a	0.117±0.041 a	0.279±0.131 a
NO ₃	0.086±0.012 a	0.068±0.008 a	0.071±0.009 a
NH ₄	0.022±0.001 a	0.021±0.001 a	0.024±0.003 a
Cl	0.041±0.006 a	0.049±0.005 a	0.037±0.003 a
HCO ₃	1.415±0.077 a	1.447±0.061 a	1.164±0.073 b
Micro-elements (µmol/l)			
Fe	6.218±0.923 a	6.102±1.212 a	6.577±1.070 a
Mn	0.126±0.023 a	0.103±0.027 a	0.228±0.045 b
Cu	1.350±0.321 a	1.448±0.208 a	1.520±0.333 a
Zn	0.012±0.001 ac	0.013±0.001 ab	0.020±0.004 b
B	4.489±0.764 a	4.768±0.631 a	5.315±0.709 a
Nutrient status (mg/kg)			
Ca	3049.00±204.47 ac	2732.13±173.80 ab	2235.41±148.58 b
Mg	628.33±32.52 ac	549.86±32.12 ab	492.40±38.54 b
K	136.85±9.365 a	101.94±5.070 b	102.16±3.495 b
Na	6.188±0.360 a	6.236±0.813 a	7.400±3.203 a
P	12.635±2.142 a	12.694±2.266 a	17.771±3.320 a
Exchangeable cations (cmol(+)/kg)			
Ca	15.215±1.020 ac	13.633±0.867 ab	11.155±0.741 b
Mg	5.171±0.268 ac	4.526±0.264 ab	4.053±0.317 b
K	0.351±0.024 a	0.261±0.013 b	0.262±0.009 b
Na	0.027±0.002 a	0.027±0.004 a	0.032±0.014 a
Chemical properties			
pH	7.878±0.036 ab	7.930±0.046 ac	7.763±0.051 b
pH(H ₂ O)	8.279±0.075 a	8.047±0.068 b	8.347±0.047 a
pH(KCl)	7.450±0.054 a	7.489±0.048 a	7.562±0.046 a
EC(mS/cm)	0.163±0.009 a	0.181±0.011 a	0.184±0.030 a
P-Bray I (ppm)	5.543±0.589 a	5.825±0.334 a	6.431±0.527 a
Organic Carbon (%)	0.425±0.069 a	0.334±0.030 a	0.281±0.047 a
CEC (cmol(+)/kg)	17.298±0.935 a	16.056±0.637 a	13.612±0.510 b
S-value	20.764±1.077 a	18.447±0.870 a	15.502±0.637 b
Base saturation (%)	120.18±2.278 a	114.28±2.049 a	113.95±1.884 a
Soil texture			
Sand > 2mm (%)	17.878±1.355 a	14.664±1.190 a	17.581±1.150 a
Sand < 2mm (%)	88.250±1.271 a	89.440±1.134 a	90.549±1.152 a
Silt (%)	8.289±1.013 a	8.493±1.093 a	6.337±0.906 a
Clay (%)	3.467±0.513a	2.067±0.135 b	3.114±0.378 a

All values ±SEM represent results obtained from sample size (n=85).

² Statistical significant differences are indicated by alphabetic letters (p < 0.05). The same letters indicate no significant differences while those with different letters indicate significant difference at p<0.05 (Tukey's HSD).

³ EC – electrical conductivity; ppm – parts per million; CEC – cation exchange capacity.

For Zn, the western aspect was significantly higher than the eastern aspect with values 0.02 $\mu\text{mol}/\ell$ and 0.012 $\mu\text{mol}/\ell$, respectively (Table 7.2). Although the results indicated that neither Fe, Cu nor B differ significantly, the western aspect revealed the highest concentrations of these micro-nutrients followed by the southern aspect and the lowest values on the eastern aspect. Sheoran *et al.* (2010) reported that solubility of these metals increases in more acidic environments, and a link can be seen here as the lowest pH, although not acidic, was found on the western aspect.

Almost all exchangeable cations showed significant differences between the different aspects except for Na. The exchangeable cations followed the trend $\text{Ca} > \text{Mg} > \text{K} > \text{Na}$ for the eastern, southern and western aspects (Table 7.2). On the eastern aspect, K concentrations were significantly higher than both southern and western aspects, while Ca and Mg at the eastern aspect were only significantly higher than the western aspect, with values for Ca, Mg and K ranging from 15.215 $\text{cmol}(+)/\text{kg}$, 5.171 $\text{cmol}(+)/\text{kg}$ and 0.351 $\text{cmol}(+)/\text{kg}$, respectively (Table 7.2). All tested exchangeable cations were well above ideal values (Appendix B; Table B1 – Amended from Haagner (2008))

CEC was significantly higher on the eastern and southern aspects with values 17.298 $\text{cmol}(+)/\text{kg}$ and 16.056 $\text{cmol}(+)/\text{kg}$ respectively (Appendix B; Table B1). This was related to higher organic carbon content, reflecting the large contribution of base cations associated with the organic carbon (Table 7.2). This result conforms with other findings (Tegene, 2000; Eshetu *et al.*, 2004; Yimer, 2007) in that soils with higher organic carbon content have a correlation with higher CEC.

Nutrient status followed the same trend as the exchangeable cations with $\text{Ca} > \text{Mg} > \text{K} > \text{Na}$ for the three different aspects. Eastern aspect again showed significantly higher Ca and Mg than the western aspect, while K was significantly higher than both the southern and western aspects (Table 7.2). No significant differences were evident for Na and P, but the western aspect did present higher values (Appendix B; Table B1).

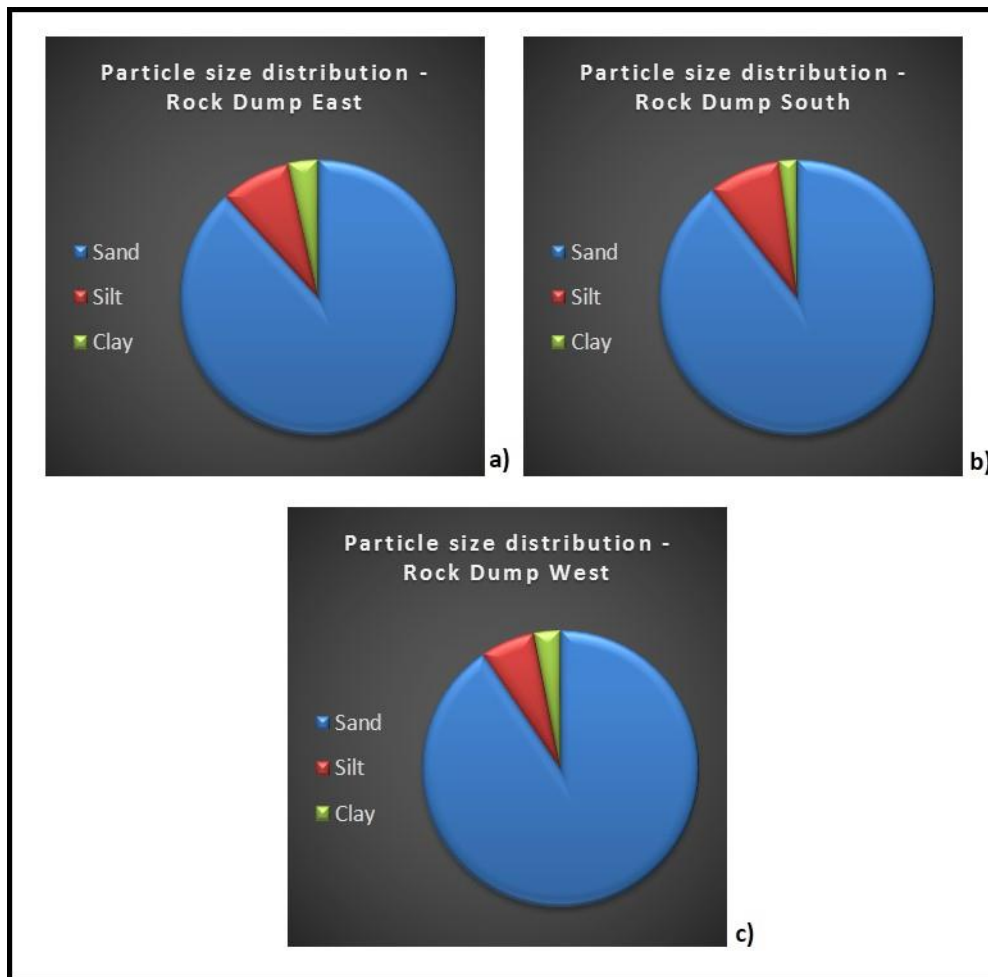


Figure 7.2: Soil particle size distribution of the different aspects on the rock dump. a –eastern aspect; b - southern aspect; and c - western aspect.

Figure 7.2 illustrates the soil particle distribution or soil textural composition (% sand, silt and clay). As was previously shown for the RD, sand particles dominated the different aspects (Figure 7.2), with 88.25 % sand on the eastern, 89.44 % on the southern and 90.549 % on the western aspects. In mine soils, particles smaller than 2 mm are accountable for the majority of water and nutrient holding capacity (Sheoran *et al.*, 2010). Sandy textured mine soil's capability to store water or nutrients is not as good as finer textured soils like silts and clays (Sheoran *et al.*, 2010). Only clay % showed significant differences between the aspects on the RD, with the southern aspect revealing significantly lower clay content (2.067 %) than both eastern (3.467 %) and western (3.114 %) aspects (Figure 7.2 & Table 7.2). A possible explanation for this occurrence may be due to the large plateau on the second rehabilitation level (32 years) (Chapter 3; Figure 3.2), which could have prevented adequate leaching, and due to the sampling design resulting in the plateau, where the clay accumulates, being under sampled. Although the silt % had a higher overall content than clay, none of the aspects differed significantly; however, eastern and southern aspects were closely matched, while the western aspect revealed less silt content.

7.1.3 Topographic position

Most of the tested macro-elements (Ca, Mg, K, Na PO₄, SO₄, NO₃ and HCO₃) were found to be significantly different between the terraces and slopes on the RD (Table 7.3). All of the above mentioned revealed significantly higher concentrations on the slopes (Tukey's HSD test – $p < 0.05$) (Table 7.3). Even though NH₄ and Cl were not significantly different they also showed higher values on the slopes. As for the micro-elements only Fe ($p = 0.919$) and Mn ($p = 0.498$) did not differ significantly, however, the remainder of the tested metals Cu, Zn and B did reveal significance. Cu and B were both significantly higher on the slopes while Zn was higher at the terrace sites on the RD ($p < 0.05$).

The nutrient status of both the slopes and terraces also followed the same trend with Ca > Mg > K > Na (Table 7.3) (Appendix B; Table B1). Only Mg, Na and P showed significant differences, with Mg and P being significantly higher on the terrace sites of the RD, while Na was significantly higher on the slope sites. P concentrations were practically three times more on terrace sites than on the slope sites. These high P concentrations can be ascribed to the down slope mobility in the soil which increases the susceptibility to leaching. Lehmann and Schroth (2003) provides support in stating that P concentration may also be lost if surface soil particles are eroded during runoff. This may be the reason for such high P concentrations on the terrace positions, due to more erosion on the slopes which leads to the accumulation on terraces.

Of all exchangeable cations (Ca, Mg, K and Na) tested, only Mg and Na differed significantly between the two different topographic sites (Table 7.3) (Appendix B; Table B1), Mg concentrations were significantly higher ($p < 0.001$) on the terraces, while Na ($p = 0.042$) was higher on the slopes. One reason for the high Mg concentrations on the terraces can be explained by the fact that the tailings facilities are capped with approximately 250 – 300 mm of vermiculite waste from nearby mining operations. Vermiculite is chemically a complex hydrous silicate of magnesium (20 – 25 % Mg) and aluminium with varying amounts of iron (Schoeman, 1989; Malandrino *et al.*, 2006). More importantly, vermiculite is a good amendment for chemical stabilization of contaminated soils as it retains metal pollutants and significantly reduces the uptake of metals by plants. As the vermiculite contact time with polluted soil increases, its effectiveness increases (Malandrino *et al.*, 2011).

Table 7.3: Soil physical and chemical characteristics of the two different topographic sites (Terrace & Slope) on the Rock Dump.

Properties	Rock Dump – Topography	
	Terrace	Slope
Sample size (n)	18	27
Macro-elements (mmol/ℓ)		
Ca	0.297±0.013 a	0.624±0.043 b
Mg	0.176±0.009 a	0.268±0.025 b
K	0.205±0.009 a	0.343±0.020 b
Na	0.075±0.004 a	0.180±0.050 b
PO ₄	0.005±0.000 a	0.007±0.001 b
SO ₄	0.032±0.002 a	0.269±0.087 b
NO ₃	0.052±0.005 a	0.098±0.009 b
NH ₄	0.018±0.001 a	0.026±0.001 a
Cl	0.039±0.004 a	0.048±0.004 a
HCO ₃	1.094±0.049 a	1.648±0.029 b
Micro-elements (μmol/ℓ)		
Fe	5.687±0.988 a	6.935±0.819 a
Mn	0.127±0.026 a	0.168±0.028 a
Cu	0.465±0.102 a	2.540±0.206 b
Zn	0.016±0.002 a	0.013±0.001 b
B	3.528±0.460 a	6.337±0.593 b
Nutrient status (mg/kg)		
Ca	2128.06±107.81 a	3291.380±141.01 a
Mg	629.27±15.20 a	471.70±35.99 b
K	114.97±5.100 a	108.38±6.024 a
Na	3.822±0.377 a	9.650±1.975 b
P	20.39±2.479 a	7.174±0.368 b
Exchangeable cations (cmol(+)/kg)		
Ca	10.62±0.538 a	16.42±0.704 a
Mg	5.179±0.125 a	3.882±0.296 b
K	0.295±0.013 a	0.278±0.015 a
Na	0.017±0.002 a	0.042±0.009 b
Chemical properties		
pH	7.685±0.029 a	8.070±0.018 b
pH(H ₂ O)	8.400±0.043 a	7.977±0.052 a
pH(KCl)	7.665±0.016 a	7.313±0.042 a
EC(mS/cm)	0.126±0.005 a	0.235±0.017 b
P-Bray I (ppm)	4.813±0.301 a	7.174±0.368 a
Organic Carbon (%)	0.189±0.018 a	0.518±0.040 b
CEC (cmol(+)/kg)	13.79±0.331 a	17.82±0.699 b
S-value	16.11±0.581 a	20.63±0.831 b
Base saturation (%)	115.61±1.632 a	116.11±1.901 a
Soil texture		
Sand > 2mm (%)	20.470±0.797 a	11.884±0.788 a
Sand < 2mm (%)	93.341±0.393 a	85.029±1.015 b
Silt (%)	4.798±0.461 a	11.177±0.933 b
Clay (%)	1.861±0.201a	3.794±0.286 b

All values ±SEM represent results obtained from sample size (n=85).

² Statistical significant differences are indicated by alphabetic letters (p < 0.05). The same letters indicate no significant differences while those with different letters indicate significant difference at p<0.05 (Tukey's HSD).

³ EC – electrical conductivity; ppm – parts per million; CEC – cation exchange capacity.

An explanation for the higher Na concentration on the slopes can be ascribed to Na being readily mobile in the biosphere and is known to form either volatile or easily soluble compounds which in return is more susceptible to leaching (Kabata-Pendias, 2011).

Sadhu *et al.* (2012) stated that mineral weathering increases pH due to the release of Ca, Mg and K into the soil. There is some accordance with this finding as the Ca concentration of 16.42 cmol(+)/kg, although not significant, were higher on the slopes together with a pH value of 8.07. In contradiction, the Mg and K concentrations of 5.179 cmol(+)/kg and 0.295 cmol(+)/kg respectively were higher on the terraces with a significantly lower pH value of 7.685 (Appendix B; Table B1).

Soils with higher clay content (Table 7.3 and Figure 7.3) can store more organic carbon and small differences in clay % can result in significant differences in soil organic carbon (SOC) in rehabilitated mine soil. This result conforms to other studies with significantly higher clay % on the slopes and consequently significantly higher SOC found on the RD slope positions with higher clay content (Müller & Höper, 2004; Chodak & Niklińska, 2012; Pasayat & Patel, 2015).

As mentioned before, CEC is strongly influenced by pH and total organic carbon content. A clear link can again be seen between CEC, pH and organic carbon content, as all revealed significant differences between the slope and terrace positions (Table 7.3). All of which were significantly higher on the slopes (Appendix B; Table B1).

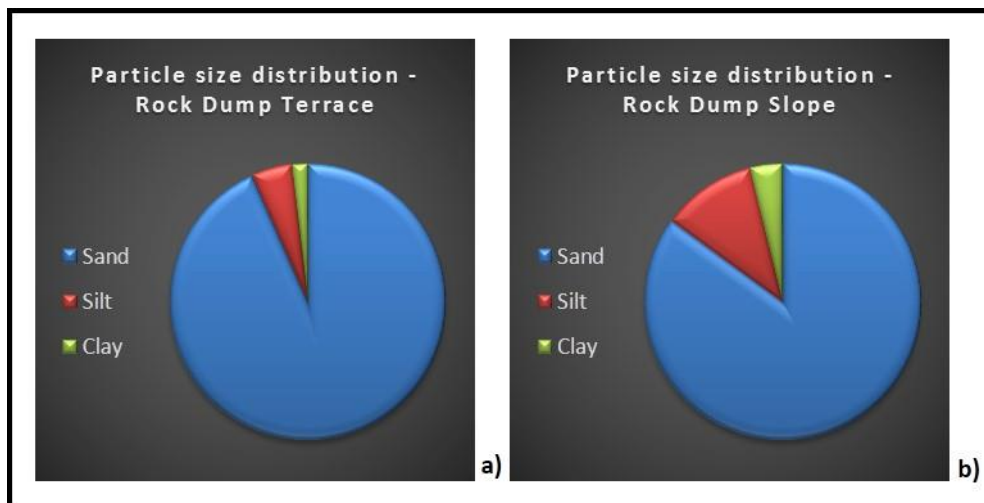


Figure 7.3: Soil particle size distribution of the different topographic positions (Terrace & Slope) on the rock dump. a – Terrace; b Slope.

Soil texture on the slopes and terraces were once more characterised by coarser sand fragments representing more than 85 % of the total soil particles. Sand, silt and clay particle distribution differed significantly, with the sand % significantly higher on the terrace and both silt and clay with

significant higher percentages on the slopes. It can be deduced that the slopes are quite stable regarding vegetation establishment and percentage ground cover as it showed that more fine particles are present on the slopes. This result conforms to the findings of Yimer *et al.* (2006) who also found that the finer soil particles were transported or leached down the slope. These soil characteristics are recognised for their significant role in supporting plant growth through storage, water and nutrient supply, aeration and easier penetration of roots (Schoenholtz *et al.*, 2000; Rezaei & Gilkes, 2005).

7.2 Tailings Dam soil

7.2.1 Post-rehabilitation age

The Tailings Dam (TD) is the waste facility for fine tailings originating after the copper extraction process. These tailings are primarily derived from carbonite ore and most of the sulphides have been removed by the floatation process (Moukodi, 2008).

Four different ages on the TD were sampled: 20, 24, 30 and 32 years post rehabilitation (Table 7.4). From all the macro-elements tested, only PO₄ revealed differences showing significantly higher PO₄ values at the oldest (32) and youngest (20) ages. Although no further significant differences were noted, the 32 year post rehabilitation age showed higher concentrations of the remaining elements (Table 7.4). 'Newer' or younger tailings generally consist of high levels of minerals and leaching results in mineral concentrations increasing downslope (Ni & Zhang, 2007), in this case where the oldest level is situated. Another factor to keep in mind is that two nearby volcanic pipes contain vermiculite and phosphate, and was also mined by Foskor's Mining Division (Moukodi, 2008). Some of this material might have also ended up on the TD, especially in the oldest levels.

Only Fe and Zn revealed significant differences regarding the tested micro-elements between the four different post rehabilitation ages on the TD (Table 7.4). Both Fe and Zn had significantly higher concentrations on the oldest post rehabilitation age (32 years). Although not significantly different, Mn and B indicated an increasing trend while Cu indicated a decreasing trend with age. The decreased Cu concentration can be ascribed to the fact that modern tailings have a much lower metal concentration than historic tailings due to new improved mineral extraction technologies which leads to less Cu being deposited on the youngest age levels (Dold, 2008; Mendez & Maier, 2008). Also, Mn, Zn and Cu are less available and tied up into insoluble forms when in high pH soils, much the same is the case for Fe, but can be amplified by poor drainage or wet conditions (Ghosh & Singh, 2005).

The nutrient status of all four post rehabilitation ages indicated the same trend with $Ca > Mg > K > Na$ (Table 7.4) (Appendix B; Table B1). Only Ca ($p < 0.001$), K ($p = 0.009$) and Na ($p = 0.001$) revealed significant differences between the different ages. Ca, K and Na indicated the highest values on the youngest rehabilitation age (20 years) after which it decreased with age to the lowest values at 24 and 30 years, to where it ultimately increased once more at the oldest age (32 years). Hence, both the youngest and oldest age levels indicated significantly higher concentrations. 'Newer' or younger tailings consist of high levels of minerals and as a result of the act of leaching mineral concentrations usually increase downslope (Ni & Zhang, 2007). Even though Mg did not differ significantly ($p = 0.102$) between the different ages it followed the same trend as it was highest at 20 years, decreased with age up to 30 years and increased again at 32 years.

Of all the tested exchangeable cations, Ca, K and Na were significantly different between the different TD ages leaving only Mg that didn't reveal any significant values. A similar trend is witnessed as Ca, K, Mg (although not significant) and Na indicated significantly higher concentrations at the youngest (20 years) and oldest (32 years) post rehabilitation age. All of which starts with the higher values at 20 years, decreases with age at 24 and 30 years and again increases at 32 years (Table 7.4). Results of Gitari *et al.* (2009) indicated that Na was one of the elements with the highest leached rate. Gitari *et al.* (2009) goes further in saying that the highest weathering took place on older levels which in turn increases leaching of minerals.

The tested element concentrations on the TD over time were similar to that of the RD (Table 7.1), where the highest values occurred on the oldest post rehabilitation ages, and the important role of mineral leaching of the upper/younger age levels downslope (Ni & Zhang, 2007).

As explained earlier for the RD, CEC is highly dependent on organic carbon content and pH (Kabata-Pendias, 2001; Herselman, 2007; Roy *et al.*, 2012) (Appendix B; Table B1). CEC again follows the trend of significantly higher values recorded for the youngest and oldest post rehabilitation ages ($p < 0.05$), but no clear link is observed, as the SOC and pH does not seem to have the same trends as the RD. Organic carbon and pH did not reveal any significant difference between the post-rehabilitation ages ($p > 0.05$). pH value ranged from 7.755 to 7.967 which indicates slightly to moderately alkaline soils (Ifelola & Alaba, 2014).

Table 7.4: Soil physical and chemical characteristics of the four different post rehabilitation ages on the Tailings Dam.

Properties	Tailings Dam – Age			
	20	24	30	32
Sample size (n)	12	11	12	11
Macro-elements (mmol/ℓ)				
Ca	0.525±0.036 a	0.521±0.121 a	0.490±0.021 a	1.088±0.576 a
Mg	0.267±0.015 a	0.339±0.110 a	0.257±0.011 a	0.511±0.248 a
K	0.399±0.031 a	0.360±0.050 a	0.276±0.014 a	0.443±0.130 a
Na	0.114±0.010 a	0.104±0.038 a	0.068±0.002 a	0.157±0.044 a
PO ₄	0.025±0.009 a	0.005±0.000 b	0.005±0.000 b	0.043±0.017 a
SO ₄	0.217±0.049 a	0.398±0.277 a	0.087±0.010 a	1.008±0.918 a
NO ₃	0.292±0.089 a	0.174±0.020 a	0.253±0.049 a	0.386±0.109 a
NH ₄	0.020±0.003 a	0.018±0.002 a	0.022±0.003 a	0.017±0.003 a
Cl	0.047±0.005 a	0.048±0.008 a	0.047±0.009 a	0.117±0.050 a
HCO ₃	1.286±0.042 a	1.195±0.069 a	1.388±0.065 a	1.238±0.109 a
Micro-elements (μmol/ℓ)				
Fe	3.485±0.942 a	6.645±2.004 a	3.211±0.657 a	27.367±13.74 b
Mn	0.104±0.023 a	0.107±0.044 a	0.116±0.021 a	0.183±0.07 a
Cu	1.403±0.625 a	0.909±0.244 a	0.955±0.184 a	0.773±0.16 a
Zn	0.010±0.000 a	0.010±0.000 a	0.040±0.007 a	0.148±0.04 b
B	2.628±0.524 a	3.033±0.658 a	3.017±0.796 a	6.094±1.77 a
Nutrient status (mg/kg)				
Ca	3154.50±89.88 a	2600.32±80.51 b	2835.83±48.85 bc	3012.16±109.88 ac
Mg	480.182±37.01 a	376.295±36.73 a	369.700±37.80 a	437.188±33.90 a
K	113.182±7.61 a	85.636±10.67 a	68.575±9.71 b	97.406±9.04 a
Na	5.159±0.80 a	2.523±0.27 b	2.550±0.33 b	3.625±0.50 a
P	12.171±2.71 a	17.085±2.74 a	10.805±2.27 a	11.945±2.78 a
Exchangeable cations (cmol(+)/kg)				
Ca	15.741±0.448 a	12.976±0.402 b	14.151±0.244 bc	15.031±0.548 ac
Mg	3.952±0.305 a	3.097±0.302 a	3.043±0.311 a	3.598±0.279 a
K	0.290±0.020 a	0.220±0.027 a	0.176±0.025 b	0.250±0.023 a
Na	0.022±0.003 a	0.011±0.001 b	0.011±0.001 b	0.016±0.002 a
Chemical properties				
pH	7.918±0.047 a	7.755±0.074 a	7.967±0.033 a	7.790±0.106 a
pH(H ₂ O)	8.144±0.029 a	8.357±0.043 b	8.141±0.029 a	8.090±0.055 a
pH(KCl)	7.752±0.045 a	7.891±0.043 b	7.917±0.085 b	7.718±0.055 a
EC(mS/cm)	0.213±0.012 a	0.222±0.055 a	0.187±0.006 a	0.388±0.181 a
P-Bray I (ppm)	4.602±0.163 a	4.519±0.185 a	4.778±0.186 a	4.438±0.188 a
Organic Carbon (%)	0.317±0.045 a	0.311±0.031 a	0.378±0.046 a	0.681±0.250 a
CEC (cmol(+)/kg)	15.226±0.416 a	13.062±0.323 b	13.107±0.328 b	14.283±0.328 a
S-value	20.006±0.702 a	16.303±0.475 b	17.381±0.423 bc	18.894±0.469 ac
Base saturation (%)	130.837±1.312 b	124.952±2.081 a	132.704±0.893 b	132.306±1.340 b
Soil texture				
Sand > 2mm (%)	22.684±1.566 a	12.602±1.787 b	12.708±2.592 b	18.259±2.935 ab
Sand < 2mm (%)	88.978±0.860 a	91.989±1.304 a	91.016±0.678 a	87.825±2.955 a
Silt (%)	8.120±0.955 a	5.588±1.297 a	6.898±0.499 a	9.675±2.732 a
Clay (%)	2.902±0.291 a	2.423±0.053 a	2.087±0.364 a	2.500±0.483 a

All values ±SEM represent results obtained from sample size (n=89).

² Statistical significant differences are indicated by alphabetic letters (p < 0.05). The same letters indicate no significant differences while those with different letters indicate significant difference at p<0.05 (Tukey's HSD).

³ EC – electrical conductivity; ppm – parts per million; CEC – cation exchange capacity.

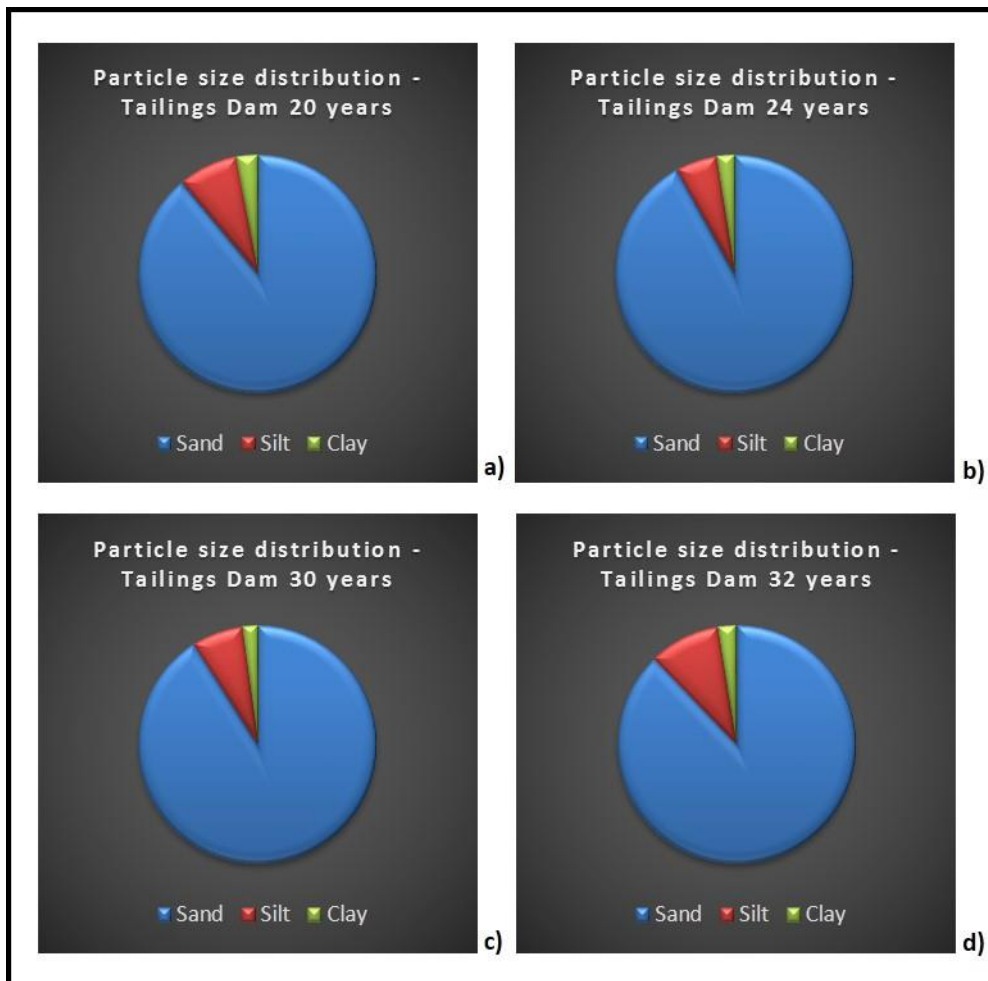


Figure 7.4: Soil particle size distribution of the different rehabilitation ages on the tailings dam. a – 20 years; b - 24 years; c - 30 years; d - 32 years.

Regarding the soil particle size distribution between the different post rehabilitation ages on the TD, only sand particles larger than 2 mm had significant differences ($p < 0.05$) (Table 7.4 & Figure 7.4). The youngest tailings ages 20 years revealed a significantly greater percentage of sand ($> 2\text{mm}$) at 22.684 % than both 24 and 30 years with 12.602 % and 12.708 %, respectively. Although the oldest tailings level contained slightly more sand ($> 2\text{mm}$) than the intermediate ages, it did not differ significantly ($p > 0.05$). Although no significant differences was notable, both the silt and clay percentages were somewhat higher on the youngest (20 years) and oldest (32 years) post rehabilitation ages, with respective values for silt (8.12 % & 9.675 %) and clay (2.902 % & 2.5 %). Post rehabilitation ages of 24 and 30 years revealed a reasonable decrease compared to the youngest and oldest ages, with silt percentage ranging from 5.588 % to 6.898 % and clay percentage from 2.423 % to 2.087 %, respectively. Other studies have found similar results (Brubaker *et al.*, 1993; Tegene, 1997; Yimer *et al.*, 2006), as fine soil fractions were transported and/or leached from higher altitudes down the slopes leaving behind larger sand fractions as was the case on the TD where silt and clay percentages increased with rehabilitation age. Ersahin *et al.* (2006) and Ifelola and Alaba (2014) stated that higher clay percentages in soil

improves its CEC capacity and it also corresponds with the findings in this study, as the highest clay percentage and the highest CEC capacity occurs at the youngest and oldest post rehabilitation ages (Table 7.4).

7.2.2 Aspect

Macro-elements concentrations on the different aspects of the TD showed significant differences for K, Na and Cl between the various aspects (Tukey's HSD test – $p < 0.05$) (Table 7.5). The western aspect revealed significantly higher Na and Cl concentrations than both the southern and eastern aspects, while K on the western aspect was only significantly higher than the southern aspect. Even though none of the other tested macro-elements revealed any significantly different concentrations, overall the highest concentration of macro-elements were found on the western aspect (Table 7.5). While only HCO_3 showed significant differences on the aspects of the RD (Table 7.2), the western and southern aspects revealed the highest macro-element concentrations on the RD.

Cu and B were the only micro-elements that indicated significant differences between the three different aspects of the TD ($p < 0.05$). Again the western aspect yielded significantly higher concentrations of Cu and B. Cu was found to be significantly higher than both the eastern and southern aspects, while B was only significantly higher than the southern aspect (Table 7.5). Cu concentration on the Western aspect, at $1.998 \mu\text{mol}/\ell$, were more than twice as high than the eastern aspect at $0.746 \mu\text{mol}/\ell$, and more than five times higher in comparison to the southern aspect at $0.376 \mu\text{mol}/\ell$. Interestingly, when compared to the results from the different aspects on the RD (ranging between $1.350 \mu\text{mol}/\ell$ and $1.520 \mu\text{mol}/\ell$), the concentrations on the TD were generally lower. Although the western aspect on the TD was marginally higher than that on the RD, the southern and western aspects were well below the measured Cu amounts on the RD. A paucity of information is available as it is not quite clear why such high concentrations of certain metals occur on different aspects. Although it can be deduced, specifically in the case of Cu, that the tailings wall were originally constructed at the western side of the dam which then led to higher accumulation of Cu concentrations.

Similar patterns were revealed for the B concentration on the western aspect being almost twice as much, at $5.664 \mu\text{mol}/\ell$, than that of the eastern aspect, at $3.381 \mu\text{mol}/\ell$, and more than four times higher in comparison with the southern aspect, at $1.236 \mu\text{mol}/\ell$. Again a similar trend was observed on the RD (Table 7.2), with the highest micro-element concentrations on the western aspect. Overall the western aspect revealed the highest quantities of micro-elements, except for Fe, which was the highest on the eastern aspect (Table 7.5). Of the three aspects, the southern

aspect harboured the lowest concentrations in terms of micro-element concentration content on the TD.

When considering the nutrient availability between the three different aspects, only Mg was significantly different ($p < 0.05$) (Table 7.5). The eastern and southern aspects held the highest levels of Mg at 433.31 mg/kg and 469.60 mg/kg, respectively. Mg concentrations of 343.35 mg/kg were significantly lower on the western aspect (Appendix B; Table B1). Considering that Ca and K indicated no significant differences ($p > 0.05$) among the three aspects, the highest amounts of these nutrients were found on the eastern aspect. Only Ca on the RD revealed similar trends, with the highest concentration on the eastern aspect (Table 7.2).

Of all the exchangeable cations (Ca, Mg, K and Na) tested, only Mg differed significantly between the three different aspects (Table 7.5) ($p < 0.05$) (Appendix B; Table B1). Mg concentrations were significantly lower on the western aspect than on the southern aspect. As mentioned earlier, studies have shown that mineral weathering increases pH due to the release of Ca, Mg and K into the soil (Sadhu *et al.*, 2012), but this does not seem to correlate with the findings on the TD. The pH values did not differ significantly between the different aspects with similar values of around 7.8 ($p > 0.05$) (Table 7.5). A dissimilar pattern is witnessed on the RD as Ca, Mg and K were significantly higher on the eastern aspect together with significantly higher pH values (Table 7.2).

Table 7.5: Soil physical and chemical characteristics of the three aspects (east, south and west) on the Tailings Dam.

Properties	Tailings Dam – Aspect		
	East	South	West
Sample size (n)	16	14	16
Macro-elements (mmol/ℓ)			
Ca	0.475±0.027 a	0.428±0.025 a	1.022±0.392 a
Mg	0.239±0.012 a	0.252±0.014 a	0.542±0.187 a
K	0.322±0.024 ac	0.302±0.022 a	0.486±0.092 bc
Na	0.086±0.005 a	0.068±0.004 a	0.175±0.043 b
PO ₄	0.025±0.008 a	0.006±0.001 a	0.018±0.008 a
SO ₄	0.124±0.030 a	0.120±0.018 a	1.024±0.649 a
NO ₃	0.238±0.056 a	0.192±0.026 a	0.378±0.078 a
NH ₄	0.020±0.002 a	0.022±0.002 a	0.016±0.003 a
Cl	0.042±0.004 a	0.033±0.004 a	0.113±0.033 b
HCO ₃	1.292±0.057 a	1.280±0.069 a	1.252±0.059 a
Micro-elements (μmol/ℓ)			
Fe	12.906±6.303 a	3.260±0.669 a	8.130±2.396 a
Mn	0.129±0.035 a	0.072±0.020 a	0.158±0.041 a
Cu	0.746±0.092 a	0.376±0.066 a	1.998±0.580 b
Zn	0.047±0.018 a	0.025±0.007 a	0.059±0.020 a
B	3.381±0.472 ac	1.236±0.128 a	5.664±1.312 bc
Nutrient status (mg/kg)			
Ca	2962.35±71.143 a	2798.80±106.396 a	2870.69±75.799 a
Mg	433.31±23.091 ab	469.60±47.694 ac	343.35±30.672 b
K	97.49±6.190 a	100.73±13.201 a	74.17±7.639 a
Na	3.50±0.474 a	2.83±0.440 a	3.98±0.544 a
P	13.94±2.223 a	11.85±2.461 a	13.00±2.161 a
Exchangeable cations (cmol(+)/kg)			
Ca	14.782±0.355 a	13.966±0.531 a	14.325±0.378 a
Mg	3.566±0.190 ab	3.865±0.393 ac	2.826±0.252 b
K	0.250±0.016 a	0.258±0.034 a	0.190±0.020 a
Na	0.015±0.002 a	0.012±0.002 a	0.017±0.002 a
Chemical properties			
pH	7.841±0.053 a	7.892±0.066 a	7.860±0.062 a
pH(H ₂ O)	8.175±0.029 a	8.223±0.048 a	8.188±0.046 a
pH(KCl)	7.736±0.031 ac	7.885±0.082 ab	7.907±0.051 b
EC(mS/cm)	0.188±0.009 a	0.176±0.007 a	0.383±0.127 a
P-Bray I (ppm)	4.721±0.134 a	4.546±0.170 a	4.430±0.171 a
Organic Carbon (%)	0.375±0.033 a	0.290±0.033 a	0.590±0.212 a
CEC (cmol(+)/kg)	14.035±0.322 a	14.079±0.451 a	13.591±0.309 a
S-value	18.614±0.496 a	18.102±0.654 a	17.358±0.483 a
Base saturation (%)	132.295±0.872 a	128.547±1.835 ab	127.701±1.776 b
Soil texture			
Sand > 2mm (%)	18.680±1.679 a	18.592±2.318 a	11.594±2.046 b
Sand < 2mm (%)	91.095±0.605 a	90.404±1.318 a	88.303±2.072 a
Silt (%)	6.296±0.622 a	7.342±1.314 a	9.201±1.899 a
Clay (%)	2.609±0.245 a	2.254±0.239 a	2.495±0.315 a

All values ±SEM represent results obtained from sample size (n=89).

² Statistical significant differences are indicated by alphabetic letters (p < 0.05). The same letters indicate no significant differences while those with different letters indicate significant difference at p<0.05 (Tukey's HSD).

³ EC – electrical conductivity; ppm – parts per million; CEC – cation exchange capacity.

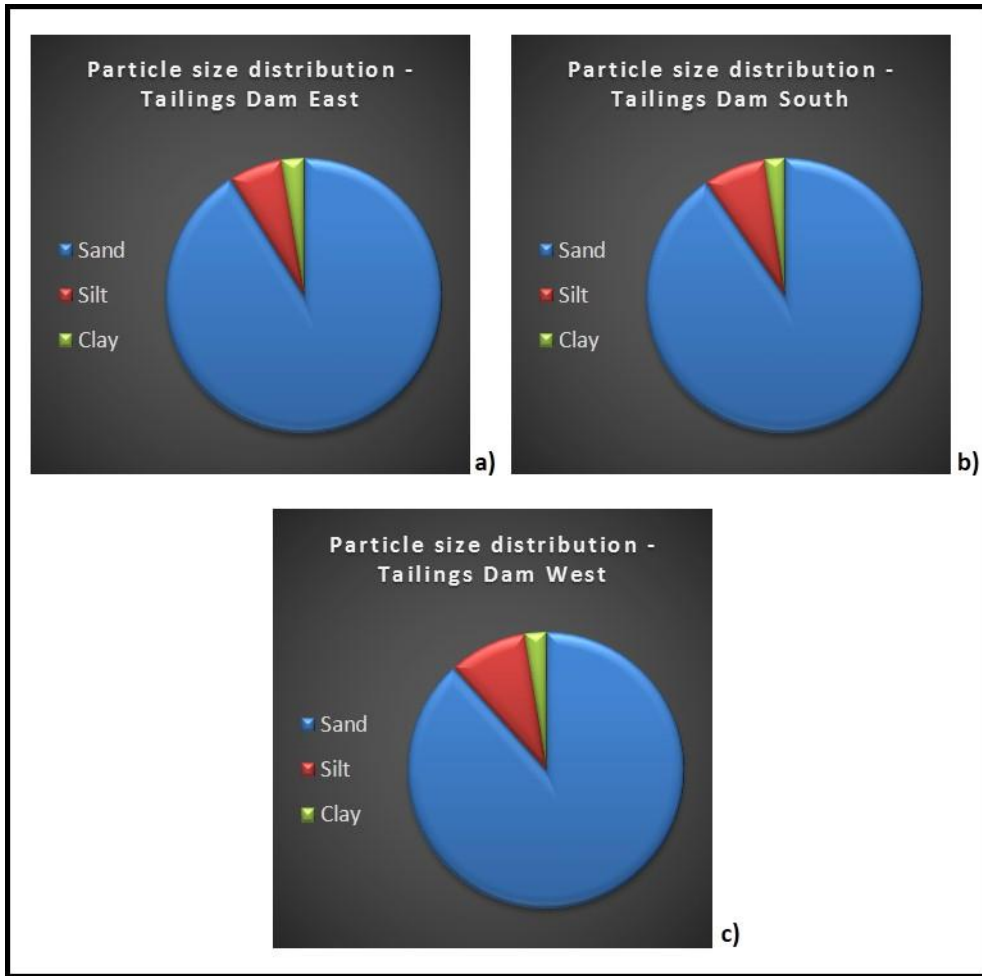


Figure 7.5: Soil particle size distribution of the different aspects on the tailings dam. a – eastern aspect; b - southern aspect; and c - western aspect.

Figure 7.5 illustrates the soil particle distribution or soil textural composition (% sand, silt and clay). Similar patterns are witnessed on the RD (Table 7.2 and Figure 7.2) as sand particles smaller than 2 mm also dominated the different aspects with 91.095 % sand on the eastern, 90.404 % on the southern and 88.303 % on the western aspects. Only sand particles larger than 2 mm revealed significant differences ($p < 0.05$), indicating significantly less sand ($> 2\text{mm}$) for the western aspect. The western aspect, although not significant, showed marginally more silt % than the eastern and southern aspects, nevertheless generally the three aspects were quite similar regarding the soil particle distribution (Table 7.5 & Figure 7.5).

7.2.3 Topographic position

Looking back at the soil physical and chemical properties tested for the different topographic positions of the RD, 24 of the 37 element concentrations showed significant differences between the terrace and slope positions. Soil physical and chemical characteristics of TD were more similar between positions, as only 16 of the 37 tested elements showed significant differences (Table 7.6).

Mg, PO₄, SO₄, Cl and HCO₃ were found to be significantly different between the terraces and slopes on the TD ($p < 0.05$) (Table 7.6). As previously shown for the RD, significant higher macro-element concentrations were recorded on the slopes (Table 7.3.). A similar pattern is recognized on the TD as Mg, SO₄, and HCO₃ were significantly higher on the slopes, while PO₄ and Cl were significantly higher on the terraces. Even though the rest of the tested macro-elements weren't significantly different they also showed higher values on the slopes ($p > 0.05$).

As for the micro-elements, only Zn did not show significant variance between positions. However, the remaining elements Fe, Mn, Cu and B were highly significant and showing exceedingly elevated concentrations on the terrace positions ($p < 0.001$). The same trend occurred on the RD with highly elevated micro-element concentrations on the slope positions (Table 7.3). As stated previously, vermiculite is a good amendment for chemical stabilization of contaminated soils as it retains metal pollutants and significantly reduces the uptake of metals by plants, and could be deduced that different quantities of vermiculite were used on the different topographic positions.

The nutrient status of both the slopes and terraces also followed the same trend with Ca>Mg>K>Na (Table 7.6) (Appendix B; Table B1). Only P showed a highly significant difference, with P being significantly higher on the terraces of the TD ($p < 0.001$), being four times more on the terrace than on the slope positions. A distinctly similar result was found on the RD topographic positions with P concentrations three times higher on the terrace positions than the slopes (Table 7.3). This may be due to more erosion susceptibility on the slopes which in turn increases the transporting and/or leaching of P downward where it accumulates on the terraces (Lehmann & Schroth, 2003).

Table 7.6: Soil physical and chemical characteristics of the two different topographic sites (Terrace & Slope) on the Tailings Dam.

Properties	Tailings Dam – Topography	
	Terrace	Slope
Sample size (n)	23	23
Macro-elements (mmol/ℓ)		
Ca	0.441±0.029 a	0.814±0.237 a
Mg	0.236±0.011 a	0.430±0.114 b
K	0.298±0.019 a	0.435±0.057 a
Na	0.095±0.013 a	0.122±0.025 a
PO ₄	0.031±0.008 a	0.005±0.000 b
SO ₄	0.162±0.030 a	0.624±0.394 b
NO ₃	0.249±0.043 a	0.288±0.057 a
NH ₄	0.019±0.002 a	0.019±0.001 a
Cl	0.085±0.020 a	0.037±0.007 b
HCO ₃	1.058±0.044 a	1.496±0.025 b
Micro-elements (μmol/ℓ)		
Fe	17.197±5.622 a	0.927±0.112 b
Mn	0.218±0.035 a	0.029±0.007 b
Cu	1.574±0.356 a	0.484±0.080 b
Zn	0.048±0.018 a	0.043±0.009 a
B	4.989±0.857 a	2.071±0.294 b
Nutrient status (mg/kg)		
Ca	2771.46±63.78 a	3016.46±65.37 a
Mg	431.63±27.74 a	399.16±25.69 a
K	110.96±6.532 a	71.64±6.172 a
Na	4.000±0.452 a	2.950±0.353 a
P	21.13±1.969 a	5.141±0.017 b
Exchangeable cations (cmol(+)/kg)		
Ca	13.83±0.318 a	15.05±0.326 a
Mg	3.552±0.228 a	3.285±0.211 a
K	0.285±0.017 a	0.184±0.016 a
Na	0.017±0.002 a	0.013±0.002 a
Chemical properties		
pH	7.668±0.052 a	8.051±0.011 b
pH(H ₂ O)	8.236±0.039 a	8.146±0.020 b
pH(KCl)	7.767±0.036 a	7.883±0.047 a
EC(mS/cm)	0.181±0.010 a	0.307±0.077 b
P-Bray I (ppm)	4.040±0.130 a	5.141±0.017 b
Organic Carbon (%)	0.446±0.028 a	0.391±0.130 a
CEC (cmol(+)/kg)	13.68±0.292 a	14.15±0.285 a
S-value	17.68±0.467 a	18.53±0.416 a
Base saturation (%)	128.85±0.870 a	131.11±1.399 a
Soil texture		
Sand > 2mm (%)	20.544±1.414 a	12.521±1.667 b
Sand < 2mm (%)	91.685±0.572 a	88.485±1.361 b
Silt (%)	5.519±0.604 a	9.339±1.239 a
Clay (%)	2.796±0.239 a	2.176±0.1907 a

All values ±SEM represent results obtained from sample size (n=89).

² Statistical significant differences are indicated by alphabetic letters (p < 0.05). The same letters indicate no significant differences while those with different letters indicate significant difference at p<0.05 (Tukey's HSD).

³ EC – electrical conductivity; ppm – parts per million; CEC – cation exchange capacity.

Soil pH was significantly higher on the slopes of the TD ($p < 0.05$), following a similar pattern to the RD (Table 7.3). Increasing base anions such as bicarbonate (HCO_3) were mainly responsible for alkalinity in the soil (Merry, 2004; Moukodi, 2008). It seems that the significantly higher concentrations of HCO_3 on the slopes correlate with the significantly higher pH value on the slopes, and the lower concentrations of HCO_3 on the terraces with the lower pH value on the terraces (Table 7.6).

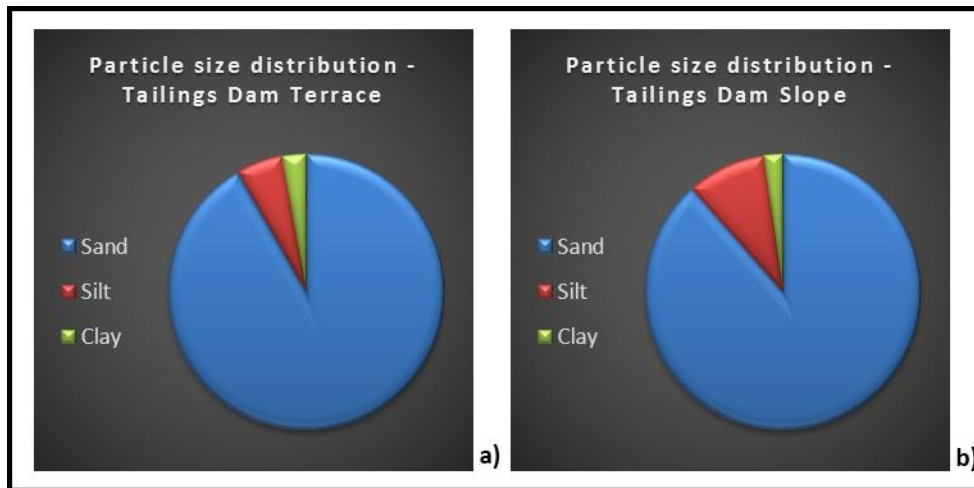


Figure 7.6: Soil particle size distribution of the different topographic positions (Terrace & Slope) on the tailings dam. a – Terrace and b - Slope.

Figure 7.6 illustrates the soil particle distribution or soil textural composition (% sand, silt and clay) of the different topographic positions on the TD. Sand particles >2 mm were significantly higher on the terraces with 20.544 % compared to 12.521 % on the slopes ($p < 0.05$) (Table 7.6 & Figure 7.6). The same can be seen for the <2 mm sand particles which were significantly higher on the terraces with 91.685 %, in comparison with the 88.485 % of the slopes ($p < 0.05$). Silt and clay percentages did not differ significantly ($p > 0.05$), although 9.339 % silt was found on the slopes and 5.519 % on the terraces and 2.176 % clay on the slopes and 2.796 % on the terraces (Table 7.6).

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Chapter 8 – Conclusion

8.1 Chapter 5

The vegetation on the tailings facilities is part of a thin biological cover that represents the only barrier between the hazardous tailings material and the surrounding environment. This study has made the following findings regarding the effect of three spatial and temporal variables on the vegetation of overburden (rock dump) and slimes (tailings dam) storage facilities:

- A total of 94 herbaceous plant species were recorded for the Rock Dump (RD) and Tailings Dam (TD).
- Only a selected few grass (Poaceae) and forb species (Asteraceae and Fabaceae) were responsible for small variations in composition between post rehabilitation ages, aspects and topographic positions on the RD and TD. Variations were the result of changes in abundance of species and not due to variations in the floristics (species turnover).
- Different post rehabilitation ages, aspects and topographic position do not affect floristic composition to such an extent that a significant dissimilarity could be identified across the RD and TD. The prevalent species on the tailings facilities showed that colonisation was localised (overlap of 45 species between the RD and TD) and fulfil a wide range of ecosystem functions on the tailings facilities. Key grass species reflects the tolerance and colonising ability in hostile tailings environments, together with key forb species, most of which belong to the nitrogen-fixating Fabaceae.

8.1.1 Post rehabilitation age

- Herbaceous vegetation and debris cover was low and bare soil and rock cover high on all post rehabilitation ages on the RD and TD. However, the RD and TD reacted differently in terms of cover on post rehabilitation ages.
- The oldest post rehabilitation age on the RD maintained the highest herbaceous vegetation and debris cover while the intermediate age (24 years) on the TD had the highest herbaceous vegetation and debris cover. The oldest post rehabilitation age on the RD and intermediate age (24 years) on the TD had the lowest bare soil and rock cover.

- Different biomass patterns were witnessed on the different post rehabilitation ages. On the RD the intermediate age (32 years) had the highest biomass, while on the TD the youngest age revealed the highest vegetation biomass values.
- Herbaceous species richness and diversity did not reveal trends consistent with post rehabilitation age on the RD and TD. Highest species richness was found on the oldest post rehabilitation age of the RD, revealing increased species richness with time. While the highest species richness was on the youngest age level of the TD. Youngest age on the RD showed the highest species diversity and the highest species diversity occurred on the oldest age on the TD.

8.1.2 Aspect

- The RD and TD reacted similarly in terms of cover regarding different aspects.
- The eastern aspects had the highest herbaceous vegetation cover with the lowest bare soil and rock cover.
- Similar patterns of biomass on the RD and TD occurred between the different aspects. The western aspect had the highest biomass on both the RD and TD, followed by the southern then eastern aspect on the RD and eastern then southern aspect on the TD.
- Fluctuations of herbaceous species richness and diversity values on the RD and TD only displayed similar trends of lowest richness and diversity on the western aspect. Highest species richness and diversity values occurred on the eastern aspects on the RD and on the southern aspect on the TD.

8.1.3 Topographic position

- The RD and TD also reacted in a similar manner regarding vegetation cover of different topographic positions, but not with bare soil and rock cover. Slope positions revealed highest vegetation cover and the lowest bare soil and rock cover. On the TD terrace topographic positions, the lowest bare soil and rock cover was recorded.
- Similar patterns of biomass on the RD and TD was identified between the different topographic positions. Both the RD and TD terrace positions had the highest biomass.
- Fluctuations of herbaceous species richness and diversity values on the RD and TD were similar regarding different topographic positions. Terrace topographic positions had the highest species richness and diversity on both the RD and TD. Where topographic positions were benchmarked against natural Mopaneveld the RD and TD exhibited a lack of species. However, species richness and diversity were more affected on the slope positions than on the terraces.

In other words, the RD's slope positions of the eastern aspect on the oldest post rehabilitation age had the highest vegetation cover. The TD's slope position of the eastern aspect on the intermediate post rehabilitation age (24 years) had the highest cover. Regarding biomass the RD's terrace positions of the western aspect on the intermediate post rehabilitation age (32 years) had the highest values. On the TD's terrace position of the western aspect on the youngest post rehabilitation age the highest biomass was recorded. In summary the RD's oldest post rehabilitation age had the highest species richness and the youngest age the highest species diversity. While the terrace topographic position on the eastern aspect maintained the highest herbaceous species richness and diversity. In the case of the TD, conversely, the youngest post rehabilitation age had the highest species richness and the oldest age the highest species diversity. Similar to the RD, the terrace topographic position on the TD had the highest species richness and diversity while on the contrary the southern aspects maintained the highest species richness and diversity (Figure 8.1; Appendix C).

8.2 Chapter 6

General conclusion that can be drawn from the PLFA analysis in this results chapter is that similar variations in microbial biomass and community structure occurred on both the RD and TD despite the fact that the TD is in a much more active state and under different management regimes than the RD. These variations for the TD were more prominent than those for the RD, and it can be deduced that there is an on-going management regime due to the active nature of the TD. Although the microbial biomass indicated higher overall values for the TD, similar developments over time of rehabilitation were noticed on the RD.

- Oldest post rehabilitation ages (lowermost levels) of both the RD and TD had the highest microbial biomass.
- Eastern aspects of the RD and TD had the highest microbial biomass.
- Slope topographic positions of both the RD and TD had the highest microbial biomass.

In other words, the slope positions of eastern aspects on the oldest post rehabilitation age maintained the highest microbial biomass. On the contrary, the terrace of Western aspects on the intermediate post rehabilitation age maintained the lowest microbial biomass.

The soil microbial community structure showed distinct differences between the RD and TD post rehabilitation ages.

- On the RD, the concentration of TBSats indicative of Gram-positive bacteria and the concentration of Monos representative of Gram-negative bacteria, increased with time to the highest values at the oldest post rehabilitation age.
- On the TD, TBSats and Monos also increased with time, but had the highest values on the intermediate post rehabilitation ages. Gram-positive bacteria are considered to be K-strategists and represent a more established community than the Gram-negative bacteria, which are considered to be R-strategists. It can thus be concluded that the elevated levels of Gram-negative bacteria could possibly be the response of these r strategists to the presence of excessive nutrients.
- In terms of the microbial community structures of different aspects the RD and TD only reacted similarly to the highest values on the Eastern aspect, followed by the Western and Southern with the lowest structural group values.
- Different topographic positions on the RD and TD had the same result as slopes maintained higher structural group values than terraces.

To summarize, aspect and topography is predictable with regards to microbial structural groups independent of the type of tailings facility. However, different post rehabilitation ages are rather site (tailings) specific to determine where structural groups dominate. In the case of the RD it is the oldest post rehabilitation age and on the TD it is the intermediate age levels (24 and 30 years) (Figure 8.1; Appendix C).

8.3 Chapter 7

Soil is a vital natural resource that is non-renewable on human time-scale, and vegetation establishment and stabilization is the most successful practice in attaining sustainable rehabilitation of mine tailings facilities. Since soil is the growth medium for all vegetation, it is important to assess and improve the soil quality.

8.3.1 Post rehabilitation age

- Metal content (micro-elements: Fe, Mn, Cu, Zn, B) of the RD and TD reacted similarly with the highest concentrations on the oldest post rehabilitation ages due to the effect of leaching.

- RD and TD reacted differently in terms of nutrient status (exchangeable cations: Ca, Mg, Ca, Na, P). On the RD the highest nutrient concentrations occurred on the oldest post rehabilitation age, while the highest nutrient concentrations was found on the youngest post rehabilitation age of the TD. As an active facility, the nutrient status of the TD can be a direct function of the chemical ameliorants added regularly to rehabilitate new levels.
- Electrical conductivity (EC) values were extremely low on all post rehabilitation ages on both the RD and TD.
- Organic carbon (OC) of the RD increased with age to the highest content on the oldest post rehabilitation age. The OC content showed no trend consistent with rehabilitation age on the TD, although the oldest age similarly contained the highest OC content.
- Post rehabilitation ages of the RD and TD were characterized by high sand percentage fractions and low clay content.
- The pH values of the different post rehabilitation ages, aspects and topographic positions indicated strong alkaline conditions. This has important implications for the potential generation of acid mine drainage at PMC.

8.3.2 Aspect

- Highest metal concentrations were prominent on the western aspects of both the RD and TD.
- Although most exchangeable cations had highest values on the eastern aspects of the RD and TD, Na and P were highest on the western aspect of the RD and Mg and K were highest on the southern aspect of the TD.
- The RD and TD reacted similar with regards to pH, the southern aspect had the highest pH values. Once more pH values were strongly alkaline in general.
- EC was also extremely low between the different aspects of the RD and TD as was the case between the different post rehabilitation ages.
- OC content differed between the different aspects on the RD and TD. The eastern aspect on the RD had the highest OC, whereas the western aspect on the TD revealed the highest OC content.
- Once more all the aspects on the RD and TD were characterized by high sand percentage fractions and low clay content.

8.3.3 Topographic position

- The RD and TD reacted similar in terms of nutrient status with the slope positions holding the highest Ca and Na, and the terraces the highest Mg, K and P concentrations.
- Regarding metal content, the RD and TD were dissimilar between the topographic positions. Highest metal concentrations on the RD were found on the slope positions, whereas the terrace positions on the TD had the highest metal concentrations.
- The slope positions on the both the RD and TD had the highest pH values. Again, strongly alkaline pH values characterized the different topographic positions.
- EC was also extremely low between the different topographic positions on the RD and TD.
- Regarding OC, slope positions on the RD showed the highest content and terrace positions on the TD had the highest OC content.
- Both slope and terrace positions contained high sand fractions and low clay content (Figure 8.1; Appendix C).

Facility	Variable	Score	Best performance
Rock Dump	(1.1) Age 28	-0.33	
	(1.2) Age 32	-0.67	
	(1.3) Age 42	1	→ Oldest level
	(2.1) East	3.33	→ Eastern aspect
	(2.2) South	-2	
	(2.3) West	-1.33	
	(3.1) Slope	1	→ Slope position
	(3.2) Terrace	-1	
Tailings Dam	(1.1) Age 20	-0.33	
	(1.2) Age 24	-0.67	
	(1.3) Age 30	1	→ Oldest levels
	(1.4) Age 32	0.33	
	(2.1) East	1.67	→ Eastern aspect
	(2.2) South	-1	
	(2.3) West	-0.67	
	(3.1) Slope	-0.33	
	(3.2) Terrace	0.33	→ Terrace position

Figure 8.1: Score values* indicating best performances of the Rock Dump and Tailings Dam based on the tested variables in terms of post rehabilitation ages, aspects and topographic positions. Performance scores obtained from Appendix C (Table C1-12).

*Score values determined by dividing the total scores of structure, diversity and microbes by 3. (Appendix B; Table B1-12).

Appendix A:
Simper Analyses

Table A1: ANOSIM results for different post rehabilitation ages on the Rock Dump

Taxon	Rock Dump – Age					Life form
	Av. dissim	Contrib. %	Cumulative %	Mean abund. 1	Mean abund. 2	
Overall	82.45			28 years	32 years	
<i>Cenchrus ciliaris</i>	11.62	14.1	14.1	8.36	8.41	Perennial
<i>Enneapogon cencroides</i>	10.8	13.1	27.2	7.29	8.79	Annual
<i>Tephrosia purpurea</i>	9.677	11.738	38.93	3.11	2.08	Perennial
<i>Aristida congesta</i>	8.616	10.45	49.38	0.0714	13.4	Perennial
<i>Stipagrostis hirtigluma</i>	7.576	9.189	58.569	1.14	9.15	Annual
<i>Heteropogon contortus</i>	4.27	5.179	63.75	0	5.59	Perennial
Overall	82.89			28 years	42 years	
<i>Enneapogon cencroides</i>	14.14	17.06	17.06	7.29	13.9	Annual
<i>Cenchrus ciliaris</i>	11.03	13.3	30.37	8.36	6.78	Perennial
<i>Aristida adscensionis</i>	7.008	8.455	38.82	1.86	8.16	Annual
<i>Tephrosia purpurea</i>	5.469	6.599	45.42	4.43	1.32	Perennial
<i>Tridax procumbens</i>	4.972	5.999	51.42	3.64	3.05	Annual
<i>Pennisetum setaceum</i>	3.888	4.69	56.11	2.14	1.54	Perennial
Overall	84.8			32 years	42 years	
<i>Enneapogon cencroides</i>	11.92	14.06	14.06	8.79	13.9	Annual
<i>Cenchrus ciliaris</i>	10.27	12.11	26.17	8.41	6.78	Perennial
<i>Aristida congesta</i>	8.709	10.27	36.44	13.4	2.7	Perennial
<i>Stipagrostis hirtigluma</i>	7.635	9.003	45.45	9.15	2.7	Annual
<i>Aristida adscensionis</i>	5.853	6.902	52.35	0.971	8.16	Annual
<i>Heteropogon contortus</i>	4.396	5.184	57.53	5.59	0.73	Perennial

Table A2: ANOSIM results for different aspects on the Rock Dump

Taxon	Rock Dump – Aspect					
	Av. dissim	Contrib. %	Cumulative %	Mean abund. 1	Mean abund. 2	Life form
Overall	84.3			East	South	
<i>Cenchrus ciliaris</i>	11	13.05	13.05	6.56	9.57	Perennial
<i>Enneapogon cencroides</i>	10.75	12.75	25.8	7.32	10.9	Annual
<i>Aristida congesta</i>	6.696	7.943	33.74	0.24	8.23	Perennial
<i>Aristida adscensionis</i>	6.689	7.934	41.68	1.16	8.57	Annual
<i>Stipagrostis hirtigluma</i>	5.932	7.037	48.71	1.84	5.91	Annual
<i>Tephrosia uniflora</i>	4.064	4.821	53.54	3.84	0	Perennial
<i>Pennisetum setaceum</i>	3.772	4.474	58.01	1.68	2	Perennial
<i>Tridax procumbens</i>	3.736	4.432	62.44	1.6	3.54	Annual
Overall	84.99			East	West	
<i>Enneapogon cencroides</i>	14.22	16.73	16.73	7.32	14.1	Annual
<i>Cenchrus ciliaris</i>	10.19	11.99	28.72	6.56	6.2	Perennial
<i>Tephrosia purpurea</i>	6.552	7.71	36.43	0.04	5.68	Perennial
<i>Stipagrostis hirtigluma</i>	6.351	7.473	43.91	1.84	6.96	Annual
<i>Aristida congesta</i>	5.033	5.922	49.83	0.24	10.5	Perennial
<i>Tephrosia uniflora</i>	4.406	5.184	55.01	3.84	0	Perennial
<i>Heteropogon contortus</i>	4.109	4.835	59.85	1.72	4.2	Perennial
Overall	84.87			South	West	
<i>Enneapogon cencroides</i>	12.89	15.19	15.19	10.9	14.1	Annual
<i>Cenchrus ciliaris</i>	10.8	12.73	27.91	9.57	6.2	Perennial
<i>Aristida congesta</i>	9.553	11.26	39.17	8.23	10.5	Perennial
<i>Stipagrostis hirtigluma</i>	7.736	9.117	48.28	5.91	6.96	Annual
<i>Aristida adscensionis</i>	6.161	7.261	55.54	8.57	1.28	Annual
<i>Tephrosia purpurea</i>	5.525	6.511	62.06	0.0286	5.68	Perennial

Table A3: ANOSIM results for different topographic positions on the Rock Dump

Taxon	Rock Dump – Topography					
	Av. dissim	Contrib. %	Cumulative %	Mean abund. 1	Mean abund. 2	Life form
Overall	86.05			Slope	Terrace	
<i>Enneapogon cencroides</i>	12.77	14.84	14.84	5.24	17	Annual
<i>Cenchrus ciliaris</i>	9.936	11.55	26.38	8.27	7.05	Perennial
<i>Aristida congesta</i>	9.01	10.47	36.86	0.2	13.7	Perennial
<i>Stipagrostis hirtigluma</i>	7.788	9.051	45.91	1.11	9.43	Annual
<i>Aristida adscensionis</i>	6.341	7.37	53.28	0.933	7.97	Annual
<i>Heteropogon contortus</i>	4.405	5.119	58.4	0.0222	5.4	Perennial
<i>Pennisetum setaceum</i>	3.02	3.51	61.91	2.27	1	Perennial

Table A4: ANOSIM results for different post rehabilitation ages on the Tailings dam

Taxon	Tailings Dam – Age					
	Av. dissim	Contrib . %	Cumulative %	Mean abund. 1	Mean abund. 2	Life form
Overall	74.63			20 years	24 years	
<i>Tephrosia purpurea</i>	14.67	19.66	19.66	3.73	25.2	Perennial
<i>Sesbania bispinosa</i>	10.19	13.65	33.31	12.7	10.5	Perennial
<i>Cenchrus ciliaris</i>	8.652	11.59	44.91	11.2	15.8	Perennial
<i>Aristida scabrivalvis</i>	8.493	11.38	56.29	9.55	8.05	Annual
<i>Enneapogon cencroides</i>	5.514	7.389	63.68	8	3.18	Annual
Overall	82.97			20 years	30 years	
<i>Cenchrus ciliaris</i>	9.48	11.43	11.43	11.2	8.56	Perennial
<i>Sesbania bispinosa</i>	9.2	11.09	22.51	12.7	3.52	Perennial
<i>Stipagrostis hirtigluma</i>	9.029	10.88	33.4	0.0455	10.9	Annual
<i>Tephrosia purpurea</i>	8.246	9.939	43.33	3.73	12	Perennial
<i>Aristida scabrivalvis</i>	8.197	9.88	53.21	9.55	5.72	Annual
<i>Enneapogon cencroides</i>	6.716	8.095	61.31	8	5.04	Annual
Overall	78.89			20 years	32 years	
<i>Cenchrus ciliaris</i>	11.05	14	14	11.2	10.2	Perennial
<i>Sesbania bispinosa</i>	10.04	12.72	26.73	12.7	2.15	Perennial
<i>Indigastrium costatum</i>	8.141	10.32	37.05	8.59	5.05	Annual
<i>Stipagrostis hirtigluma</i>	6.934	8.79	45.84	0.0455	7.15	Annual
<i>Aristida scabrivalvis</i>	6.628	8.402	54.24	9.55	1.05	Annual
<i>Enneapogon cencroides</i>	6.109	7.744	61.98	8	2.85	Annual
Overall	79.76			24 years	30 years	
<i>Tephrosia purpurea</i>	16.95	21.25	21.25	25.2	12	Perennial
<i>Cenchrus ciliaris</i>	10.91	13.68	34.93	15.8	8.56	Perennial
<i>Stipagrostis hirtigluma</i>	8.879	11.13	46.06	0.909	10.9	Annual
<i>Sesbania bispinosa</i>	8.248	10.34	56.4	10.5	3.52	Perennial
<i>Aristida scabrivalvis</i>	7.291	9.141	65.54	8.05	5.72	Annual
Overall	78.01			30 years	32 years	
<i>Stipagrostis hirtigluma</i>	12.49	16.01	16.01	10.9	7.15	Annual
<i>Cenchrus ciliaris</i>	11.49	14.73	30.73	8.56	10.2	Perennial
<i>Tephrosia purpurea</i>	9.784	12.54	43.28	12	4.35	Perennial
<i>Indigastrium costatum</i>	5.962	7.643	50.92	2.96	5.05	Annual
<i>Heteropogon contortus</i>	5.436	6.969	57.89	5.04	0.6	Perennial
<i>Enneapogon cencroides</i>	5.163	6.619	64.51	5.04	2.85	Annual

Table A5: ANOSIM results for different aspects on the Tailings dam

Taxon	Tailings Dam – Aspect					
	Av. dissim	Contrib. %	Cumulative %	Mean abund. 1	Mean abund. 2	Life form
Overall	77.37			East	South	
<i>Tephrosia purpurea</i>	10.57	13.67	13.67	8.51	10.1	Perennial
<i>Aristida scabrivalvis</i>	10.37	13.4	27.06	5.58	14.4	Annual
<i>Cenchrus ciliaris</i>	10.03	12.96	40.03	12.3	10.8	Perennial
<i>Stipagrostis hirtigluma</i>	7.196	9.3	49.33	7.33	2	Annual
<i>Enneapogon cencroides</i>	6.214	8.031	57.36	6.07	6.05	Annual
<i>Sesbania bispinosa</i>	6.067	7.841	65.2	6.62	5	Perennial
Overall	78.27			East	West	
<i>Tephrosia purpurea</i>	13.07	16.7	16.7	8.51	18.3	Perennial
<i>Cenchrus ciliaris</i>	10.68	13.64	30.34	12.3	10.1	Perennial
<i>Sesbania bispinosa</i>	9.69	12.38	42.72	6.62	10.1	Perennial
<i>Stipagrostis hirtigluma</i>	7.65	9.775	52.49	7.33	2.75	Annual
<i>Indigastrium costatum</i>	5.944	7.596	60.09	3.76	5.54	Annual
Overall	77.73			South	West	
<i>Tephrosia purpurea</i>	13.52	17.39	17.39	10.1	18.3	Perennial
<i>Cenchrus ciliaris</i>	9.362	12.04	29.44	10.8	10.1	Perennial
<i>Aristida scabrivalvis</i>	8.478	10.91	40.34	14.4	0.458	Annual
<i>Sesbania bispinosa</i>	8.453	10.87	51.22	5	10.1	Perennial
<i>Indigastrium costatum</i>	5.855	7.532	58.75	3.75	5.54	Annual
<i>Enneapogon cencroides</i>	4.506	5.797	64.55	6.05	1.46	Annual

Table A6: ANOSIM results for different topographic positions on the Tailings Dam

Taxon	Tailings Dam – Topography					
	Av. dissim	Contrib. %	Cumulative %	Mean abund. 1	Mean abund. 2	Life form
Overall	78.38			Slope	Terrace	
<i>Tephrosia purpurea</i>	11.93	15.22	15.22	15.4	7.96	Perennial
<i>Cenchrus ciliaris</i>	10.44	13.32	28.54	12.3	10.6	Perennial
<i>Sesbania bispinosa</i>	8.036	10.25	38.79	6.76	7.6	Perennial
<i>Stipagrostis hirtigluma</i>	7.489	9.555	48.35	2.31	7.21	Annual
<i>Aristida scabrivalvis</i>	6.923	8.834	57.18	5.4	6.89	Annual
<i>Indigastrium costatum</i>	5.331	6.802	63.98	2.6	5.7	Annual

Appendix B:
Chemical analysis ideal values

Table C1: Chemical symbols with ionic name and form and ideal values (Amended from Haagner (2008)).

Element	Symbol	Ionic form	Ion name	Ideal value
Macro-elements				
Potassium	K	K ⁺	Potassium	20-40 mg/kg
Calcium	Ca	Ca ²⁺	Calcium	>100 mg/kg
Magnesium	Mg	Mg ²⁺	Magnesium	15-35 mg/kg
Sodium	Na	Na ⁺	Sodium	
Phosphorus	P	HPO ₄ ²⁻	Hydrogen phosphate	1.5-2.5 mg/kg
Anions (SO₄⁴⁻, NO₃³⁻, HCO₃³⁻, Cl)				36-100 mg/kg
Micro-elements				
B	B	B	Boron	18-150 mg/kg
Zn	Zn	Zn	Zinc	18-150 mg/kg
Mn	Mn	Mn	Manganese	18-150 mg/kg
Cu	Cu	Cu	Copper	18-150 mg/kg
Fe	Fe	Fe	Iron	200 mg/kg
Other cations				
Nitrogen	N	NO ₃ ⁻	Nitrate	80-165 mg/kg
	N	NH ₄ ⁺	Ammonium	80-165 mg/kg
Sulfur	S	SO ₄ ²⁻	Sulfate	36-100 mg/kg
Carbon	C	CO ₃ ²⁻	Carbonate	n/a
Other chemical variables		Explanation		
Organic C		Organic C		n/a
CEC		Cation Exchange Capacity		5-20 cmol/kg
EC		Electrical Conductivity		0.6-1 mS/cm
pH(KCl)		Acidity/Alkalinity		5.5-7
pH(H₂O)		Acidity/Alkalinity		5.5-7.2

Appendix C:
PMC SCORING

Table B1: Rock Dump post rehabilitation ages scoring in terms of structure, species diversity and microbes.

RD	28	32	42
Composition	-	-	-
Forb cover	-	-	-
Grass cover	-	-	-
Bare soil cover	-	-	-
Debris cover	-	-	-
Biomass	-	-	-
Structure	0	0	0
Total species	-	-	-
Total individuals	<32	>28	-
Margalef's richness	-	-	-
Pielou's evenness	-	-	-
Shannon-Wiener	-	-	-
Simpson's diversity	-	-	-
Diversity	-1	1	0
Microbial biomass	<42	<42	>32; >28
NSats	-	-	-
MBSats	-	-	-
TBSats	<42	<42	>32; >28
Monos	-	-	-
Polys	>32; >42	<28	<28
Microbes	0	-3	3
Score	-0.33	-0.67	1

Table B2: Rock Dump post rehabilitation ages scoring in terms of physical and chemical soil properties.

RD	28	32	42
Macro-elements	<42; <32	<42; >42; >28	<32; >32; >28
Micro-elements	<42; <32	<42; >28	>32; >28
Nutrient status	<42; <32	>28	>28
Exchangeable cations	<42; <32	>28	>28
Chemical properties	<42; <32	>28	>28
Soil texture	<42; <32	>28	>28
Score	-12	5	7

Table B3: Rock Dump aspects scoring in terms of structure, species diversity and microbes.

RD	East	South	West
Composition	-	-	-
Forb cover	-	-	-
Grass cover	-	-	-
Bare soil cover	>S; >W	<E	<E
Debris cover	>S; >W	<E	<E
Biomass	-	-	-
Structure	4	-2	-2
Total species	-	-	-
Total individuals	-	-	-
Margalef's richness	-	-	-
Pielou's evenness	-	-	-
Shannon-Wiener	-	-	-
Simpson's diversity	-	-	-
Diversity	0	0	0
Microbial biomass	>S; >W	>W; <E	<E; <S
NSats	>S	<E	-
MBSats	-	-	-
TBSats	>S; >W	<E	<E
Monos	-	-	-
Polys	>S	<E; <W	>S
Microbes	6	-4	-2
Score	3.33	-2	-1.33

Table B4: Rock Dump aspects scoring in terms of physical and chemical soil properties.

RD	East	South	West
Macro-elements	>W	>W	<E; <S
Micro-elements	>W	>W	<E; <S
Nutrient status	>W; >S	<E	<E
Exchangeable cations	>W; >S	<E	<E
Chemical properties	>S; <W	>W; <E; <W	<S; >S; >E
Soil texture	>S	<E; <W	>S
Score	7	-6	4

Table B5: Rock Dump topographic positions scoring in terms of structure, species diversity and microbes.

RD	Slope	Terrace
Composition	-	-
Forb cover	-	-
Grass cover	-	-
Bare soil cover	-	-
Debris cover	-	-
Biomass	-	-
Structure	0	0
Total species	<Te	>Sl
Total individuals	<Te	>Sl
Margalef's richness	-	-
Pielou's evenness	-	-
Shannon-Wiener	-	-
Simpson's diversity	-	-
Diversity	-2	2
Microbial biomass	>Te	<Sl
NSats	>Te	<Sl
MBSats	>Te	<Sl
TBSats	>Te	<Sl
Monos	>Te	<Sl
Polys	-	-
Microbes	5	-5
Score	1	-1

Table B6: Rock Dump topographic scoring in terms of physical and chemical soil properties.

RD	Slope	Terrace
Macro-elements	>Te	<Sl
Micro-elements	<Te; >Te	>Sl; <Sl
Nutrient status	<Te; >Te	>Sl; <Sl
Exchangeable cations	<Te; >Te	>Sl; <Sl
Chemical properties	>Te	<Sl
Soil texture	<Te; >Te	>Sl; <Sl
Score	2	-2

Table B7: Tailings Dam post rehabilitation ages scoring in terms of structure, species diversity and microbes.

TD	20	24	30	32
Composition	-	-	<32	>30
Forb cover	-	-	-	-
Grass cover	-	-	-	-
Bare soil cover	<32	-	-	>20
Debris cover	<32	-	-	>20
Biomass	-	-	-	-
Structure	-2	0	-1	3
Total species	>24	<20	-	-
Total individuals	>32	>32	-	<20; <24
Margalef's richness	>24	<20	-	-
Pielou's evenness	-	<32	-	>24
Shannon-Wiener	>24	<20; <32	-	>24
Simpson's diversity	>24	<20; <32	-	>24
Diversity	5	-6	0	1
Microbial biomass	>24; >30	<20; <32	<20; <32	>30; >24; >20
NSats	<30; <24	>32; >20	>32; >20	<30; <24
MBSats	<30; <24	>32; >20	>32; >20	<30; <24
TBSats	-	-	-	-
Monos	-	-	-	-
Polys	<30; <24	>32; >20	>32; >20	<30; <24
Microbes	-4	4	4	-3
Score	-0.33	-0.67	1	0.33

Table B8: Tailings Dam post rehabilitation ages scoring in terms of physical and chemical soil properties.

TD	20	24	30	32
Macro-elements	<24; <30	>20; >32	>20; >32	<24; <30
Micro-elements	<32	<32	<32	>30; >24; >20
Nutrient status	>24; >30	<32; <30; <20; >30	<20; <24; <32	>24; >30
Exchangeable cations	>24; >30	<32; <20; >30	<20; <24; <32	>24; >30
Chemical properties	<24; <30; >24; >30	>20; >30; >32; <20; <32	<24; >32; >20; <32; <20	<24; <30; >24; >30
Soil texture	>24; >30	<20	<20	-
Score	3	-2	-7	5

Table B9: Tailings Dam aspects scoring in terms of structure, species diversity and microbes.

TD	East	South	West
Composition	-	<W	>S
Forb cover	-	-	-
Grass cover	>S; >W	<E	<E
Bare soil cover	>W	-	<E
Debris cover	>S; >W	<E	<E
Biomass	-	-	-
Structure	5	-3	-2
Total species	-	-	-
Total individuals	-	-	-
Margalef's richness	-	-	-
Pielou's evenness	-	-	-
Shannon-Wiener	-	-	-
Simpson's diversity	-	-	-
Diversity	0	0	0
Microbial biomass	-	-	-
NSats	-	-	-
MBSats	-	-	-
TBSats	-	-	-
Monos	-	-	-
Polys	-	-	-
Microbes	0	0	0
Score	1.67	-1	-0.67

Table B10: Tailings Dam aspects scoring in terms of physical and chemical soil properties.

RD	East	South	West
Macro-elements	<W	<W	>S; >E
Micro-elements	<W	<W	>S; >E
Nutrient status	-	>W	<S
Exchangeable cations	-	>W	<S
Chemical properties	<W; >W	-	>E; <E
Soil texture	<W	<W	>S; >E
Score	-5	-1	4

Table B11: Tailings Dam topographic positions scoring in terms of structure, species diversity and microbes.

TD	Slope	Terrace
Composition	-	-
Forb cover	-	-
Grass cover	-	-
Bare soil cover	<Te	>Sl
Debris cover	<Te	>Sl
Biomass	-	-
Structure	-2	2
Total species	-	-
Total individuals	-	-
Margalef's richness	-	-
Pielou's evenness	-	-
Shannon-Wiener	-	-
Simpson's diversity	-	-
Diversity	0	0
Microbial biomass	-	-
NSats	-	-
MBSats	-	-
TBSats	-	-
Monos	-	-
Polys	>Te	<Sl
Microbes	1	-1
Score	-0.33	0.33

Table B12: Tailings Dam topographic positions scoring in terms of physical and chemical soil properties.

TD	Slope	Terrace
Macro-elements	>Te; <Te	<Sl; >Sl
Micro-elements	<Te	>Sl
Nutrient status	<Te	>Sl
Exchangeable cations	-	-
Chemical properties	>Te	<Sl
Soil texture	>Te	<Sl
Score	0	0

Appendix D:

**PLOT NUMBERS, SITE, ASPECT, TOPOGRAPHIC
POSITION AND GPS COORDINATES**

PLOT	SITE	ASPECT	TOPOGRAPHIC POSITION	Latitude	Longitude
1	ROCK DUMP (RD)	South	SLOPE	24 00.660	31 08.930
2	ROCK DUMP (RD)	West	SLOPE	24 00.605	31 08.903
3	ROCK DUMP (RD)	West	TERRACE	24 00.845	31 08.862
4	ROCK DUMP (RD)	West	TERRACE	24 00.580	31 08.858
5	ROCK DUMP (RD)	West	SLOPE	24 00.408	31 08.943
6	ROCK DUMP (RD)	West	TERRACE	24 00.398	31 08.912
7	ROCK DUMP (RD)	West	SLOPE	24 00.118	31 09.022
8	ROCK DUMP (RD)	West	TERRACE	24 00.100	31 08.992
9	ROCK DUMP (RD)	West	TERRACE	24 00.003	31 09.108
10	ROCK DUMP (RD)	West	SLOPE	24 00.038	31 09.123
11	ROCK DUMP (RD)	West	SLOPE	24 00.047	31 09.072
12	ROCK DUMP (RD)	West	TERRACE	24 00.003	31 09.060
13	ROCK DUMP (RD)	West	SLOPE	23 59.992	31 09.128
14	ROCK DUMP (RD)	West	SLOPE	24 00.018	31 08.923
15	ROCK DUMP (RD)	West	SLOPE	24 00.165	31 08.902
16	ROCK DUMP (RD)	West	SLOPE	24 00.293	31 08.868
17	ROCK DUMP (RD)	West	SLOPE	24 00.510	31 08.783
18	ROCK DUMP (RD)	West	SLOPE	24 00.703	31 08.713
19	ROCK DUMP (RD)	West	SLOPE	24 00.210	31 09.028
20	ROCK DUMP (RD)	West	TERRACE	24 00.210	31 09.002
21	ROCK DUMP (RD)	West	SLOPE	24 00.393	31 08.995
22	ROCK DUMP (RD)	West	TERRACE	24 00.388	31 08.965
23	ROCK DUMP (RD)	West	SLOPE	24 00.487	31 08.967
24	ROCK DUMP (RD)	West	TERRACE	24 00.479	31 08.947
25	ROCK DUMP (RD)	West	SLOPE	24 00.563	31 08.952
26	ROCK DUMP (RD)	West	TERRACE	24 00.560	31 08.926
27	ROCK DUMP (RD)	South	SLOPE	24 00.617	31 08.963
28	ROCK DUMP (RD)	South	TERRACE	24 00.650	31 08.940
29	ROCK DUMP (RD)	South	SLOPE	24 00.642	31 09.027
30	ROCK DUMP (RD)	South	TERRACE	24 00.647	31 08.973
31	ROCK DUMP (RD)	South	SLOPE	24 00.667	31 09.095
32	ROCK DUMP (RD)	South	TERRACE	24 00.676	31 08.976
33	ROCK DUMP (RD)	South	SLOPE	24 00.717	31 09.168
34	ROCK DUMP (RD)	South	TERRACE	24 00.685	31 09.033
35	ROCK DUMP (RD)	South	SLOPE	24 00.752	31 09.225
36	ROCK DUMP (RD)	South	TERRACE	24 00.727	31 09.056
37	ROCK DUMP (RD)	East	SLOPE	24 00.732	31 09.302
38	ROCK DUMP (RD)	South	TERRACE	24 00.722	31 09.094
39	ROCK DUMP (RD)	East	SLOPE	24 00.815	31 09.283
40	ROCK DUMP (RD)	South	TERRACE	24 00.802	31 09.125
41	ROCK DUMP (RD)	East	TERRACE	24 00.812	31 09.277
42	ROCK DUMP (RD)	South	TERRACE	24 00.764	31 09.176
43	ROCK DUMP (RD)	South	SLOPE	24 00.865	31 09. 200
44	ROCK DUMP (RD)	South	TERRACE	24 00.852	31 09.196

45	ROCK DUMP (RD)	South	SLOPE	24 00.698	31 09.000
46	ROCK DUMP (RD)	South	TERRACE	24 00.797	31 09.229
47	ROCK DUMP (RD)	South	SLOPE	24 00.751	31 09.064
48	ROCK DUMP (RD)	South	SLOPE	24 00.812	31 09.146
49	ROCK DUMP (RD)	South	SLOPE	24 00.782	31 08.797
50	ROCK DUMP (RD)	South	TERRACE	24 00.779	31 08.814
51	ROCK DUMP (RD)	South	SLOPE	24 00.904	31 08.857
52	ROCK DUMP (RD)	South	TERRACE	24 00.747	31 08.883
53	ROCK DUMP (RD)	South	SLOPE	24 00.966	31 08.921
54	ROCK DUMP (RD)	South	TERRACE	24 00.897	31 08.868
55	ROCK DUMP (RD)	South	SLOPE	24 00.988	31 09.076
56	ROCK DUMP (RD)	South	TERRACE	24 00.808	31 08.949
57	ROCK DUMP (RD)	South	SLOPE	24 00.996	31 09.173
58	ROCK DUMP (RD)	South	TERRACE	24 00.910	31 08.942
59	ROCK DUMP (RD)	South	SLOPE	24 00.868	31 09.300
60	ROCK DUMP (RD)	South	TERRACE	24 00.950	31 09.096
61	ROCK DUMP (RD)	South	TERRACE	24 00.898	31 09.177
62	ROCK DUMP (RD)	South	TERRACE	24 00.952	31 09.182
63	ROCK DUMP (RD)	South	TERRACE	24 00.887	31 09.083
64	ROCK DUMP (RD)	East	TERRACE	24 00.853	31 09.289
65	ROCK DUMP (RD)	South	TERRACE	24 00.825	31 09.037
66	ROCK DUMP (RD)	East	SLOPE	24 00.341	31 09.533
67	ROCK DUMP (RD)	East	SLOPE	24 00.524	31 09.423
68	ROCK DUMP (RD)	East	TERRACE	24 00.344	31 09.541
69	ROCK DUMP (RD)	East	TERRACE	24 00.520	31 09.429
70	ROCK DUMP (RD)	East	SLOPE	24 00.332	31 09.559
71	ROCK DUMP (RD)	East	SLOPE	24 00.528	31 09.437
72	ROCK DUMP (RD)	East	TERRACE	24 00.383	31 09.570
73	ROCK DUMP (RD)	East	TERRACE	24 00.542	31 09.442
74	ROCK DUMP (RD)	East	TERRACE	24 00.220	31 09.652
75	ROCK DUMP (RD)	East	SLOPE	24 00.194	31 09.638
76	ROCK DUMP (RD)	East	SLOPE	24 00.217	31 09.637
77	ROCK DUMP (RD)	East	TERRACE	24 00.197	31 09.643
78	ROCK DUMP (RD)	East	TERRACE	23 59.906	31 09.733
79	ROCK DUMP (RD)	East	SLOPE	23 59.907	31 09.723
80	ROCK DUMP (RD)	East	TERRACE	23 59.908	31 09.714
81	ROCK DUMP (RD)	East	SLOPE	23 59.912	31 09.703
82	ROCK DUMP (RD)	East	SLOPE	23 59.891	31 09.761
83	ROCK DUMP (RD)	East	SLOPE	24 00.182	31 09.746
84	ROCK DUMP (RD)	East	SLOPE	24 00.420	31 09.562
85	ROCK DUMP (RD)	East	SLOPE	24 00.644	31 09.422
86	TAILINGS DAM (TD)	West	TERRACE	23 59.334	31 10.487
87	TAILINGS DAM (TD)	West	SLOPE	23 59.831	31 10.493
88	TAILINGS DAM (TD)	West	TERRACE	24 00.055	31 10.614
89	TAILINGS DAM (TD)	West	SLOPE	24 00.048	31 10.620
90	TAILINGS DAM (TD)	West	TERRACE	24 00.302	31 10.760

91	TAILINGS DAM (TD)	West	SLOPE	24 00.299	31 10.766
92	TAILINGS DAM (TD)	South	TERRACE	24 00.366	31 10.850
93	TAILINGS DAM (TD)	South	SLOPE	24 00.358	31 10.852
94	TAILINGS DAM (TD)	South	TERRACE	24 00.434	31 11.062
95	TAILINGS DAM (TD)	South	SLOPE	24 00.422	31 11.066
96	TAILINGS DAM (TD)	South	TERRACE	24 00.588	31 11.373
97	TAILINGS DAM (TD)	South	SLOPE	24 00.582	31 11.384
98	TAILINGS DAM (TD)	East	TERRACE	24 00.345	31 11.515
99	TAILINGS DAM (TD)	East	SLOPE	24 00.346	31 11.505
100	TAILINGS DAM (TD)	East	TERRACE	24 00.148	31 11.458
101	TAILINGS DAM (TD)	East	SLOPE	24 00.150	31 11.446
102	TAILINGS DAM (TD)	East	TERRACE	23 59.926	31 11.360
103	TAILINGS DAM (TD)	East	SLOPE	23 59.921	31 11.351
104	TAILINGS DAM (TD)	East	TERRACE	23 59.693	31 11.366
105	TAILINGS DAM (TD)	East	SLOPE	23 59.692	31 11.356
106	TAILINGS DAM (TD)	East	TERRACE	23 59.500	31 11.227
107	TAILINGS DAM (TD)	East	SLOPE	23 59.537	31 11.250
108	TAILINGS DAM (TD)	East	TERRACE	23 59.450	31 11.238
109	TAILINGS DAM (TD)	East	SLOPE	23 59.451	31 11.225
110	TAILINGS DAM (TD)	East	TERRACE	23 59.391	31 11.279
111	TAILINGS DAM (TD)	East	SLOPE	23 59.400	31 11.478
112	TAILINGS DAM (TD)	East	TERRACE	23 59.411	31 11.328
113	TAILINGS DAM (TD)	East	TERRACE	23 59.393	31 11.485
114	TAILINGS DAM (TD)	East	TERRACE	23 59.482	31 11.440
115	TAILINGS DAM (TD)	East	SLOPE	23 59.374	31 11.485
116	TAILINGS DAM (TD)	East	TERRACE	23 59.522	31 11.489
117	TAILINGS DAM (TD)	East	TERRACE	23 59.363	31 11.481
118	TAILINGS DAM (TD)	East	TERRACE	23 59.584	31 11.528
119	TAILINGS DAM (TD)	West	SLOPE	23 59.794	31 10.407
120	TAILINGS DAM (TD)	West	TERRACE	23 59.796	31 10.394
121	TAILINGS DAM (TD)	West	SLOPE	24 00.079	31 10.593
122	TAILINGS DAM (TD)	West	TERRACE	24 00.081	31 10.579
123	TAILINGS DAM (TD)	West	SLOPE	24 00.330	31 10.748
124	TAILINGS DAM (TD)	West	TERRACE	24 00.339	31 10.736
125	TAILINGS DAM (TD)	South	SLOPE	24 00.404	31 10.906
126	TAILINGS DAM (TD)	South	TERRACE	24 00.414	31 10.908
127	TAILINGS DAM (TD)	South	SLOPE	24 00.523	31 11.195
128	TAILINGS DAM (TD)	South	TERRACE	24 00.534	31 11.197
129	TAILINGS DAM (TD)	South	SLOPE	24 00.621	31 11.392
130	TAILINGS DAM (TD)	South	TERRACE	24 00.624	31 11.387
131	TAILINGS DAM (TD)	East	SLOPE	24 00.482	31 11.551
132	TAILINGS DAM (TD)	East	TERRACE	24 00.477	31 11.553
133	TAILINGS DAM (TD)	East	SLOPE	24 00.152	31 11.487
134	TAILINGS DAM (TD)	East	TERRACE	24 00.149	31 11.490
135	TAILINGS DAM (TD)	East	SLOPE	23 59.951	31 11.390
136	TAILINGS DAM (TD)	East	TERRACE	23 59.940	31 11.398

137	TAILINGS DAM (TD)	East	SLOPE	23 59.725	31 11.377
138	TAILINGS DAM (TD)	East	TERRACE	23 59.715	31 11.391
139	TAILINGS DAM (TD)	West	SLOPE	23 59.791	31 10.322
140	TAILINGS DAM (TD)	West	TERRACE	23 59.799	31 10.324
141	TAILINGS DAM (TD)	West	SLOPE	24 00.146	31 10.605
142	TAILINGS DAM (TD)	West	TERRACE	24 00.155	31 10.596
143	TAILINGS DAM (TD)	West	SLOPE	24 00.375	31 10.739
144	TAILINGS DAM (TD)	West	TERRACE	24 00.379	31 10.732
145	TAILINGS DAM (TD)	South	SLOPE	24 00.441	31 10.860
146	TAILINGS DAM (TD)	South	TERRACE	24 00.445	31 10.848
147	TAILINGS DAM (TD)	South	SLOPE	24 00.558	31 11.230
148	TAILINGS DAM (TD)	South	TERRACE	24 00.585	31 11.254
149	TAILINGS DAM (TD)	South	SLOPE	24 00.639	31 11.388
150	TAILINGS DAM (TD)	South	TERRACE	24 00.645	31 11.385
151	TAILINGS DAM (TD)	East	SLOPE	24 00.396	31 11.561
152	TAILINGS DAM (TD)	East	TERRACE	24 00.389	31 11.569
153	TAILINGS DAM (TD)	East	SLOPE	24 00.150	31 11.512
154	TAILINGS DAM (TD)	East	TERRACE	24 00.144	31 11.509
155	TAILINGS DAM (TD)	East	SLOPE	23 59.918	31 11.400
156	TAILINGS DAM (TD)	East	TERRACE	23 59.900	31 11.409
157	TAILINGS DAM (TD)	East	SLOPE	23 59.697	31 11.404
158	TAILINGS DAM (TD)	East	TERRACE	23 59.709	31 11.415
159	TAILINGS DAM (TD)	West	SLOPE	23 59.850	31 10.353
160	TAILINGS DAM (TD)	West	TERRACE	23 59.864	31 10.362
161	TAILINGS DAM (TD)	West	SLOPE	24 00.139	31 10.561
162	TAILINGS DAM (TD)	West	TERRACE	24 00.141	31 10.551
163	TAILINGS DAM (TD)	West	SLOPE	24 00.379	31 10.703
164	TAILINGS DAM (TD)	West	TERRACE	24 00.389	31 10.696
165	TAILINGS DAM (TD)	South	SLOPE	24 00.459	31 10.839
166	TAILINGS DAM (TD)	South	TERRACE	24 00.468	31 10.837
167	TAILINGS DAM (TD)	East	SLOPE	24 00.412	31 11.577
168	TAILINGS DAM (TD)	East	TERRACE	24 00.392	31 11.582
169	TAILINGS DAM (TD)	East	SLOPE	24 00.121	31 11.508
170	TAILINGS DAM (TD)	East	TERRACE	24 00.100	31 11.502
171	TAILINGS DAM (TD)	East	SLOPE	23 59.933	31 11.418
172	TAILINGS DAM (TD)	East	TERRACE	23 59.927	31 11.427
173	TAILINGS DAM (TD)	East	SLOPE	23 59.750	31 11.398
174	TAILINGS DAM (TD)	East	TERRACE	23 59.748	31 11.409