

**CHANGES IN FLORISTIC AND FUNCTIONAL
COMPOSITION ON A COMPLEX OF GOLD TAILINGS
DAMS NEAR CARLETONVILLE, NORTH WEST
PROVINCE, FROM 1996 TO 2014**



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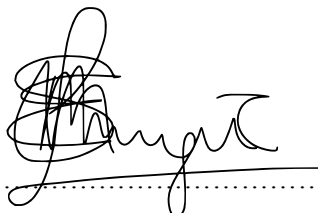
A research report submitted to the Faculty of Science, University of the Witwatersrand,
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Coursework and Research Report.

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Declaration

I, Mike Maguranyanga, declare that this research report, apart from the contributions mentioned in the acknowledgements, is my own, unaided work. It is submitted for the Degree of Master of Science (MSc) by coursework and research report to the University of the Witwatersrand. It has not been presented before for any degree or examination to any other University.

A handwritten signature in black ink, appearing to read 'Mike Maguranyanga', is written over a horizontal dotted line.

(Signature of candidate)

16th day of Sept. 2016

Abstract

A vegetation survey was carried out in July 2014 on the substrates of 5 tailings dams by selecting 10 sampling sites which were previously used as sampling plots during the 1996/97 survey of Weiersbye *et al.* (2006). At each sampling site a 100m transect horizontally across the substrate and covering all levels of the tailings dam from the flat top to the toe paddock was established. Each transect was surveyed for the frequency of the species occurring and these were categorized based on their mode of colonization (natural, intentionally introduced and persisting) while tailings were collected by digging approximately 20cm into the ground for soil sample collection per substrate. The recorded species were then divided using Raunkier's classification categories into growth forms and a comparison was done between the two surveys (2014 versus 1996/7) to identify the species that were lost, those that were still persisting and the new ones that had colonized over time. A total of 51 species (over 15ha) in 36 genera within 14 families were recorded on the tailings dams, compared to 168 species (over 765ha), 98 genera and 59 families found in the previous study. Families with the most species in 2014 were similar to those of the 1996/97 survey, following the dominance order of Poaceae >Asteraceae >Fabaceae >Anacardiaceae, with the percentage frequency of grasses (Poaceae) noted to have almost doubled over this period. Compared to 6 species common across the substrates in the previous study, the later survey recorded 12 common species (6 of the species occurring on all substrates) but overall both studies found vegetation cover to be high (above 65%) on flat tops and berms with species richness being high on the toe paddock>slopes>tops and berms and substrates susceptible to low nutritional (N,P,K,C) value. Indigenous plant species (54.9%) were dominating the tailing dams and were mostly perennials (82.3%) that were naturally colonizing and persisting (72.5%) on the tailings dams (similar to the 1996/97 survey), while alien (45.1%) plant species comprised annuals/biennials (17.7%) that were intentionally introduced (27.5%) prior to the 1996/97 survey by contractors. The ceased ameliorative initiatives since the first survey are believed to have significantly contributed to a decrease in herbaceous species richness, which formed the majority of the introduced species in the former survey (58.8% compared to 29.4%) as they depended on the supplementary additions of fertilizers and lime. Approximately 117 species, 62 genera and 45 families (including Chenopodiaceae, which was dominant) were lost over the 17 years period, the majority of these were introduced prior to the 1996/97 vegetation survey, while only *Ficus* sp. was the only new species colonizing apart from the increase noted in alien species (some invasive in nature). The decrease in species richness has encouraged woody and semi-woody (35.3%) and grasses (35.3%) to dominate the slimes reaffirming their potential as temporal and long term rehabilitation species that have developed physiological tolerance to acidic conditions, salinity and heavy metal pollution. In conclusion, this study has identified the species that can be used for phytoremediation to provide long terms solutions for dust, air and water pollution and soil erosion suppression for rehabilitation of these contaminated lands (Appendix 8). The survey also helps to identify species that are able to naturally colonize and persist on the tailings dams without supplements, making them ideal economic species to use for rehabilitation. Results also highlight the negative impacts of the lack of ameliorative supplementations, which in turn affects the floristic composition and structure on these tailings dams over time.

Keywords: Aerial cover, Macronutrients, Tailings dams, Species richness, Tailings Storage Facilities (TSFs) and Vegetation survey

Dedication

This research report is dedicated to Isabel Weiersbye and Prof Ed Witkowski for all the support they provided me with during my study period. I would also like to extend my appreciation to Maguranyanga. E (my dad) for his undying love and support since I started school. Lastly my special mention goes to ALL my friends for their support and love which kept me going.

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ABBREVIATIONS

GDP	-	Growth Domestic Product
JSE	-	Johannesburg Stock Exchange
EC	-	Electrical Conductivity
UNEP	-	United Nations Environment Program
CEC	-	Cation Exchange Capacity
WHO	-	World Health Organization
DWAF	-	Department of Water Affairs
OM	-	Organic Matter
TSF	-	Tailings Storage Facility
AGA	-	AngloGold Ashanti
S A	-	South Africa

DEFINITION OF TERMS

Dormant tailings dams - these were dams that showed no sign of fresh deposits (grey material) and were confirmed to have not been utilized at least 2 years' prior conducting the 2014 study. Such dams showed a grey- red color particularly on top which is a sign of long time of oxidation and were very dry.

Active tailings dams - all dams that showed clear signs of fresh deposits that were grey in color with wet soils were treated as active. Some of these had not been utilized for depositing atleast for a year prior the study but were now being deposited with slimes again.

Mean of means - this referred to the value obtained after summing up the individual site means and divide them by ten (10) or adding all the means per substrate and divide them by seven (7).

Short – lived perennials - these plants persist for several years and then decline and fade away.

Biennials - plants that have a lifecycle with a span of two years. Then normally flower and produce seeds in their second year.

Annuals - plants that goes through their whole lifecycle in one growing season.

Perennials - these are plants that can survive in frost temperatures and live for more than two years.

Plant vegetation cover - percentage of ground surface covered by vegetation

Climate variability - The way climate fluctuates yearly above or below a long-term average value.

CHAPTER ONE

1.0 Introduction and Literature Review

Mining activities have been noted to be one of the major pillar stones of African countries (Corpuz, 1997; Kitula, 2005) as they are reported to significantly contribute to the budget of several economies. South Africa's own mining industry is placed 5th in the world (Chamber of Mines, 2012a) accounting for about 18% of the Growth Domestic Product (GDP) (Chamber of Mines, 2014). The mining sector contributes directly to the establishment of the Johannesburg Stock Exchange (JSE), infrastructure development and acts as a milestone for the development of other economic sectors thus lifting the local economy of South Africa.

Historically, mining was viewed as a multi-contributor to foreign exchange of the economy, to employment creation and as the major revenue tax generator (Fedderke and Pirouz, 1998) as some regarded it as the locomotive of the economy for development. The actual contribution of mining to employment creation has become one of the most arguably debated topics. Environmentalists feel that its contribution to employment is not significant as reported but rather it poses significant threats to the environments and issues revolving around sustainability (UNEP, 1997).

The process of mining generates different kinds of waste including rock overburden and mine development rock (Das and Choudhury, 2013). The former type of rock results from the development of surface mines, while the latter is a by-product of mineral extraction from underground mining. Generally, mining activities have an inherently disruptive tendency to environments (Kitula, 2005) and produce large amounts of waste (UNEP, 1997) that has detrimental effects on the receiving environment if not properly managed. Areas which are polluted by mining waste are deeply associated with low water retention (WHO, 1996), low cation exchange capacity (CEC), extreme pH, high electrical conductivity (EC) (Conesa *et al.* 2007; Mining Facts, 2014) as well as heavy metals pollution, deficient nutrient quantities and low organic matter (OM) (Akala and Lal, 2001; Asensio *et al.* 2011; Barrutia *et al.* 2011).

One of the problems that mining activities pose on the environment is not just of pollution of the soils and destruction of ecosystems but the amount of space required to stockpile the waste (soil, debris, etc) generated from the extraction process (Anon, 2000). Waste piles are normally kept within the lease area of the mine, or sometimes on public areas to contain the waste; but in several cases their environmental impacts can reach distances further than expected if not quarantined (Anon, 2005). Therefore bigger mines overall produce huge volumes of waste compared to small scale mines but if the small mines increase in numbers, this could worsen the current challenges of waste dumps being experienced already in South Africa, particularly in the Witwatersrand Basin.

Mineral extraction produces large volumes of waste varying between different types of minerals of extraction. Copper mines were estimated to generate 110tons of waste ore and 200 tons of overburden (Anon, 2005) per ton of copper while gold mines produce about 200tons of waste (Chamber of Mines, 2004) per ton of gold and the waste comprise of soil, rock waste and finely ground tailings. In South Africa as of 1997, approximately 468 million tons of mineral waste were being generated annually and about 221 million tons were from gold mining industry of Witwatersrand (DWAF,

2001; Chamber of Mines, 2004) making it the largest single source of waste (Oelofse *et al.* 2007b). Open cast mining has been reported to be pollution intensive compared to underground mining method with studies carried out estimating it to generate waste that is eight – ten times more than that from underground mining (Anon, 2000; 2005). As the high-grade minerals deposits depletes approaching finite, the extraction process produces more waste as the lower grade reserves are utilized (Anon, 2003).

Waste produced from the processing of ore after grinding and milling is in the form of slurry (Ritcey, 1989; Anon, 2000; 2003) commonly referred to as tailings/slimes and is stored in the Tailings Storage Facilities (TSF) sometimes referred to as Tailings Dam or Tailings Management Facility (TMF) to prevent land contamination and pollution although in most cases they always find their way into the environment. As a result of the boom increase that was once experienced during the gold era of Egoli, these tailings drastically increased particularly in the Witwatersrand Basin. An estimate of 120 dumps covering an area of about 400km² in the goldfields of the Witwatersrand (AngloGold Ashanti, 2004; Weiersbye *et al.* 2006; Oelofse *et al.* 2007b) have been identified comprising approximately 6 billion tons of uranium and gold tailings (Chevrel *et al.* 2003). Due to poor planning and lack of suitable disposal site availability, this has resulted in some of the tailings dams being placed on natural pans, wetlands and catchment areas as well as water courses leading to extreme cases of pollution (Meerts and Grommesch, 2001) when waste and mine process water is disposed into pans and unprotected evaporation dams.

Several investments and energy has been channelled towards establishing the chemical and physical composition of the tailings and remarkable success has been achieved through short and long term studies that have been done in several countries across the globe including South Africa. Some of the local studies (Witkowski and Weiersbye 1998a; Weiersbye *et al.* 1999; Winde *et al.* 2004a,b; Weiersbye and Cukrowska 2005) that have been done have enabled researchers and environmental managers to develop and implement different trial treatments in a bid to rehabilitate the polluted areas and tailings dams.

1.1 Tailings dams layout

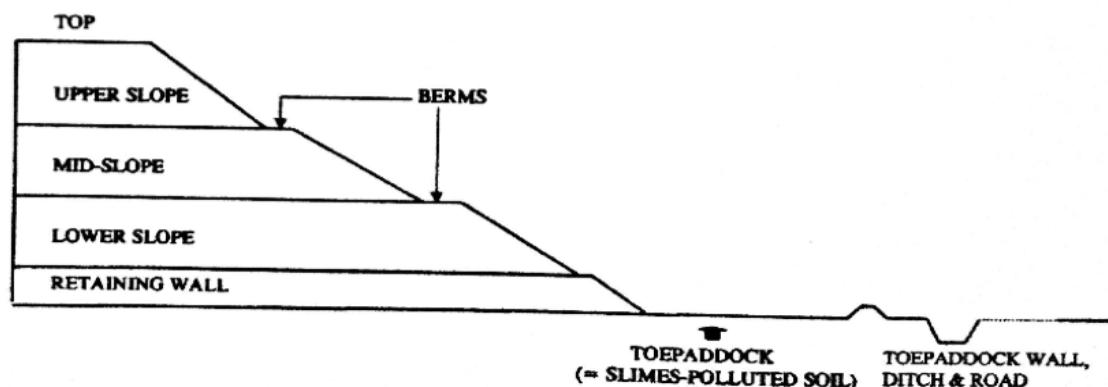


FIGURE 1: Aspect of a gold tailings dam subdivided into different substrate levels.
Source: Weiersbye *et al.* (2006)

1.1.1 Tailings dam description

Tailings are a result of mineral processing and beneficiation which produces slurry (Anon, 2005; Weiersbye *et al.* 2006). The type of ore as well as the physical and chemical methods used to extract the target product has been noted to determine the characteristics of the tailings (Anon, 2000; 2003). Although ores differ from mineral to mineral, tailings constitute of the common problematic elements such as pyrite, arsenic, calcite, barite, cyanide, mercury, fluorite and quartz (Bradshaw *et al.* 1978; Walder and Chavez, 1995; Boulet and Larocque, 1998; Witkowski and Weiersbye, 1998; Weiersbye *et al.* 2006).

Tailings have become a growing concern in the mining sector, all issues emanating from their chemical composition that includes toxic compounds that have detrimental effects on the human health and safety and as well as disastrous impacts on the environment. A number of factors are considered in designing the TSF. These include, (i) selecting the most suitable site, (ii) method of storage to be used as well as (iii) the method of discharging the waste that is applied (Ritcey, 1989). The physical conditions of the ground and the nature of the surrounding environment have an influential role in the TSF's methods of construction thus the linked processes from designing to decommissioning of the TSFs (Ripley, 1996). Baseline studies are used in determining the impacts of the TSF construction on all aspects of the environment (EC, 2004) which includes the social, economic and the associated risk of operation (Vick, 1990; EC, 2004).

Despite having all the above mentioned factors being considered before construction of the TSF (Figure 1), to mitigate and minimise chances of TSFs failures, events of dam failure continue to be recorded with the most recent being in Brazil in 2015. These tailings then stream flow into the environment as either runoff or seepage (Garcia *et al.* 2005) resulting in soil contamination and land pollution (Vick, 1990; EC, 2004). The process by which the environment becomes polluted from the contamination of the tailings is called Acid Mine Drainage (AMD) (Garcia, *et al.* 2005) and this can have detrimental impacts on the environment (Vick, 1990; Witkowski and Weiersbye, 1998; Anon, 2005) as well as the vegetation communities (Donahue, *et al.* 1990). Some of the environmental implications other than AMD include contamination of the streams as a result of surface run-off from impounded areas, contamination of water and air due to erosion of solidified tailings, aesthetic modification to the environment and dust pollution from the dried-out tailings from the slopes as the presence of pyrite is not conducive for vegetation growth on TSFs thus increased dust levels in the nearby areas (Oelofse *et al.* 2007b).

Cases of AMD have been on the rise particularly in the Witwatersrand Basin since the time tailings dams have been noted to be on the increase (McKenna *et al.* 2003). The continuous modernization of mining technologies as well as rehabilitation techniques over the years seeks to address this and initiatives of reprocessing and reclaiming the mine dumps (tailings dams) using modernized technologies such as Reuse and Reprocess (R^2), etc.

1.2 The influence of tailings on plant growth

Gold tailings constitute of major problematic sulphide of the conglomerate together with galena, pyrrhotite, chalcopyrite, arsenopyrite and cobaltite (Anhaesser, 1987; Weiersbye, *et al.* 2006). These sulphides when oxidised form sulphates and strong acids that have detrimental impacts and effects on the environment. Such compounds alter soil chemical composition making it toxic while lowering the pH to inhospitable conditions for plant establishment (Witkowski and Weiersbye, 1998; Weiersbye *et al.* 2006; Smirnova *et al.* 2009).

The deposition of sulphides and heavy metals into the environment alters the physio-chemical properties of the soils (Witkowski and Weiersbye, 1998a). Tailings waste result in acidic conditions in the soil which in-turn influences the availability of the present nutrients to the plants creating nutritional imbalances in the soils (Witkowski and Weiersbye, 1998a). Apart from the chemical alteration, tailings particles are small in size (clay size), fine in texture (Clausen, 1973) and siliceous in nature. This results in poor aeration of the tailings dams due to high levels of compaction in the soil (Clausen, 1973) leading to lower microbial activity (Wong, 1985 and Harris *et al.* 1996;) thus the absence of organic matter which is an essential component in the soil that improves soil fertility and plant growth. Slimes contain primary compounds (pyrophyllite and quartz) that are unreactive, which when coupled with lack of organic matter in the slimes, affects the cation exchange capacity (CEC) as well as the pH (Bosch, 1987). In turn this determines the nutrients that can be released to the plants for utilization.

When exposed to water and air due to the large surface area of the dams, the tailings are oxidised, producing sulphuric acid and ferric hydroxide (James and Mrost, 1965). The yellow colour of the old tailings dams is a result of this iron in the ferric hydroxide. A steep gradient in pH and acidity is noted across the slope with the gradient dropping from the upper slope (top) to the toe paddock (Witkowski and Weiersbye, 1998a and Weiersbye *et al.* 2006). Changes in pH across the slope can also be identified by marking the changes in vegetation occurrence in the form of horizontal belts across the slopes which respond to the shifts in soil chemical properties (Witkowski and Weiersbye, 1998a).

Poor aeration in the soil, lack of organic matter or macronutrients, alkaline pH (of fresh slimes) and salinity and high toxicity from heavy metals, will collectively have a negative effect, contributing to poor soil structure and infertility of the TSFs (Johnson and Bradshaw, 1977; Witkowski and Weiersbye, 1998a). The poor soil structure in TSFs then inhibits microbial activity in the soils (Wong, 1985; Harris *et al.* 1996; Straker *et al.* 2008) making tailings dams poor environments for growth of most plants (Mendez *et al.* 2007). Lower microbial activity leads to slower decomposition and nitrogen mineralization rates, thus influencing nutrient availability to plants (Wong, 1985; Straker *et al.* 2008). Slopes have been reported to have lower number of species because of the gradient which makes them more vulnerable to soil erosion and nutrient leaching (Witkowski and Weiersbye, 1998a) thus limiting the species occurrence.

Alkaline tailings, in some instances may have little vegetation available on them but these are mostly grasses of *Eragrostis* and *Hyparrhaenia* spp. (Gaff, 1971; Krzaklewski and Pietrzykowski, 2002; Weiersbye *et al.* 2006). On acidic tailings, the microbial activity is extremely low as well as the

number of species and carbon utilization compared with soils that have not been contaminated (Moynahan *et al.* 2002). Mine tailings microbial community is predominated by sulphur oxidizing and autotrophic iron bacteria is often associated with plant death in acidic tailings (Schippers *et al.* 2000). Studies that were carried out (Weiersbye *et al.* 1998; Straker *et al.* 2006a, b, c; Straker *et al.* 2008) showed that majority of the plants that were occurring on the tailings were infected by arbuscular mycorrhizal (AM) fungi and it is slime-tolerant AM fungi that significantly contribute to host plant survival and growth in acidic slimes (Weiersbye *et al.* 1998; Straker *et al.* 2006c). The majority of the indigenous hard-seeded legumes and compatible tolerant rhizobia have also been found to positively influence the growth and survival of plant species on the tailings dams. Only species that have developed physiological and adaptive traits to tolerate the toxicity of heavy metals, acidic conditions, salinity as well as high tolerance to low moisture and low nutrient levels will persist and grow vigorously on the tailings dams (Witkowski and Weiersbye, 1998b). Intensified research has been done on the subject of using phytoremediation to stabilize polluted lands and containing tailings (Das and Choudhury, 2013). Findings of the studies show that woody and semi-woody and grass species of genera *Tamarix*, *Acacia*, *Rhus*, *Asparagus* and *Eragrostis* exhibited no signs of physiological stress despite growing on the slimes (Gaff, 1971; Weiersbye *et al.* 1998; Witkowski and Weiersbye, 1998; Dharamraj *et al.* 1999; Angus, 2005; Weiersbye *et al.* 2006)

Polluted or soils contaminated by heavy metals from the tailings tend to have an inhibition effect on the soil formation processes and plant growth (Johnson and Bradshaw, 1977; Harris *et al.* 1996; Witkowski and Weiersbye, 1998a; b). Limited growth is experienced in plants on degraded lands such as on the slimes as there is no continuous supply of nutrients due to lack of organic matter (Harris, *et al.* 1996). On the other hand, in polluted soils plant growth is actually restricted by the toxicity of the heavy metals (Zinc, Nickel, Lead and Copper) (Wong, 1987). In addition, mining processes heavily disturb natural ecosystems by periodically burying the surface soil layers, which makes it difficult for vegetation to colonize these areas again after mining activities (Bradshaw, 2000).

As a result of the tailings dams being inhospitable to most intolerant plants (plant species that cannot resist toxicity on the tailings), only tolerant species are found on the tailings dams based on the (i) season of the year, (ii) nature of the slope and (iii) the chemical properties of the soil from the parent material (Wong, 1985). According to Southam and Beveridge (1992) and Mendez *et al.* (2007), tailings dams are familiar in supporting the growth of highly stressed heterotrophic microbial community with studies of Weiersbye *et al.* (2006), showing that more vegetation is found on the top, flat berms and on the base (lower slope and toe paddock) than on the slopes across the 7 substrata of the tailings slopes (see Figure 1).

1.3 Efforts made towards rehabilitation of Tailings Dams

The need to maintain a healthy environment for sustainable development has across the world pushed most institutions and organizations to seek the most effective ways of rehabilitating these disturbed areas, particularly with mining activities. This has seen the crafting of new and stringent legal instruments, revision of management plans, enforcement of the policies and laws for compliance to ideal set standards as well as the adoption of modern technologies.

From the studies that were carried out across the globe, it has been noted that apart from the factors mentioned earlier that influence plant growth on tailings dams, tailings vegetation establishment in arid and semi-arid regions are affected by physicochemical attributes (Munshower, 1994). These attributes include the high temperatures on the tailings dam surface, high winds and low precipitation, which all adds to the building of excessive salt concentrations (22 dS/m) (Munshower, 1994). High evaporation rates and low water infiltration tendencies (hence high run-off – which increases with slope steepness) also contributes to increased salinity levels which negatively impact the growth of any vegetation.

Due to poor fertility of the tailings dams, trials have been done to improve the fertility of the soils by fertilization and irrigation of the tailings dams (Weiersbye *et al.* 2006). The main goal in doing this was to be able to have vegetation on the slopes to reduce the air and dust pollution in windy conditions as well as limiting soil erosion (Warburst, 2000; Morris *et al.* 2003; US EPA, 2004; Gonzalez and Gonzalez-Chavez 2006). An estimated value of 500 tons $\text{ha}^{-1}\text{yr}^{-1}$ of soil is lost on steep slopes of tailings dams compared to the 15 tons $\text{ha}^{-1}\text{yr}^{-1}$ on agricultural lands (Blight, 1991). This is because the tailings dams are erected well above the natural contours of the ground thus making them more susceptible to wind erosion (Mizelle *et al.* 1996), but in addition the slopes are much steeper than the surrounding natural terrain. The impacts of erosion and AMD from the gold tailings dams have been reported to have detrimental impacts on the soil nutrient cycles (Witkowski and Weiersbye, 1998a), biogeochemical cycle of potential waste elements (Weiersbye, *et al.* 1999 and Weiersbye and Cukrowska, 2005) and the growth of vegetation (Witkowski and Weiersbye, 1998b and Weiersbye and Witkowski, 2003).

The implementation of new remedial programmes and execution of research studies have been helpful in addressing the issues of pollution from the mines as well as the contamination of the soils by heavy metals. But the topic at the centre of study over the years is on phytoremediation (US EPA, 1997) which encourages the use of exotic and indigenous plants to stabilize and rehabilitate disturbed areas.

From the studies that have been executed on phytoremediation till now it has been experimentally demonstrated that grassing of slopes less than 18° is cheaper than the current slopes of greater than 30° (Weiersbye and Witkowski, 1996; 1998a). Slopes with a gradient of less than 18° have been reported to have lower rates of erosion, extending the life span of grasses and thus reducing irrigation needs (Weiersbye and Witkowski, 1996). From 1994 – 2002 it was estimated that grassing trials on steeper slopes ($>15^\circ$) cost between R 70 000 – R160 000 ha^{-1} compared to the R 10 000 – R70 000 ha^{-1} on flat tops, thus making it uneconomic (Weiersbye *et al.* 2006).

This method of revegetating the tailings dams using readily available pasture grasses (i.e. with commercially available seeds) was deemed unsustainable and uneconomic (Witkowski and Weiersbye, 1998a, b; Weiersbye, *et al.* 2006). This is because grasses provide cover which is temporal (Halliday, 1978) thus its control measures on erosion becomes temporal (Blight, 1991). Grasses on tailings also require continuous maintenance, irrigation and fertilization (Weiersbye *et al.* 2006) making it costly. Despite this, grasses have been recommended due to their rapid ability to spread in space over a short time rather than their functional effectiveness (Thatcher, 1979), and this

has seen the continuous use of grasses for short term erosion and water pollution control methods (Rosner *et al.* 2001).

Apart from the grasses, quite a number tolerant plant species have been used to rehabilitate the degraded areas due to their evolutionary traits other than their inherent physiological tolerance (Bradshaw, 1993). The list includes grasses of *Cynodon dactylon* (Wong, 1982), *Festuca rubra*, *Phragmites australis* and *Typha latifolia* (Wong and Lau, 1985; Ye *et al.* 1998b) which have been reported to be effective in phytostabilization programmes of Australia and UK. In China, areas contaminated with lead (Pb)/zinc (Zn) have been identified to have *Vetiveria zizanioides* grass (Shu *et al.* 2000), *Sesbania rostrata* a leguminous herb (Yang *et al.* 1997), and *Leucaena leucocephala* a woody legume (Zhang *et al.* 2001).

The use of *V. zizanioides* has been successful for the rehabilitation of soils contaminated by heavy metals and for the treatment of leachate from the landfills using greenhouse and field trials in Queensland area of Australia (Truong and Baker, 1988). Some species and clones of trees such as willows and poplars have been reported to be effective in removing quite a significant amount of heavy metals, and thus can be found present on the tailings dams (Truong and Baker, 1988).

Apart from these recommended species approved through laboratory trials, some indigenous species have also been noted to have developed adaptive traits allowing them to persist on the slopes of the tailings dams. Such species have been identified through periodic vegetation surveys on the TSFs and contaminated areas (Weiersbye, *et al.* 2006) and have been used for trials in other areas of similar contamination for phytoremediation. These include some species of *Tamarix*, *Rhus* and *Eucalypts* which have either been introduced and have developed ecological traits for survival or that have naturally colonized the area.

1.3.1 Legislative instruments

Most of the mine tailings dump sites of arid and semi-arid areas in the world are either from inactive or abandoned mine sites (Munshower, 1994) in Northern Mexico, Western United States, Western India, Australia and South Africa (Tordoff *et al.* 2000).

The need to conserve and protect the environment for sustainability has seen formulation, revision and implementation of statutory and legislative instruments. This has helped to fulfil the principles of the National Environmental Act 36 (1998) of “Precautionary, Preventative and Polluter pays Principles” by stipulating standards of operation in the environment and requirements on specified mode of operations on the environment. Such Acts also apprehend the polluters and make sure they are held responsible for cleaning of the pollutants from the environment. Other legal frameworks put forward include the Environmental Conservation Act 73 (1989), Biodiversity Act No. 10 of 2004; Air Quality (AQ) Act No. 39 of 2004 and the National Environmental Management Act (NEMA): Protected Areas (PA) Act No. 57 of 2003 with Amendment Act No. 46 of 2003. The Conservation of Agricultural Resources Act (CARA), No. 43 of 1983 also forms part of the important pieces of legislation that provides the standards and procedures on controlling weeds and invasive plants.

The broad aim of this research was to identify the species that were occurring on the 7 substrata (upper slope, upper berms, middle slope, middle berms, lower slope, toe paddocks and the retaining

walls) of the West Wits (Mponeng and Savuka 7A,7B and 5A) tailings dams. The identified species would then be classified into their functional groups as well as estimating vegetation cover on the ground at each slope level. Colonizing behaviour (persisters or natural colonizers) of the present species was also used to categorize the species into different groups. The results obtained would be compared to those of Weiersbye, *et al.* (2006) to see if there are any changes in the vegetation structure and composition on the tailings dams. The AngloGold Ashanti Mines (West Wits) in the Witwatersrand Basin of South Africa were used as the study sites.

1.4 Problem Statement

Tailings storage facilities (TSFs) are storage sites for waste from the gold and uranium mining industry which is generated after processing. These TSFs contain of problematic mineral elements that make the soils unsuitable for plant establishment and due to poor permanent vegetation cover to stabilise the soils on TSFs. This results in contamination and pollution of surrounding environments. Vegetation growth on the tailings dams helps to reduce erosion and dust and air pollution from the tailings particles which would be blown off the TSFs in sites with poor vegetation cover. Poor nutritional value in tailings soils makes them far from ideal for plant establishment and growth. Hence the industry needs to have raised environmental awareness to prevent pollution and improve rehabilitation success. TSFs are elevated well above the natural ground contours with steeper slopes making them more susceptible to erosion and pollution. Tailings dams cover a huge area of the South Africa's deep-level mines thus causing a major concern from a biodiversity conservation perspective. As a result of few species being tolerant to the hostile conditions on the tailings dams, there is a need to continuously carry out vegetation surveys to identify suitable and resistant species for each locality. This would also help to determine which species have been persistent since 1996/7, to identify any new colonizing species since then, and the ones that have been lost.

1.5 Significance of the study

The weak soil structure, heavy metals contamination, poor aeration as well as lack of organic matter in the tailings dams makes them hostile and far from ideal for plant establishment and growth. A lack of organic matter and poor soil aeration results in very low microbial activity. The consequence is the establishment of only a temporary, short-lived, colonization/vegetation cover by plants. Only plants that develop tolerance traits to the harsh conditions have been reported to persist on the tailings dams. Over a period of time, some species are lost while others colonize the open space; this then requires a study of this nature to identify the changes in vegetation and species composition by doing vegetation surveys periodically. Hence, this study becomes highly relevant for ongoing rehabilitation efforts as it will provide information on the species present, those lost as well as any new species that have colonized the tailings dams since the first survey that was done in 1996/7 (Weiersbye, *et al.* 2006)

1.6 Objectives

The main aim of this study was to investigate the changes that have occurred in the floristic and functional composition of the gold tailings dams of AngloGold Ashanti (AGA) near Carletonville in the North West Province since the first survey that was done in 1996. A comparison of the results obtained from the two individual studies (1996/97 and 2014) would be done to identify the species

that have been lost, those that have developed physiological tolerance to the prevailing environmental stresses as well as the new species that colonized the tailings during this period.

1.6.1 Specific objectives

1. To identify the species occurring on the substrates (upper slope, upper berms, middle slope, middle berms, lower slope, toe paddocks and the retaining walls) of the tailings dams.
2. Classify the identified species into functional groups (trees, shrubs, forbs, grasses and herbs), colonizing behaviour (natural colonisers or persisters) and estimate vegetation basal cover of the slope.
3. Compare the results from this study to those of Weiersbye *et al.* (2006) to ascertain whether there are any new species that have colonized the slopes and record the species that have been lost since the 1996-7 survey.
4. To determine if there are any differences in pH, organic matter and selected nutrient elements between substrates and across the sites.

1.7 Research questions

1. Which families and genera are the most frequently occurring on the tailings dams?
2. Which functional groups in terms of growth forms (trees, shrubs, forbs, grasses and herbs), and type of colonizers are dominant on the different substrates of the tailings dams?
3. Are there any differences between the results obtained from this survey and that of Weiersbye *et al.* (2006)?
4. Are there any differences in the pH, organic matter and concentration of selected nutrient elements between substrates and across the sampling sites?

CHAPTER 2

2.1 Description of the study site

The study was carried out during early (June –July) winter of 2014 on deep –level gold mines of AngloGold Ashanti in the Witwatersrand Basin, North West province of South Africa. A single dam at Mponeng mine and 3 dams at Savuka were used as sampling sites (see Figure 2). The sites are located at the geographical coordinates of latitude 26^o25'24.5" S extending to 26^o 26' 10" S and longitude 25^o 25' 14" E extending to 27^o 25' 50" E. The tailings dams occur on rocky quartzite, shale and dolomitic soils that are acidic (Acocks, 1988; Mucina and Rutherford, 2006; Weiersbye *et al.* 2006). Located 75km southwest of Johannesburg, Carletonville occurs in the grassland biome with an altitude of 1600 – 1650m above sea level (a.s.l) (Weiersbye and Witkowski, 2002a). The soils are in the C6 and C7 subdivisions with the vegetation composition of xeric grasslands (Gh 15) and the savanna of *Acacia karoo* (Acocks, 1988; Weiersbye and Witkowski, 2002a; Mucina and Rutherford, 2006).

The surveyed area has a climate that is seasonal receiving mean annual precipitation (m.a.p) of 662mm (Schulze, 1997; Rutherford *et al.* 2006a; Weiersbye *et al.* 2006). Mean annual precipitation fluctuates between years with variation of $\pm 165.5 - \pm 198.6$ mm from the mean (Weiersbye *et al.* 2006). Extreme temperatures are a characteristic of this area with minimum and maximum temperatures reached in July (0-2 °C) and January (25-27.5 °C) respectively (Schulze, 1997; Rutherford *et al.* 2006a). Veld fires and frosts are frequent during winters with mean frost days between 150 -175 being recorded annually (Rutherford *et al.* 2006). The study area experiences high evaporation, which doubles and almost triples the amount of rainfall, received (Schulze, 1997), thus making the area dry resulting in frequent fires experienced in this area. The common features in the area include degraded areas with little vegetation cover (wastelands) and swampy lands flooded with waste from tailings dams (Weiersbye *et al.* 2006). Livestock production that includes cattle and game farming forms the major land uses supported by crop farming of maize and sunflower (Rutherford *et al.* 2006a; Weiersbye *et al.* 2006).

2.2 Slime dam selection and classification.

The tailings dams were differentiated in terms of physical appearance (age) and to a lesser extent by the chemistry of the substrate (Straker *et al.* 2007; Weiersbye *et al.* 2006; Witkowski and Weiersbye, 1998). Tailings dams that were used for the study are those that were previously used during the 1996 survey so as to enable a superimposed vegetation comparison of the same 100m transects over time. Not all the tailings dams that were sampled during the first survey could be sampled as most of them had been modified and some demolished thus only 5 dams (1 in Mponeng and 4 in Savuka) were selected for the survey (Figure 2; Appendix 7).

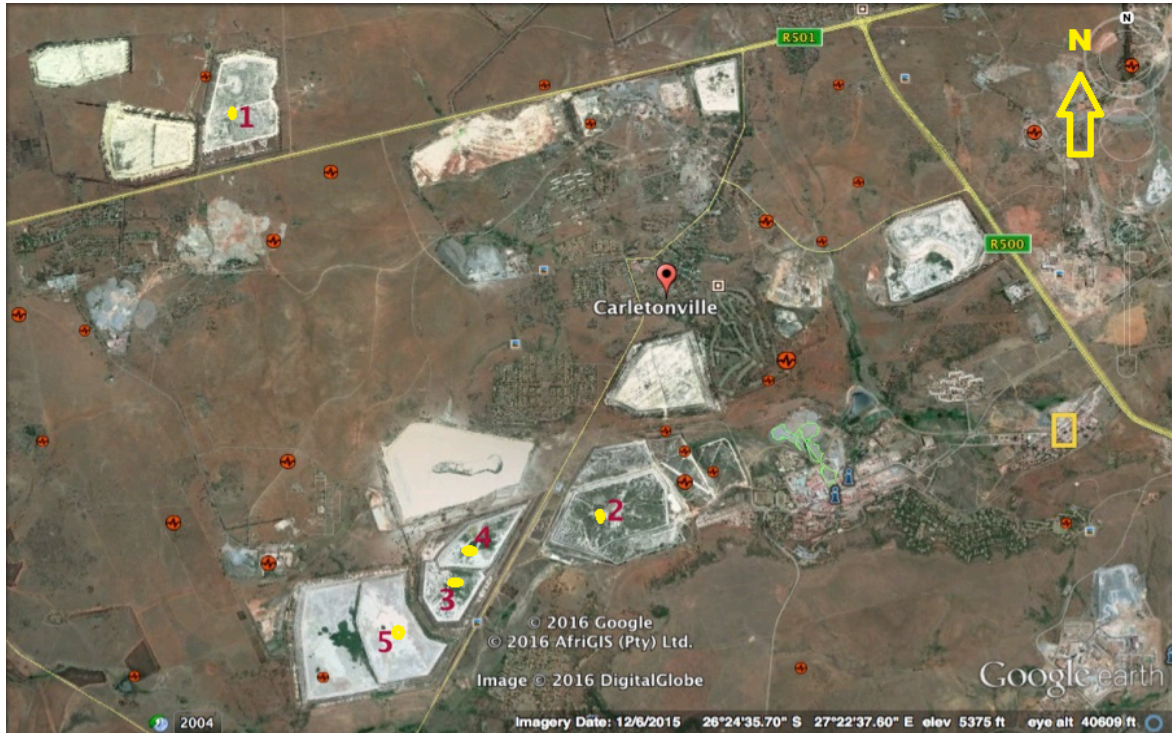


FIGURE 2: A photograph showing the sample area in Carletonville at the AngloGold Ashanti West Wits tailings dams. The numbered structures (with yellow dots) are tailings dams that were used in selecting the 10 sampling sites for the 2014 survey. (Source – Google Earth)

The age of the tailings dams could not be verified but differences in vegetation composition and soil (tailings colour) was used to differentiate the age of dams. It was assumed that the young dams were those that had greyish soils across all the slopes while the medium aged showed greyish upper slopes with red bottom made of sand. Dams that were regarded as old dams, which looked red-orange in colour across all substrates, are in an oxidation state. The current activity at each dam (active or dormant) was used to classify the tailings dams into different classes.

According to the historical information that was obtained from the contractors, all the dams had not been vegetated and ameliorated at least 8 years before the 2014 survey. The list of species that were previously introduced (intentionally) and naturally colonizing prior the 1996 survey were obtained from the list of species that were recorded during the first vegetation survey of Weiersbye *et al.* 2006. Poor record keeping made it difficult to establish the actual age of the current existing dams. As a result, the physical characteristics like soil colour and the vegetation composition structure were used to categorize the tailings dams. Other features that were used to classify the dams were the remains of old plantings and irrigation pipes (Witkowski and Weiersbye, 1998a). A total of 10 transects were chosen as sampling sites with nine of them having grassing attempts ceased prior the 1996/97 survey. Only transect/site seven showed recent evidence of repeated grassing attempts. These could be evidenced by the grasses that were occurring in complexes of mixed species, suggesting that some attempts had been repeated and failed (Weiersbye *et al.* 2006).

The physical and chemical properties in substrates were used to subdivide the slope into different classes (Figure 1; Weiersbye *et al.* 2006). In descending order of the substrates, the slope comprised of the flat tops, upper slope and berm, middle slope, lower berms and slope, retaining wall and the toe paddocks. Retaining walls are made of soil and rock which is mixed with slimes while a toe paddock is a small patch of grassland that is usually between 20 – 60 m wide surrounding the bottom of the dam. In most cases (particularly in young and active dams), toe paddocks are usually covered in slimes making them lower in pH (strongly acidic) and frequently damp (Witkowski and Weiersbye, 1998a). During the survey, it was difficult to separate the retaining walls and the lower slope as a result of the grey slimes covering the substrates making them appear as one thing. Thus during the survey, the results were amalgamated as lower slope & retaining wall. When slimes are deposited, their initial pH is alkaline (10 – 12). This is due to the chemicals that are used in the processing but after exposure to oxygen for some time, they are oxidised becoming acidic. Tailings dams that have been dormant and in-active for longer periods generally have pH which is strongly acidic (Weiersbye *et al.* 2006). Substrates that are far from the source of slimes (lower slope, retaining wall and toe paddock) have a pH that is acidic while those close to the top (upper slope and upper berms) are alkaline. On active dams, the top flat area is usually alkaline but may become acidic as a result of oxidation especially on in-active dams.

2.3 Sampling methods

A list of species that were intentionally introduced, naturally colonizing and persisting on the tailings dams prior the 1996/97 survey was obtained from the compiled list in Weiersbye *et al.* 2006 publication (Comparison study). Information regarding the last vegetating trials was gathered from the contractor (Brian Dawson) who was onsite and vegetation reports (Weiersbye and Witkowski, 1998 – unpublished) to AngloGold Ashanti. A replicate survey of 100m line transects across the 10 different sites occurring on five tailings dams were done during winter (July 2014) for two weeks. The line transects were identified and marked using the transportation pipes on the slopes (mostly on the corner of the dam) as reference starting points (the method used in during the 1996 survey) (Figure 3). Ten transects that were selected occurred on at least five separate tailings dams with each aspect represented (Appendix 1) in selecting sites. Approximately 70 different slopes with equal number of toe paddocks were thoroughly assessed during the survey across the 10 sites, particularly on the toe paddocks and lower slope & retaining walls.

The survey comprised of small-scale vegetation cover assessments, identification and classification of the vegetation structure into different functional groups (grasses, forbs and herbs, trees and shrubs) and species composition (frequency of each family and species) on the 70 slopes. All the data that were recorded from the 100m belt transects were categorically separated into 7 substrates on the

tailings dam (Figure 1). The frequency of each species present on the tailings dams was recorded and for species that could not be identified in the field, representative specimens were collected and pressed for identification. Specimens that were collected were identified using plant guides of Coates-Palgrave (1996), Retief and Herman (1997) and making a comparison with the specimens at the University of Witwatersrand APES C.E. Moss Herbarium.

Plant vegetation cover was estimated using the visual estimation method within 100m line transects. This involved walking along each substrate horizontally marking 5 m rectangular plots and using visual estimation to score the overall percentage vegetation cover within each plot. Overall vegetation cover referred to the total cover of all species without singling out each species.



FIGURE 3: Photographs showing examples of the study sites, as well as the pipes that were used as referral points on each site in marking the 100m belt transects on the tailings dams. (Top Left – Site 2; Top Right – Site 8; Bottom Left – Site 6 7 Bottom Right – Site 9). These were superimposition of the 1996/97 transects.

Soil samples that were collected from cut boxes between 10-20cm deep (Figure 4) from the 70 slopes across the sites were packed into small polyethylene plastics for transportation. Soil samples were kept in the cold storage room to avoid development of fungi. The samples were later analyzed for conductivity, salinity, pH and temperature using standard methods of Anderson and Ingram, (1993), organic carbon (Walkley- Black) (Jackson, 1973) and macronutrients (Nitrogen, Carbon, Sulphur) (Chapman and Pratt, 1961)

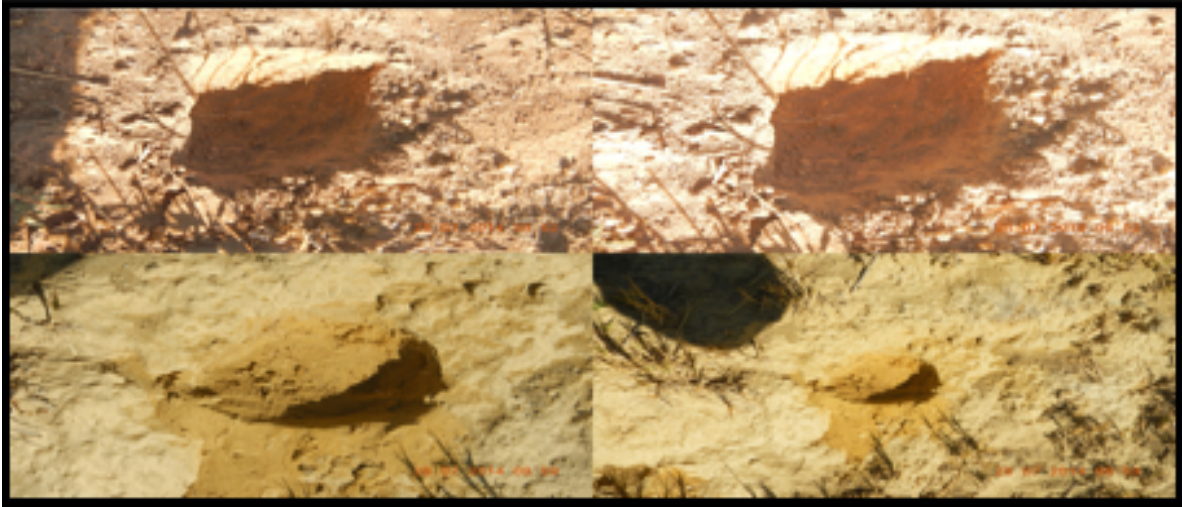


FIGURE 4: A photographic collage showing samples of 20cm shallow holes that were dug on each substrata across the sites of the surveyed tailings dams for soil sample collection.

2.4 Data classification

All the varieties of different species that were recorded and identified in the 100m belt transect survey (n=51) were separated according to their occurrence frequency (in percentage) overall across the 10 sites, between dams of different age (young, medium and old) and per substrate class. The relative frequency and number of species per family on each substrate and across the sites was also calculated during the vegetation survey. The identified species during the survey were further categorized into either being, (i) indigenous to S.A or alien including the alien species, (ii) naturally colonizing, persists or to have been intentionally introduced prior the 1996 survey, (iii) annual or perennial habit, (iv) monocotyledons and dicotyledons and (v) according to their growth forms (trees, shrubs, herbs and forbs and grasses). For study purposes, persisters were considered to be plants that were present before the tailings dam construction (list obtained from the initial survey of 1996/97) while natural colonizers were those that were present on the substrates solely, or on top of being present on toe paddocks or retaining walls (Weiersbye *et al.* 2006). Non-woody species that were occurring on the retaining walls were all categorized as natural colonizers.

2.5 Data analysis

Data were analysed by Univariate ANOVA tests, using IBM SPSS Statistics version 22 to test if there were any differences in the variables (pH, EC, Eh, Nitrogen, Carbon, Sulphur, organic carbon, species richness and vegetation cover) across the ten sites and five dams. Pairwise and Tukey's comparison tests were used for finer scale differences between sites and substrates.

CHAPTER 3

RESULTS

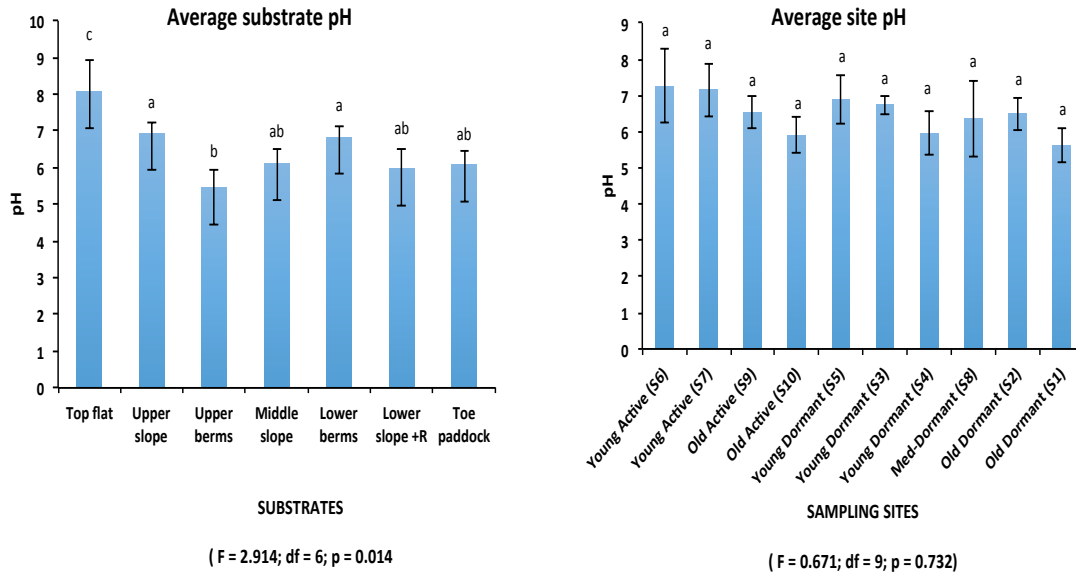


Figure 5: Mean (+ S.E.) substrate pH left (substrates ordered from top to the bottom) and site pH right (dams numbered from young active to old dormant) from the collected soils samples. Different superscript letters above the bars indicate significant differences between substrates and then sampling sites.

3.1 Average substrate pH

There were significant differences in pH ($F = 2.914$; $df = 6$; $p = 0.014$) (Appendix 4) across the vertical substrates and between alkaline and acidic substrates ($F = 22.523$; $df = 5$; $p < 0.001$) (Appendix 6). The top flat areas had high alkaline pH, while the upper slope and lower berms were neutral in pH (Appendix 2). Middle slope, Toe paddock, Lower slope & retaining wall and Upper berms were all acidic in that order of increasing acidity (Appendix 2) towards lower pH values. The top flat areas were generally different to all other substrates and showed a decreasing pattern of pH from the top flat area to the toe paddock becoming more acidic (trend varies though between old & young dams as well as between active & dormant dams) (Figure 5 and Appendix 2).

3.1.1 Average site pH

Overall, pH did not vary across the sites ($F = 0.671$; $df = 9$; $p = 0.732$) (Appendix 5). The Old dormant (S1), Old Active (S10) and Young dormant (S4) were acidic in that order of acidity towards being neutral and alkaline (Appendix 1). The Medium dormant (S8), Old dormant (S2), Old active (S9), Young dormant (3) and Young dormant (5) showed a shift from being acidic to neutral while the Young active 7 and 6 were alkaline respectively (Appendix 2).

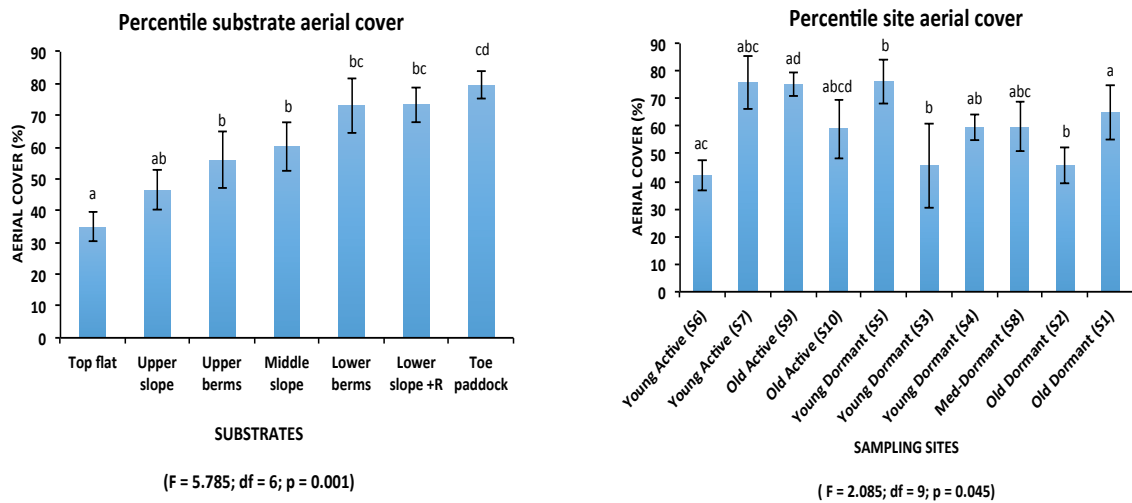


Figure 6: Mean (+ S.E.) substrate plant vegetation cover left (substrates ordered from top to the bottom) and site plant vegetation cover right (dams numbered from young active to old dormant) from the collected soils samples. Different superscript letters above the bars indicate significant differences between substrates and then sampling sites.

3.2 Percentage plant vegetation cover

Plant vegetation cover varied significantly among the substrates ($F = 5.785$; $df = 6$; $p = 0.001$) (Appendix 4), across the sampling sites ($F = 2.085$; $df = 9$; $p = 0.045$) (Appendix 5) and between alkaline and acidic substrates ($F = 2.528$; $df = 5$; $p = 0.038$) (Appendix 6). More of the variation was noted between substrates than across the sites (Figure 6) and could be deduced from the p-values (Appendix 4 and 5). Among substrates, generally high vegetation cover was recorded on berms and toe paddocks, which are flat surfaces (Weiersbye *et al.* 2006; Appendix 2). The lower slope and retaining walls occupied the second category of being substrates with high plant vegetation cover while the upper slope and top flat areas had lower vegetation cover in that respective order. By classifying the substrates into two pH classes ($pH < 6$ and $pH > 6$), toe paddocks of $pH < 6$ had higher plant vegetation cover followed by the slopes < 6 and tops and berms with $pH > 6$ (Appendix 3). Low vegetation cover was recorded on slopes ($pH > 6$) and tops and berms $pH < 6$.

Across the sampling sites, plant vegetation cover was high on Young dormant (S5), Old dormant (S2) and Young dormant (S3) respectively (Figure 6). The old dormant (S10), Med-dormant S8, Young Active (S7) and Young dormant (S4) had satisfactory vegetation cover which was slightly above average cover in that descending order. Low plant vegetation cover was recorded on the Old active (S9), Young active (S6) and Old dormant (S1) (Figure 6).

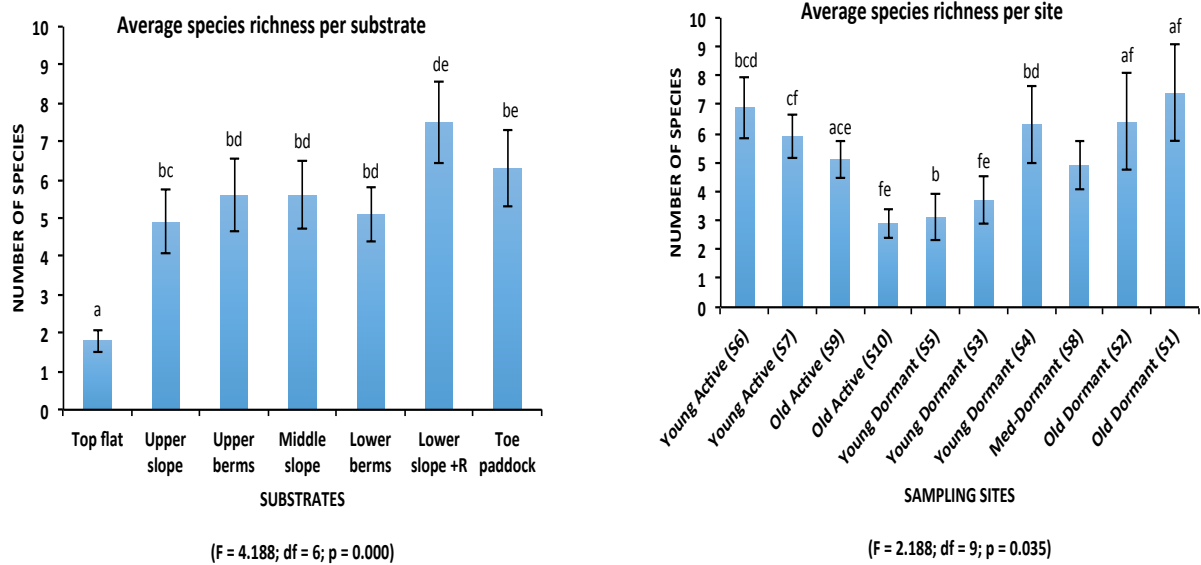


Figure 7: Mean (+ S.E.) substrate species richness, left (substrates ordered from top to the bottom) and site mean species richness right (dams numbered from young active to old dormant) from the collected soils samples. Different superscript letters above the bars indicate significant differences between substrates and then sampling sites.

3.3 *Species richness*

The number of species significantly differed among substrates ($F = 4.188$; $df = 6$; $p = 0.000$) (Appendix 4), across the sampling sites ($F = 2.188$; $df = 9$; $p = 0.035$) (Appendix 5) and no variation was recorded between acidic and alkaline substrates ($F = 1.941$; $df = 5$; $p = 0.100$) (Appendix 6). More variation was recorded among substrates compared to the sites (Appendix 4 and 5; Figure 7). The highest species richness was recorded on the lower slope & returning wall, toe paddock, middle slope and upper and lower berms respectively, while top flat had the least number of species (Appendix 2). Old Active (S10) had a high number of species overall while the Old dormant (S1), Old active (S9), Young active (S7), Old dormant (S2) and Young dormant (S3) had average species richness respectively. Low species richness was recorded on the Young active (S6), Young dormant (S5) and (S4) in that decreasing order of dominance (Appendix 2; Figure 7).

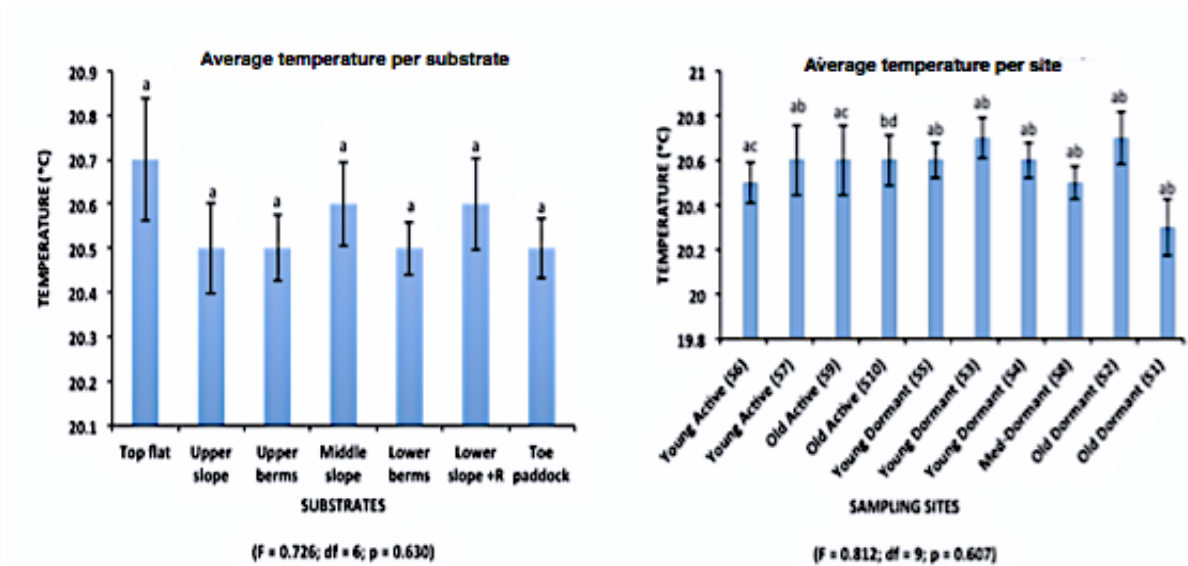


Figure 8: Mean (+ S.E.) substrate temperature (°C), left (substrates ordered from top to the bottom) and site site mean temperature (°C) right (dams numbered from young active to old dormant) from the collected soils samples. Different superscript letters above the bars indicate significant differences between substrates and then sampling sites.

3.4 Temperature

Temperature showed no significant variation among substrates ($F = 0.726$; $df = 6$; $p = 0.630$) (Appendix 4) and across the sites ($F = 0.812$; $df = 9$; $p = 0.607$) (Appendix 5) but between substrates of ($pH < 6$ and $pH > 6$), there were significant variations ($F = 2.470$; $df = 5$; $p = 0.042$) (Appendix 6). Most of the substrates, which includes the Upper slope, Lower berms, Lower slope & retaining wall and Toe paddock had temperature within the same range (20.5°C) while the top flat and middle slope were slightly higher ($\pm 2^{\circ}\text{C}$) and upper berms low in temperature (Appendix 2). Only the Young active (S6) and Old dormant (S10) which recorded relatively higher and lower temperatures respectively, compared to other sites significantly differed with the other sites (Appendix 2, Figure 8), while the other sampling sites had temperature within the same range between $20.5 - 20.6^{\circ}\text{C}$. Relatively high temperature was recorded on tops and berms ($pH > 6$), slopes ($pH > 6$) and Toe paddock ($pH > 6$) while Toe paddock ($pH < 6$), tops and berms ($pH < 6$) and slopes ($pH < 6$) had low temperatures in that respective order of decreasing to the least (Appendix 3).

Table 1: Average percentage carbon recorded from soil samples that were collected on all substrates of each sampling site (sites listed from young active to old dormant) on a mine complex (AngloGold Ashanti gold tailings) in the Carletonville area in the North West Province

Sites	Young Active (S6)	Young Active (S7)	Old Active (S9)	Old Active (S10)	Young Dormant (S5)	Young Dormant (S3)	Young Dormant (S4)	Med-Dormant (S8)	Old Dormant (S2)	Old Dormant (S1)	Mean of Means
Site Mean (%)	0.47 ^{ab}	0.79 ^{ab}	0.37 ^{bc}	0.71 ^{ab}	0.57 ^{ab}	0.55 ^{ab}	0.44 ^{ab}	0.48 ^{ab}	0.90 ^{ad}	0.62 ^{ab}	0.59
Standard Error	0.09	0.35	0.04	0.16	0.14	0.15	0.11	0.09	0.20	0.15	
S.E of Means						0.053					
DF						9					
F Value						0.994					
P Value						0.455					

Different superscript letters after the means indicate significant differences between sampling sites.

Table 1a: Average percentage carbon recorded from soil samples that were collected on all substrates of each sampling site (substrates listed from the top to the bottom) on a mine complex (AngloGold Ashanti gold tailings) in the Carletonville area in the North West Province .

Substrate	Substrate Mean (%)	Standard Error	S.E of Means	DF	F Value	P Value
Top flat	0.47 ^{ab}	0.11				
Upper slope	0.45 ^{ab}	0.10				
Upper berms	0.39 ^{ac}	0.07				
Middle slope	0.56 ^{abe}	0.14	0.053	6	1.762	0.122
Lower berms	0.60 ^{abe}	0.10				
Lower slope & retaining wall	0.80 ^{bde}	0.24				
Toe paddock	0.86 ^{ef}	0.15				
Mean of Means	0.59					

Different superscript letters after the means indicate significant differences between substrates.

3.5 Carbon

There were no variations in the percentage carbon within substrates ($F = 1.762$; $df = 6$; $p = 0.122$) (Appendix 4, Table 1a), across the sites ($F = 0.994$; $df = 9$; $p = 0.455$) (Appendix 5, Table 1) and alkaline and acidic substrates ($F = 1.378$; $df = 5$; $p = 0.244$) (Appendix 6). The substrates overall had low percentage carbon but toe paddock and lower slope & retaining wall had relatively higher carbon content compared to other substrates (Appendix 2, Table 1a). Lower berms and middle slopes had average percentage carbon while relatively low percentage carbon was recorded on top flat, upper slope and upper berms following that order of decrease. The Old dormant (S2), Young active (S7), Old active (S10) and Old dormant (S1) were high in carbon percentage in that order from the highest to the least (Appendix 2, Table 1). Relatively average carbon levels were recorded on Young dormant

(S5) and (S3) while Med-dormant (S8), Young active (S6), Young dormant (S4) and Old active (S9) resembled low percentage carbon substrates (Appendix 2). Toe paddocks with (pH >6 and pH <6) had higher percentage carbon while slopes (pH >6) and tops and berms (pH<6) were average in carbon levels (Appendix 3). Slopes (pH <6) and Tops and berms (pH>6) recorded the lowest carbon percentage amongst the substrates of different pH categories.

Table 2: Average percentage organic carbon recorded from soil samples that were collected on all substrates of each sampling site (sites listed from young active to old dormant) on a mine complex (AngloGold Ashanti gold tailings) in the Carletonville area in the North West Province.

Sites	Young Active (S6)	Young Active (S7)	Old Active (S9)	Old Active (S10)	Young Dormant (S5)	Young Dormant (S3)	Young Dormant (S4)	Med-Dormant (S8)	Old Dormant (S2)	Old Dormant (S1)	Mean of Means
Site Mean (%)	0.32 ^{ad}	0.58 ^{ab}	0.25 ^{ad}	0.49 ^{ab}	0.47 ^{ab}	0.30 ^{ad}	0.33 ^{ad}	0.32 ^{ad}	0.74 ^{bc}	0.55 ^{ab}	0.43
Standard Error	0.07	0.28	0.03	0.12	0.15	0.11	0.12	0.12	0.15	0.15	
S.E of Means							0.046				
DF							9				
F Value							1.209				
P Value							0.307				

Different superscript letters after the means indicate significant differences between sampling sites.

Table 2a: Average percentage organic carbon recorded from soil samples that were collected on all substrates of each sampling site (substrates listed from the top to the bottom) on a mine complex (AngloGold Ashanti gold tailings) in the Carletonville area in the North West Province.

Substrates	Substrate Mean (%)	Standard Error	S.E of Means	DF	F Value	P Value
Top flat	0.26 ^{ac}	0.09	0.046	6	2.717	0.021
Upper slope	0.28 ^{ab}	0.08				
Upper berms	0.25 ^{ad}	0.07				
Middle slope	0.50 ^{aef}	0.11				
Lower berms	0.38 ^{aef}	0.09				
Lower slope & retaining wall	0.67 ^{cef}	0.19				
Toe paddock	0.68 ^f	0.13				
Mean of Means	0.43					

Different superscript letters after the means indicate significant differences between substrates.

3.6 Organic carbon

Percentage organic carbon showed significant variation between substrates ($F = 2.717$; $df = 6$; $p = 0.021$) (Appendix 4, 2a) but it did not differ across the 10 sampling sites ($F = 1.209$; $df = 9$; $p = 0.307$) (Appendix 5, Table 2) and between alkaline and acidic substrates ($F = 1.881$; $df = 5$; $p = 0.110$) (Appendix 6). The toe paddock and lower slope & retaining wall had higher organic carbon content respectively. While the upper slope had average levels of organic carbon, all the other substrates had relatively low percentage organic carbon with the upper berms having the least carbon content (Table 2a; Appendix 2). Old dormant (S2), Young active (S7) and Old dormant (S1) had percentage organic carbon levels that were above average while the other sampling sites were below an average threshold (Appendix 2, Table 2). Although there were no variations between alkaline and acidic substrates (Appendix 2), Tops and berms with ($pH > 6$ and $pH < 6$) and slopes with ($pH > 6$) had higher percentage of organic carbon while the lowest amount of organic carbon was recorded on the Toe paddock ($pH > 6$).

Table 3: Average percentage sulphur recorded from soil samples that were collected on all substrates of each sampling site (sites listed from young active to old dormant) on a mine complex (AngloGold Ashanti gold tailings) in the Carletonville area in the North West Province.

Sites	Young Active (S6)	Young Active (S7)	Old Active (S9)	Old Active (S10)	Young Dormant (S5)	Young Dormant (S3)	Young Dormant (S4)	Med-Dormant (S8)	Old Dormant (S2)	Old Dormant (S1)	Mean of Means
Site Mean (%)	0.39 ^a	0.17 ^a	0.17 ^a	0.37 ^a	0.18 ^a	0.14 ^a	0.45 ^a	0.34 ^a	0.11 ^a	0.45 ^a	0.28
Standard Error	0.16	0.04	0.03	0.15	0.04	0.03	0.28	0.11	0.03	0.33	
S.E of Means							0.049				
DF							9				
F Value							0.754				
P Value							0.658				

Different superscript letters after the means indicate significant differences between sampling sites.

Table 3a: Average percentage sulphur recorded from soil samples that were collected on all substrates of each sampling site (substrates listed from the top to the bottom) on the AGA Carletonville.

Substrates	Substrate Mean (%)	Standard Error	S.E of Means	DF	F Value	P Value
Top flat	0.28 ^b	0.02	0.049	6	0.687	0.661
Upper slope	0.18 ^b	0.02				
Upper berms	0.25 ^b	0.003				
Middle slope	0.40 ^b	0.01				
Lower berms	0.15 ^b	0.01				
Lower slope & retaining wall	0.44 ^b	0.02				
Toe paddock	0.24 ^b	0.01				
Mean of Means	0.28					

Different superscript letters after the means indicate significant differences between substrates.

3.7 Sulphur

There were no variations in sulphur content between substrates ($F = 0.687$; $df = 6$; $p = 0.661$) (Appendix 4, Table 3a) and across the 10 sampling sites ($F = 0.754$; $df = 9$; $p = 0.658$) (Appendix 5, Table 3). Alkaline and acidic substrates showed no significant differences ($F = 1.353$; $df = 5$; $p = 0.752$) in percentage sulphur content (Appendix 6). Overall the substrates had low sulphur levels but relatively lower Figures were recorded on the upper slope and lower berms while lower slope & retaining wall and middle slope had significantly high sulphur content (Appendix 2). Across the sampling sites, only Old dormant (S1) and Young dormant (S4) had relatively high content of sulphur while Old dormant (S2) and Young dormant (S3) recorded lowest percentage sulphur respectively (Appendix 2, Table 3). Slopes of $pH < 6$ had higher sulphur content while toe paddocks $pH < 6$ had the lowest sulphur levels recorded and the other substrates were in the same rang (0.2 – 0.3%) with low percentage sulphur (Appendix 3)

Table 4: Average percentage nitrogen recorded from soil samples that were collected on all substrates of each sampling site (sites listed from young active to old dormant) on a mine complex (AngloGold Ashanti gold tailings) in the Carletonville area in the North West Province

Sites	Young Active (S6)	Young Active (S7)	Old Active (S9)	Old Active (S10)	Young Dormant (S5)	Young Dormant (S3)	Young Dormant (S4)	Med-Dormant (S8)	Old Dormant (S2)	Old Dormant (S1)	Mean of Means	
Site Mean (%)	0.041 ^a	0.039 ^a	0.00 ^a	0.019 ^a	0.041 ^a	0.013 ^a	0.010 ^a	0.007 ^a	0.041 ^a	0.024 ^a	0.024	
Standard Error	0.027	0.027	0.00	0.012	0.026	0.010	0.010	0.006	0.017	0.010		
S.E of Means							0.005					
DF							9					
F Value							0.921					
P Value							0.513					

Different superscript letters after the means indicate significant differences between sampling sites.

Table 4a: Average percentage nitrogen recorded from soil samples that were collected on all substrates of each sampling site (substrates listed from the top to the bottom) on a mine complex (AngloGold Ashanti gold tailings) in the Carletonville area in the North West Province

Substrates	Substrate Mean (%)	Standard Error	S.E of Means	DF	F Value	P Value
Top flat	0.025 ^b	0.019	0.005	6	0.703	0.648
Upper slope	0.021 ^b	0.018				
Upper berms	0.004 ^b	0.003				
Middle slope	0.020 ^b	0.009				
Lower berms	0.019 ^b	0.008				
Lower slope & retaining wall	0.039 ^b	0.019				
Toe paddock	0.037 ^b	0.0014				
Mean of Means	0.024					

Different superscript letters after the means indicate significant differences between substrates.

3.8 Nitrogen

Percentage nitrogen between substrates ($F = 0.703$; $df = 6$ $p = 0.648$) (Appendix 4, Table 4a), across sites ($F = 0.921$; $df = 9$; $p = 0.513$) (Appendix 5, Table 4) and between alkaline and acidic substrates ($F = 0.531$; $df = 5$; $p = 0.436$) (Appendix 6) showed no significant variation. The lower slope & retaining wall and the toe paddock had a relatively higher nitrogen content ranging between 0.37 – 0.39% while the upper berms had the lowest nitrogen levels (Table 4). Sampling sites Old dormant (S2), Young dormant (S5), Young active (S6) and Young active (S7) had relatively slightly higher nitrogen levels compared to other sites while Old active (S9) had the least percentage nitrogen (Appendix 2). Toe paddock with $pH > 6$ and $pH < 6$ and slopes $pH < 6$ had higher nitrogen content respectively (Appendix 3) while overage to low nitrogen levels were recorded on slopes $pH > 6$, Tops and berms $pH < 6$ and Tops and berms respectively.

Table 5: Mean (+ S.E.) electrical conductivity (EC) recorded from soil samples that were collected on all substrates of each sampling site (sites listed from young active to old dormant) on a mine complex (AngloGold Ashanti gold tailings) in the Carletonville area in the North West Province .

Sites	Young Active (S6)	Young Active (S7)	Old Active (S9)	Old Active (S10)	Young Dormant (S5)	Young Dormant (S3)	Young Dormant (S4)	Med-Dormant (S8)	Old Dormant (S2)	Old Dormant (S1)	Mean of Means
Site Mean ($\mu\text{S}/\text{cm}$)	649.3 ^a	665.7 ^a	905.0 ^a	494.3 ^a	470.1 ^a	648.6 ^a	882.6 ^a	214.5 ^a	394.1 ^a	780.0 ^a	610.4
Standard Error	251.7	240.4	330.4	141.6	221.3	296.7	362.7	24.8	161.9	278.6	
S.E of Means											77.762
DF											9
F Value											0.771
P Value											0.644

Different superscript letters after the means indicate significant differences between sampling sites.

Table 5a: Mean (+ S.E.) electrical conductivity (EC) recorded from soil samples that were collected on all substrates of each sampling site (substrates listed from the top to the bottom) on a mine complex (AngloGold Ashanti gold tailings) in the Carletonville area in the North West Province

Substrates	Substrate Mean ($\mu\text{S}/\text{cm}$)	Standard Error	S.E of Means	DF	F Value	P Value
Top flat	756.5 ^b	196.8	77.762	6	1.071	0.389
Upper slope	904.1 ^b	274.5				
Upper berms	485.7 ^b	150.2				
Middle slope	649.3 ^b	215.8				
Lower berms	752.8 ^b	266.4				
Lower slope & retaining wall	396.1 ^b	118.3				
Toe paddock	328.4 ^b	162.1				
Mean of Means	610.4					

Different superscript letters after the means indicate significant differences between substrates.

3.9 Electrical conductivity (EC)

Electrical conductivity (EC) was high on the upper slope, top flat area, and lower slope and middle slope respectively (Table 5a). The upper berms, lower slope & retaining wall and toe paddock showed low electrical conductivity but no significant variation was recorded within the substrates ($F = 1.071$; $df = 6$; $p = 0.389$) (Appendix 4). There were no significant differences across the sampling sites ($F = 0.771$; $df = 9$; $p = 0.644$) (Appendix 5, Table 5) and between substrates of $pH > 6$ and $pH < 6$ ($F = 0.982$; $df = 5$; $p = 0.436$). The old active (S9) and young dormant (S4) recorded the highest electrical conductivity while the med- dormant (S8) had the lowest Ec. Other sampling sites were within the same range between 395 – 660microns (Table 5). Overall slopes with $pH > 6$ showed higher electrical conductivity together with tops and berms $pH < 6$ and tops and berms $pH > 6$ respectively. The toe paddocks $pH > 6$ had the lowest electrical conductivity.

Table 6: Percentages of naturally colonizing, persisting and introduced plant species on each substrate class for the sampled tailings dams. Values in parentheses are the actual number of taxa identified (species, subspecies and varieties, $n = 51$).

Slope	No. of species	Establishment			Origin		Total no. of species
		Natural	Intentionally introduced	Persisters	Indigenous	Alien	
Tops and berms ($pH > 6.0$)	21	47.6 (10)	47.6 (10)	4.8 (1)	52.4 (11)	47.6 (10)	9
Tops and berms ($pH < 6.0$)	22	50.0 (11)	40.9 (9)	9.1 (2)	59.1 (13)	40.9 (9)	11
Slopes ($pH > 6.0$)	28	64.3 (18)	35.7 (10)		50.0 (14)	50.0 (14)	8
Slopes ($pH < 6.0$)	28	53.6 (15)	39.3 (11)	7.1 (2)	53.6 (15)	46.4 (13)	9
Toe paddock ($pH > 6.0$)	18	66.6 (12)	44.4 (8)		50.0 (9)	50.0 (9)	7
Toe paddock ($pH < 6.0$)	28	57.1 (16)	32.1 (9)	3.6 (1)	57.1 (16)	42.9 (12)	10
TOTAL	51	64.7 (33)	27.5 (14)	7.8 (4)	54.9 (28)	45.1 (23)	14

* The number of species (No. of species) referred to in the table are different species recorded per substrate thus 51 refers to the overall number of different species occurring across substrates of all the study sites.

*TOTAL in this context refers to the overall summation of different species occurring across all the substrates in all sites compared to values given inside table which are totals within each substrate.

3.10 Method of establishment (Natural versus Introduced)

The vegetation survey yielded a total of 51 species that belonged to at least 37 genera and 14 families (Appendix 1). Species that were identified were categorized according to their method of establishment (natural and introduced) as well as indigenous or alien. Approximately 64.7% of the plants recorded were natural colonizers (list in 1996/97 list of natural colonizers) while 27.5% of the plants comprised of those that were intentionally introduced prior the 1996/97 study with the remaining 7.8% consisting of persistent species dating from the former study (Table 6, Appendix 1). Asteraceae constituted about 30.3% of the natural colonizers dominated by the species of *Tagetes minuta* and *Bidens pilosa* while *Eragrostis* spp., *Pennisetum* spp. and *Andropogon* spp. dominated the natural colonizers of the Poaceae family, which contributed approximately 27.3%. The Poaceae (grass) family provided about 80% of the plant vegetation cover both on slopes and toe paddocks. Fabaceae, Anacardiaceae and Solanaceae families constituted the 18.3% of the natural colonizers with *Melilotus alba* and *Acacia* spp. (Fabaceae), *Rhus* spp (Anacardiaceae) and *Solanum* spp. (Solanaceae) dominating their respective families (Appendix 1). Intentionally introduced plants were dominated by *Cynodon dactylon*, *Hyparrhenia* spp and *Cortaderia jubata*, which belong to Poaceae family accounting for 57.1% of species in this category while Fabaceae and Tamaricaceae and Myrtaceae and Asphodelaceae constituted 14.3 % and 7.1% respectively in that order of frequency and abundance across the substrates (Appendix 1; Table 6). Persisting plants comprised of the *Aristida* spp. (Poaceae), *Senecio* spp. (Asteraceae) and *Acacia* spp. (Fabaceae).

3.11 Origin of plant species (Indigenous versus Alien)

The species that were recorded were also classified into indigenous and alien plants. Approximately 54.9% (28 species) of the plant species identified on the tailings dams were indigenous while 23 species (45.1%) of the plants identified (Table 6: Appendix 1) were alien species that were either intentionally introduced or naturally colonizing the tailings dams prior the 1996/7 surveys. The dominating families in alien plants included the Asteraceae (4 species), Fabaceae (4 species) and Poaceae and Anacardiaceae (3 species each) in that order of dominance in species abundance, frequency with Poaceae family providing high plant vegetation cover. The genera of *Rhus* spp, *Tamarix* spp, *Eragrostis* spp, *Solanum* spp and *Acacia* spp were the most represented in the alien plants respectively, while other representative families included the Myrtaceae (*Eucalyptus* spp), Tamaricaceae, Solanaceae (*Solanum* spp), Phytolaccaceae (*Phytolacca octandra*) and Verbenaceae (*Verbena bonariensis*) and Asclepiadaceae (*Asclepias fruticosa*) (Appendix 1; Table 6). Indigenous plants species identified were highly dominated by the grasses of the genera *Hyparrhenia*, *Andropogon*, *Pennisetum* and *Aristida* in that order of frequency and plant vegetation cover (Appendix 1) contributing to the 53.6% of Poaceae to the total indigenous species recorded. Asteraceae was also well represented constituting about 21.4% to the indigenous plants but only the *Senecio* spp were dominating the family. Other families recorded include the Asparagaceae (*Asparagus* spp), Asphodelaceae (*Aloe greatheadii*), Euphorbiaceae, Moraceae (*Ficus ingens*) and Fabaceae (*Tephrosia longipes*) (Appendix 1; Table 6).

Overall, naturally colonizing plants had a higher percentage ratio to intentionally introduced and persisting plants on the toe paddocks and slopes (pH > 6) while low percentage ratio was recorded on the tops and berms (pH > 6). The highest number of natural colonizing species was recorded on both

slopes of (pH > 6 and pH <6) and toe paddock with pH < 6 (Table 6: Appendix 1) while low species count on natural colonizers was recorded on tops and berms pH > 6. Intentionally introduced recorded a high percentage ratio on the tops and berms (pH >6 and pH <6), toe paddock (pH >6) and slopes (pH <6) while slopes (pH >6) had a low percentage ratio of intentionally introduced species to natural colonizers and persisters. The slopes (pH <6) and the tops and berms (pH >6), had a higher number of introduced species, while toe paddocks had the lowest number of intentionally introduced plant species (Table 6). Persisters had a high percentage ratio on the tops and berms (pH <6) and slopes (pH <6) while toe paddocks had low percentage ratio. Slope and tops and berms with (pH <6) had the highest number of persisting plants while slopes and toe paddocks (pH >6) recorded lower species count (Table 6: Appendix 1).

Indigenous species recorded high percentage ratio to alien on the tops and berms (pH <6), toe paddock (pH <6) and slopes (pH <6) while it was low on slopes (pH >6). The slopes and toe paddocks (pH <6) recorded the highest species count of indigenous plants with the toe paddock and tops and berms (pH > 6) recording the least number of indigenous species. Alien plant species recorded highest on the slopes (pH >6) > toe paddock (pH >6) > and tops and berms (pH >6), while the tops and berms (pH <6) had the lowest number of alien species (Table 6).

Table 7: Percentage of taxa occurring on particular substrates within plant families (n=14) during 2014 survey. Values in brackets are the actual number of species found.

Families	Substrates	Tops & berms (pH > 6) N = 21	Tops & berms (pH < 6) N = 22	Slopes (pH > 6) N = 28	Slopes (pH < 6) N = 28	Toepaddock (pH > 6) N = 18	Toepaddocks (pH < 6) N = 28	All substrates Combined N = 51
Anacardiaceae		4.76 (1)	9.1 (2)	3.57 (1)		5.56 (1)	3.57 (1)	5.88 (3)
Asclepiadaceae		4.76 (1)	4.54 (1)		3.57 (1)		3.57 (1)	1.96 (1)
Asparagaceae		4.76 (1)	9.1 (2)	7.14 (2)	7.14 (2)	11.11 (2)	7.14 (2)	3.92 (2)
Asphodelaceae							3.57 (1)	1.96 (1)
Asteraceae		14.32 (3)	13.6 (3)	21.43 (6)	10.71 (3)	22.22 (4)	21.43 (6)	19.62 (10)
Eurphorbiaceae			4.54 (1)					1.96 (1)
Fabaceae		9.52 (2)	4.54 (1)	10.71 (3)	14.3 (4)		14.3 (4)	9.8 (5)
Moraceae		4.76 (1)			3.57 (1)			1.96 (1)
Myrtaceae				3.57 (1)	3.57 (1)	5.56 (1)		3.92 (2)
Phytolaccaceae					3.57 (1)			1.96 (1)
Poaceae		47.6 (10)	45.5 (10)	39.3 (11)	42.86 (12)	44.43 (8)	32.14 (9)	35.3 (18)
Solanaceae				3.57 (1)		5.56 (1)	3.57 (1)	3.92 (2)
Tamaricaceae		4.76 (1)	4.54 (1)	7.14 (2)	7.14 (2)		7.14 (2)	5.88 (3)
Verbenaceae		4.76 (1)	4.54 (1)	3.57 (1)	3.57 (1)	5.56 (1)	3.57 (1)	1.96 (1)

* The total number of actual species per substrate according to families is given by the values in parentheses (N = 51).

3.12 Species classification

A total of 51 species that belonged to 14 families (Table 7) and 36 genera (Appendix 1) were recorded during the 2014 vegetation survey on the tailings dams. The dominant families were Poaceae, Asteraceae, Fabaceae, Anacardiaceae and Tamaricaceae in that respective order of frequency and species richness. Toe paddocks recorded the highest number of species particularly grasses (perennial and annual), forbs and herbs and trees (Appendix 1). Species of *Hyparrhenia hirta*, *Cynodon dactylon* and *Cortaderia jubata* dominated in the grasses while *Bidens pilosa*, *Tagetes minuta*, *Cirsium vulgare* and *Senecio consanguinensis* were most represented with the Asteraceae family on the toe paddocks. *Acacia mearnsi*, *A. karroo* and *M. alba* were the dominant species of Fabaceae while *Rhus* spp and *Tamarix* spp were difficult to distinguish into different subspecies.

While the toe paddocks recorded the highest number of species, the other substrates followed the same trend in family dominance but varied in the frequency and species richness as well as the plant vegetation cover (Appendix 1: Table 7) of each species per substrate. Tops and berms (pH >6) had the lowest number of species and followed the same pattern of dominance in the recorded families as the other substrates and the grass species were noted to have the highest percentage cover on this substrate compared to other substrates. The Anacardiaceae family was absent on slopes (pH <6) only while toe paddocks (pH >6) recorded no Fabaceae species. Asphodelaceae, Eurphorbiaceae and Phytolaccaceae genera were only present on the toe paddocks (pH <6), tops and berms (pH <6) and slopes (pH <6) respectively (Table 7). *Eucalyptus* genus, which belonged to the Moraceae family, was recorded on the tops and berms (pH >6) and slopes (pH <6) only while *Solanum* species only existed on the slopes and toe paddocks (pH >6).

Overall, most represented families were Poaceae, Asteraceae, Fabaceae, Anacardiaceae and Tamaricaceae (Table 7). Grass species of genus *Eragrostis*, *Hyparrhenia*, *Aristida* and *Pennisetum* had high number of species while *Cynodon dactylon* provided greater proportion of the plant vegetation cover. Asteraceae was dominated by genera *Senecio* with *T. minuta* and *B. pilosa* recording most frequently, while *Acacia* species represented the Fabaceae family. Only *Rhus* species were recorded in the Anacardiaceae family together with *Tamarix* spp resembling the Tamaricaceae family. Other families recorded included Asparagaceae (*Asparagus* spp), Solanaceae (*Solanum* spp), Myrtaceae (*Eucalyptus* spp), Moraceae (*Ficus* spp), Asclepiadaceae (*Asclepias fruticosa*), Asphodelaceae (*Aloe greatheadii*), Eurphorbiaceae (*Clutia monticola*), Phytolaccaceae (*Phytolacca octandra*) and Verbenaceae (*Verbena bonariensis*).

Table 8: Categorization of plants species recorded on the West Wits tailings dams as percentages. Values in parentheses are actual number of species found.

Substrates	Annual & Biennial herbs (excl. grasses)	Perennial & resprouting herbs & forbs (excl. grasses)	Annual & Biennial grasses	Perennial grasses	Shrubs & Trees	Total annuals	Total perennials
Tops & berms (pH > 6.0)	8.7 (2)	4.4 (1)	13.0 (3)	39.1 (9)	34.8 (8)	21.7 (5)	78.3 (18)
Tops & berms (pH < 6.0)	4.4 (1)	13.0 (3)	4.4 (1)	43.5 (10)	34.8 (8)	8.7 (2)	91.3 (21)
Slopes (pH > 6.0)	14.3 (4)	10.7 (3)	0.0 (0)	42.9 (12)	32.1 (9)	14.3 (4)	85.7 (24)
Slopes (pH < 6.0)	10.3 (3)	6.9 (2)	10.3 (3)	37.9 (11)	34.5 (10)	20.7 (6)	79.3 (23)
Toe paddocks (pH > 6.0)	15.8 (3)	5.3 (1)	5.3 (1)	42.1 (8)	31.6 (6)	21.1 (4)	78.9 (15)
Toe paddock (pH < 6.0)	17.9 (5)	7.1 (2)	7.1 (2)	28.6 (8)	39.3 (11)	25.0 (7)	75.0 (21)
All substrates combined	11.8 (6)	17.6 (9)	5.9 (3)	29.4 (15)	35.3 (18)	17.7 (9)	82.3 (42)

3.13

Perennials versus Annuals/Biennials

The study surprisingly recorded perennial species to be dominant on the tailings during the vegetation survey (Table 8) and a large proportion of them were deciduous in nature. Natural colonizing and persisting plants comprised the majority of the perennial plants while the short-lived perennials and annuals were mostly intentionally introduced (Table 8, Table 6 and Appendix 1). Recorded plant species showed that only a few species that are perennials and indigenous were intentionally introduced to the tailings dams of AngloGold Ashanti West Wits prior the 2014 survey.

Perennials which were comprised of shrubs and trees, grasses and herbs and forbs dominated slimes and constituted about 82.3 % while the annuals/biennials were mainly herbs and few grass making the remaining 17.7% (Table 8). Shrubs and trees formed majority of the perennials (42.9%) followed by perennial grasses (35.7%) and the least represented were perennial and resprouting herbs and forbs with 21.4 %. Most represented genera were *Rhus*, *Tamarix*, *Asparagus*, *Eucalyptus* and *Acacia* (shrubs and trees); *Eragrostis*, *Hyparrhenia* and *Andropogon* (grasses) and forbs/herbs of genera *Clusia* and *Medicago* (Appendix 1). Annual plant species were dominated herbs (66.7%) and grasses (33.3%) all contributing to the overall 17.7% of total annuals (Table 8). The existing annuals and biennials recorded on the tailings dams were species of *Bidens pilosa*, *Tagetes minuta*, *Circum vulgare*, and *Senecio* spp, (all herbs) and grass species of *Aristida adscensionis*, *Agrostis lachnartha* and *Pennisetum macrourum* in that respective order of dominance and frequency (Appendix 1).

Overall, perennials were more dominant on the tops and berms (pH < 6.0) and it was mostly grasses and herbs and forbs that formed greater part of the recorded species and vegetation cover on the tailings dams. The ratio in this substrate showed a disproportionality, as the annual species were very low and this pattern was commonly observed across all the substrates, except for the toe paddocks (pH < 6.0) where annuals constituted at least 25% of the recorded species (Table 8).

Table 9: Percentage occurrence of the monocotyledonous and dicotyledonous plant species found on the tailings dams. Values in parentheses are actual numbers of species and subspecies found

Substrates	Dicotyledons	Monocotyledons
Tops and berms (pH >6.0)	45.5 (10)	54.5 (12)
Tops and berms (pH <6.0)	45.5 (10)	54.5 (12)
Slopes (pH > 6.0)	51.9 (14)	48.1 (13)
Slopes (pH < 6.0)	48.1 (13)	51.9 (14)
Toe paddocks (pH > 6.0)	42.1 (8)	57.9 (11)
Toe paddock (pH < 6.0)	55.6 (15)	44.4 (12)
All substrates combined	58.8 (30)	41.2 (21)

3.14 Monocotyledons versus Dicotyledons

The tailings dams recorded a slightly higher number of dicotyledonous plants compared to monocotyledonous plant species (Table 9 and Appendix 1). Although Monocotyledons were overall low in numbers, they dominated majority (4 out of 6) of the substrates on the tailings dams particularly with grass species. Dicotyledons were noted to be to dominant on the slopes (pH > 6.0) and Toe paddock (pH < 6.0) and these mostly comprised of shrubs and trees as well as the forbs and herbs (Table 8). Asteraceae (33.3%), Fabaceae (16.7%) and Anacardiaceae (10%) were the dominant families in Dicotyledons plant species while Poaceae (85.7%) and Asparagaceae (9.5%) formed the majority of the Monocotyledons (Table 7 and Appendix 1). Interestingly, Anacardiaceae species were absent on the slopes (pH < 6.0) while other dicotyledons species including *Aloe greatheadii* (only present on the toe paddock with pH < 6.0), *Stoebe vulgaris* (recorded on tops and berms, pH > 6.0) and *Phytolacca octandra* (present on slopes with pH < 6.0) were noted to be occurring on particular substrates only (Appendix 1). Monocotyledons were fairly distributed across all the substrates of the slime and particularly grasses provided much of the plant vegetation cover on the slope.

3.15 Comparison between the 1996/97 and 2014 vegetation surveys

The vegetation survey of 2014 found fewer species compared to the 1996/97 survey, which recorded a high number of species (Weiersbye *et al.* 2006, Table 10 and Appendix 1) although there were differences in the total area covered with the former study sampling a smaller area. Both surveys found the families of Poaceae, Asteraceae, Fabaceae and Anacardiaceae to be dominant overall across the substrates in that order of dominance and abundance. Although the studies shared the same trends in families dominance, differences were noted in the percentage frequency of each family over time as grasses (Poaceae) almost doubled their population and cover while overall slight increase between 2.1 - 2.4% in percentage occurrence of Asteraceae and Anacardiaceae was recorded (Table 1). The Fabaceae family recorded a drop in the percentage by approximately 0.7% but still remained within the same range of frequency with the results obtained in the previous study. Approximately 27 families, 62 genera and about 100 species and subspecies were lost over the 17 years period from 1997 to 2014. Most of the major families lost include the intentionally introduced families of Chenopodiaceae (*Atriplex*, *Bassia* and *Chenopodium* spp), Amaranthaceae (*Amaranthus*, *Alternanthera*, *Gomphrena* spp) and Aizoaceae. Naturally colonizing plant species of genera *Ziziphus* and *Celtis* belonging to Rhamnaceae and Ulmaceae families were also formed

part of the list of species lost over this period. Other families that were lost over this 17 years period were amelioration; fertilization and vegetating of slimes stopped include Cucurbitaceae (n=6), Rubiaceae (n=6), Convolvulaceae (n=5), Ebenaceae (n=4) and Juncaceae (n=1) (Weiersbye *et al.* 2006 Appendix 1). The only new family recorded during the 2014 survey was the Moraceae that comprised species of *Ficus ingens* (Appendix 1) and the rest were present during 1996/97 studies. Overall, former study found 59 families while the later study recorded a total of 14 families with only 1 family being new colonizing the tops and berms (pH > 6.0) and slopes (pH < 6.0) (Appendix 1).

Indigenous species were notably high more than triple the amount of alien plant species recorded during the 1996/97 vegetation surveys while the later study yielded a ratio of almost 1:1 with indigenous plants exceeding the alien with only 9.8% (Table 6 and Table 10). But in general both studies recorded a higher number of indigenous to alien species although the recent survey showed an increase in alien species which is almost double the value recorded in the early study of Weiersbye *et al.* (2006). The dominance of families on acidic and alkaline substrates has changed over time. The previous survey showed that plant species followed the order of dominance in the sequence of Asteraceae>Poaceae>Fabaceae>Chenopodiaceae on acidic substrates while the recent vegetation survey reported the species to occur in the order of Poaceae>Fabaceae>Asteraceae>Anacardiaceae (Table 10). Alkaline substrates showed a shift in dominance between Fabaceae and Asteraceae where Asteraceae plant species have increased exceeding the Fabaceae species. From the previous survey, Anacardiaceae and Chenopodiaceae formed part of the dominant families on the tops, slopes and berms (pH >6) but these reduced in frequency as well as numbers with the later family being completely lost and Tamaricaceae comprising part of the dominant families (Table 10, Appendix 1).

Overall, perennials were noted to be dominating over annuals and biennials in total numbers in both cases of vegetation survey but changes in dominance on plant growth forms was recorded. The 1996/97 surveys concluded that woody to semi-woody species that comprised of forbs and herbs formed the majority of the species yet the recent survey reported a surprisingly increase in the grass species by 12.4%, shrubs and trees (17%) and a 50% decrease in forbs and herbs (Table 10). The percentage frequency for natural & persisting plant species slightly decreased over the 17 years period while intentionally introduced species recorded a 14.1% increase across the substrates (Table 10, Weiersbye *et al.* 2006 – Appendix 1). A total of 6 species were found to be common on all substrates of the slimes during the 1996/97 surveys with a similar figure recorded during the 2014 survey. But overall, a total of 12 species were commonly dominant, occurring on at least 85.7% of the substrates, and comprising mostly grasses (Appendix 9). Approximately 36 genera were recorded during the recent vegetation survey compared to the 98 that were found in 1996/97 study majority of the lost genera were those that had been intentionally introduced prior the 1996/97 survey (Appendix 1, Weiersbye *et al.* 2006 – Appendix 1). Both studies showed trends of species richness being high on toe paddock>slopes>tops and berms, substrates being low in nutrient content (shown by presence of some grasses and forbs) and recorded vegetation cover to be high on flat tops and berms (Weiersbye *et al.* 2006).

Table 10: Summary table showing a comparison of results obtained between the 1996/97 and the 2014 vegetation surveys that were done on a mine complex (Anglogold Ashanti gold tailings) in the Carletonville area in the North West Province.

Parameter	1996/97 survey results	2014 survey results
Number of species found	168 species in 765ha (0.22 spp./ha)	51 species in approx. 15ha (3.4 spp./ha)
Dominant species recorded	Poaceae 23.4% Asteraceae 17.2% Fabaceae 10.5% Anacardiaceae 3.8%	35.5% 19.6% 9.8% 5.9%
Number of families found	59 families	14 families
Origin of species	Indigenous 76.1% Alien 23.9%	54.9% 45.1%
Order of species dominance Tops, berms and slopes (pH < 6.0) Tops, berms and slopes (pH > 6.0)	Asteraceae>Poaceae>Fabaceae>Chenopodiaceae Poaceae>Fabaceae>Asteraceae>Anacardiaceae>Chenopodiaceae	Poaceae>Fabaceae>Asteraceae>Anacardiaceae Poaceae>Asteraceae>Fabaceae>Tamaricaceae
Species growth patterns	Perennials 84.6% Annuals / Biennials 15.4%	82.3% 17.7%
Method of establishment	Natural + Persisting species 86.6% Intentionally introduced 13.4%	72.5% 27.5%
Growth forms	Shrubs and trees 18.3% Forbs and herbs (perennials & annuals) 58.8% Grasses (perennials & annuals/biennials) 22.9%	35.3% 29.4% 35.3%
No. of common species on acidic and alkaline substrates.	6	12 (see appendix 9)
Vegetation cover	High	High
Species richness order of dominance	High	High
Nutrient content	Toe paddock > Slopes > Tops and berms Low across all substrates	Toe paddock > Slopes > Tops and berms Low across all substrates
No. of genera found	98	36

CHAPTER 4

4.1 DISCUSSION

The study yielded a lower number of plant species compared to the 1996/97 surveys and this decrease in species richness could be attributed to a number of factors. Prior the surveys of Weiersbye *et al.* (2006), revegetation attempts and several trials were done as dust and erosion control measures (Thatcher 1979; Weiersbye and Witkowski, 1998; Weiersbye *et al.* 2006) with series of grassing attempts being done at regular intervals between 1932 and 2006 (Weiersbye *et al.* 2006). These revegetation attempts together with ameliorative initiatives such as leaching, liming, fertilization and irrigation that were constantly recurring accounts to the high number of plant species that were recorded prior the 2014 survey. Grass species were mostly selected for revegetation of slimes as they could easily spread and provide basal cover that mitigates for wind and soil erosion (Blight, 1991). This came to a halt after the 1996/97 surveys as it was proved to be ecologically and economically unsustainable (Witkowski and Weiersbye 1998a,b, Weiersbye *et al.* 2006). The grass species which were being used provided temporary plant vegetation basal cover (Halliday, 1978) a short term measure (Blight, 1991) that required consistency to achieve successful long term erosion and dust control measures. The ceasure of these ameliorative activities could be one of the major reasons that resulted in significant reduction of the total number of species (Weiersbye and Witkowski, 1998) as tailings dams naturally does not support various forms of plant growth (Grime, 1979) except those that develops ecological adaptive tolerance (Bradshaw 1970; Mehary 1994) to the toxicity and poor nutrient content (O'Connor and Bredenkamp, 1997) of the slimes thus surviving through time to naturally colonize the tailings dams.

Greater proportion of the species that were lost between the two studies over the 17 years period comprised mostly of species that were intentionally introduced prior the 1996/97 (Table 10, Appendix 1 and Weiersbye *et al.* 2006 – Appendix 1). A similar trend of rapid decline in introduced species on tailings dams is common on tailings dams once amelioration is ceased (Weiersbye and Witkowski, 1998; Weiersbye *et al.* 2006). Majority of the introduced species during the early survey were herbaceous and weedy species that depended hugely on liming, fertilization and supplementary watering or irrigation (Weiersbye *et al.* 2006). Since amelioration stopped post the 1996/97 survey, this explains the decrease in forbs and herbs (herbaceous) plants and increase in grasses (Table 10, Appendix 1) during the 2014 survey. Grass species colonization confirms the low/poor nutrient content (particularly nitrogen) (O'Connor and Bredenkamp, 1997) recorded across the substrates during 2014. The existence of *Stoebe vulgaris* on site 2 could suggest the presence of high nitrogen availability (Roux, 1969) while the absence of *Cenchrus ciliaris* grass across several sites acts a reminiscent of poor nutrient content (O'Connor and Bredenkamp, 1997; Weiersbye *et al.* 2006). Only 2 *S. vulgaris* stumps were recorded across all the sites while *C. ciliaris* were recorded on several sites indicating the low nitrogen levels across the substrates and sites (Appendix 1).

Apart from the cessation of amelioration activities and adaptation failure, the decline in species richness could also be attributed to climatic variability and season of sampling. Changes in management of tailings dams by different contractors over this period could also have resulted in some species loss as they might have different species of preference to use as phytoremedial species (Weiersbye pers. comm.). Climatic predictions showed that temperatures have increased at least 1.5 times more than the global predictions of 0.65°C (IPCC, 2007; WIREs Clim Change 2014) over half a century. In South Africa, temperatures have

been reported to have increased by 0.13 °C from 1960 – 2003, with a further increase of 1.2 °C by 2020 (Kruger and Shongwe, 2004). Precipitation is anticipated to decline and become more erratic as well as unpredictable resulting in increased dry spell days (IPCC, 2007; WIREs Clim Change 2014). An estimated 5.4% decrease in precipitation is also predicted in South Africa by 2020 (Kruger and Shongwe, 2004) leading to high speculations that these high inter-annual & decadal variations might have had a significant role in the negative impacts felt particularly with ecosystems changes. Ecosystems and plant species are sensitive to slight changes in climatic variables (temperature, precipitation and rain days) (Bazzaz 1990, Jensen 2000 and IPCC 2007). So the fluctuations in the climatic variables over the period of study, could also have influenced the changes that have been recorded in the species composition as plants have different levels of tolerance and adaptation to disturbances. These climatic variations have been noted to be occurring at a faster rate than the rate at which species can adapt (IPCC, 2007; Hoffmann and Sgro, 2011; Merila and Hendry, 2013). This mismatch between the two rates has naturally resulted in species decline and some to extinction together with fragmentation of habitats and reduced productivity of ecosystems. Reduced ecosystems productivity leads to strong competition which also explains the loss of species particularly those that do well only in nutrient rich areas with lesser competition. The intermediate disturbance theory (IDT) allows for new species to colonize an area once a disturbance has occurred. The invasion of the area of study by invasive species could be a true reflection of disturbances that have been occurring in the area encouraging the colonization (Hoffmann and Sgro, 2011). This confirms the results of the 2014 vegetation survey, which shows a double increase in alien species while indigenous species are decreasing. Such invasive plants include the *Acacia mearnsii*; *Phragmites australis*, *Cortaderia jubata*, *Tamarix* and *Rhus* spp and these species exist on almost every site and on at least 50% of the substrates.

Changes in ecosystems structures as a result of disturbances can be illustrated in the shift in order of families between the 2 surveys (Table 10) where Asteraceae is displaced by Poaceae, loss of Chenopodiaceae and introduction of Tamaricaceae and Anacardiaceae as part of the dominant families yet symbolizing the decline in nutrient content of the sites as grasses colonize more of the substrates and sites (Grime, 1979; Weiersbye and Witkowski, 1998). Overall the two studies (1996/97 and 2014) shared the same trends of families dominating across the substrates, which is a distinctive ability of the species belonging to these families to be tolerant to the toxicity of heavy metals found on the tailings dams (Weiersbye *et al.* 2006). Several studies that have been done including that of Witkowski and Weiersbye, 1998b; Weiersbye *et al.* 1998 and Dye *et al.* 2005 found that hard-seeded legumes together with the *Rhus* species do not suffer heavily compromised growth under acidic conditions of the slimes or Acid Mine Drainage (AMD) (Weiersbye *et al.* 2006). This reaffirms the findings of the recent survey where woody species were noted to have increased double (Table 10) as they can adapt better to polluted soils of the slimes (Angus, 2005).

Majority of the species recorded were perennials that comprised of natural colonizers and persisting plant species occurring in great numbers on flat surfaces. These species occurred particularly on the south and west slopes with high moisture content and low temperatures. The most favoured substrates by plants included the tops & berms and toe paddocks, a trend previously identified in the 1996/97 study (Weiersbye *et al.* 2006). This could be as a result of high erosional activities occurring on the slopes (Weiersbye and Witkowski, 1998) while pH also influenced and contributed to the low number of species on the marginally acidic to alkaline (pH > 6) substrates (these substrates are also far from the seed sources on the ground) (Weiersbye *et al.* 2006). On sites that were located on active dams, the numbers of plant

species existing on the top substrates were also influenced by the slurry that was being frequently deposited. Deposition of fresh slimes frequently does not allow the oxidation of the tailings making them alkaline as well as accumulates the toxic components such as pyrite resulting in high E_c and low nutrient content. It is a combination of these conditions that create an inhospitable environment for plant growth on the young and active tailings dams. The naturally colonizing species formed much of the perennials and these were dominated by the woody and semi-woody species a familiar type of growth form within the locality (Bredenkamp and Brown, 1995a,b; Retief and Herman, 1997). This colonization of the tailings by woody and semi-woody species convincingly suggests that these are the potential plant growth forms for the rehabilitation of the tailings dams (Weiersbye *et al.* 2006).

Although natural colonizers and persisting plant species formed majority of the plant species found. Their actual contribution to vegetation basal cover was low in both studies (1996/97 and 2014) compared to intentionally introduced species that had lower number of species richness but contributed significantly to the total vegetation basal cover. Studies that have been done (Straker *et al.* 2006a, b) concludes that most of the persisting plant species on tailings dams are infected by arbuscular mycorrhizal (AM) fungi and it is the tolerance of these AM fungi to slimes that significantly contribute to the host plant's growth and survival in acidic slimes (Weiersbye *et al.* 1998; Weiersbye *et al.* 2006; Straker *et al.* 2006c). Overall, the slight decline in the natural species and increase in the introduced species could be accounted by the invasion of the invasive species (*Tamarix* spp., *Phragmites* spp., etc) that were introduced.

Trends that illustrate species distribution across the tailings dams show that some species are only identified to be occurring on particular substrates preferably the western facing slopes. This is because these western slopes have cooler temperatures and are usually high in moisture content encouraging plant growth. Preference in aspects is an indication of an adaptive physiological tolerance to fluctuations in variables and essentials for plant growth which include the availability of nutrients and differences in moisture content (Gaff and Ellis, 1974; Weiersbye *et al.* 2006). Grass species that include *Sporobolus* and *Eragrostis* are normally associated with high tolerance to dry conditions and occur on arid substrates particularly the east-facing slopes (Gaff, 1971; Weiersbye *et al.* 2006). Some plant species have been noted to develop tolerance to the saline and high conductivity nature of the slimes (Witkowski and Weiersbye, 1998a, Weiersbye *et al.* 2006) thus enabling them to naturally inhabit either the marginal acidic to alkaline ($pH > 6$ or $= 6$) substrates of the tailings dams. Such plant species include the *Tamarix* spp., which exhibit high levels of physiological tolerance to natural selection pressure (Mehary, 1994) which encompasses low essential macronutrients (Nitrogen, Potassium, Phosphorus, Magnesium and Calcium), high concentration of heavy metals and salinity (Weiersbye *et al.* 2006). Studies (Witkowski and Weiersbye, 1998; Weiersbye and Witkowski, 2002b) have shown that plant species occurring on tailings dams are able to maintain their regeneration potential but show signs of depressed seed viability and production levels when compared to those occurring on unpolluted soils (Weiersbye *et al.* 2006). *Rhus* species (particularly *R. lancea*) and the grasses *C. dactylon* and *H. hirta* have become commonly utilized for rehabilitation purposes because of their capability to vigorously grow in AMD yet maintaining high evapotranspiration rates (Dye *et al.* 2005) and ability to tolerate salinity as well as acidic environments respectively (Weiersbye *et al.* 2006).

The plant functional growth forms showed that shrubs and trees increased to almost double over the period. This is because most of the trees that were present prior to both studies have been reported to survive for long periods (a clear sign of physiological tolerance) (Weiersbye *et al.* 2006). Apart from the

already existing tree species, introduced tree species such as the Tamarix spp., Rhus spp., Acacia spp. and Eucalyptus spp. seemed to have adapted well on the tailings dams, resulting to the recorded increases. Grasses also increased during the same time, almost 1.5 times, mainly because they are adapted to the low nutrient conditions and their temporal nature (Witkowski and Weiersbye, 1998; Dharamraj *et al.* 1999; Angus, 2005). A total of 12 species were identified to be common across all the substrates and sites compared to six that were recorded in the former study. Most of these common species were alien introduced species that have been invading open spaces (Appendix 9).

4.2 CONCLUSION

The 2014 vegetation survey yielded a lower number of plant species (51 species) compared to the 1996/7 survey. Amongst these species, only six (6) were common to all substrates with an additional seven (7) occurring on at least 85.7% of the substrates. Approximately 66.7% of the species common to all substrates were grasses while the other seven common species comprised of shrubs & trees and herbs as well as small proportion of grasses (Appendix 9). The most represented families were Poaceae, Asteraceae, Fabaceae and Anacardiaceae in that order of dominance (a similar trend recorded in the 1996/97 survey). This result reaffirms the suggestion that was made by several studies that species of these families have developed excellent adaptive mechanisms which allows them to survive and vigorously grow in polluted soils of the tailings dams. Species listed in Appendix 8 summarizes the potential phytoremedial species that can be used for rehabilitation of similar gold tailings dams. This list was developed from the species that were exhibiting satisfactory progress of colonizing the tailings dams since the ameliorative initiatives were stopped post the 1996/97 survey till the 2014 vegetation survey. Majority of the species that were excellent colonizers have been noted to be indigenous species naturally occurring, but a remarkable improvement has been recorded with some alien species that were introduced prior the 1996/97 survey and have naturally colonized the tailings dams over the 17 years' period. Greater proportion of the species that were lost during the period between the two surveys were mainly herbaceous plants that were introduced prior the 1996/97 as most of them dependent on supplementary initiatives (liming, fertilization, leaching & irrigation) for their growth (Weiersbye and Witkowski, 1998). This explains why the 2014 survey recorded a 50% decrease in herbaceous plants while woody, semi-woody and grasses have almost doubled. All the 117 species that were lost, accounts for the decrease in 62 genera and 45 families that was recorded between the two surveys. A large proportion (82.3%) of the species colonizing were perennials, dominated by shrubs & trees, grasses and resprouting herbs & forbs. Annuals & biennials contributed to the remaining 17.7% with herbs dominating compared to annual grasses. Overall, the contribution of perennials to annuals between the two surveys did not change significantly although there was a 2.3% decrease in the former and a similar increase to the latter. An increase in the dominance by grasses is an indication of how these tailings maybe be suffering from poor nutritional value including macronutrients (particularly Nitrogen, Carbon & Organic carbon) as well as lack of organic matter. Basal vegetation cover recorded was noted to be high on flat surfaces which were not highly susceptible to erosion compared to slopes in both surveys. A comparison of the chemical composition between dams of the two surveys could not be done as there is no baseline data for first survey as well as data for each particular plot (all data pooled) thus limiting the level of analysis to area (Carletonville) level. In conclusion, the results of this study shows that the management and contractors in the rehabilitation industry should not only use of indigenous plant species, but also need to consider alien species that have a great potential of naturally colonizing on the tailings dams. Such species also have high capacity to providing sustainable basal cover, dust control and erosion control than the previously utilized indigenous species some of which were lost.

4.3 RECOMMENDATIONS

Based on the results that were obtained from this vegetation survey where only Carletonville was used as a study site, these can be used as baseline or referral points that gives a hint of what has happened over time. But for conclusive comparison purposes, I would recommend that:

- This study is repeated in the 2 other districts (Klerksdorp and Welkom) that were surveyed in 1996/7, so that the findings can be concluded based on a larger sample, which is a true representative of the initial survey.
- A survey of the similar nature is conducted during the wet season so as to be able to identify all the species including those only appear during the rainy season as the initial survey included both seasons.
- A better method of estimating each species frequency be used particularly with grasses species colonies which would be a complex of different species difficult to estimate.

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APPENDICES

APPENDIX 1: Percentage frequency of species and subspecies within each substrate and dam age class for plants found in the 100m transects.

Sample size (no. of slopes)	Tops and berms (pH > 6)		Tops and berms (pH < 6)		Slopes (pH > 6)		Slopes (pH < 6)		Toe paddocks (pH > 6)		Toe paddocks (pH < 6)		Overall
	16	14	14	20	10	25	5	90					
Anacardiaceae (n = 3)													
Rhus lancea	2.9	1.6	0.0	0.0	0.0	2.7	0.0	1.4					
Rhus pyroides	0.0	1.7	0.0	0.0	0.0	0.0	0.8	0.6					
Rhus gracillima	0.0	0.0	3.2	0.0	0.0	0.0	0.0	0.5					
Asclepiadaceae (n = 1)													
Asclepias fruticosa	1.6	1.5	0.0	3.2	0.0	2.7	1.3						
Asparagaceae (n = 2)													
Asparagus larinus	0.0	3.1	1.1	6.3	1.0	3.2	2.1						
Asparagus suaveolens	1.7	2.9	3.2	2.5	2.7	6.3	2.8						
Asphodelaceae (n = 1)													
Aloe greatheadii	0.0	0.0	0.0	0.0	0.0	3.2	0.7						
Asteraceae (n = 10)													
Berkheya insignis	0.0	2.9	0.0	0.0	0.0	4.8	1.1						
Bidens pilosa	4.7	0.0	1.7	4.7	2.7	6.5	3.7						
Cirsium vulgare	0.0	0.0	0.0	1.6	4.3	9.7	1.9						
Helichrysum caespititium	0.0	4.4	0.8	0.0	0.0	0.0	0.6						
Osteospermum leptolobium	0.0	0.0	0.8	3.2	0.0	0.0	0.3						
Senecio erubescens	0.0	0.0	3.2	0.0	0.0	0.0	0.1						
Senecio consanguinensis	8.8	0.0	0.0	0.0	0.0	9.7	2.1						
Stoebe vulgaris	1.7	0.0	0.0	0.0	0.0	0.0	0.2						
Tagetes minuta	0.0	9.6	3.8	0.0	10.2	12.6	9.2						
Tripteris aghillana	0.0	0.0	1.8	0.0	1.6	3.4	1.0						

APPENDIX 1 Cont: Percentage frequency of species and subspecies within each substrate and dam age class for plants found in the 100m transects.

	Tops and berms (pH > 6)		Tops and berms (pH < 6)		Slopes (pH > 6)		Slopes (pH < 6)		Toe paddocks (pH > 6)		Toe paddocks (pH < 6)		Overall
	16	14	20	10	25	5	0.4						
Sample size (no. of slopes)	16	14	20	10	25	5							
Euphorbiaceae (n = 1)													
<i>Clusia monticola</i>	0.0	3.7	0.0	0.0	0.0	0.0	0.4						
Fabaceae (n = 5)													
<i>Acacia karroo</i>	1.4	3.2	0.0	14.4	0.0	29.3	2.4						
<i>Acacia mearnsii</i>	0.0	0.0	1.2	0.0	0.0	3.6	1.6						
<i>Medicago sativa</i>	4.2	0.0	0.0	0.9	0.0	0.0	0.7						
<i>Melilotus alba</i>	0.0	0.0	5.4	3.8	0.0	1.4	2.5						
<i>Tephrosia longipes</i>	0.0	0.0	0.8	4.2	0.0	1.6	1.3						
Moraceae (n = 1)													
<i>Ficus ingens</i>	1.4	0.0	0.0	2.6	0.0	0.0	0.6						
Myrtaceae (n = 2)													
<i>Eucalyptus melliodora</i>	0.0	0.0	1.2	0.0	2.4	0.0	0.9						
<i>Eucalyptus</i> spp	0.0	0.0	0.0	0.9	0.0	0.0	0.4						
Phytolaccaceae (n = 1)													
<i>Phytolacca octandra</i>	0.0	0.0	0.0	9.2	0.0	0.0	2.1						
Poaceae (n = 18)													
<i>Agrostis laechnartha</i>	4.6	0.0	0.0	1.2	0.0	0.0	3.2						
<i>Andropogon eucommis</i>	3.9	0.0	0.0	0.0	2.6	0.0	1.8						
<i>Andropogon gayanus</i>	2.1	0.0	0.0	0.0	6.0	6.3	2.1						
<i>Aristida adscensionis</i>	1.3	0.0	0.0	9.4	4.6	5.2	3.7						
<i>Aristida congesta</i>	0.0	0.0	1.4	0.0	1.9	0.0	1.4						
<i>Cenchrus ciliaris</i>	0.0	1.7	0.0	2.6	0.0	1.1	8.2						

Chloris gayana 0.0 0.0 2.1 3.5 0.0 0.0 0.0 1.2

APPENDIX 1 Cont: Percentage frequency of species and subspecies within each substrate and dam age class for plants found in the 100m transects.

<i>Cortaderia jubata</i>	0.0	12.4	1.8	0.0	0.0	0.0	0.0	0.0	9.6
<i>Cynodon dactylon</i>	32.0	65.0	58.0	42.0	7.4	82.4	44.2	44.2	44.2
<i>Eragrostis chloromeles</i>	2.4	24.2	1.8	10.7	39.6	44.2	29.7	29.7	29.7
<i>Eragrostis curvula</i>	16.4	28.4	2.9	18.2	32.5	45.6	19.3	19.3	19.3
<i>Eragrostis racemosa</i>	0.0	4.1	0.0	10.1	0.0	0.0	6.2	6.2	6.2
<i>Hypparhenia hirta</i>	6.2	18.4	4.1	19.6	31.4	36.8	16.3	16.3	16.3
<i>Hypparhenia gazensis</i>	0.0	0.0	2.8	0.0	0.0	24.1	6.1	6.1	6.1
<i>Pennisetum clandestinum</i>	0.0	6.8	0.0	17.2	0.0	0.0	4.2	4.2	4.2
<i>Pennisetum macrourum</i>	3.2	19.1	11.4	4.6	0.0	0.0	6.3	6.3	6.3
<i>Phragmites australis</i>	40.4	16.8	9.4	24.1	0.0	48.4	7.2	7.2	7.2
<i>Sporobolus africanum</i>	0.0	0.0	6.4	0.0	13.9	0.0	7.5	7.5	7.5

Solanaceae (n = 2)

Solanum mauritanium 0.0 0.0 0.0 0.0 0.0 6.4 0.0 1.7

Solanum sisymbriifolium 0.0 0.0 4.8 0.0 0.0 0.0 9.2 2.2

Tamaricaceae (n = 2)

Tamarix spp. (*usneoides*,
gallica, *ramosissima*) 3.9 2.4 6.9 1.2 0.0 0.0 5.9 9.5

Verbenaceae (n = 1)

Verbena bonariensis 7.0 1.4 16.4 29.4 11.0 17.6 16.2

* Taxa that were intentionally introduced at some stage during tailings dam vegetating attempts prior to survey in 1996. (No vegetation attempts were done post the 1996 survey).

+ Taxa that were naturally present on slimes during this survey, and were also introduced to gold tailings dam trials subsequent to this survey (1996 to 2000).

APPENDIX 2: Parameters that were recorded per each substrate across the 10 sampling sites of Mponeng, Doornfonten and Savuka tailings dams.

Site	Slope	pH	Ec	Eh	Temp	Carbon	Nitrogen	Sulphur	Organic carbon	Vegetation cover	No. of species
Mponeng NE	Top flat	4.07	1894	376.3	20.4	1.09	0.06	0.34	1.02	15	2
Mponeng NW	Top flat	6.07	1345	406.4	20.3	0.31	0	0.06	0.28	25	3
Doornfontein S	Top flat	10.5	546	267	20.5	0.33	0	0.17	0.05	57	3
Doornfontein W	Top flat	10.2	986	437	20.7	0.37	0	0.47	0.14	38	1
Doornfontein NNW	Top flat	9.7	21.36	176.4	20.9	0.23	0	0.3	0.08	45	1
Savuka (Red soils) SW	Top flat	12.3	6.31	292.8	21	0.26	0.19	0.17	0.19	25	0
Savuka (Red soils) SE	Top flat	9.7	459	264	21.4	0.29	0	0.21	0.11	50	2
Savuka (Red soils) dormant - N	Top flat	11.2	234	331	20.4	0.37	0	0.58	0.06	38	2
Savuka (Red soils) NE	Top flat	8.4	1287	320	21.4	0.31	0	0.23	0.28	40	2
Savuka (Red soils) W	Top flat	7.9	786	187	20.2	1.14	0	0.31	0.39	15	2
Mponeng NE	Upper slope	5.82	174.5	375.5	20	0.92	0.03	0.1	0.9	35	6
Mponeng NW	Upper slope	7.3	164.8	366.9	20.3	0.22	0	0.25	0.22	65	8
Doornfontein S	Upper slope	6.8	2380	349.2	20.7	0.23	0	0.06	0.09	72	5
Doornfontein W	Upper slope	6.81	2024	129.8	20.8	0.25	0	0.2	0.17	35	2
Doornfontein NNW	Upper slope	5.11	410	447.8	20.5	0.43	0.18	0.3	0.41	50	1
Savuka (Red soils) SW	Upper slope	6.16	1748	375.2	20.2	0.34	0	0.02	0.21	10	3
Savuka (Red soils) SE	Upper slope	8	283.3	348.7	20.7	0.35	0	0.23	0.12	68	3
Savuka (Red soils) dormant - N	Upper slope	7.95	223.7	155.6	20.4	0.32	0	0.33	0.07	30	7
Savuka (Red soils) NE	Upper slope	7.55	1292	254.6	21.1	0.33	0	0.09	0.25	55	9
Savuka (Red soils) W	Upper slope	7.91	341	287.5	20.4	1.15	0	0.17	0.36	45	5
Mponeng NE	Upper berm	4.32	1748	425.6	20.7	0.25	0	0.16	0.21	55	7
Mponeng NW	Upper berm	4.93	157.1	384.2	20.3	0.91	0.02	0.09	0.78	90	5
Doornfontein S	Upper berm	7.63	548	279.8	20.5	0.46	0	0.21	0.24	80	6
Doornfontein W	Upper berm	3.86	554	359.8	20.3	0.29	0	0.21	0.25	19	3
Doornfontein NNW	Upper berm	7.74	269.8	270.9	20.7	0.34	0	0.07	0.33	90	2
Savuka (Red soils) SW	Upper berm	5.36	509	425.7	20.7	0.59	0.02	1.15	0.27	10	4
Savuka (Red soils) SE	Upper berm	4.05	398	458.2	20.3	0.27	0	0.04	0.14	58	5
Savuka (Red soils) dormant - N	Upper berm	4.32	163.2	443.7	20.8	0.24	0	0.13	0.08	45	4
Savuka (Red soils) NE	Upper berm	7.56	422	382.9	20.4	0.26	0	0.17	0.09	42	7

APPENDIX 2 (Cont): Parameters that were recorded per each substrate across the 10 sampling sites of Mponeng, Doornfontein and Savuka tailings dam:

Site	Slope	pH	Ec	Eh	Temp	Carbon	Nitrogen	Sulphur	Organic Carbon	Vegetation cover	No. of species
Mponeng NE	Mid – slope	4.07	694	437.2	20.6	0.22	0	2.39	0.2	37	6
Mponeng NW	Mid – slope	7.75	379.5	289.4	20.9	0.95	0.03	0.15	0.73	70	7
Doornfontein S	Mid – slope	7.66	228.4	184.7	20.9	0.3	0	0.17	0.27	78	4
Doornfontein W	Mid – slope	6.01	2357	166.8	20.5	1.05	0.07	0.04	1	65	2
Doornfontein NNW	Mid – slope	6.47	385	242	20.4	1.14	0.07	0.15	1.13	93	7
Savuka (Red soils) SW	Mid – slope	7.8	1280	126.4	20.8	0.36	0	0.06	0.24	10	4
Savuka (Red soils) SE	Mid – slope	6.18	168.5	312.2	21	0.38	0.02	0.15	0.36	65	6
Savuka (Red soils) dormant - N	Mid – slope	5.05	324	360.5	20.7	0.42	0	0.35	0.4	60	4
Savuka (Red soils) NE	Mid – slope	5.04	224	408.3	20.4	0.38	0	0.19	0.22	45	4
Savuka (Red soils) W	Mid – slope	5.01	453	342.6	20	0.35	0.01	0.37	0.43	78	12
Mponeng NE	Lower berms	5.59	519	308.4	20.4	0.25	0	0.14	0.14	45	7
Mponeng NW	Lower berms	7.62	331	341.4	20.8	1.08	0.05	0.08	0.83	95	4
Doornfontein S	Lower berms	6.62	68.3	362.1	20.2	0.33	0	0.04	0.04	85	6
Doornfontein W	Lower berms	4.68	215.6	354.2	20.6	0.39	0	0.05	0.18	85	5
Doornfontein NNW	Lower berms	7.51	101.3	280	20.7	0.65	0.02	0.17	0.34	95	3
Savuka (Red soils) SW	Lower berms	7.63	787	248.4	20.8	0.93	0.07	0.17	0.72	92	3
Savuka (Red soils) SE	Lower berms	6.53	1956	164.7	20.5	0.96	0.04	0.3	0.67	45	6
Savuka (Red soils) dormant - N	Lower berms	7.25	237.5	157.3	20.5	0.67	0.01	0.1	0.36	80	3
Savuka (Red soils) NE	Lower berms	7.44	2558	262.8	20.4	0.33	0	0.3	0.3	18	4
Savuka (Red soils) W	Lower berms	7.32	754	304.1	20.5	0.42	0	0.19	0.23	90	10
Mponeng NE	Lower slope	7.61	202.6	156.7	21.1	0.48	0.02	0	0.46	57	9
Mponeng NW	Lower slope	7.03	215.9	128.6	21	1.02	0.06	0.06	0.99	91	6
Doornfontein S	Lower slope	5.76	498	254.6	20.7	1.04	0.05	0.17	0.69	90	8
Doornfontein W	Lower slope	7.6	36.5	174.1	20.8	0.24	0	2.1	0.2	80	4
Doornfontein NNW	Lower slope	6.25	347.1	265.2	20.6	0.99	0.02	0.17	0.85	90	4
Savuka (Red soils) SW	Lower slope	3.65	16.03	417.8	20.6	0.22	0	0.71	0.18	85	5
Savuka (Red soils) SE	Lower slope	7.15	1053	169.4	20.2	2.79	0.2	0.23	2.2	50	11

APPENDIX 2 (Cont): Parameters that were recorded per each substrate across the 10 sampling sites of Mponeng, Doornfonten and Savuka tailings dams.

Site	Slope	pH	Ec	Eh	Temp	Carbon	Nitrogen	Sulphur	Organic Carbon	Vegetation cover	No. of species
Savuka (Red soils) dormant - N	Lower slope	3.12	113.5	402.7	20.2	0.4	0	0.82	0.33	70	6
Savuka (Red soils) W	Lower slope	4.59	1018	374.7	20.3	0.45	0.04	0.09	0.52	75	7
Mponeng NE	Toepaddock	6.79	227.5	176.3	20.5	1.1	0.06	0.04	0.94	52	11
Mponeng NW	Toepaddock	5.52	165.1	342.1	20.6	1.8	0.13	0.06	1.36	95	8
Doornfontein S	Toepaddock	6.39	271.5	145.6	20.4	1.19	0.04	0.18	0.71	65	4
Doornfontein W	Toepaddock	4.74	4.84	338.4	20.3	0.52	0	0.1	0.36	92	3
Doornfontein NNW	Toepaddock	5.05	1756	305.6	20.3	0.24	0	0.08	0.13	70	4
Savuka (Red soils) SW	Toepaddock	7.79	199	265.8	20.8	0.56	0.01	0.48	0.41	87	7
Savuka (Red soils) SE	Toepaddock	7.75	342	269.5	20.4	0.5	0.01	0.04	0.46	80	11
Savuka (Red soils) dormant - N	Toepaddock	5.45	205.3	367.4	20.4	0.95	0.04	0.06	0.92	95	8
Savuka (Red soils) NE	Toepaddock	4.89	92.2	379.2	20.7	0.59	0	0.13	0.35	76	4
Savuka (Red soils) W	Toepaddock	6.37	20.59	236.4	20.9	1.18	0.08	1.23	1.11	83	3

APPENDIX 3: Table of results for the variables that were analyzed between acidic (pH <6) and alkaline (pH >6) substrates across the slopes of 10 sites that were surveyed.

Source	Dependent variable	Slopes (pH > 6)	Slopes (pH < 6)	Tops and berms (pH >6)	Tops and berms (pH < 6)	Toe- paddock (pH >6)	Toe-paddock (pH < 6)	p value
Slope	pH	7.14	4.72	8.10	4.80	7.02	5.13	.000*
	Ec	778.515	392.503	642.921	698.033	212.118	444.688	.436
	Eh	237.455	382.170	285.700	377.692	218.720	346.540	.000*
	Temp	20.655	20.400	20.683	20.425	20.600	20.460	.042*
	Carbon	.664	.483	.477	.501	.906	.820	.244
	Nitrogen	.025	.031	.008	.021	.040	.034	.752
	Sulphur	.235	.549	.218	.242	.394	.086	.254
	Organic	.509	.428	.726	.624	.281	.320	.110
	No. of species	6.050	5.900	3.611	5.000	7.200	5.400	.100
	Veg cover	58.700	62.500	61.389	44.333	73.400	85.600	.038*

The asterisk (*) indicates variables, which significantly varied across the substrates of the slope.

APPENDIX 4: Univariate ANOVA results between substrates.

Source	Dependent variable	Type III sum of squares	df	Mean square	F Value	Sig
Slope	pH	44.768	6	7.461	2.914	.014*
	Ec	2704211.469	6	450701.912	1.071	.389
	Eh	95188.471	6	15864.745	1.988	.081
	Temp	.393	6	.065	.726	.630
	Carbon	1.937	6	.323	1.762	.122
	Nitrogen	.008	6	.001	.703	.648
	Sulphur	.708	6	.118	.687	.661
	Organic	2.079	6	.346	2.717	.021*
	Veg cover	15588.771	6	2598.129	5.785	.000*
	No. of species	184.571	6	30.762	4.188	.001*

APPENDIX 5: Univariate ANOVA results between sites

Source	Dependent variable	Type III sum of squares	df	Mean square	F Value	Sig
Site	pH	18.848	9	2.094	.671	.732
	Ec	3026794.729	9	336310.525	.771	.644
	Eh	29754.540	9	3306.060	.349	.954
	Temp	.659	9	.073	.812	.607
	Carbon	1.749	9	.194	.994	.455
	Nitrogen	.016	9	.002	.921	.513
	Sulphur	1.173	9	.130	.754	.658
	Organic	1.552	9	.172	1.209	.307
	Veg cover	10453.271	9	1161.475	2.085	.045*
	No. of species	159.943	9	17.771	2.188	.035*

APPENDIX 6: Univariate ANOVA results between alkaline and acidic substrates

Source	Dependent variable	Type III sum of squares	df	Mean square	F Value	Sig
Slope (alkaline and acidic)	pH	131.390	5	26.278	22.523	.000*
	Ec	2081680.952	5	416336.190	.982	.436
	Eh	265657.383	5	53131.477	10.233	.000*
	Temp	.982	5	.196	2.470	.042*
	Carbon	1.311	5	.262	1.378	.244
	Nitrogen	.005	5	.001	.531	.752
	Sulphur	1.103	5	.221	1.353	.254
	Organic	1.295	5	.259	1.881	.110
	No. of species	85.244	5	17.049	1.941	.100
	Veg cover	7237.227	5	1447.445	2.528	.038*

APPENDIX 7: Dam location for each of the 10 sampling sites that were used during the 2014 vegetation survey in Carletonville.

SITE	DAM	ASPECT	DAM AGE	DAM ACTIVITY STATUS
1	1	East	Old	Dormant
2	1	South	Old	Dormant
3	2	South	Young	Dormant
4	2	West	Young	Dormant
5	2	North	Young	Dormant
6	3	S West	Young	Active
7	3	W East	Young	Active
8	4	N West	Medium	Dormant
9	5	West	Old	Active
10	5	West	Old	Active

APPENDIX 8: List of species that showed suitable phytoremedial properties between the 1996/97 and 2014 vegetation surveys that were done on the tailings dams in Carletonville.

Species	
Grasses (tolerant to low nutrient areas & provide good basal cover)	Forbs & herbs (most species ideal for basal cover)
<i>Cynodon dactylon</i>	<i>Tagetes minuta</i>
<i>Eragrostis chloromelas</i>	<i>Verbena bonariensis</i> *
<i>Eragrostis curvula</i>	<i>Bidens pilosa</i>
<i>Hyparrhenia hirta</i>	<i>Senecio consanguineus</i>
<i>Cortaderia jubata</i> *	<i>Cirsium vulgare</i> *
<i>Cenchrus ciliaris</i>	<i>Phytolacca octandra</i> *
<i>Sporobolus africanum</i>	<i>Melilotus alba</i>
<i>Phragmites australis</i>	
<i>Aristida adscensionis</i>	
<i>Agrostis lachnarta</i>	
Trees & shrubs (tolerant to polluted areas)	
<i>Rhus lancea</i>	
<i>Rhus pyroides</i>	
<i>Rhus gracillima</i>	
<i>Tamarix spp</i> *	
<i>Acacia karroo</i>	
<i>Acacia mearnsii</i> *	
<i>Asparagus laricinus</i>	
<i>Asparagus suaveolens</i>	
<i>Asclepias fruticosa</i>	
<i>Solanum mauritianum</i> *	
<i>Solanum sisymbriifolium</i> *	

An asterisk (*) after species names shows those that are invasive in nature & have been declared as invasive species in South Africa..

