

An analytical investigation of the biophysical factors that inhibit successful ecological restoration of gold tailings dams

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ABSTRACT

The sphere of influence of gold tailings dams has a considerable detrimental impact on the environmental quality of numerous aquatic and terrestrial ecosystems and directly or indirectly affects human living standards. It is therefore of utmost importance to find a persistent *modus operandi* to restore this wasteland and to mitigate the negative results associated with these tailings dams, which mainly include air, soil and water pollution. The inherent nature of gold tailings material though, does not submit to the expectations of ecological principles derived from natural systems after ecological restoration is applied. It is therefore necessary to investigate and describe this unnatural medium with its associated characteristics, and the responses of vegetation as reflected by ecosystem development. Through this ecological assessment, restoration techniques could be refined, which could lead to sustainably viable solutions.

This study investigates various integrated facets of gold tailings revegetation, focusing on the soil-vegetation interaction, and the proposal of numerous variables to describe and evaluate ecological performance within the framework of sustainability. Through the assimilation of basic quantitative data and monitoring of restoration performance at different time intervals, the stability and long-term effectiveness of ecological restoration of gold tailings media at various stages of the remediation curve is assessed. An overview of restoration indicates that only a more holistic approach in the form of ecological reconstruction should drive ecological remediative processes, and using existing scientific criteria, which are based on basic ecological principles, self-sustaining ecosystem development could be achieved.

Results from soil analysis, vegetation abundance and species performance data of pot trials and field surveys, were multivariately and statistically analysed to establish significant limiting and interacting variables, which determine the performance of revegetated systems. The influence of these topoedaphic variables, which included macro- and microclimatological factors, soil physical and chemical parameters and eventually plant species resemblance, was established through the assessment of experimental growth models, and soil and vegetation dynamics on established revegetated gold tailings dams. The manipulation of these variables through soil profile reconstruction, which implies physical fraction reshuffling and either chemical dilution or enhancement, as well as aspect (microclimatological) and soil chemical changes, showed major responses to seedling abundance, species composition and secondary successional associated characteristics.

The major existing need for ecological standards criteria were also addressed through the assessment of a statistically sound method, which was based on scientifically derived floristic information.

Several ecological indicators of functional return were identified and the method used was further extended not only to indicate the re-occurrence of ecological sensitivity indicators, but also to give clarity on the functional performance and ecological blending of the revegetated areas.

The question surrounding the characterisation of these ecologically dissimilar areas as separate systems with different (new) ecological principles was, however, highlighted through this study and future research should focus on defining these principles as well as short- and long-term modelling of revegetated areas.

The contribution of this research to restoration ecology is significant with regards to the intensive investigation and explanation of characteristics and processes that will drive ecological succession and determine restoration success.

Key terms:

Ecological function success; Ecological restoration; Gold tailings dams; Restoration monitoring; Seedling persistence; Soil chemical dynamics; Soil dispersivity; Soil physical rectification; Soil profile reconstruction; Vegetation dynamics.

OPSOMMING

Die nuwe-effekte van goudslikdamme lei tot aansienlike skadelike impakte op omgewingskwaliteit en beïnvloed verskeie akwatiese en terrestriële ekosistels binne hul invloedssfeer, wat direk of indirek menslike lewenstandaard benadeel. Die impakte sluit lug, water en grondbesoedeling in, en daarom is dit van die uiterste belang om 'n *modus operandi* te vind om die slikoppervlaktes te restoureer na die oorspronklike natuurlike toestand voor versteuring, om so die negatiewe effekte van die slikdamme hok te slaan. Dit wil voorkom asof die inherente aard van goudslik die oorsaak is dat plantegroei op gerestoureerde slikdamme nie gedikteer kan word volgens ekologiese beginsels wat afgelei is van natuurlike sistels nie. Daarom is dit noodsaaklik om dié onnatuurlike materiaal en geassosieerde kenmerke te beskryf en die reaksie van plantegroei, wat deur ekosisteel ontwikkeling weerspieël word, te bestudeer. Deur ekologiese ondersoeke kan restaurasie tegnieke verfyn word en kan 'n volhoubare oplossing meer haalbaar wees.

Die studie ondersoek verskeie geïntegreerde fassette van goudslikrestourasie, en fokus op ekologiese prestasie deur die plant-bodem interaksie te beskryf en te evalueer binne die raamwerk van volhoubaarheid. Deur die interpretasie van basiese kwantitatiewe data en moniteringsresultate oor verskillende tidsintervalle van vroeëre gerestoureerde slikdamme, is die stabiliteit en langtermyn effektiwiteit van restaurasie vir verskillende fases van die remediërings kurwe bepaal. 'n Oorsig oor restaurasie toon dat slegs 'n meer holistiese benadering, wat as ekologiese rekonstruksie beskryf kan word, as dryfveer moet dien. Deur van bestaande wetenskaplike inligting, wat gebaseer is op basiese ekologiese beginsels, gebruik te maak, kan selfonderhoudende ekosisteel ontwikkeling bereik word.

Betekenisvolle beperkende faktore vir goudslikrestourasie en interaktiewe veranderlikes verantwoordelik vir ekologiese prestasie is ondersoek deur data verkry van potproewe en veldbepalings, meerveranderlik en statisties te ondersoek. Die invloed van die topo-edafiese faktore, wat makro- en mikroklimatologiese faktore, grondfisies en -chemiese faktore, en uiteindelik plantspesie weerspieëling insluit, is deur onderskeidelik potproef groeimodelle, en grond- en plantegroei dinamika studies op gerestoureerde goudslikdamme ondersoek.

Die manipulasie van die grondfisies en -chemiese veranderlikes deur grondprofiel rekonstruksie het betekenisvolle invloed gehad op saailing frekwensie, spesiesamestelling en sekondêr suksessioneel geassosieerde kenmerke. Die bodemveranderinge het grond fisiese optimalisering en chemiese verbetering deur verdunning of kunsmis toevoegings ingesluit. Aspek (mikroklimatologiese invloede) het ook betekenisvolle gevolge vir saailing vestiging getoon.

Die behoefte wat daar bestaan om ekologiese sukses kriteria neer te lê is ook aangespreek deur 'n statistiese metode te ondersoek, wat gebaseer is op wetenskaplik gederiveerde floristiese data. Verskeie ekologies funksionele indikatore is geïdentifiseer en die metode is uitgebrei deurdat dit die terugkeer van sensitiwiteits indikatore uitwys, sowel as duidelikheid verskaf oor die funksionele prestasie en ekologiese inskakeling van die gerestoureerde areas.

Die ondersoek rondom die vergelykende kwantifisering van hierdie ekologies gewysigde areas en normaaltoestande as onderskeie stelsels van veld kwaliteit, het bewys dat goudslik ekologie deur verskillende (nuwe) sturende beginsels geaktiveer word, en dit was opvallend regdeur die studie. Toekomstige navorsing moet dus fokus op die definiëring van hierdie beginsels, en ook verder op die kort en lang termyn modellering van die dinamika van gerestoureerde areas konsentreer.

Die intensiewe ondersoek en verklaring in die studie van kenmerke en prosesse wat ekologiese suksessie beïnvloed, en dus restourasie sukses bepaal, lewer 'n betekenisvolle navorsingsbydrae vir restourasie ekologie.

Sleutelterme:

Ekologies funksionele sukses; Ekologiese restourasie; Goudslikdamme; Restourasie monitering; Saailing vestiging; Grondchemie dinamika; Grond dispersiwiteit; Grondfisiese regstelling; Grondprofiel rekonstruksie; Plantegroei dinamika.

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LIST OF ABBREVIATIONS

ABC	Average basal cover
C.V.	Coefficient of variation
CCA	Canonical correspondence analysis
DCA	Detrended correspondence analysis
FSI	Functional Success Index
RDA	Redundancy analysis
SC	Success criteria
SR	Success ratio
SS	Sewage sludge
Super P	Superphosphate
Tukey HSD test	Tukey Honest Significant Difference test
TS	Topsoil
VC	Vermicompost
WTS	Water Treatment Sludge

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CHAPTER 1

THE BIOPHYSICAL FACTORS THAT INHIBIT SUCCESSFUL ECOLOGICAL RESTORATION OF GOLD TAILINGS DAMS

INTRODUCTION

Extensive gold mining result in the most frequent mine residue deposit in South Africa, and although economically important and a provider of employment and training for local people, this industry is damaging thousands of hectares of biologically diverse areas (Milton, 2001), scarring ecosystems irreparably (Thatcher, 1979). Gold mine tailings are being processed at a rate of 370 million tons per year, accounting for 81% of the total waste stream in the country (Rösner *et al.*, 2001), which already covers some 400 km² of productive land (Winde, 2001). The abundance of these tailings dams result in a mosaic of fragmented natural grassland. These occurrences not only disrupt the ecological function of this poorly conserved biome, but also degrade the environmental quality to the detriment of all organisms, impacting considerably on the environmental quality of human living standards.

It is of utmost importance and to the benefit of gold mines, the natural environment, and the public at large to find a sustainable solution to mitigate the negative effects associated with these wastes. The affected areas should be returned to full productivity, not only in the interest of biological systems that co-developed and are dependent on the interactive and mutual ecological support of these missing areas, but also for the co-existence of mankind with the hazards that tailings dams pose. The coupled adverse off-site impacts associated with tailings dams include geotechnical instability, erosion of tailings by wind and water, and contamination of surface and ground waters (Evans, 2000). These risks necessitate the development of suitable techniques to counteract and minimise environmental damage resulting from pollution posed by these wastes, and to optimise the potential ecological capacity for post-land use purposes.

The obvious and proven solution for the problems that are posed by gold tailings is to rectify the limiting physical habitat criteria and chemical limitations to such an extent that a self-sustaining ecological system develops over time through natural succession. Remediative efforts were however applied to gold mine tailings dams since 1894, but neither success of establishing lasting vegetation cover on the side slopes, nor the development of stable and diverse ecological systems on these dams were recorded over the years (Barker, 1984). The major rehabilitation practices

presented revegetation outcomes on an agricultural basis (Thatcher, 1979) under semi-permanent irrigation (Milton, 2001) with no recorded long-term success. These efforts complied only with the minimum requirements, which primarily focussed on limiting erosion of the tailings media, and to confine air and water pollution.

It therefore seems that the approach that drove these techniques was a major limiting factor in previous restoration efforts. Vegetative stabilisation is still the most successful and long-term answer for tailings revegetation (Johnson *et al.*, 1994, Carroll *et al.*, 2000) counting on the fibrous roots systems of grasses which serve to bind micro-aggregates through the release of mucilaginous cementing agents such as polysaccharides (Haynes & Swift, 1990), and the natural process of succession to develop a self-sustaining vegetation cover.

The combination of the chemical-ameliorative and ecological approaches is applied with relative success today (Johnson *et al.*, 1994), but a possible new paradigm towards ecological restoration should though be phased in to ensure ecological sufficiency of the restored vegetation cover. The science and technology of ecological restoration must be developed within a sustainability framework (Cairns, 2000), which should be the basis for such an approach.

To regain the development of landscape success (Kentula, 2000) on gold tailings dams, the biophysical characteristics should be thoroughly analysed to determine a strategy for the reinstatement of ecological capacity. This environmental setting within which the growth media is analysed and rectified is highly important in terms of plant growth and the long-term survival within this harsh environment (Weiersbye & Witkowski, 1998b). Therefore, geotechnical slope characteristics, aspect, soil physical and chemical characteristics, and the overall climate of the area have profound effects on species persistence and successional colonisation of gold tailings dams. It seems that the challenge to sustainably revegetate gold tailings is to understand the chemical, physical and biological functioning of the tailings media, and to focus research towards an ideal restoration product.

An extensive literature review provided the necessary background information regarding some of the biophysical limiting factors associated with the revegetation of gold tailings material. Numerous problem areas within the ecological context were identified through the literature study and a short outline of these factors is presented.

This study will therefore focus analytically on the soil physical and chemical interaction of gold tailings material with vegetation. The floristic response to these variables are further quantified to establish biophysical limiting factors posed by the tailings material, and to determine criteria to evaluate restoration success. Multivariate and statistical analysis will therefore be applied to

indicate associations and correlations between the different variables. The contribution of the identification of critical success factors for restoration could finally result in a more systematic, clear and significant approach towards successful restoration.

The objective of restoration should be to recreate sustainable ecosystems based on ecological principles (Bradshaw, 1996) and therefore, successful restoration of disturbed areas can only be achieved if the ecology of these areas is completely understood. Overburden recovery through vegetation growth is however limited by physical habitat criteria of the spoils (Van Wyk, 1994), as this altered environment is not in harmony with the ecology of the surrounding area (Bradshaw & Chadwick, 1980). The topoeidaphic disequilibria therefore have to be described to determine what the main limiting factors of gold tailings revegetation are.

Since tailings dams are elevated above the natural ground contours, they are particularly exposed to the ill effects of wind and water erosion and these unprotected areas present homogenous and unlimited reserves of particulates (Weyersby & Witkowski, 1998a). Gold tailings material is exceptionally susceptible to erosion due to its poor physical characteristics (Blight, 1989). The poor textural material properties, combined with the effect of the extremely steep slopes of the tailings dams, render it impossible to protect slopes indefinitely from severe water erosion, risking long-term geotechnical instability and possible future pollution (Olyphant & Harper, 1995; Evans, 2000). It is therefore necessary to determine the interaction of soil physical properties and seedling establishment. The detrimental impact of gold tailings erodibility and more specifically the dispersibility of the media on sediment delivery processes have not been quantified yet. Furthermore, the implications of these soil physical characteristics for plant establishment and succession, is poorly described (Rourke, 2000). Data on erodibility of tailings material are limited (Sheridan *et al.*, 2000) and therefore the degree of mass transport of tailings material has not even been quantified to any viable extent. A self-perpetuating ecological system will, however, only develop sustainably if primary and secondary successional processes are recovered (Jochimsen, 1996), implicating that the hostile soil-seed contact area on tailings dams, combined with the detriment posed by erodibility of tailings material and slope gradient, must be seriously addressed to achieve lasting rehabilitation success. Therefore, it would be necessary to investigate various ameliorative approaches through different soil profile reconstruction amendments. The question should however be asked to what extent it is physically and financially possible to recreate soil profiles, and if the results are ecologically sound (Van Wyk, 2002).

The productivity and persistence of vegetation on rehabilitated gold mine tailings is to a large degree a function of the interaction of revegetated plants with the physical, chemical and microbiological conditions of the induced soil profile (Jochimsen, 1996; Bradshaw, 1997). The success of soil profile development will also determine the long-term survival of the established vegetation. Species endurance, diversity and succession have not produced satisfying results after restoration attempts on tailings dams (Weiersbye & Witkowski, 1998b). The selection of native plant species occurring in communities surrounding the tailings dams could also be experimented with, which could be the key to ensure gradual recovery of ecological function on tailings dams. The necessity to investigate intensive amelioration of gold tailings material under dryland conditions is therefore of extreme importance (Envirogreen, 2000), to establish to what extent gold tailings could be biologically restored. It could also lead the way to establish ecological criteria, which could culminate in standards to measure restoration success and to determine the desirability of site closure.

Levelling of slopes, as well as physical and chemical soil profile reconstruction with the exclusive introduction of native plant species are, however, already accepted as International Code of Best Practice in restoration practices today (Mining Association Canada, 1998), but has not been implemented in South Africa yet. This approach of total restoration is however more expensive, but sustainable revegetation success will be more likely. It will therefore be necessary to investigate the principles and viability of this approach.

The use of native grass species for revegetation purposes is one of the most debated subjects in restoration ecology today (Van Wyk, 2002), as it is not always possible to establish these species, but it is assumed that through the process of natural succession, the species surrounding the revegetated area will reclaim the site. According to Bradshaw (1997), this is however not the case on revegetated land. Derelict land is characterised by distinct floras over time due to the habitat differences that exist in such areas (Bradshaw & Chadwick, 1980). However, due to the conditions created through site amelioration and seed mixtures selected by restoration practices, only a small number of species often establish, which leads to monoculture domination and eventually, ecosystems of low diversity (Roberts et al., 1981). The vegetation of tailings dams are further seldom studied and are therefore relatively unknown, while this information may bear important knowledge on the ecological and environmental conditions that persist on these tailings dams (Morgental *et al.*, 2001). The measurement of the adequacy of restoration of gold tailings material, and more specifically to what degree various biological spheres and ecological functions and values of habitats have been restored and returned, should be addressed. The extent to which

the rectified growth medium will contribute to sustainable nutrient cycling, and its capacity to support a healthy vegetation cover, eventually enabling ecosystem development, is also largely unknown (Schwenke *et al.*, 1999; Brown, 2000). It is therefore necessary to determine what the dynamic trend of species occurrence is in response to the physically restored and chemically amended growth media. Furthermore it should be determined whether soil profile development is evident, and if the identified dominant species will persist on the rectified growth media, while facilitating plant community succession.

Additionally, very limited information is available about the ecological processes that drive ecosystem regeneration after restoration occurred (Van Wyk, 1994). The species occurring on the tailings dams persist under continual irrigation and as a result of heavily fertilised growth media, which include excessive liming for latent and potential acidity, macro- and microelement deficiency amendments and added sewage sludge for soil physical, -organic matter and microbiological optimisation (Van Deventer *et al.*, 2001).

Ecological performance of restoration projects is not yet predictable with great certainty (Thom, 1997). The degree to which these revegetated gold tailings dams contribute to the return of ecological function, measured in terms of the surrounding environment, is still largely unknown. Until recently, little attention was given to the quantification of terrestrial restoration projects' success. Few studies have developed and applied ecological success criteria objectively (Kentula, 2000), leading to uncertainty about variables that should be used to conduct requisite assessments and evaluation of restoration projects. The measurement of the adequacy of restoration of gold tailings dams, and more specific, to what degree the various functions and values of habitats have been recreated and returned, should be addressed.

As species form an important component of ecosystems, it can be used as ecological indicators (Morgental *et al.*, 2001) and monitoring thereof could describe its comparative dynamics over time. Species are normally associated with specific soil conditions and can be used as indicators of such conditions (Bradshaw, 1997). The evaluation of the ecological interpreted results is however difficult, as there is as yet no set of comparative standards available (Hatting *et al.*, 2001). Developing indicators of chosen habitat functions, and creating statistical representations of natural, local reference sites for comparison to the functional development of the restored habitat is therefore used to evaluate ecological restoration success (Jochimsen, 1996). Monitoring of restored areas over time can also contribute in the selection of techniques for future restoration (Pastorok *et al.*, 1997).

Monitoring is however a new concept for revegetated areas, and although certain principles based on monitoring experience of natural systems are used (Morgental *et al.*, 2001), other attributes

might be better indicators of ecosystem development and sustainability on tailings material after restoration.

The continuation of monitoring of revegetated systems is necessary to adequately demonstrate trends in tailings chemistry related to species abundance, in order to identify when the revegetated systems have become truly self-sustaining.

RESEARCH OBJECTIVES

It became evident that there are mainly five aspects that should be addressed to contribute to a better understanding of the biophysical limiting factors surrounding the attainment of sustainable restoration of gold tailings dams. The following challenges were identified as research objectives for this study:

1. What the main approach followed to revegetate gold tailings dams comprise of, and how the current restoration paradigm manifests in practice.
2. How gold tailings media physically differ from other media, and what the influences of the physical properties are on vegetation establishment and persistence.
3. To what extent it is possible for indigenous species to reclaim physically and chemically amended gold tailings media after soil profile reconstruction has occurred and after introducing a seedbank.
4. What the initial dynamic soil and vegetational trends of restored gold tailings are and to what extent these changes affect sustainability of the vegetation cover on the side slopes of the revegetated gold tailings dams.
5. How restoration success could be measured and monitored through the resemblance of the functional vegetation characteristics.

The ecological restoration of devastated land is now well recognised as a specialised branch of ecology (Johnson *et al.*, 1994), investigating the nature of discard material, optimising the growth media, and studying the developmental response of the introduced vegetation. The worldwide use of vegetative stabilisation of tailings dumps in itself provides motivation for further research (Thatcher, 1979).

These five actuality research questions are therefore addressed in this study to contribute to both the philosophical and ecological pool of knowledge, and to reduce uncertainty regarding crucial decisions in the future managerial context as well.

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CHAPTER 2

A NEW PHILOSOPHICAL APPROACH NEEDED FOR SUSTAINABLE GOLD MINE TAILINGS RESTORATION

CHAPTER OVERVIEW

The mining industry generates the largest amounts of solid waste in South Africa and the world. These wastes have a considerable impact on the quality of human lives and the natural environment. This account especially for gold mine tailings, which is the most frequent mine residue deposit in South Africa, and is mostly situated in and around urban areas. Mine tailings processing usually results in elevated final landforms with angle-of-repose side slopes, and the coupled adverse off-site impacts that include geotechnical instability, erosion of tailings by wind and water, and contamination of surface and ground waters. It is of utmost importance and in the interest of gold mines, the natural environment, and the public at large to find a sustainable solution to mitigate the negative effects that these wastes pose. Remediative efforts were applied to gold mine tailings dams since 1894, but neither success of establishing lasting vegetation cover on the side slopes, nor the development of stable and diverse ecological systems were recorded over the years. The major restoration practices presented revegetation outcomes on an agricultural basis under semi-permanent irrigation with no long-term success. These efforts complied only with the minimum requirements, which included to limit erosion of the tailings media, and to confine air and water pollution. It seems that the outcomes of the restoration philosophies and approaches followed over time could be the reason for poor gold tailings restoration successes. It is evident that a new holistic framework is needed for ecological restoration, to accomplish self-perpetuating ecosystems after remediative action. Not only the mining industry, but also the legislative authorities and restoration industry will have to accept that total restoration, or ecological reconstruction, is the only way to ensure the development and persistence of stable and diverse ecosystems.

A NEW PHILOSOPHICAL APPROACH NEEDED FOR SUSTAINABLE GOLD MINE TAILINGS RESTORATION

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ABSTRACT

Gold tailings restoration has been a challenging discipline since the first attempts were made. The poor soil physical and chemical characteristics of the media limited restoration success to such an extent that numerous approaches developed during the past century, which steered attempts to persist vegetation on gold tailings dams. This study presents a historic overview of gold tailings revegetation and highlights several faultlines in restoration approaches. A new hierarchical framework, based on the principles of ecological reconstruction, is investigated to strive towards the achievement of sustainable restoration outcomes. It was clear that a new holistic and interdisciplinary approach, based on pre-planned ecological designs and post-restoration monitoring, is the only way to achieve self-sustaining revegetated systems on tailings dams.

Keywords:

Restoration approach; Gold tailings restoration; Ecological reconstruction; Restoration stages; Ecosystem monitoring.

INTRODUCTION

Mining has been undertaken in South Africa for more than a century (Dixon, 1998) and although economically important and a provider of employment for local people, it is damaging thousands of hectares of biologically diverse environments (Milton, 2001). The mining processes bear vast volumes of waste material (Bradshaw & Chadwick, 1980), which is stored on the surface mainly in the form of tailings material (Rösner, 2001). Since 1886, about six billion tons of tailings have been produced by the gold mining industry alone, covering some 400 square kilometers (Winde, 2001). There are approximately 400 massive tailings dams in South Africa (from coal, gold and base metal mining) (MJRS, 1996), of which more than 270 were identified as gold mine tailings dams (Rösner, 2001). In 1987 there were already 740 small gold tailings dams and sand dumps, covering 44 000 hectares of productive land (Keyter, 1987). The bulk of this discard will always be disposed and stored on the surface and poses a long-term threat for man and the natural environment.

The gold mine industry fragmented natural vegetation communities and physically created an acid generating desert on the South African Highveld, stretching across the goldfields from Virginia to Evander. The need to return this devastated land to a norm where the ecological function and natural productivity is reinstated is of utmost importance from a sustainability point of view. Waste quantities from gold/uranium and platinum mining sectors are estimated to amount to 120 million tons per annum, and the average total annual tailings waste production in South Africa is estimated at 318 million tons (Versveld *et al.*, 1998). In 1996, a total volume of 377 million tons of tailings was produced by the mining sector, accounting for 81% of the total waste stream in South Africa (Engineering News, 1997).

The immense degradation of ecological systems resulting from the generation and storage of these amounts of waste, as well as public awareness and international pressure resulted in stricter environmental legislation at the turn of the previous century. Given the increasing pressure to maintain high environmental standards throughout the life cycle of the mine, which is exerted by the authorities, private organisations and individuals, the need for revegetation is widely recognised. Therefore, the associated financial liability of mining operations has increased dramatically over the past ten years (Peart, 2001). Mining companies must not only set aside sufficient funds to restore current tailings impoundments properly, but should also anticipate the means to mitigate future environmental liabilities that may arise from the thousands of hectares of unstable and pollutive residue deposits (Anon, 1996). Most of these gold tailings storage facilities are situated in or around built-up areas (Bradshaw & Chadwick, 1980; Rösner, 2001) and the importance to rehabilitate them to a sustainable extent is critical, not only to eliminate pollution hazards, but to be available for possible future landuses (Hannan, 1984). As such, environmental liabilities are a growing financial concern for the mining industry with far-reaching implications (Anon, 1996). This is

especially the case for older mines, which neglected to budget for the replacement of environmental capital and where the remediation effort could cost more than the total income generated over the entire lifespan of the mine.

It is evident that mines accept environmental liabilities and are willing to invest in revegetation of the tailings dams, but until proof of sustainable restoration outcomes is presented, no hurried restoration will commence (Williams, 1996). In order to convince mining companies to spend large sums of money on restoration, they must believe that the end product is sustainable. The focus of ecological restoration therefore needs to shift from a short-sighted paradigm, which mitigates pollutive impacts and postpones environmental responsibility, to a more holistic, integrated and ecological approach. This might imply higher initial cost input, but a scientifically based end-product, which complies with the norms derived from basic ecological principles, will deliver a sustainable end result.

In the past, research focused on rectification of the medium by botanical means. Plant species that were able to tolerate the medium were identified, experimented with, and established on the tailings dams (SAGEP, 1979; Marsden, 1985). In time these tolerators would ameliorate the medium with organic material and nutrients, sustaining the medium for future growth (Erasmus, 1998). This proved to be unsuccessful (Weiersbye & Witkowski, 1998). The emphasis of research on vegetation-medium interactions has shifted to a soil scientific approach in the past eight years (Van der Nest, 1998), in which the chemical and physical conditions of the tailings material are rectified in order to promote natural succession (Envirogreen, 2000). It seems that the challenge lies in the understanding of the chemical, physical, ecological and microbiological functioning of the perturbed areas, and to focus research towards an ideal restoration product – to optimise the ecological potential, which will result in food chain mobilisation and biological magnification on the devastated land (Cairns & Atkinson, 1994).

REASSESSING TERMINOLOGY

Within a South African context, the perceived main problems pertaining to gold restoration within an environmental framework are the lack of clarity over the definition of the word restoration, and the vague link between the stated restoration objectives and the desired end points (Mackenzie & Riechardt, 2001). These problems have resulted in a 'lack of faith' of industry in the 'value' of restoration (Mudder, 2001). It is therefore necessary to clarify the definitions pertaining to ecologically remediative efforts.

The differences between ecological restoration, reclamation, and rehabilitation of land devastated by mining activities are discussed extensively throughout literature (Johnson *et al.*, 1994; Wali, 1999). These remediative actions imply in essence exactly the same on ground level, but the qualitative differences are entangled within academic technicalities. The objectives and end-goal of these actions are, however, similar. A modern term that overarches the differences and eliminate confusion should be proposed and it is therefore important to define what is implied by physically and ecologically sustaining mine spoils, comparing the commonalities between restoration, reclamation and rehabilitation. Following is a short outline of integrated definitions:

Both restoration and rehabilitation attempt to restore the ecological services by approximate recreation of natural communities through physical and biological interventions at first, and then it self-sustains by the availability of a reconstructed source of nutrients and the maintenance of biodiversity (WRI, 2001). The difference, however, lies in the use of indigenous or exotic species. Whether the goals are to restore the original natural ecosystem or to produce an acceptable alternative, ecological principles should underlie all good restoration schemes (Johnson *et al.*, 1994).

Restoration can be used as a blanket term to describe all activities which seek to upgrade damaged land or to re-create land that has been destroyed, and to bring it back to beneficial use in a form in which the biological potential is restored (Bradshaw & Chadwick, 1980). It is thus a process by which an area is returned to its original state prior to perturbation of any sort (Harris *et al.*, 1996). Furthermore it implies the return of an ecosystem to a close approximation of its condition prior to disturbance, using indigenous species (Cairns, 1995) or a replication of the conditions that existed prior to the disturbance of the site (Barbour, 1992).

Reclamation is a process by which previously unusable land is returned to a state whereby some use may be made of it (AMRH, 1989). The organisms originally present on the undisturbed site will be able to invade the 'new' site after reclamation was carried out. It is thus the first stage of restoration (Cairns, 1995). Reclamation is inhibited though, by the fact that the end use and the original use will differ and biological function changes over time due to the disturbance (Harris *et al.*, 1996).

This term was originally used over the years and led to the connotation that after a reclamation input, or only amelioration of the medium, plant succession will lead to the invasion of the discard and vegetation communities will develop spontaneously through natural reclamation of the bare surface.

It should be proposed, however, that this term has become inappropriate and should not be used further in future applications with regards to the ecological remediation of devastated land. The term leads to confusion in the literature. This confusion arises as the reclamation of tailings rather implies to reclaim excess gold from tailings material (Rösner *et al.*, 2001) that could not be extracted using historical processing methods, but is now possible through advanced technology.

Rehabilitation is a process which occurs when a piece of derelict land formerly had no growth at all, but with careful fertilisation and landscaping works, may be used to grow a limited number of plant species (Harris *et al.*, 1996). Through human input, a disturbed area is recovered to a landform and productivity that it enjoyed before disturbance took place (Tomlinson, 1984), often using a mixture of exotic and indigenous species. Rehabilitation in the wider sense can best be described as rehabilitating tailings dams to a stable physical state by means of vegetation which is naturally surviving and propagating, or made suitable for a predetermined use (DME, 1995). Furthermore, providing a proper water management system to prevent erosion and pollution of surface and sub-terranean water, and by natural means treat any polluted water (DME, 1995). The historic reason is also still relevant, and that is to prevent any form of atmospheric pollution (Marsden, 1985).

The term, rehabilitation also leads to confusion (Hobbs, Undated) as it can be applied to describe repairing activities to a number of spheres including social, economic, medical, physical and ecological.

These comparisons only highlight the need for consistent definition and use of terms in the field of restoration ecology. Consistent definitions are necessary for clear communication and they facilitate setting unambiguous goals for establishing effective programs for improving our environment. Wali (1999) states, with regards to the different terms used, that in the ultimate analysis it is not important what name the recovery processes resorts to, but by how well it is done. Therefore, these preventative and mitigating measures must be carried out in such a way that it is permanent, self-supporting, maintenance free and eventually, self-sustaining (Hannan, 1984).

The similarity of these concepts however, lies in the processes and aims of these different approaches of repairing damaged ecosystems. If a remediative effort is carried out, three aims are possible (Cairns & Atkinson, 1994):

- The first is restoration, in which an attempt is made to put back exactly what was there prior to the disturbance. It is unlikely that this state of grace can either quite be achieved, as the original ecosystem will have had the benefit of many centuries or millennia of development.

- Secondly it is possible to aim for something which is similar to (but less than) full restoration, which by using the human analogy, we can call rehabilitation. It can be argued that all restoration will in fact be rehabilitation.
- The third possibility is that no attempt is made to restore what was present originally. Instead, there is replacement of the original ecosystem by another ecosystem which is simpler, less diverse, but more productive (Solomon, 2002).

The context in which all three the above-mentioned aims converge includes the overarching aim and end-goal which is: A plant community that is established should develop into a stable, self-perpetuating ecological community which will fit in with the vegetation or landuse of the surrounding environment (Tomlinson, 1984).

More attention must however be paid to the quality of the remediative result and this quality could be measured in terms of landscape, productivity, diversity, and origin of the plant and animal communities in the context of the surrounding environment.

No ecological remediative effort on gold tailings dams could achieve these aims over the past 115 years (Weiersbye & Witkowski, 1998) and it could be speculated that the philosophies in which ecological restoration were carried out, were one of the main reasons for failure. The question should however be asked if current ecologically remediative efforts are truly carried out in the framework of total restoration (Van Wyk, 1994), and if the answer does not lie in ecological reconstruction. This implies to physically reconstruct every possible environmental baseline variable that can be amended to the norm of the surrounding veld to such an extent that the same habitat, diversity and productivity are reinstated to a sustainable extent.

RESTORATION APPROACHES OVER THE LAST CENTURY

Essentially, the objectives of the restoration of tailings dams by means of vegetation are: Long term stability of the land surface, which ensures that there is no surface erosion by water or wind, the reduction of leaching throughputs, the lessening of the amount of potentially toxic elements released into local watercourses and groundwaters; development of a vegetated landscape or ecosystem in harmony with the surrounding environment; and with some positive value in an aesthetic, productivity, or conservation context (Johnson *et al.*, 1994).

It took almost a century to establish that these objectives must be met before closure can be granted to a revegetated tailings disposal site. But it is really the paradigm or restoration approach that is followed, which drives the objectives that will be met and determine the outcome and sustainability of an ecologically remediative effort.

Due to the enormous volume and mass, it is impossible to transport or remove the tailings material to areas where it does not pose harm to anyone. Several attempts to reuse the material (e.g. brickmaking) (Struthers, 2002) were also unsuccessful due to the cohesionless characteristics of the tailings material. It was realised that the nuisance tailings dams presented were no temporary problem but there to stay, and therefore strategies to stabilise the tailings were assessed, leaving three possibilities (Down, 1975):

- Physical/Mechanical strategy (Tailings dams are planned better and covered with debris, waste rock, topsoil, water, straw, windbreaks, rubbish or any accessible by-products).
- Chemical stabilisation (Application of an appropriate reagent with the waste to provide a crust resistant to erosion. This include calcium, ammonium or sodium lignio-sulphonates.)
- Vegetative stabilisation.

It was proven over time that very few physical and chemical stabilisation resulted in permanent solutions (Down, 1975; Johnson *et al.*, 1994). Vegetative stabilisation showed the best results to limit erosion and pollution. It was much more cost-effective and sustainable outcomes were a possible prospect (Marsden, 1985).

Several approaches to revegetate gold tailings dams were applied over the years as objectives, technology and research in the field advanced, resulting in the combination of approaches and alternating techniques. None of these approaches have, however, come up with a sustainable solution to date. Mainly three approaches were followed over time, which include the *Agricultural*, *Adaptive* and *Ameliorative* approaches (Jeffrey *et al.*, 1975, Johnson *et al.*, 1994, Tordoff *et al.*, 2000).

The *Agricultural approach* dates back to the earliest attempts of gold tailings restoration. The same conventional principles of erosion, soil amendments, and agricultural vegetation were applied to establish a vigorous root system to bind the media. The use of this approach was a failure though, due to the fact that restoration is not an agricultural discipline, but an integrated and multi-disciplinary scientific approach is needed to assess this complex man-made problem. There is nothing natural about tailings material and therefore, more than agricultural principles are needed to sustain vegetation on these spoils.

The *Adaptive approach* emphasises the selection of the most suitable species, sub-species, cultivars and eco-types to meet and tolerate the rigours of the extreme conditions. In addition, but not necessarily, the tailings material may be improved by using amendments to achieve optimum establishment and long-term vegetation growth. This approach is simple but is constrained by the availability of suitable tolerators in some areas and exotic species are often introduced.

The *Ameliorative approach* is currently widely used and relies on achieving optimum conditions for plant growth by improving the chemical (and physical) nature of tailings material using lime, organic matter and fertiliser. The most suitable species commercially available are sown under irrigation on the tailings dams, of which the edaphic properties have been modified in accordance with the vegetation to be introduced (and supposedly with the land use objectives). The use of this approach shows quick results, requires less forward planning, and is less labour intensive.

The history of attempts to establish vegetation on gold tailings dams in South Africa is intertwined with these approaches and none of them produced proven sustainable results. The question of longevity of the vegetation established was one of the greatest areas of ignorance (Down, 1975) and could have been the reason for numerous restoration failures over the years.

Restoration of gold mine spoils in South Africa by means of vegetation date back early in the previous century, with the first efforts documented in 1894 (Gunn, 1973). The main reason for the restoration were already then to limit the nuisance brought by the dust blown off the dumps, causing eye and respiratory diseases. Their approach for restoration was shortsighted and only focused on immediate and cost-effective solutions. Rehabilitating these spoils by means of vegetation was however the first option considered and techniques preceding the agricultural approach were applied, but the vegetation could not be established properly and did not last (Cook, 1971). It is therefore clear that the restoration of gold tailings dams were underestimated since these first attempts were made.

Other measures were taken from 1911 onwards, which included physical methods, covering tailings dams using by-products generated from the mines' operational processes (Cook, 1971). These techniques included spraying the tailings with different mixtures of water and slime, oil and molasses and mixtures of precipitated mud from the neutralisation of acid mine waters with calcium oxide, and black mud consisting of the overburden from fireclay deposits (Thatcher, 1979). The addition of water mixtures to the tailings material weakened the structural stability, and clayey or similar soils were used as cover in an attempt to stabilise the material, but proved to be non-permanent. The direct covering method, in which the dumps were "blanketed" with any suitable debris, waste rock, ash or soil was then applied, but was just another unsatisfactory solution (Thurlow, 1937). In the 1930's it was realised that remediative efforts needed a systematic and scientific approach and the adaptive approach was applied for the first time. Experiments and studies were conducted on several tailings dams and various varieties of indigenous and exotic plants were tried (Gunn, 1973). The overall results were disappointing and provided little encouragement for the most optimistic idea of establishing a lasting protective vegetation cover on the tailings dams.

In the rare cases where vegetation did grow on the dump, transported soil and organic matter were present. The plants rooted only in this layer, ceasing when the dump material below was encountered (Thatcher, 1979).

During the 1940's, the mechanical strategy returned and tailings dams and sand dumps were covered with soil from excavations for the construction of skyscrapers, and household and industrial rubbish (Cook, 1971). After public outcry, some of the dumps were levelled and grass types were selected, but trees and flowerbeds with common garden flowers were subsequently planted (Gunn, 1973).

In the early 1950's post-landuse options of tailings dams and sand dumps were evaluated and in 1953 an investigation of the stability, chemical characteristics and significance of pollution from the tailings dams were conducted (James, 1966). Finding a solution was considered top priority and three basic problems were pointed out (Chenik, 1960).

- No vegetation established on the dams, which had been in existence for fifty years.
- Vast areas needed to be revegetated and these surfaces increased faster each year, and
- Species would have to be chosen according to their ability to grow and reproduce, as well as withstand climatic conditions. These included severe frosts, rainless winters and scorching summers.

A fourth problem, that that was only acknowledged later on, was the influence of landform on restoration success (Thatcher, 1979).

- Wind erosion from the top, flat surface of the tailings dam and
- Water erosion from the slope, side and toe of the tailings dam.

The agricultural and adaptive approach gained momentum from here onwards and after careful consideration it was decided to re-examine the possibility of establishing vegetation on the tailings dams (Cook, 1971). Agricultural techniques were used from 1959 onwards and principles arising from agricultural research were applied to rehabilitate the tailings dams. The tailings material was ameliorated with suitable combinations of lime, fertiliser, compost, manure and sawdust (James, 1966). A number of exotic and indigenous grasses, trees, shrubs, succulents and bushes were planted using seed and vegetative material (Cook, 1971). Successful (exotic) species were sown in areas where vegetation failed to grow and seed were resown with extra lime and fertiliser being added (Chenik, 1960). It became evident that each tailings dam had its own peculiar characteristics depending on type of the rock milled and microclimate of the area.

Maintenance free vegetation cover was always a challenge for researchers in the restoration field and in the 1960's, the first step in the right direction were investigated. The dryland method was proposed by Chenik (1960) and this method was entirely dependent on natural rainfall. When the vegetation established by this method failed, it was thought initially that the lack of nutrients, and not the acidity, was of major limiting factor in the establishment of plant growth. But when restoration products of the previous ten years started to degrade, research revealed that the failure experienced was related to the high acidity of the tailings, which remained practically unaltered both after the addition of sufficient lime initially for its neutralisation, and after subsequent additions of further lime.

This led to the development of a method using leaching to alter the acidity of tailings, as the addition of lime was not the sole answer (James & Mrost, 1965). This technique proved to be successful to some extent, not only for the leaching effect, but to constantly supply the vegetation with water.

Gold tailings revegetation in the 1970's was characterised by the challenge to better the techniques and information that was developed during the previous 25 years. New techniques were introduced and included reed paddocks that were set up to minimise wind erosion, and water pipes were installed to leach the tailings. The combination of the agricultural and adaptive approaches was however still dictating the research. In 1974, a new ecological ameliorative approach was proposed (Jeffrey *et al.*, 1975). This approach "recognises that to achieve permanent revegetation of a toxic, sterile and infertile site, we have really to synthesize an ecosystem". This was the start of a more holistic approach towards restoration worldwide.

The high cost of establishment and maintenance of a plant cover on the tailings dams gave rise to the idea that an indigenous and self-maintaining cover would be the answer to erosion, pollution and aesthetic problems of the tailings dams over the long term (Barker, 1985). The shortcomings of the traditional revegetation products were assessed and included: The small number of grass species, the dominating monocultures, the absence of any indigenous woody plants and the relative absence of animal life due to the fact that revegetated tailings dams are maintained as artificial "ecosystems" (Jeffrey *et al.*, 1975; Barker, 1985).

The *Ecological approach* therefore places the emphasis on the importance of establishing biological processes such as nitrogen fixation, decomposition, nutrient cycling and retention, and important biotic interactions (Johnson *et al.*, 1994). These parameters indicate proper ecosystem functioning, which is as important as the careful selection of plant species in providing the primary vegetation structure (Bradshaw, 1990). This approach came one step closer to reach sustainable restoration but for the next 15 years, no lasting vegetation cover could be established (Bamberg, 1996).

The ecological approach is based on the principles of a natural process, namely plant succession. This implied that the establishment of pioneer species on a tailings dam would create favourable circumstances over time for the reclamation by transitional and climax species (Cairns, 1995; Barker, 1985). This process proved to occur on numerous mine spoils after restoration was carried out, but not on gold mine tailings. It seems that the ecological approach posed only half the final answer.

RESTORATION TODAY

More recently, in the mid to late 1990's, a combination of the ameliorative and ecological approach is used and relies heavily on neutralisation of tailings material (Envirogreen, 2000). Various new techniques are applied which include the application of sewage sludge, liming for total acid forming potential of the top layer of tailings material, indigenous species are introduced and the restoration products are closely monitored. The techniques associated with this approach will prevent the effect of re-acidification of the surface layers (neutralise potential acidity), thereby enabling the establishment of a sustainable cover (Envirogreen, 2000). These current methods can be likened to revegetation but no restoration has taken place to the extent that environmental impacts are being addressed (Erasmus, 1998).

It further has to be opened that restoration of mine spoils became a business with operational budgets, profit margins, shares and competition. With this economic framework in mind, the ecological approach is used as a marketing tool, with scientific accountability and proven sustainable products not necessarily being applied. Clients must be satisfied with restoration proposals and objectives are moulded to suit the green image of mining companies. Restoration expenditures are determined by the tractability and money margins presented by mining companies and not by acceptable ecological outcomes of the restoration product. Therefore, restoration is often carried out on the fringe of scientific acceptability, to meet minimum product criteria and to comply with company expectations and regulatory requirements.

It is clear however that the perspective in the first world countries changed over the past twenty years with regards to expenditures on ecological restoration and the replacement of environmental capital (Tomlinson, 1984; WRI, 2001). To restore mine tailings may provide an opportunity to reconstruct the native habitat (Williams, 1996) and it is in this spirit that a pro-active approach brought a shift in emphasis to the paradigm and strategies originally used. This shift included a change from a segmented recipe procedure and integration on small scale, to a multidisciplinary pre-planned ecologically designed system that is installed as soon as restoration commences.

PRINCIPLES OF ECOLOGICAL RECONSTRUCTION

Ecosystems have several important characteristics. They firstly and most importantly undergo natural development. A newly available land surface starts to evolve from the weathering of bedrock. The raw skeletal material undergoes secondary weathering with associated soil profiles that form and the release of nutrients (Brady, 1984). Plants with the best tolerance of the environmental extremes colonise the area and contribute organic matter to the soil, enabling the environment to sustain different and larger species (Tainton, 1999). One group of species is replaced by another through primary succession, and progressively a more substantial and complex ecosystem develops (Cairns, 1995). The structure becomes more complex by an increase in the number of species and their ecological diversity. The ecological function increases through biomass retention and nutrient circulation (Harris *et al.*, 1996).

It would therefore be extraordinarily difficult to restore ecosystems to their precise pre-disturbance condition (Cairns, 1995) since:

- Each ecosystem is the result of a sequence of climatic, biological, and other events unlikely to be repeated in precisely the same way.
- Commonly, the structural and functional attributes of the ecosystem before disturbance are not precisely documented.
 - The communities and even species that once inhabited the ecosystem may no longer be physiologically identical with the race, subspecies, etc. formerly inhabiting the damaged ecosystem.
 - Remediative inputs are seldom sustainable.

A good indication of the restoration success will thus be the degree of biological succession that occurs over time (Brenner, 1995). As already mentioned, there is no substantial evidence that natural succession occurs on gold tailings dams, even after the best ameliorative efforts and ecological planning.

This compels us to use another approach – we must establish the conditions and plants that we want there, and not remediate the tailings to some extent and wait for natural succession to accelerate ecosystem development. This is ecological reconstruction.

Four main stages can be proposed for ecological reconstruction (Tongway & Murphy, 1999) but a one-dimensional approach is presented in the literature. Therefore it is adapted to a multi-dimensional pyramid (Figure 1) of which the capacity for development cannot be quantified, allowing dimension for development within each phase, especially for the end-goal. The presentation of ecosystem creation/development as a pyramid conveys the idea that ultimate success is built on the firm foundation of earlier successful stages. Each succeeding phase depends upon the satisfactory resolution of issues in the first phase.

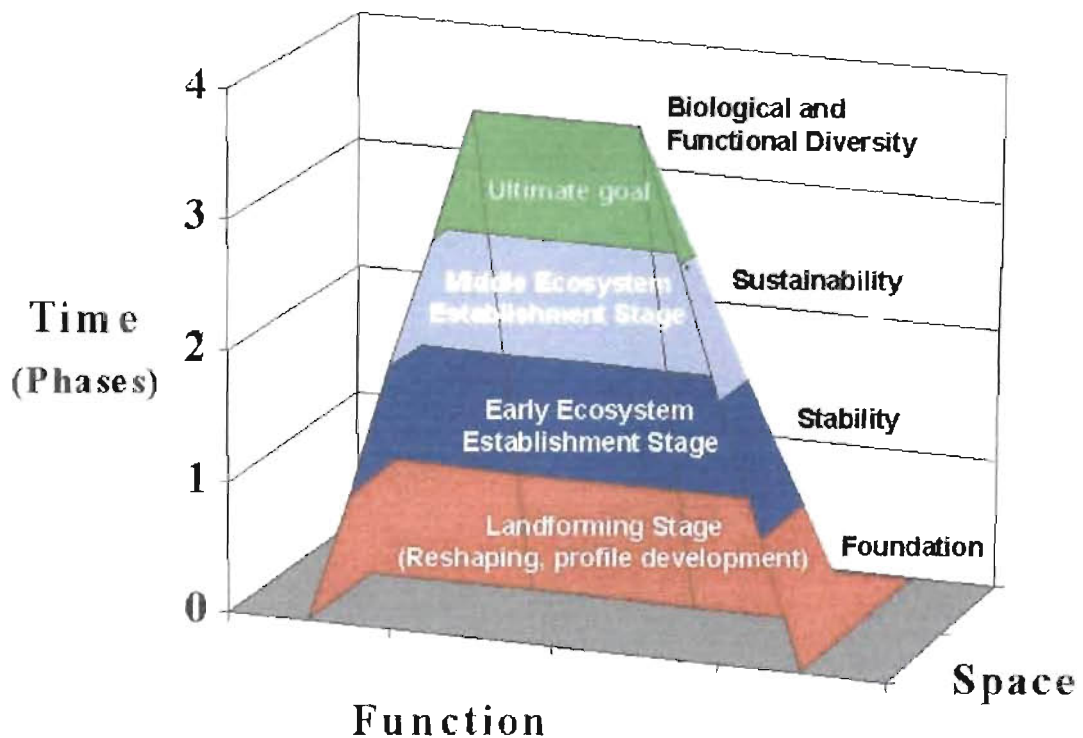


Figure 1: Restoration stages.

The first phase, the foundation - probably the most neglected and underestimated step - is critical in that there will be many technically problems to solve. These include alteration of inappropriate landforms, adverse spoil properties and acid mine drainage attenuation (Tongway & Murphy, 1999). An ecosystem may further be technically stable without being biologically sustainable, or sustainable to some extent, without having completely achieved biological and functional diversity (Brenner, 1995).

The stability phase (Early Ecosystem Establishment stage) largely refers to erosion stability, rather than ecosystem stability, which is included in the sustainability stage in this context. After initial set-up, a short period of regression occurs, and erosion with partial geotechnical instability can be expected. There will for example be a need for planning and design criteria to be established to avoid the creation of a landscape: soil: biota combination with too low a potential to resist and stabilise initial erosion, and overcome microclimatological limitations.

The achievement of biophysical sustainability (Middle Ecosystem Establishment stage) is clearly related to biological development. In this phase, factors such as the selection of functional grass, forbs and tree species, their ratio of seed mixtures which will result in the appropriate frequency and cover, initiation of seed production and active nutrient cycling processes are planned and carried out. The post-landuse objectives should play a primary role in these issues and the degree of conservation and biodiversity need to be resolved by this stage (Van Wyk, 1994).

Change over time, which might result from variable impacts, is a key characteristic in ecosystems and crucial changes will occur in both structure and functioning of the restoration product. Ecosystem development plotted as the development of a number of indicator values over time could therefore be part of the evidence rendered for the satisfaction of completion criteria (Tongway & Murphy, 1999). The parameters used as indicators should be scientifically based edaphic and biological indicators, and numerous studies should support the use of these functional variables. A number of possible indicators that can be monitored over time are presented in Table 1.

Table 1: Indicators that can be used to monitor ecosystem development over time.

<u>Indicator</u>	<u>Monitoring Criteria</u>
1. Geotechnical stability	Assess stability of created landscape, the influence of the phreatic zone on the structural stability and seepage.
2. Erosion features	Assess the nature and severity of current soil erosion, likelihood of soil detachment, and mobilization by mechanical disturbance.
3. Soil cover	Assess soil profile development, crust formation and effect of evaporation.
4. Micro-topography	Assess temperatures on different slopes, influence of surface roughness for water infiltration.
5. Nutrient cycling	Assess the availability of surface organic matter for decomposition and nutrient cycling.
6. Biotic acceptability of soil	Fertility, microbiological diversity, micro and macro invertebrate diversity and root development.
7. Plant species	Assess the species composition, frequency and basal cover of the plants and compare it with the norm of the surrounding environment.
8. Animal species	Assess the abundance of insects, birds and small mammals on the rehabilitated site.
9. Ecological function	Assess the degree of the reinstatement of ecological stability, ecosystem structure development and the evolution of original function.
10. Impact on surrounding environment	Evaluate to what degree the original contribution of this site to the surrounding environment is restored in terms of water run-off, supply of nutrients, biotic inter-actions and micro-climatological aspects.

Monitoring should occur along permanent transects established in analogue and restored landscapes and indicator data must be obtained from them at the same time intervals (Tongway & Murphy, 1999). These indicator values could be re-analysed and processed to a certain value of weight within the context of ecosystem development. One should resist prescribing that restored sites should have the same indicator values as analogue sites, although this criterion might have some merit. Restoration inputs could, however, optimise ecological function and the desirability of this factor is debatable.

Figure 2 depicts a hypothetical example of the increase in ecological reconstruction success over time. Indicator 1 may, for example, be the biotic acceptability of the soil, which is very low immediately after restoration occurred, but shows a net increase over time. Indicator 2 resembles landform features for example, which start with a moderate value but declines over time due to erosion, and increase thereafter as a result of the colonisation of plants. It could therefore be proposed that a mean resultant could be derived from these indicators, which will characterise the return of ecological function (Tongway, 1997).

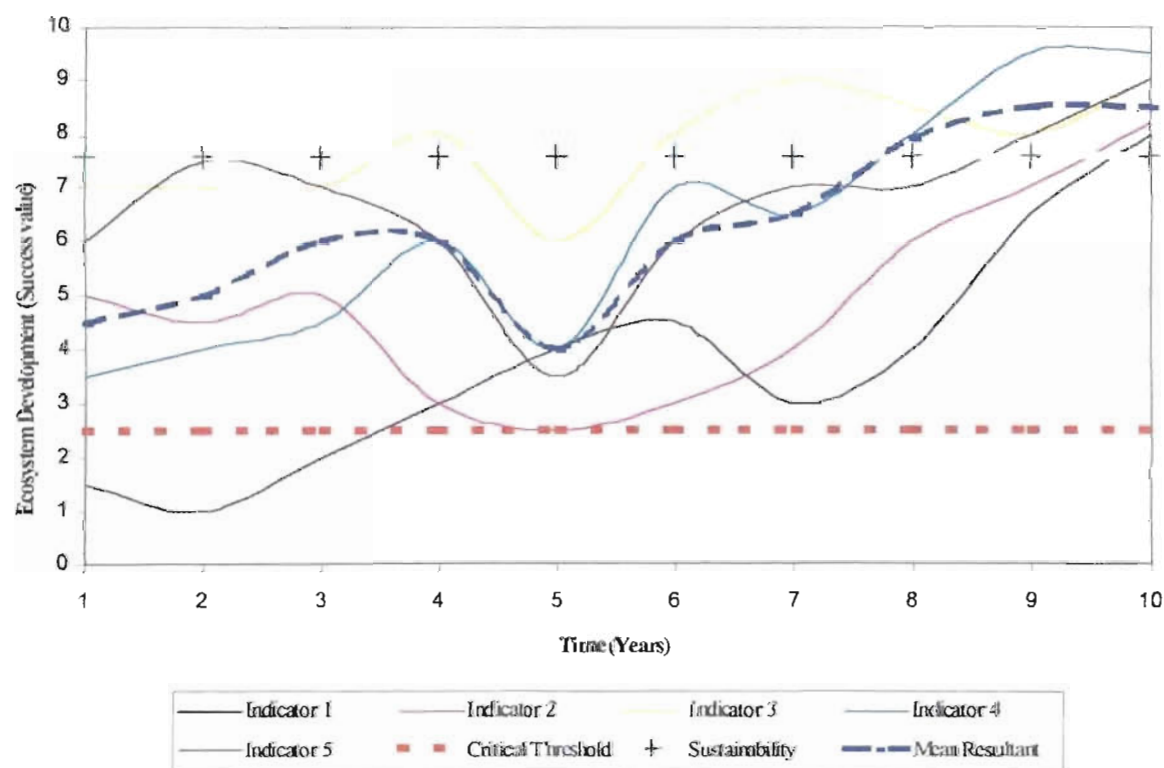


Figure 2: Relative values of ecological indicators to evaluate ecological reconstruction success.

The true success of restoration should be measured along this 'ecologicalising' gradient. The gradient will describe the degree of ecological recovery and restoration success. The

measurement of this 'ecologicalising' input will be difficult and many years will have to pass to witness the success of the reconstruction effort. Ecological state-and-transition phases must be noticed over the years as it is another characteristic implying dynamics in response to certain naturally or human induced events in ecosystems (Tainton, 1999).

A critical threshold range is also included on the graph and represents stability minima. If the mean resultant decreases beneath this line, the restoration product is more vulnerable to climatic events and stochastic occurrences (Tongway & Murphy, 1999). The longer the created ecosystem remains below this threshold, the more at risk its ultimate success of achieving system stability becomes.

A sustainability value is included on the graph and each indicator could be compared individually, or the mean value could show whether ecosystem development is on track. Once all the indicators reach values above this sustainability range, the end-goal is reached and the ecosystem does not need further additions or inputs to be self-sustaining. Monitoring should go on to detect possible degradation of the ecosystem over time (Envirogreen, 2000).

Restoration of a damaged ecosystem should further not be limited to approximating local pre-impact conditions, but should also consider mitigating damage within the landscape. This would include minimising off-site degradation caused by the reclaimed ecosystem (Cairns & Atkinson, 1994).

More principles of ecological reconstruction are presented in Table 2.

Table 2: General principles for ecological reconstruction of tailings sites.

(Adapted from Milton (2001).)

-
1. Set clear ecologically and economically feasible goals for restoration.
 2. Do not rely on traditional restoration approaches.
 3. Budget sufficient time and money for restoration and monitoring.
 4. Reconstruct the landform by mimicking the original uneven shape of the landscape.
 5. Create a mineral sink for sustainable ecosystem development by reintroducing unweathered material.
 6. Recreate a suitable soil profile able to retain and capture resources (Organic matter, nutrients and water).
 7. Salvage living components of the ecosystem.
 8. Use locally adapted, indigenous plant and animal species.
 9. Enable plants and animals to assist in the restoration process.
 10. Keep good records of results obtained through monitoring.
-

The question undoubtedly needs to be asked why ecological restoration in South Africa never moved out of the second phase as proposed in Figure 1. A possible answer could be that the foundation phase was underestimated and that landform inhibited successful restoration (and still does). Another reason may be the fact that the mining industry still awaits a better solution and carries on with the postponement strategy.

THE ULTIMATE END GOAL

In many instances during the restoration of gold tailings dams, the establishment of a quick vegetative cover is the prime consideration, and not the development of habitat diversity (Bradshaw & Chadwick, 1980).

In the past the establishment of habitat diversity occurred, at least in part, as a result of natural succession with little, if any, preplanning (Jeffrey *et al.*, 1975). Restoration efforts did not integrate these restored habitats into complete harmony with the site or the surrounding landscape (AMRH, 1989).

Discarded areas are often reclaimed as homogenous habitats, covered with monocultures, which lack the biological diversity that existed prior to mining activity and fail to take the regional biodiversity into account as well (Brenner, 1995). As a consequence, revegetated mine sites exhibit a much lower alpha biodiversity (Winterhalder, 1995). Current post-mining landuses include minimal vegetative diversity that is limited to non-native members of two families, which include the *Fabaceae* (legumes) and *Poaceae* (grasses) (Johnson *et al.*, 1994).

It is thus possible that by providing habitat heterogeneity during restoration, to re-establish the functions and values that existed on the site prior to mining to some extent. By providing a mosaic of terrestrial and wetland habitats, it may be possible to enhance the biodiversity of the region, including wildlife habitats for rare and endangered species (Brenner, 1995).

An effective strategy to enhance biodiversity would therefore be to introduce random or planned diversity into as many as possible restoration practices and to devise ways of sustaining and enhancing any diversity already present in the newly revegetated system.

In order to engender a degree of biological diversity that is stable and in a state of equilibrium with its environment, it is necessary to diversify the environment during the restoration process (Winterhalder, 1995). This can be done in a number of ways, which must be based on a thorough ecologically evaluated pre-plan. Firstly, micro-topographical and micro-climatological diversity should be reinstated through recontouring of the tailings landform (Hannan, 1984). Uplands, wetlands, drainage patterns and lakes and ponds should be planned, and the creation of a series of ridges and valleys will also provide an opportunity to enhance habitat diversity (Brenner, 1995). Geological diversity should be reinstalled, by

interposing a gravel or cover layer (Richard *et al.*, 1996) between the tailings surface and the ameliorated tailings material. This layer could act as a capillary break and will inhibit the upward diffusion of salts, stabilise the tailings, and act as a sustainable nutrient source if natural processes of erosion commence (AMRH, 1989). The most direct way to create nutritional diversity in a growth medium is to vary the application of fertiliser or other sources of nutrients in the reinstated profile (Winterhalder, 1995). An indirect approach would include to select plant species that will deliberately alter the nutritional status of the soil.

Soil faunal abundance and diversity can also be enhanced by the use of topsoil (Jeffrey *et al.*, 1975), and although it is rarely economically feasible to cover the whole tailings deposit with even a thin layer of soil, the introduction of patches or islands of topsoil may be beneficial. The use of some soil from a plant community that represents the climax population for the area should be applied, even if only a small amount is introduced as a seed source and microbial inoculums. The propagules in the topsoil will germinate and in-situ succession may result. The use of seed from native plant species obtained from local and on-site sources, as well as transplanting locally adapted plant species into specially prepared spots, will enhance sustainability (Bamberg, 1996).

These spots will act as loci for continued natural revegetation. Plant populations are furthermore not homogeneous entities as resembled by the monocultures occurring currently on tailings dams. Genetic diversity is just as important as species diversity (Winterhalder, 1995) and will ensure long-term functional stability through environmental extremities (Milton, 2001). Genetic diversity will not only enable species to inhabit a larger number of microsites and adapt to environmental changes, but will also lead to the recombination and the formation of genotypes that are better suited to the degraded habitat than any of the mother plants.

It is clear from the literature that there are several prerequisites to engender sustainability of a rehabilitated site.

- There should be as much diversification of the environment as possible.
- Not only the species, but also the genotypes should be diversified.
- Biodiversity should be achieved at community level in order to preserve mutualistic relationships between different species of plant, animals and microorganisms.

The role of animals in the restoration process is vastly underestimated and therefore understudied, but great importance is assigned more and more to the importance that animals have in the return of ecological structure (Cairns & Atkinson, 1994). Several faunal studies on rehabilitated sites have shown that certain plant species facilitate particular animal invasions, and those animals may alter sites to favour additional plant and animal immigrations (Majer, 1989).

When the reconstruction of habitat function is successful, the post management plan should optimise the restored value of the restoration product. The post-landuse program should compliment the value of restoration not only for the net value of the introduced ecosystem, but in the context of conservation. These areas could serve as areas that will relieve the severe habitat fragmentation, act as migration corridors for animals in urban areas and be planned as urban open spaces.

FINAL THOUGHTS

The time has come for South African mining companies to realise that the only way ahead is to realign policies regarding ecological restoration with international best practice. Numerous first world countries operate on strict standards for restoration, (MAC, 1998; Environment Australia, 1999; Illinois DNR, 2000) introducing a pro-active restoration approach and replacing environmental capital to an optimum extent through intense research, modelling and ultimately ecological reconstruction.

The constant failure of gold tailings restoration can be ascribed to the poorly informed approaches applied over the years, which were based on a lack of knowledge and driven by shortsighted ideas. A new holistic restoration framework is needed, which will include an approach that does not focus on saving through neglecting the replacement of environmental capital but has only one aim, which is total restoration. This implies restoration to such an extent that it will comply in all ways with pre-planned ecological objectives, reinstating ecological function and constantly using the surrounding veld as the norm with respect to uncertainty and variables. This should be the greatest challenge for ecological restoration science.

Essentially, current research should be strongly focused on the success of the restoration goal, producing a sustainable post-mining physical environment by establishing ecosystem processes (Mudder, 2001). A multi-disciplinary approach could thus be a buffer against possible failure of restoration and through integration of expertise, a product might result that could ensure a holistic approach and a sustainable solution.

However, a more realistic view, at least in the short term, may be to have a long-term vision for sustainability, incorporating an immediate goal to protect the environment by re-establishing basic ecosystem function (Spain, 1996).

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CHAPTER 3

QUANTIFYING THE EFFECT OF THE DISPERSIVE NATURE OF GOLD MINE TAILINGS MATERIAL ON GRASS SPECIES SEEDLING ESTABLISHMENT

CHAPTER OVERVIEW

The ecological rehabilitation industry has recognised the influence of the inherent susceptibility of gold tailings to erosive processes in principle but the effect of the dynamic complexity of dispersion characteristics of tailings material, as a result of its physical properties, has, however, in practice largely been ignored. The detrimental impact of gold tailings erodibility, and more specifically the dispersibility of the media, on sediment delivery processes and its implications for plant establishment and natural succession, is poorly described. Data on erodibility of gold tailings material are limited and therefore the degree of mass transport of tailings material has not been quantified to any significant extent. More attention has been paid to mass wasting studies in the past, using soil-engineering techniques based on data derived from subsoils with significantly less complex properties, to predict the extent of tailings erosion, and nowadays to assist in the design and creation of reformed landscapes from tailings dams. The poor textural material properties, combined with the effect of the extremely steep slopes of the tailings dams, render it impossible to protect slopes indefinitely from severe water erosion, risking long-term geotechnical instability and possible future pollution. Rill and inter-rill incision are the main contributing water erosion forces that result in the degradation of gold tailings dams and can only be limited through slope stabilisation by means of a persistent vegetation cover. A self-perpetuating ecological system will, however, only develop to a sustainable extent if primary and secondary successional processes are recovered, implying that the hostile soil-seed contact area on tailings dams, combined with the detriment posed by erodibility of tailings material and slope gradient, must be seriously addressed to achieve lasting rehabilitation success. In this study, the dispersivity of gold tailings media is quantified, and the effect of this erodibility parameter on the establishment of grass species seedling establishment is explored.

QUANTIFYING THE EFFECT OF THE DISPERSIVE NATURE OF GOLD MINE TAILINGS MATERIAL ON GRASS SPECIES SEEDLING ESTABLISHMENT

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ABSTRACT

The effect of the silty and cohesionless characteristics of gold tailings media on sediment delivery has not been intensively studied. Erosion losses of this highly erodible media are also underestimated by calculations of the RUSLE. The dispersivity of the media therefore needs to be quantified more accurately. Effects of the dispersivity on seedling establishment of revegetated tailings dams are also poorly described. The influence of tailings dispersivity on favourable seed-soil contact niches could therefore explain plant successional processes on tailings dams. The objectives of this study included the quantification of the soil physical characteristics of gold tailings material to determine the dispersivity of the media, and to relate the effects of this parameter to seedling establishment performance. Gold tailings material from 9 tailings dams were collected and analysed, and pot trial experiments, which consisted of various ratios of tailings material and topsoil, were laid out, and physically and chemically analysed. It was established that gold tailings media have an exceptionally high Silt Dispersivity Index of 41,85%, compared to 15,51% of soil, explaining the high erodibility of the material. The SDI was successfully rectified in the pot trials and seedling abundance correlated positively with the coarse sand fraction (0,86), pH (0,9) and [P] (0,8), and negatively with the SDI (-0.74). Seedling persistence correlated the best with Ca, Mg, and K concentrations. Through multivariate analysis it was also established that climate did not have a significant effect on seedling establishment.

This research proposes that new erodibility values should be investigated for tailings media, which could be related to the dispersivity indices. Furthermore, the high SDI of gold tailings could inhibit successional processes, especially at steep slopes. Soil physical amelioration is therefore indispensable for the enhancement of the regenerative potential of gold tailings dams.

Keywords:

Erodibility; Gold tailings; Restoration; Seedling establishment; Soil dispersivity index.

INTRODUCTION

Gold mine tailings residue is fine-grained, cohesionless and silty material, which tends to be highly erodible (Blight, 1989; DME, 1995). Due to the physical and chemical characteristics of the tailings particles, it is extremely susceptible to erosion and is readily dissected by water erosion (Olyphant & Harper, 1995), leading to geotechnical landform instability and pollution safety hazards through dust and contaminant distribution to nearby areas (Evans, 2000). Erosion control is a principal concern as it is a prerequisite for slope stability and ultimately successful revegetation, with associated landscape stability of tailings dams. Successes of efforts to contain the tailings material permanently to the perimeter of the dams are, however, few, and the lack of erosion control could pose serious ecological problems as it escapes from the confines of the storage areas and is deposited in low lying areas, on agricultural land and inevitably causes extensive siltation of streams (Dorren & Blight, 1986) as well as degradation of soils (Bradshaw, 1999). The establishment of vegetation is therefore widely accepted as the only sustainable solution to prevent surface erosion from mine tailings (Johnson *et al.*, 1994). Conventional grassing, however, limits erosion only by 58,5% (Van Rensburg *et al.*, 1997), leading to 41,5% uncontained and exposed tailings media being deposited in the terrestrial and aquatic ecosystems of the surrounding environment. The soil physical characteristics such as the inherent susceptibility of the medium to erosion resulting from the particle fraction composition, primarily affects the sustainability of the vegetation cover (Van der Nest, 1998), adding to the exponential degradation of the tailings media by the aggravating erosive effect of runoff water and its relation to slope angle and slope length. The effect of soil physical characteristics on vegetation establishment and persistence on mine tailings has not been thoroughly studied, and the importance of this factor for sustainable revegetation has often been overlooked as high restoration costs are involved. It is, however, necessary to quantify the influence of this parameter on vegetation establishment on tailings media, as the soil physical characteristics might have a significant influence on vegetation persistence and community succession.

Very limited published literature is available on the quantities of gold tailings losses through erosion, and the inherent susceptibility factors of the media affecting erosion rates are also poorly understood (DME, 1995). Although the principles of physical and chemical characteristics' influence on erodibility are applied to determine erosion quantities, it seems that the nature of this unnatural medium does not submit to the predictions of simulation models, based on the observations of previously described cases. The RUSLE, which is the most widely used erosion estimation equation (Dorren & Blight, 1986; Hatting *et al.*, 2001) underestimates erosion from gold tailings dams (Figure 1) as the Erodibility Index value (K) is a lumped agricultural subsoil based parameter (Sheridan *et al.*, 2000b) and ineffective to predict mine discard loss (acknowledged by Wang *et al.*, 2001).

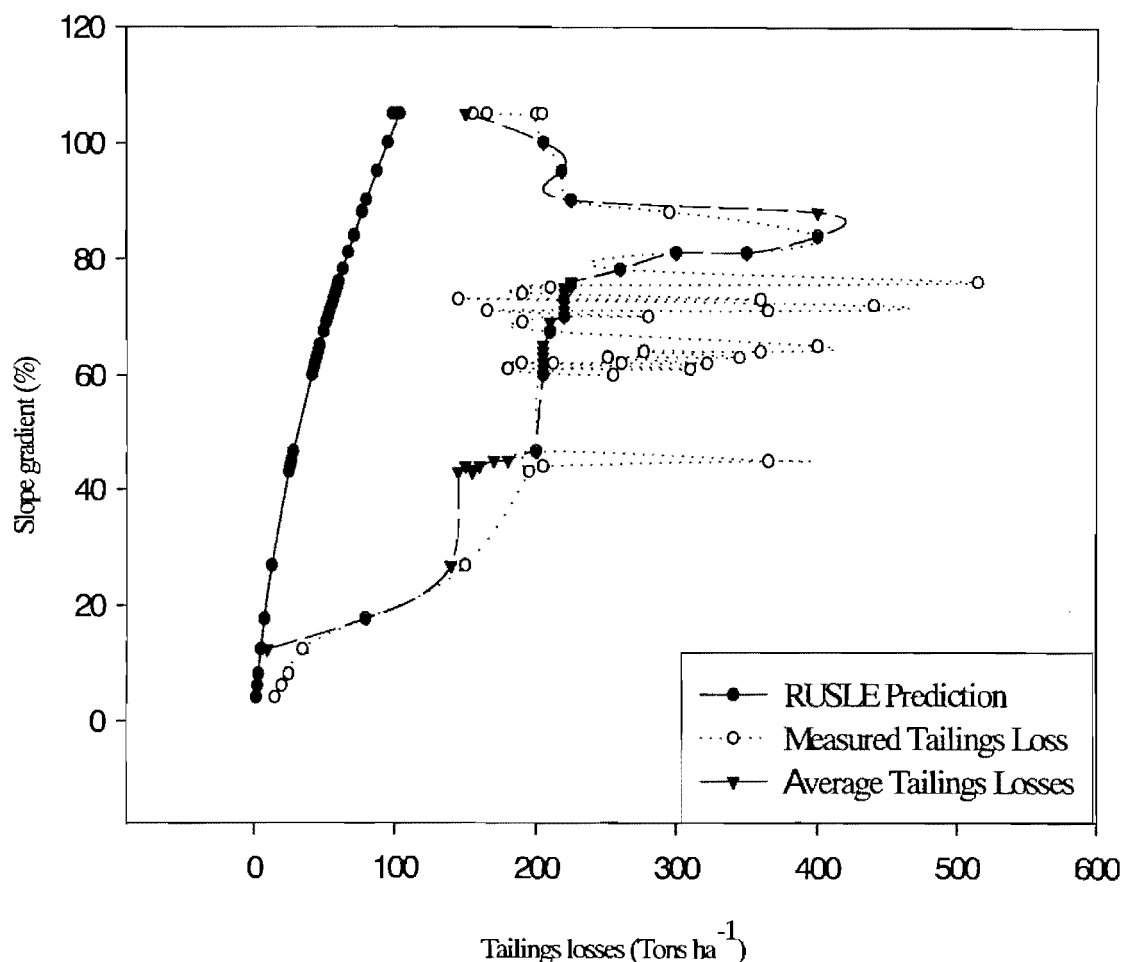


Figure 1: Comparison between measured erosion losses and RUSLE predictions. (Data obtained from Dorren and Blight, 1986; DME, 1995; Van Rensburg *et al.*, 1997)

The physical and chemical characteristics of mine overburdens are, however, different from those of agricultural soils, resulting in significant differences in erodibility (Sheridan *et al.*, 2000a). It was evident from the few existing mine discard erodibility studies that the Erodibility Index (K) is often undervalued, as the generalised erodibility values derived from agricultural subsoils are applied and does not allow for the extremely high dispersivity encountered, resulting from the unnatural fine-sand dominated particle size distribution of the tailings media. Therefore new K values should be proposed for mine discard in the use of these equations. The dispersivity of the tailings media, which is quantified by the Silt Dispersivity Index (SDI) and the Clay Dispersivity Index (CDI) (Mbagwu & Bazzoffi, 1998; Sheridan *et al.*, 2000b), could be used to characterise the erodibility of the tailings media. The response of vegetation establishment and persistence correlated with these dispersivity indices could also provide insights on the effectiveness of revegetation to limit tailings erosion.

The importance of investigating the inherent nature of gold tailings media and its associated susceptibility to erosion unfold in the expectation of the extent to which revegetation will persist after expensive restoration inputs, and the quantification of the effectiveness of revegetation could culminate in soil quality standards for ecological restoration.

The objectives of this study were to:

- Quantify the physical nature of gold tailings material.
- To determine and compare the Silt Dispersivity Index (SDI) and Clay Dispersivity Index (CDI) of gold tailings, coal discard and soil.
- To report the results of physical rectification on recreated soil profiles with regards to the SDI and CDI.
- To determine the affinity of seedling establishment and initial vegetation persistence towards the influence of climatic and soil physical and chemical parameters.
- To determine the correlation between seedling establishment and dispersivity.

Soil erodibility and dispersivity

Soil erodibility (K) accounts for the influence of the intrinsic soil properties (Wang *et al.*, 2001) on the susceptibility of a soil to erode (Gray & Leiser, 1982). The contribution of these intrinsic properties to the liability of soil erosion (or conversely the resistance of the soil to the effect of erosion factors) is a function of the soil's properties, particularly its physical characteristics (Rorke, 2000). These include soil texture, permeability, moisture content, soil structure, size and stability of structural aggregates (Dvorak & Novak, 1994; Wang *et al.*, 2001), humus content of the soil and saturation of the soil's sorption complex with basic cations (Mbagwu & Bazzoffi, 1998). Although it can only be defined in relation to specific erosive forces (Rorke, 2000), the evaluation of the soil physical characteristics will indicate to what extent dispersivity of the media could be expected.

The dispersibility of a soil includes the resistance towards micro-aggregate binding breakdown by physical and chemical erosive processes, which is determined by the compositional volume of the silt and clay particle fractions (<0.02mm) of a medium (which are the particle fractions most susceptible to erosion (Wang *et al.*, 2001)). The SDI and CDI, which are determined through the complete physical and chemical dispersion of the tailings media, could therefore be successfully applied to determine the erodibility status of tailings media.

MATERIALS AND METHODS

Determining the soil physical nature of gold tailings material

The soil physical properties of gold tailings material were determined from nine different gold tailings dams. Five samples on each of the aspects of the dams were randomly collected (20 samples per dam made up to a composite sample) and three samples of the composite samples were analysed for each dam.

- Particle size distribution of the tailings media was determined by the sedimentation and pipette technique described by Day (1965), which involves the physical and chemical dispersion of the tailings samples.
 - Air-dry, 25 g samples were completely dispersed by the addition of 10 mL of sodium hydroxide and 10 mL of 10% sodiumhexametaphosphate to 1 liter of deionised water, and end over shaking for 16 hours.
- For the investigation of the dispersion indices, 25 g of air-dry tailings sample was added to 1 liter of deionised water (no other chemicals were added) and the pipette method was applied again to determine the particle fractions (as described by Dong *et al.* (1983) and Sheridan *et al.* (2000b)).
 - The Clay Dispersivity Index (CDI) was calculated as the ratio of the mass of clay (<0.002 mm) in suspension after end over shaking for 30 minutes in deionised water, to the mass of clay following complete chemical and mechanical dispersion.
 - An equivalent methodology was used to determine the Silt Dispersivity Index (Particle size class: 0.02 mm < SDI > 0.002mm).

Results for the analysis are presented in Table 1.

Determining the relation between dispersivity and seedling establishment

Gold tailings material was collected for a pot trial experiment from an un-rehabilitated gold mine tailings dam (26° 49' S, 26° 27' E), and topsoil was collected at this mine's open cast soil storage facility. Soil physical and chemical analyses were conducted for both the media (Table 2). Seven treatments with 3 replications of each (21 in total) were laid out in an enclosed area, in 40 dm³ containers (surface area of 0.09 m²), punched at the top to allow run-off of standing water, and at the bottom to allow free drainage. The trial variation is presented in Table 3.

- The object of the physical amelioration was to improve the physical characteristics of the tailings, increasing the ratio of particles greater than 0.2 mm fraction to the particles smaller than this fraction. A further objective was to determine to what extent the high dispersivity values of tailings material could be enhanced to reduce erodibility, and also

to establish the correlation between vegetation establishment and reconstructed particle size distribution (reduced dispersibility).

- Tailings material and topsoil were weighed separately with a Camry (100kg x 500g) scale to compose the sum of a pre-determined desired ratio (to a total mass of 40kg). The expressed percentage values of the contents thus represent the value by mass, and not by volume.
- The weighed fractions (pre-determined ratios) were then mixed thoroughly using a soil splitter. This resulted in a reconstructed soil profile (depth of 0,4 m) with a ratio-determinant homogeneous distribution of particle sizes.

The soil particle distribution and dispersivity values of the different treatments were determined using similar techniques as described above. Results of the soil physical and chemical properties are presented in Tables 4 a & b.

To establish the effect of the recreated soil physical profile and related dispersivity indices on seedling establishment:

- Seed of nine native grass species, which were made up to a predetermined ratio, were sown on the different trial variations. These species included *Aristida congesta* subsp. *barbicollis* Roem. & Schult., *Chloris gayana* Kunth, *Cymbopogon plurinodes* Stapf. Ex Burt davy, *Cynodon dactylon* (L.) Pers. var *dactylon*, *Digitaria eriantha* Steud., *Enneapogon cenchroides* Roem. & Schult. (C.E. Hubb.), *Eragrostis curvula* (Schr.) Nees, *Heteropogon contortus* (L.) Roem. & Schult., and *Themeda triandra* Forssk..
- Seedling assessments were conducted on a monthly basis, counting the total number of seedlings that established on each of the different treatments. The data for the seedling fluctuations are presented in the addendum (Table A). The data derived before the winter period represent the initial establishment data and the data thereafter, the persistence data.

The experiment was conducted over an eight-month period (two months before and after winter) and was exposed to environmental conditions with total rainfall of 296 mm over the time. Air temperature extremities ranged from 31.1°C, to -7.9°C, with a mean daily temperature of 20.9°C during the seedling establishment period (first six weeks after seeding). Although climate did have a significant impact on seedling establishment, the average seedling abundance did visually reflect the merits of each of the treatments.

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Data analysis

- Statistical analysis was performed making use of StatSoft Statistica Release 6.
- Multivariate analysis was applied to interpret the seedling data in relation to the physical and chemical characteristics respectively, using CANOCO (Ter Braak, 1996) (Ver. 4).

- Canonical correspondence analysis (CCA), which is a unimodal direct ordination technique, was initially applied to indicate the direct determining gradients.
- Detrended correspondence analysis (DCA) is an improved eigenvector ordination technique and was applied to establish the indirect gradients that were derived from the higher variation datasets. This technique is based on reciprocal averaging (RA), but RA's arch distortion is corrected. The method proved to establish grounds for further multivariate analysis, to characterise the primary determinant gradients (Kent & Coker, 1997).
- Redundancy analysis (RDA), which is a refined Principal Component Analysis (PCA) technique, was therefore applied, and allows for the linear direct ordination of low variation datasets, which enable more accurate interpretation of short gradient results.

RESULTS AND DISCUSSION

The statistically significant results posed in Table 1 (very low standard deviation and $p < 0.05$) (Shapiro-Wilk's W test) indicate that gold mine tailings media have a very high silt dispersivity index (SDI) and a relative high clay dispersivity index (CDI).

Table 1: Results of the soil physical analysis for the tailings media from the 9 different gold tailings dams. The fractions are expressed as a percentage.

	(%)	IN CALGON				IN WATER		DISPERSIVITY	
		Coarse sand	Fine sand	Silt	Clay	Silt	Clay	SDI	CDI
Mine 1	Avg.	2.9	79.4	13.1	2.8	6.5	0.3	49.5	11.1
	Stdev.	0.5	0.8	0.8	0.2	0.6	0.2	7.1	7.6
Mine 2	Avg.	0.6	62.3	28.6	6.8	7.4	0.4	25.8	6.3
	Stdev.	0.3	1.1	1.1	0.2	0.9	0.2	2.0	3.3
Mine 3	Avg.	0.2	34.2	55.2	8.6	16.4	0.8	29.8	9.3
	Stdev.	0.1	0.7	0.9	0.3	0.4	0.1	1.1	1.2
Mine 4	Avg.	0.1	46.8	42.5	8.7	28.8	0.4	67.7	5.0
	Stdev.	0.0	0.6	0.8	0.2	1.5	0.2	4.7	2.1
Mine 5	Avg.	11.3	72.1	13.2	1.6	6.7	0.4	50.9	26.7
	Stdev.	0.5	0.2	0.3	0.3	0.4	0.3	2.9	17.7
Mine 6	Avg.	0.6	63.9	28.9	4.40	12.7	1.3	43.9	30.0
	Stdev.	0.1	0.4	0.3	0.1	0.8	0.2	2.6	5.3
Mine 7	Avg.	0.5	43.4	39.4	15.0	20.4	2.9	51.8	19.3
	Stdev.	0.1	0.2	0.8	0.9	0.7	0.1	2.8	1.6
Mine 8	Avg.	1.1	58.7	36.1	2.7	8.2	0.2	22.9	8.4
	Stdev.	0.1	1.1	0.9	0.2	1.0	0.1	2.9	4.2
Mine 9	Avg.	0.2	49.4	42.1	6.0	14.5	2.5	34.5	41.4
	Stdev.	0.2	0.3	0.6	0.2	1.1	0.3	2.6	4.9
Tailings Total	Avg.	1.9	56.7	33.2	6.3	13.5	1.0	41.9	17.5
	Stdev.	0.2	0.6	0.7	0.3	0.8	0.2	3.2	5.3

Table 2: Soil physical and chemical results for the trial media.

		Tailings media	Topsoil
Soil Physical	mm		
Coarse sand	0.2 - 2	26.9	55.6
Fine sand	0.02 - 0.2	45.3	8.9
Silt	0.002 - 0.02	21.1	20.4
Clay	< 0.002	6.7	15.0
Soil Chemical	Units		
Ca	mg kg ⁻¹	451.1	137.5
Mg	mg kg ⁻¹	37.9	76.7
K	mg kg ⁻¹	16.0	40.0
Na	mg kg ⁻¹	12.5	12.4
P (Bray)	mg kg ⁻¹	3.8	5.9
B (Warm water)	mg kg ⁻¹	0.3	N.a.
pH (H ₂ O)		3.7	5.3
CEC	cmol(+) kg ⁻¹	2.7	5.0
EC	mS m ⁻¹	220	N.a.
Cation ratios	Ca:Mg	11.9	1.8
	Mg:K	2.4	1.9
	Ca+Mg/K	12.3	5.4

N.a. – Not analysed

Table 3: Layout of the different treatments.

(A 3% organic component in the form of vermicompost was amended in all the treatments except for the control)

Trial	Amelioration details
Ctrl	No amelioration, 100% Tailings medium (Control)
A	20%Topsoil, 77% Tailings medium
B	30%Topsoil, 67% Tailings medium
C	40%Topsoil, 57% Tailings medium
D	50%Topsoil, 47% Tailings medium
E	60%Topsoil, 37% Tailings medium
F	Ideal Physical Amelioration: 40% Coarse sand, 35% Fine sand, 20% Silt, 5% Clay

Table 4a: Results of the soil physical analysis performed on the different treatments.

	IN CALGON				IN WATER		DISPERSIVITY	
	Coarse sand (%)	Fine sand (%)	% Silt	% Clay	% Silt	% Clay	SDI (%)	CDI (%)
Ctrl	10.4	45.3	35.9	8.4	14.5	1.4	40.4	16.3
A	20.2	45.2	28.2	6.4	9.4	0.4	33.1	6.3
B	26.0	41.6	25.4	7.0	5.4	0.4	21.1	5.2
C	32.0	38.2	23.2	6.6	4.6	0.3	19.8	4.7
D	34.0	34.9	23.0	8.0	3.4	0.5	14.6	6.4
E	36.7	32.0	22.7	8.6	2.8	0.6	12.4	6.6
F	39.9	37.7	15.9	6.4	2.3	0.4	14.6	6.5

Table 4b: Results of the soil chemical analysis performed on the different treatments.

	Ca	Mg	Na	K	P	pH	CEC	EC	Ca:Mg	Mg:K	Ca+Mg/K
	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹		cmol(+) kg ⁻¹	mS m ⁻¹			
Ctrl	451.0	37.9	12.5	16.0	3.8	3.7	2.66	445	11.9	2.4	30.6
A	922.2	189.7	50.0	155.1	77.1	4.0	6.77	457	4.9	1.2	7.2
B	881.0	201.0	63.6	260.9	108.2	4.8	6.99	516	4.4	0.8	4.2
C	840.5	221.0	77.1	366.7	139.2	5.6	7.29	575	3.8	0.6	2.9
D	800.6	272.5	80.0	382.5	146.6	4.7	7.56	634	2.9	0.7	2.8
E	760.6	323.9	82.9	398.3	154.1	5.7	7.84	693	2.4	0.8	2.7
F	694.0	302.7	77.2	328.7	166.2	6.4	7.13	605	2.3	0.9	3.0

Compared to a study conducted by Sheridan *et al.* (2000b) on the dispersivity indices of coal discard and adjacent soils, gold tailings have a much higher SDI and CDI than both the comparative media (Figure 2). From the results, gold tailings material has an average SDI of $45,85\% \pm 3.16$ and CDI of $17.50\% \pm 5.32$, compared to the soil SDI and CDI averages of 15.51% and 4.81% (Sheridan *et al.*, 2000b) respectively. These high dispersivity values explain the highly erodible nature of gold tailings material.

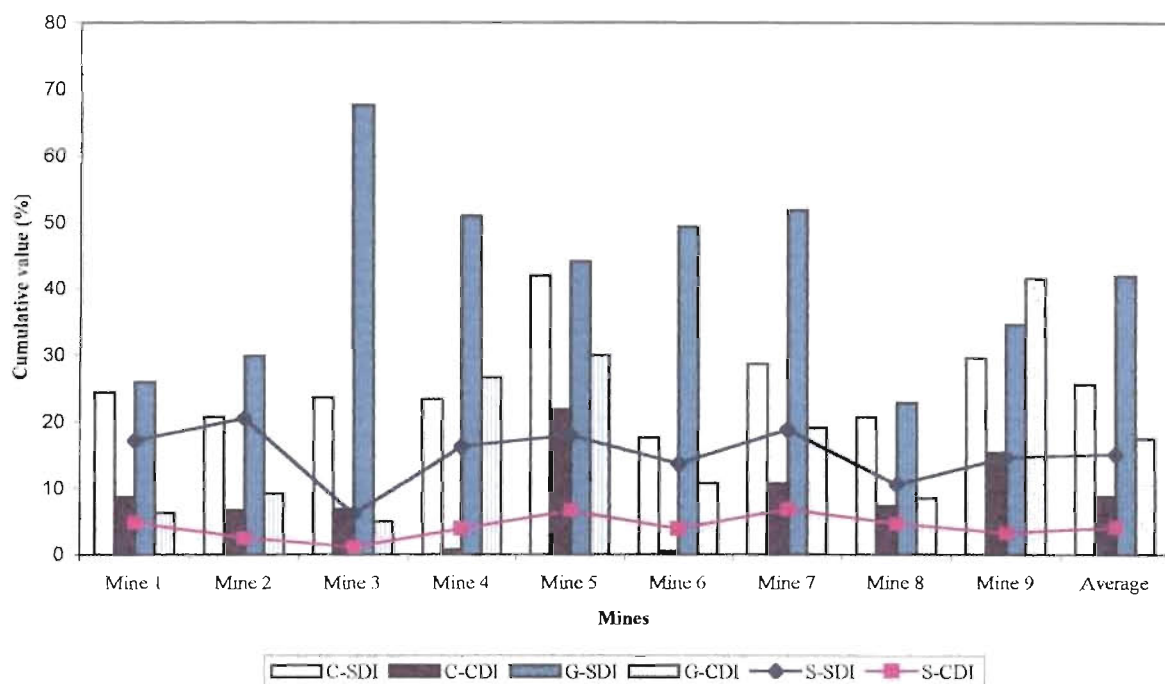


Figure 2: Comparative SDI and CDI values for gold tailings (G-SDI/G-CDI), coal ash dumps (C-SDI/C-CDI) and soils (S-SDI/S-CDI).

Significant results were also obtained from the pot trial experiment and successful soil physical profile reconstruction was accomplished (Table 4a). The different combinations of soil physical particles in the various treatments resulted in the proportional reshuffling of the compositional volume of silt and clay and lead to a decrease in the SDI and CDI of the treatments (Figure 3). The SDI was lowered from $40,38\%$, and the CDI from $16,26\%$ (Control), to $14,57\%$ and $6,51\%$ respectively (Treatment F), with a gradual decrease over all the treatments.

It was determined furthermore that the accomplishment of the decrease in the SDI and CDI in the treatments resulted in an increase in seedling establishment, which is depicted in Figure 3. The seedling data were statistically analysed and significant differences were found between

seedling establishment rates for the different treatments ($p < 0.05$) (Shapiro-Wilk's W test). The SDI was successfully rectified for treatments D, E and F, but the CDI could only be lowered to $\pm 7\%$. Seedling establishment, however, showed a significant increase once the treatment consisted of 50% or more topsoil, and once the SDI was lowered beneath the SDI average for soils. It further seemed that seedling establishment is more a function of the SDI than the CDI.

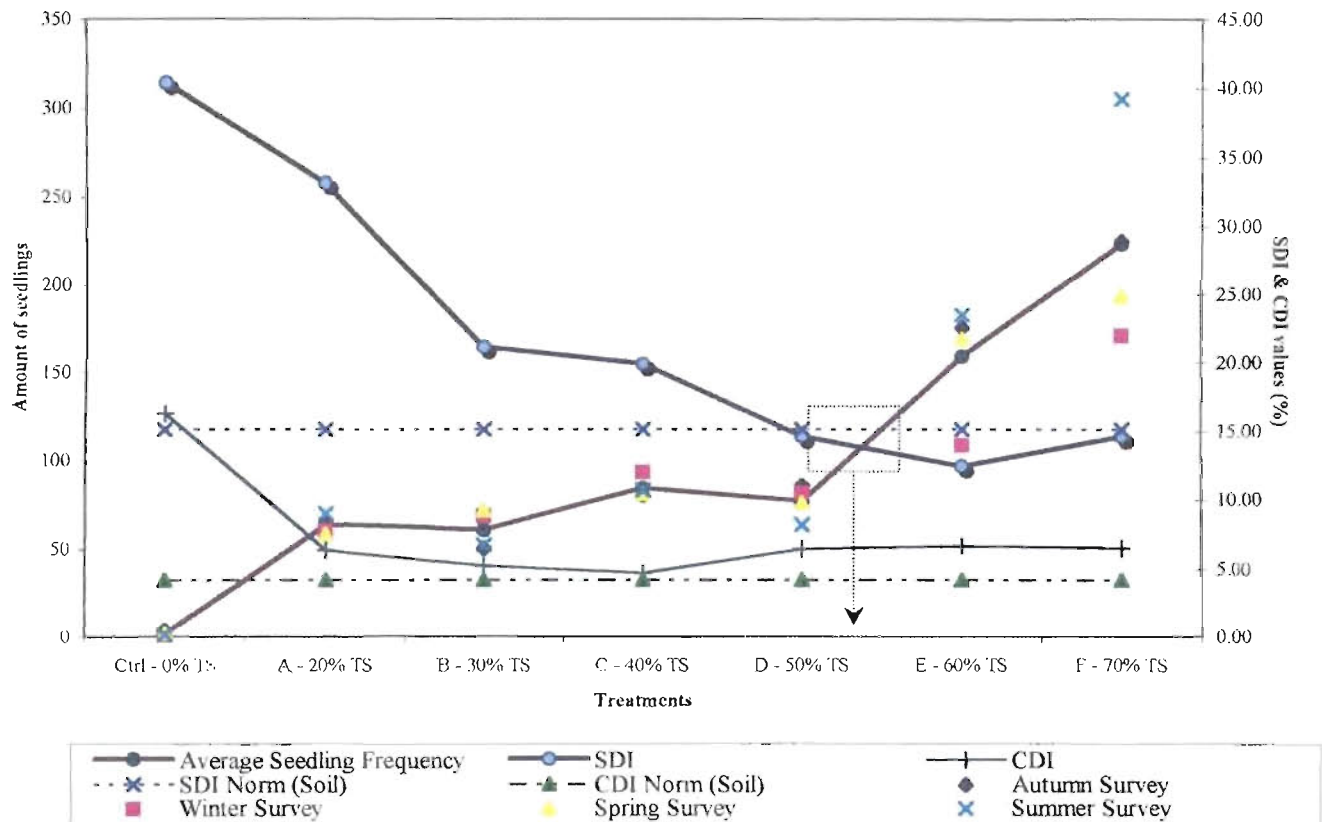


Figure 3: Relation between SDI, CDI, and seedling establishment for the different treatments. (TS = Topsoil)

This phenomenon of an increase in seedling establishment with associated treatments could, however, also be ascribed to a number of other factors, which include tailings physical rectification, chemical dilution of the tailings material, or even the climatological influences. Multivariate ordination analysis (CANOCO) was therefore applied to determine which factors were the main associative and determinant variables for seedling establishment on recreated tailings profiles.

Unimodal direct gradient analysis was firstly performed to establish the direct interrelations between all the possible variables and its influence on seedling establishment for the different treatments. According to the data presented in Figure 4, seasonal climatic variation did not have any significant influence on the seedling performance of the different treatments. The derived gradient along the first axis that could explain the seedling affinities is weak though (Eigenvalue = 0.014), and the only significant variables responsible for the gradient are the soil physical properties (Coarse sand, Silt), although the chemical parameters could also have an influence on the position of the treatments in the ordination (P, Ca).

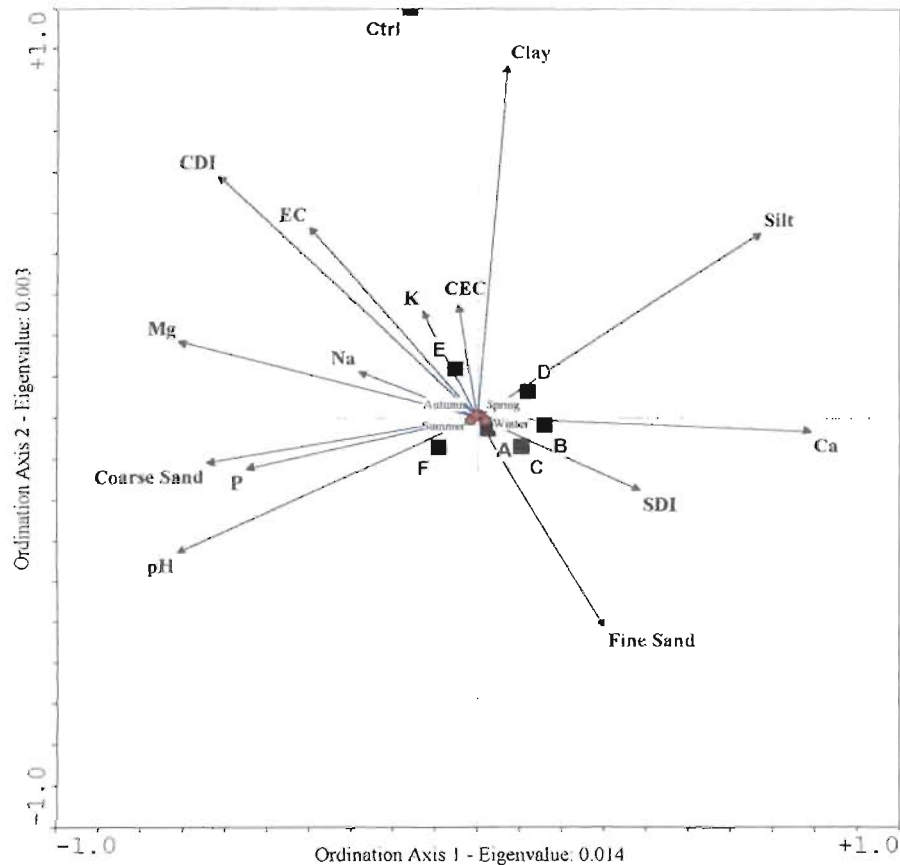


Figure 4: CCA Ordination biplot determining the association of different variables with seedling establishment. It is shown that seasonality did not have any significant influence on seedling establishment.

Indirect gradient analysis was performed to distinguish the affinity of certain treatments towards specific variables. Detrended Correspondence Analysis (DCA) was applied to group specific associations that could identify the affinity of seedling establishment towards certain parameters. Once again, a weak gradient along the first axis (Eigenvalue = 0.079) characterises the variation, but it is once more clear that the soil physical gradient derived

(Figure 5) determines the treatment distribution in the ordination figure, and that the chemical variables of the treatments did not play a major role in initial seedling establishment (although it significantly affected seedling persistence – Table A)). The CDI, Silt and Fine sand variables, as well as the CDI and Clay parameters are isolated in the graph, with the different treatments posing the least affinity towards the 3rd and 4th quadrants. The treatments showed the greatest affinity towards the Coarse sand fraction, with the associated better chemical conditions resulting from the high degree of dilution (1st quadrant).

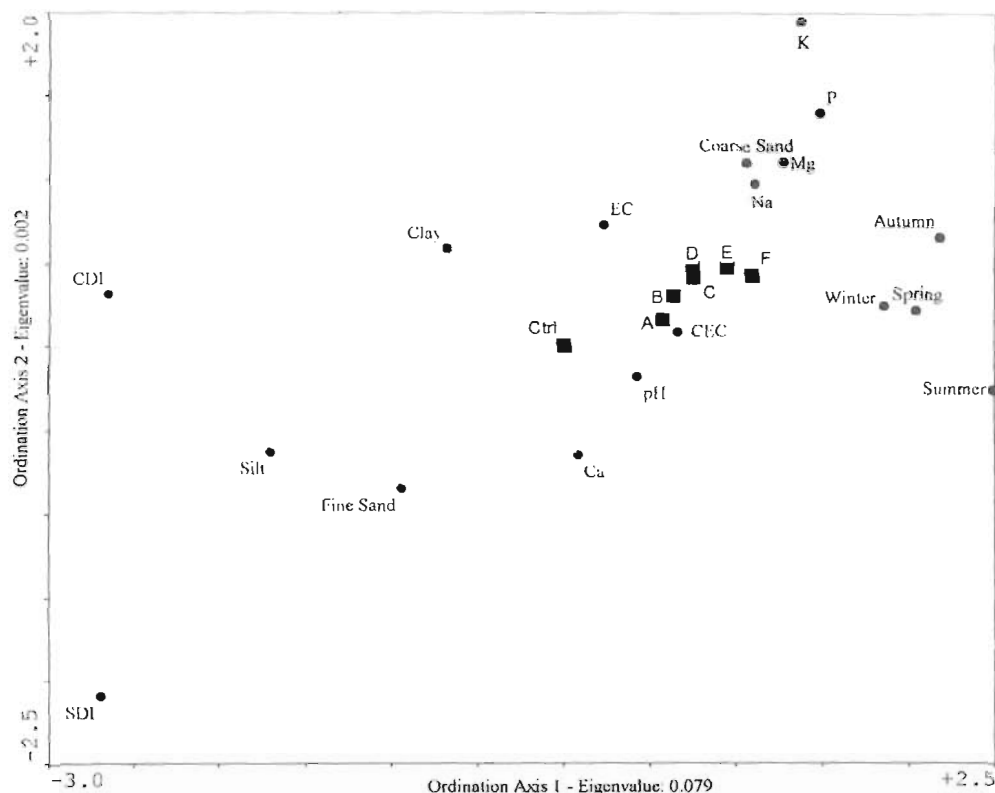


Figure 5: DCA Ordination biplot depicting the influential affinities for seedling establishment in the various treatments.

It was, however, necessary to investigate what the determinant factors were for seedling establishment in each of the respective treatments, and which variables steered individual treatment performance. Linear direct gradient analysis in the form of Redundancy analysis (RDA) was therefore applied, analysing the soil physical and chemical data, in relation to seedling establishment results for the different treatments. As proposed by the data presented in Figure 6, the distribution of treatments was once again determined by a significant soil physical gradient (Eigenvalue = 0.974), and this ordination shows that seedling establishment associates with the soil physical properties of the different treatments, confirming the findings of the preceding performed ordinations.

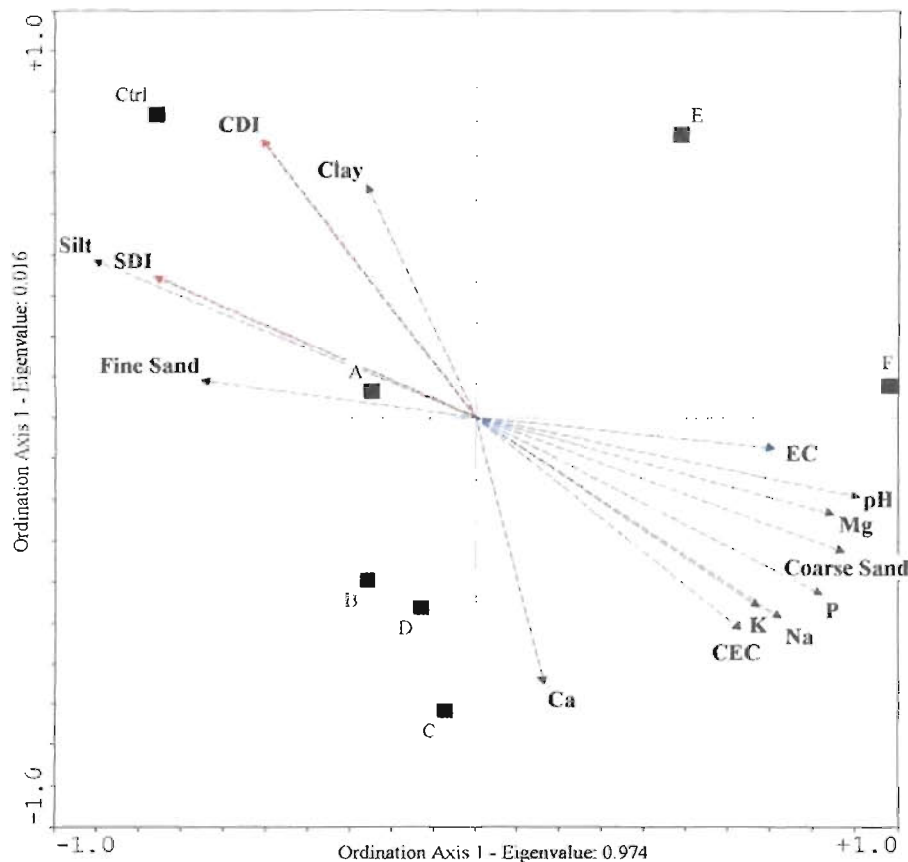


Figure 6: RDA Ordination biplot depicting the distribution of treatments along a physically hostile and physically optimised gradient, as reflected by seedling establishment of the different treatments.

The gradient could also be described as a seedling abundance gradient, showing that treatments A, B, C and D did not differ significantly, proposing that there will only be a significant increase in seedlings if the SDI would be enhanced as in treatments E and F (also acknowledged by Figure 3). It is evident that the conditions in the treatments represented in quadrants 1 and 3 shows strong affinity towards those of quadrant 2, and steep contrast towards the conditions in quadrant 1, not only confirming the correlation between seedling abundance and soil physical conditions, but also towards the soil chemical superiority of the 2nd quadrant. The low seedling abundance in treatment A was determined by the poor physical and chemical properties (1st quadrant), while the lower seedling occurrence in treatments B, C and D was a function of the intermediate soil physical and chemical characteristics. Seedling establishment in treatments E and F was much higher, based on the optimum physical conditions and more favourable chemical conditions (1st quadrant). Seedling abundance also shows a dissociative correlation with the high SDI/Silt and CDI values.

This observation not only implies limiting germination capacity of the media, but also restrictive root-media interaction, as the silt-dominated material is eroded from underneath the vegetation.

From the data presented in Figures 3 – 6 it was clear that gradual decrease in seedlings was evident with an increase in the SDI, as supported by the correlation between the seedling increase and soil physical gradients. The influence of each of the variables on seedling establishment should, however, also be quantified.

To determine the effect of each variable on seedling establishment and seedling persistence, the correlations between the variables and the seedling abundance were independently investigated for the different treatments. The factors that were statistically significant and positively correlated with seedling establishment include the Coarse sand, Mg, P and pH variables, while the silt fraction and the SDI correlated negatively with seedling establishment and persistence (Table 5).

Table 5: Correlation matrix presenting results of the statistical analysis performed on seedling data and the physical and chemical characteristics of the different treatment media. (Tables 4 and Table A)

(* - Values for which $p < 0.05$ and $r^2 > 0.55$)

Correlation Factors (r)	Initial Seedling Establishment	Seedling Persistence	Correlation Coefficient (r^2)	Statistical significance (p)
Coarse sand	0.859*	0.328*	0.7376	0.013
Fine sand	-0.639	-0.105	0.409	0.122
Silt	-0.089*	-0.155*	0.796	0.007
Clay	-0.025	0.022	0.064	0.583
SDI	-0.744*	-0.219*	0.554	0.049
CDI	-0.048	-0.024	0.231	0.275
Ca	0.138	0.048	0.019	0.768
Mg	0.833*	0.738*	0.695	0.019
Na	0.701	0.623	0.492	0.079
K	0.651	0.578	0.424	0.114
P	0.802*	0.796*	0.643	0.03
pH	0.902*	0.053*	0.814	0.006
CEC	0.606	0.059	0.367	0.149
EC	0.698	0.299	0.487	0.081

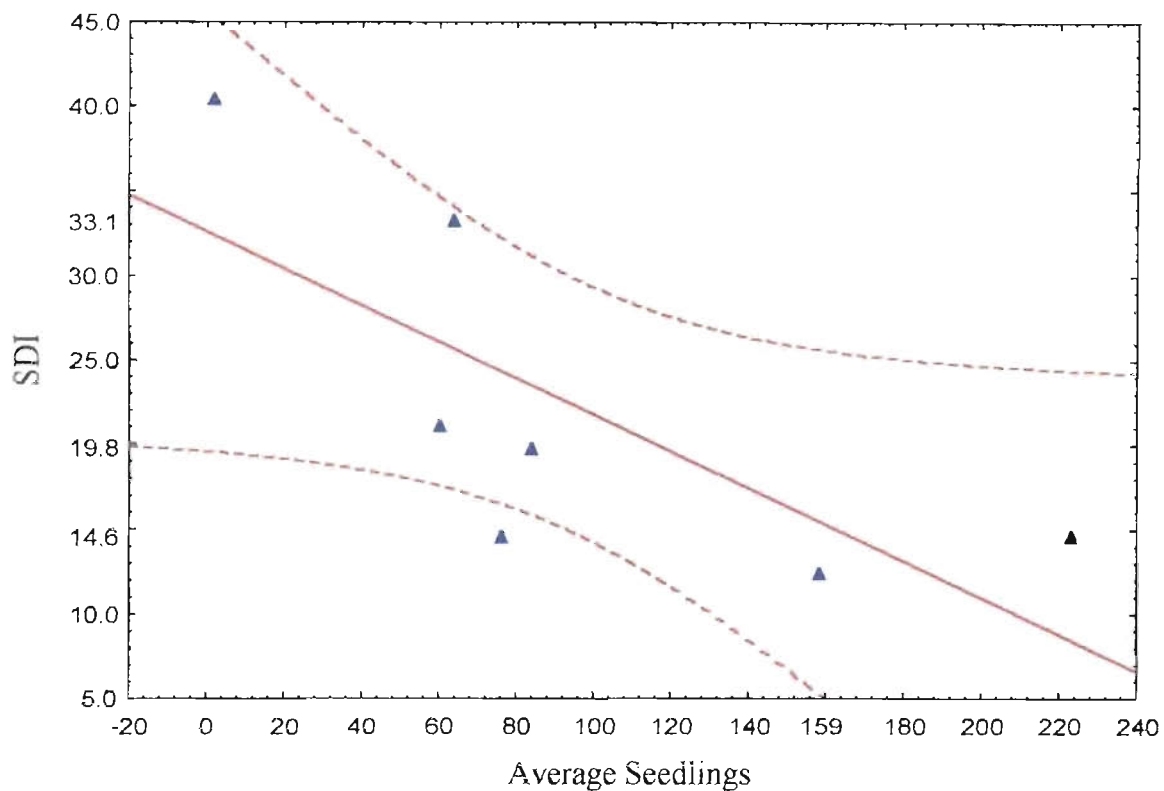


Figure 7: Scatterplot showing the relation between seedling abundance and the Silt Dispersivity Index (SDI) ($r^2 = 0.554$)

The negative correlations were bound to the soil physical properties, where seedling establishment was found to be indirectly proportional to all the soil physical variables, except for the Coarse sand fraction ($r = 0.859$). The most negative correlation typified the SDI variable ($r = -0.75$) (Figure 7), and this characteristic of gold tailings material seems to be the most direct limiting factor for successional vegetation establishment.

CONCLUSION

Gold mine tailings material has an extremely high Silt Dispersivity Index, originating from the fine-grained material properties. This high SDI results in high erodibility and difficulty to contain the media to the tailings dams, even with vegetational cover development and root stabilisation. Furthermore, both seedling establishment and persistence were limited by the high soil dispersivity indices and sustainable vegetation cover could be inhibited by this very factor, with the detrimental effect of slope on seed-soil contact and micro-niche quality not even taken into account.

The physical rectification of tailings media did, however, decrease the dispersivity indices significantly, and seedling abundance correlated very well with the proportional reshuffling of the physical properties of the different treatments. Therefore, soil physical enhancement of tailings by means of topsoil is a necessity for future gold tailings restoration. This amendment will not only ensure vegetation persistence, but will also enhance the regenerative capacity posed by the recreated soil profile. The soil physical properties also proved to have a more significant impact on seedling germination and seedling establishment, while soil chemical variability influenced seedling persistence to a larger extent.

The enhancement of soil physical quality is further correlated with ecological stability in terms of species diversity and native population succession (Winterhalder, 1995).

The RUSLE is not effective to determine long-term erosion losses of gold tailings except if the erodibility value (K), which is a direct function of the SDI and CDI, could be adapted. Dispersivity indices should further be incorporated into soil loss equation models to successfully predict tailings losses.

Soil dispersivity indices could also act as criteria for soil quality standards in the monitoring of restoration projects. Until the dispersivity of tailings media is not addressed, the forces of equilibrium will challenge the tailings structures and destroy revegetated covers over the short term.

Future research should focus on the effect of dispersivity of tailings material on vegetation establishment on slopes, specifically by means of a field experiment. The relation between rainfall intensity, tailings physical and chemical properties, slope characteristics and tailings loss should also be refined. New erodibility values for mine discard could then be derived to determine tailings losses and associated landform stability, revegetation planning and post-landuse management.

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ADDENDUM

Table A: Initial seedling establishment data (weeks 3 – 6) and seedling persistence data (weeks 20 and 26) of the seedlings in the different treatments over the 8 month period (Number of seedlings per square unit).

	Summer	Autumn					Winter			Spring	Average
	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 12	Week 20	Week 26		
Ctrl	29	20	27	30	42	40	13	0	0	13	
A	54	19	18	15	137	175	68	53	59	88	
B	28	19	10	11	93	152	76	61	72	90	
C	93	61	66	50	106	120	99	87	81	97	
D	50	30	26	14	83	178	94	69	76	104	
E	149	182	171	166	201	226	125	91	169	153	
F	289	289	315	300	308	330	186	155	193	216	

CHAPTER 4

AN EVALUATION OF PHYSICAL, CHEMICAL AND BIOLOGICAL SOIL PROFILE RECONSTRUCTION OF GOLD TAILINGS MATERIAL ON INITIAL NATIVE GRASS SPECIES ESTABLISHMENT SUCCESS

CHAPTER OVERVIEW

The productivity and persistence of vegetation on rehabilitated gold mine tailings is to a large degree a function of the interaction of revegetated plants with the physical, chemical and microbiological conditions of an induced reconstructed soil profile. The success of soil profile development will also determine the long-term survival of the established vegetation. Species endurance, diversity and succession have not produced satisfying results after restoration attempts on gold tailings material and therefore an experiment to test a more holistic approach was conducted. The selection of native plant species occurring in communities surrounding the tailings dams is the key to ensure gradual recovery of ecological function on tailings dams. It is therefore necessary to investigate different ameliorative approaches, and to identify limiting factors for native species establishment. The combination of a reconstructed soil profile, and the exclusive introduction of native species are already accepted as International Code of Best Practice in restoration practices today, but has not been implemented in South Africa yet. The necessity to investigate intensive amelioration of gold tailings material under dryland conditions is therefore of extreme importance, to establish to what extent gold tailings could be biologically restored. It could also lead the way to establish ecological criteria, which could culminate in standards to measure restoration success and to determine the desirability of site closure. A comparison of the results from physically, chemically and biologically ameliorated pot trials, with regards to reconstructed soil profile development is made, and the establishment, initial persistence and frequency of native grass species are used to describe the way to go about successful ecological restoration of gold tailings dams.

AN EVALUATION OF PHYSICAL, CHEMICAL AND BIOLOGICAL SOIL PROFILE RECONSTRUCTION OF GOLD TAILINGS MATERIAL ON INITIAL NATIVE GRASS SPECIES ESTABLISHMENT SUCCESS

Submitted (September 12, 2002): *Remediation*

ABSTRACT

This study investigates to what extent gold tailings profiles should be rectified to facilitate native species establishment and species diversity, as these species do not readily colonise revegetated tailings dams. The objective of the study was to evaluate the effect of various ameliorated treatments of gold tailings material on seedling abundance, species diversity and persistence. A pot trial experiment with different physically, chemically and biologically ameliorated tailings material was set up. Standard fertiliser applications, as well as several other waste products were used as amendments, which included topsoil, water treatment sludge, compost, sewage sludge and sewage water. Nine native grass species, of which the germinability was tested beforehand, were sown. Both seedling abundance and species frequency were assessed over an 8 month period, and the climate was also monitored. Multivariate and statistical analysis revealed significant results from the replications of the different treatments. The best treatment was the ideal physically and chemically optimised treatment, which had an average seedling abundance of 263/seedlings 0.09m², and all the sown species were present. No seedling survived on the control treatment. The physically rectified treatments had the highest diversity, and showed the best persistence after the winter period. *Digitaria eriantha* was the dominant species in these treatments, but there was a decrease in seedling abundance and species diversity with a decrease in the coarse sand fraction. *Chloris gayana*, which had the lowest germinability (2%), was the most consistent species in all the treatments and dominated the chemically amended treatments. The microbiological enriched treatments presented the best cost-effective results, and also reflected high diversity (7 species). The waste products that were applied also performed exceptionally well. Seven of the nine seeded species, however, associated only with good soil physical quality, which emphasises that native veld species will not readily colonise gold tailings dams if soil profile reconstruction does not include physical rectification.

Keywords:

Soil profile reconstruction; Restoration; Native species; Gold tailings; Physical amelioration; Soil chemical amendments; Microbiological enrichment; Water treatment sludge; Compost.

INTRODUCTION

Several techniques and methods for the establishment of vegetation on gold tailings dams are used by different restoration and mining companies with various levels of success (Low *et al.*, 1999; Hatting *et al.*, 2001; Van Deventer *et al.*, 2001). The development of a sustainable and cost-effective solution for gold tailings restoration has however evaded the market since these first revegetation attempts were carried out (Thatcher, 1979; Van Wyk & Van Rensburg, 2002). The industry interprets the aims of revegetation as a means of stabilising the discard against erosion, building up the humus content of the medium and providing an economic, self-sustaining pasture, which will reintegrate the tailings surface to full ecological productivity (Wells, 1981; Harwood *et al.* 1999) in harmony with surrounding ecosystems. The vision of complete restoration of the plant-medium interaction, coupled with the framework of eventual contribution to ecological function reinstatement, has not been supported by data of monitored soil and vegetation analysis over time. This observation leads to uncertainty, and serious questions arise about the quality of ecological restoration products, especially in terms of native species establishment success. Remediative efforts today focus on an ecological-ameliorative and soil chemical approach (Johnson *et al.*, 1994; Envirogreen, 2000), persisting the reintroduced vegetation through fertilisation and continual irrigation. Several recipe procedures are applied to establish vegetation on the tailings by ameliorating the growth medium with the amendment of lime, fertilisers and organic material (Jochimsen, 1996; Hatting *et al.*, 2001), the primary objective in mind being a quick and stabilising vegetation cover, and not necessarily the establishment of native species or the development of habitat diversity (Brenner, 1995). Restoration of tailings dams is therefore seen as another phase of the complete mining cycle and often taken for granted by mining companies. It is seldom kept in mind that the environmental setting created within which plants are expected to grow, is crucially important for the survival of the restored system, and the alteration of this artificial and harsh growth environment is not necessarily included as an option.

The extremities posed by landform and poor physical, chemical and biological characteristics of the tailings material, as well as erratic climatic influences, inhibit the initial natural establishment and colonisation of spontaneous and lasting native vegetation cover. Although the chemical and physical conditions on tailings are extreme, each of the factors in isolation is not as extreme as those often found in natural environments (DME, 1995). It is therefore the combination of the influence of the physical and chemical factors that renders the tailings' ecological capacity inhospitable to sustain microbial and plant diversity. The species established on the tailings dams are usually able to cope with the initial stressors, but the persistent and ever increasing stress of one extremity at a time slowly leads to the detriment of the established vegetation. The low pH, high silt content, and therefore poor textural properties, limit persistent vegetation cover, and pasture grass species do not establish readily

on tailings spoils through natural succession as would be expected. The formation of surface crusts and unnatural steep slopes are primarily responsible for the significant reduction in seedling emergence and succession on un-revegetated and revegetated tailings dams (Philp, 1992; Naidu, 1992). It would therefore be necessary to reach for a sustainable solution within the context of total ecological restoration, addressing the unnatural landform, amending the growth medium to full sustenance, creating resistance to soil degradation pressures and ultimately achieving voluntary ecological reclamation, with successional sequences and ideally ecosystem evolution to follow.

Successful revegetation of mine discard is a function of the multivariate interaction of topoeconomic factors, which include landform features, reconstructed soil profiles from the mine tailings' physical and chemical properties, fertilisation and management techniques, and revegetative practices (Barnhisel & Hower, 1997). Reconstruction of a soil profile on natural slopes would therefore be the basis for the colonisation and survival of native plant species, leading to community development, increased biodiversity and long-term ecological stability. Effective minesoil recovery requires tailings to be converted to soils of similar quality to those previously existing on that site (Leirós *et al.*, 1996; Ward, 2000). The success of the reconstruction of the capacity of tailings as a growth medium will therefore determine the success and sustainability of restoration inputs. Several challenges are associated with soil profile reconstruction and establishment of vegetation on mine discard. These account especially for gold tailings material, which is renowned for its high acid potential, low fertility and poor physical properties (Winterhalder, 1995; Van Deventer *et al.*, 2001). Considerable basic research is therefore necessary to determine which the most limiting factors for gold tailings restoration are, and to what extent the biological capacity of gold tailings material could be optimised to act as a sustainable sink for a self-perpetuating vegetation cover. Furthermore, responses, dynamics and persistence of fertilisers in constructed mine soils, as well as nutrient requirements of plant communities which developed on rehabilitated land are largely unknown (Bradshaw & Chadwick, 1980; Barnhisel & Hower, 1998). Fertiliser applications are currently based on the results of soil (tailings) analysis but often the "soil" is completely different from naturally occurring soils (Wells, 1981) and physical and chemical soil profile development could evolve entirely different.

It is clear that mine tailings material presents a difficult substrate for revegetation and the usual approach taken is to attempt the establishment of a relatively homogeneous cover of grasses and legumes, which exhibit a much lower alpha biodiversity than the surrounding natural sites (Winterhalder, 1995). Restoration therefore poses the opportunity to introduce native species diversity.

Composing appropriate seed mixtures has to take into account those species that are not only adapted to the site, but also tend to agglomerate within natural plant communities in the area

where restoration will be carried out (Jochimsen, 1996). It is therefore necessary to investigate which factors limit the natural establishment of these native species.

The objective of this study was to investigate by means of a trial experiment, the success of soil profile reconstruction of gold tailings, on the establishment of native grass species, applying a combination of other bulk waste/discard (excess topsoil from open-cast mining (TS), calcinated water treatment sludge (WTS) and sewage sludge (SS)), and standard restoration additives as ameliorants.

MATERIALS AND METHODS

Gold tailings material was collected from the un-rehabilitated Skeat gold mine tailings dam (26° 49' S, 26° 27' E), and topsoil was collected at this mine's open cast soil storage facility. Soil analyses were conducted for the respective tailings samples used for the physical and chemical amelioration trials, as well as for the topsoil (Table 1).

Table 1: Physical and chemical analysis results of the untreated tailings and topsoil material used in the different treatments.

		Physical treatments sample	Chemical treatments sample	Topsoil sample
Soil Physical	mm			
Coarse sand	0.2 - 2	26.9	24.3	55.6
Fine sand	0.02 - 0.2	45.2	45.7	9.0
Silt	0.002 - 0.02	21.1	23.1	20.4
Clay	< 0.002	6.7	6.7	15.0
Soil Chemical	Units			
Ca	mg kg ⁻¹	451.1	466.0	137.5
Mg	mg kg ⁻¹	37.9	100.5	76.6
K	mg kg ⁻¹	16.0	10.2	40.0
Na	mg kg ⁻¹	12.5	13.3	12.4
P (Bray)	mg kg ⁻¹	3.8	23.8	5.9
B (Warm Water)	mg kg ⁻¹	0.3	0.1	N.a.
pH (H ₂ O)		3.7	2.8	5.3
CEC	cmol(+) kg ⁻¹	2.7	3.0	5.0
EC	mS m ⁻¹	220	445	N.a.
Cation Ratios	Ca:Mg	11.9	4.6	1.8
	Mg:K	2.4	9.9	1.9
	Ca+Mg/K	12.3	55.5	5.4

N.a. – Not analysed

Seventeen treatments with 3 replications of each (51 in total) were laid out in an enclosed area in 40 dm³ containers (surface area of 0.09 m²), punched at the top to allow run-off of standing water, and at the bottom to allow free drainage. The trial variation (Table 2) included different physical (resorting under the Physical Treatment trial group for discussion on the basis of amended topsoil), and chemical, organic and microbiological ameliorative applications (resorting under the Chemical Treatment trial group on the basis of the amendment of Water Treatment Sludge (WTS)).

Table 2: Trial layout

Amelioration type	Trial	Amelioration details
<i>Control</i>	Ctrl	No amelioration, 100% Tailings material
<i>Physical</i>	P1	20%Topsoil, 77% Tailings medium, 120 tons ha ⁻¹ VC (3%)
	P2	30%Topsoil, 67% Tailings medium, 120 tons ha ⁻¹ VC (3%)
	P3	40%Topsoil, 57% Tailings, 120 tons ha ⁻¹ VC (3%)
	P4	50%Topsoil, 47% Tailings medium, 120 tons ha ⁻¹ VC (3%)
	P5	60%Topsoil, 37% Tailings medium, 120 tons ha ⁻¹ VC (3%)
	P6	Ideal Physical Amelioration: 40% Coarse sand, 35% Fine sand, 20% Silt, 5% Clay, 120 tons ha ⁻¹ VC (3%)
<i>Organic</i>	O1	60 tons ha ⁻¹ WTS, 120 tons ha ⁻¹ VC
	O2	60 tons ha ⁻¹ WTS, 10 tons ha ⁻¹ Sewage sludge
	O3	60 tons ha ⁻¹ WTS, 20 tons ha ⁻¹ Sewage sludge
<i>Chemical</i>	C1	60 tons ha ⁻¹ WTS, 120 tons ha ⁻¹ VC, 50 kg ha ⁻¹ KCl, 350 kg ha ⁻¹ Super P
	C2	60 tons ha ⁻¹ WTS, 120 tons ha ⁻¹ VC, 50 kg ha ⁻¹ KCl, 1 ton ha ⁻¹ Super P
	C3	60 tons ha ⁻¹ WTS, 120 tons ha ⁻¹ VC, 50 kg ha ⁻¹ KNO ₃ , 350 kg ha ⁻¹ Super P
	C4	60 tons ha ⁻¹ WTS, 120 tons ha ⁻¹ VC, 50 kg ha ⁻¹ KNO ₃ , 1 ton ha ⁻¹ Super P
<i>Microbiological</i>	M1	60 tons ha ⁻¹ WTS, 120 tons ha ⁻¹ VC, 10 000 l ha ⁻¹ Soil Inoculum
	M2	60 tons ha ⁻¹ WTS, 120 tons ha ⁻¹ VC, 10 000 l ha ⁻¹ Sewage Inoculum
<i>Ideal</i>	PC1	Physical: Similar to P6
		Chemical: 60 tons ha ⁻¹ WTS, 120 tons ha ⁻¹ VC, 50 kg ha ⁻¹ KNO ₃ , 350 kg ha ⁻¹ Super P

VC – Vermi-compost

WTS – Water Treatment Sludge

Super P – Super Phosphate (10.5%)

It should be mentioned that the distinctions are only made to separate between the treatments (nominal classification), and are not literally viable descriptions as most of the trials contain organic matter, are physically and chemically diluted, or nutrient and microbiologically enriched.

The experiment was exposed to environmental conditions (although in an enclosed area, evaporation data were monitored at the trial area and proved to be similar to the evaporation data of the local weather station). The dryland approach was applied.

The experimental area was located in Potchefstroom (26° 43' S, 27° 05' E), which has a representative climate of the Highveld where gold mining occurs. The experiment was carried out over a 6-month period (amelioration and seeding was carried out March 1st, which is early in autumn, and monitoring continued through winter up until September, which is early spring). Total rainfall of 274 mm was measured over this period. Air temperature extremities ranged from 31.1°C, to -7.9°C, with a mean daily temperature of 20.9°C during the seedling establishment period (first six weeks after seeding).

Physical amelioration

The object of the physical amelioration was to improve the physical characteristics of the tailings, increasing the ratio of particles greater than 0.2 mm fraction to the particles smaller than this fraction. A further objective was to reconstruct a simulated soil profile and to investigate the correlation between vegetation establishment and particle size reshuffling.

- Tailings material and topsoil were weighed separately with a Camry (100kg x 500g) scale to compose the sum of a pre-determined ratio (to a total mass of 40kg). The expressed percentage values of the contents thus represent the value by mass, and not by volume.
- The weighed fractions (pre-determined ratios) were thoroughly mixed, using a soil splitter and adding vermicompost in the process. This resulted in a reconstructed soil profile (depth of 0,4 m) with a ratio-determinant homogenous distribution of particle sizes and organic matter.

Chemical amelioration

Tailings material has poor nutrient status and the potential to generate acid from inherent pyritic content (Van Deventer *et al.*, 2001). It is therefore necessary to analyse the tailings chemically, not only to amend macro- and micro-nutrient deficiencies, but also to lime for the neutralisation of both latent and potential acidity. Amelioration of gold tailings material in practice occurs as a process which include 1) A lime programme, 2) Pre-seeding fertilisation, 3) Fertiliser with seeding, and 4) Follow-up fertiliser programs (Barnhisel & Hower, 1997). The amelioration typically include 10 – 30 tons ha⁻¹ calcitic or dolomitic lime, 150kg – 1 ton ha⁻¹ Super Phosphate (10.5%) (P = 105 g kg⁻¹), 300 kg ha⁻¹ 4:3:4 (39kg N ha⁻¹, 29 kg P ha⁻¹, 39 kg K ha⁻¹), 1 ton ha⁻¹ KCl (50,0% K) and 150 kg ha⁻¹ LAN (42 kg N ha⁻¹) (Van Deventer *et al.*, 2001).

Amendments for the chemical rectification were calculated from the soil chemical analysis. Potassium Chloride (KCl) (50% K) and Potassium Nitrate (KNO₃) (13%N, 0%P, 38%K) were

selected for the trials as nutritional amendments. KNO_3 could serve as a possible replacement for KCl as the chlorine in the latter ameliorant is regarded as a main polluter of run-off water from previously revegetated gold tailings dams, due to its high mobility (Cogho *et al.*, 1992). Superphosphate (10,5%) was added as the main phosphate supplement and Water Treatment Sludge (WTS) was amended as the liming ameliorant. It was pointed out by Van Rensburg (2002) that water treatment sludge is capable of alkalising acid-generating media such as gold mine tailings. Spontaneous vegetation establishment also occurred on previous experimental gold tailings material and amended WTS trials. An analysed sample of the WTS was with the exception of Mg and NO_3 , nutrient poor, but was characterised by a very high buffer capacity and CEC, and an alkaline nature. It has high magnesium, calcium and boron concentrations and therefore the availability of potassium could be inhibited. The ratio is however rectified by the potassium rich ameliorants. The high boron concentration of the WTS is a positive aspect as boron deficiency (as in Table 1) is a limiting factor in the restoration of acidic tailings material (Lipsett *et al.*, 1979; Van Deventer *et al.*, 2001). These characteristics give this material the combined characteristics of dolomitic lime (with a low Ca fraction) and inorganic MgNO_3 . It was, however, experimentally determined that less than 40 tons ha^{-1} would not be sufficient to neutralise potential acidity over time and 60 tons ha^{-1} was therefore recommended (Van Rensburg, 2002).

Organic amelioration

The application of organic material (vermicompost and dried aerobically digested sewage sludge) has widely been used as an amendment and as fertiliser for mine spoils reclamation (Brofas *et al.*, 2000). Not only are the physical and chemical properties of the tailings improved, but the fertility is also optimised (Sopper, 1993). The beneficial effects of organic material application on mine spoils include the improvement of structure and water holding capacity of a medium, increased biological activity, and enrichment with N, P, base cations, and micro-nutrients (Hinesly *et al.*, 1982; Edwards, 1995). The use of organic residues that have been transformed to more useful vermicompost has enormous potential in the amelioration of tailings material (Aranda *et al.*, 1999), especially with regards to soil profile development and biological optimisation of a recreated growth medium. Vermicompost was therefore incorporated as organic fraction in the designated treatments. Organic material in the form of sewage sludge is introduced in practice at rates between 20 – 100 tons ha^{-1} (Van Deventer, 2001), but for the trials, the organic component was optimised to compose of an ideal organic rich soil.

- Sterilised vermicompost was added at a rate of 120 tons ha^{-1} (or a composition of 4% of the soil profile).

In experiments conducted by Brofas *et al.* (2000) sewage sludge applications had a favourable effect on the establishment and growth of the seeded plant species. Sewage sludge is also an alternative source of nitrogen and behaves as a slow release fertiliser. Furthermore, it can act to initially increase soil pH and improve the physical character of the media (Barnhisel & Hower, 1997). It was also found that soil amended with sludge and a bacteriocide has shown greater water-stable aggregations than soil without sludge (Metzger *et al.*, 1987). Plant density increased significantly and proportionally to amended sewage sludge rates of up to 40 tons ha⁻¹ (Brofas *et al.*, 2000). The heavy metal concentrations in the soil and plant tissue, however, became unacceptable at rates higher than 30 tons ha⁻¹ and therefore:

- Sewage sludge was added to 2 designated treatments at a rate of 10 tons ha⁻¹ and 20 tons ha⁻¹ respectively.

Microbiological amelioration

The persistence of vegetation on mine spoils is often hindered by the lack of resident microflora, which aid transformation of various nutrients through biochemical reactions (Tarafdar & Rao, 1997). Bacterial functional redundancy also increases in relation to the regrowth of plant communities, and may therefore represent an important aspect of the restoration of soil biological functionality (Yin *et al.*, 2000). It is therefore necessary to enhance the micro-ecological capacity by reinstating soil microbiological diversity in gold tailings material. Microbiological activity in gold tailings is extremely low (Table 4) and as a result of the low pH, the diversity of microorganisms is limited only to a few adapted species, which dominate the tailings' rhizosphere (Thatcher, 1979). It is of considerable importance to reintroduce microbiological cultures to gold tailings to rectify and balance the soil ecology to such an extent that lasting mutualistic associations could persist.

Standard plate counts and total coliform counts for the assessment of bacteriological quality were carried out on the tailings material and topsoil, and microbial inoculation was prepared:

- For the inoculation, 1 kg of sewage sludge and 1 kg of topsoil were separately mixed with 4 liters of deionised water.
- Each mixture was shaken for 60 minutes at 220 RPM and left for 30 minutes.
- 3 Liters of the inoculums (10 000 liters ha⁻¹) were sprayed over and thoroughly mixed with the top layer of the 2 separate designated treatments.

Grass species evaluated

A vegetation survey, based on phytosociological characteristics (Jochimsen, 2001) of the area surrounding Skeat gold tailings dam, was conducted in February 2002, to serve as a guideline

for native species selection, and to recommend species that should be established in the treatments. Making use of the line-transect method described by Kent & Coker (1996) a survey of 1000 points was carried out, and the grass species composition of the area was determined. Possible species for the experiment were identified, but the limited availability of the chosen species' seed resulted in the selection of nine grass species (Table 3), which would be fit and representative for the trials. Only native grass species, categorised in four different ecological status groups (Van Oudtshoorn, 1999), were selected, using the field study as basis. Seed were locally obtained and a seed mixture ratio was determined by the average frequency of selected species occurrence resembled by the field sites. The mass of the seed was used to determine the number of seeds that composed this pre-established ratio (each seed mixture adding up to 10 g). The seed mixture was then sown on a slightly compacted seedbed, covering it with a thin layer (<5mm) of ameliorated medium of the trial variation, and firming it afterwards.

Seed germinability was assessed during the first month of the trial (after Hardwood *et al.*, 1999).

- Seed were pre-chilled (5°C) for seven days. Three hundred pure seeds from each grass species were randomly counted from five separate groups of seed. The seed were germinated on a moistened (10mL of 0,2% KNO₃ and deionised water solution) layer of Carlton towel paper in Tupper® containers (115mm x 115mm x 20mm). The containers were then marked and randomly placed in a germination incubator (26°C for 24 hours). The containers were scored for germination after 14 and 28 days.

After 28 days, seed that germinated (seeds of which the plumula and radicle were visible) were counted.

Seedling assessment

Seedling emergence was weekly assessed for 8 weeks, and temporarily discontinued after the first frost occurrence. The vegetation was assessed thereafter in weeks 12, 20 and 26, to determine the effect of winter climate on the persistence of the seedlings and the germination response after the first spring rains.

- The seedlings were counted individually, making use of a 200 mm x 200 mm grid (400cm²).
- In week 20, a species frequency assessment was also carried out, identifying the species that survived, and expressing it as a percentage of the total seedling composition for each amelioration technique. The relation that exists between species preference and amelioration technique could thus be established.

Table 3: Grass species selected for the trial: Information on the seeding ratio and results for the germinability tests.

Species	Common name	Ecological status	Growth form	Species composition at Skeat (%)	Composition of trial seed mixture (% by mass)	Average Germinability (%)	100-seed average weight (mg)
1. <i>Aristida congesta</i> Subsp. <i>barbicollis</i> Roem. & Schult	Spreading Three awn	Increaser 2	Annual or Perennial Tussock	4.5	6	16 ± 5.20	2.25 ± 0.009
2. <i>Chloris gayana</i> Kunth *	Rhodes Grass	Decreaser	Perennial, Stoloniferous	28	8	2 ± 1.73	1.01 ± 0.004
3. <i>Cymbopogon plurinodes</i> Stapf. ex Burt davy	Narrow-leafed Turpentine Grass	Increaser 1/3	Perennial, Tussock	29.8	19	13 ± 0.58	1.61 ± 0.020
4. <i>Cynodon dactylon</i> (L.) Pers. *	Couch Grass	Increaser 2	Perennial, Stoloniferous	5.8	6	2 ± 1.53	0.09 ± 0.005
5. <i>Digitaria eriantha</i> Steud. *	Common finger Grass	Decreaser	Perennial, Tussock, Stoloniferous	7.1	14	25 ± 2.52	1.55 ± 0.009
6. <i>Enneapogon cenchroides</i> Roem. & Schult. (C.E. Hubb.)	Nine-awned Grass	Increaser 2	Annual or perennial Tussock	3.1	8	1 ± 0.00	0.21 ± 0.050
7. <i>Eragrostis curvula</i> (Schrud.) Nees.	Weeping Love Grass	Increaser 2	Perennial, Tussock	12.2	8	42 ± 16.20	0.01 ± 0.001
8. <i>Heteropogon contortus</i> (L.) Roem. & Schult.	Spear Grass	Increaser 1	Perennial, Tussock	4.5	6	51 ± 6.66	5.31 ± 0.150
9. <i>Themeda triandra</i> Forssk.	Red Grass	Decreaser	Perennial, Tussock	33.4	25	1 ± 0.00	11.01 ± 0.250

* - Coated seed

Data analysis

- Multivariate analysis was applied to the seedling data, species data, and physical and chemical characteristics respectively, making use of CANOCO (Ter Braak, 1996) (Ver. 4).
- Redundancy analysis (RDA), which is a refined Principal Component Analysis (PCA) technique and allows for the ordination of low variation datasets, which result in short gradient interpretation, was applied to determine the gradients responsible for seedling abundance and species distribution in the various treatments.
- Statistical analysis was performed making use of StatSoft Statistica Release 6.

RESULTS AND DISCUSSION

The rectification of the gold tailings media proved to enhance the capacity of the restored growth medium to facilitate initial establishment of the selected native grass species. The following significant results with regards to soil profile reconstruction were achieved:

- The ratio of the coarse sand to fine sand particle distribution was significantly enhanced (Figure 1: P1 – P6 and PC1) (Figure 1).
- The pH was increased to acceptable levels for vegetation persistence.
($4.01 > \text{pH} < 8.31$)
- The cation ratios were returned to satisfactory values, but not to its approximate ideal ranges of 3 – 4 for Mg:K and 10 – 20 for Ca+Mg/Ca (Buys, 1993), except for the Ca:Mg ratios (1.5 – 4.5).
- The seedling establishment results (Table A) are quite remarkable if the extremely high EC values ($\text{EC} > 400 \text{ mS m}^{-1}$), low CEC values ($\text{CEC} < 3.7 \text{ cmol(+) kg}^{-1}$) and cation ratio imbalances are kept in mind.
- There was a significant relation between treatments, seedling abundance and species occurrence.
- The microbiological activity was significantly enhanced (Table 4).
- The results were statistically tested and the significance determined satisfied the objectives investigated in the study.

Comparative results for the accomplished soil profile reconstruction are further presented in Table 5.

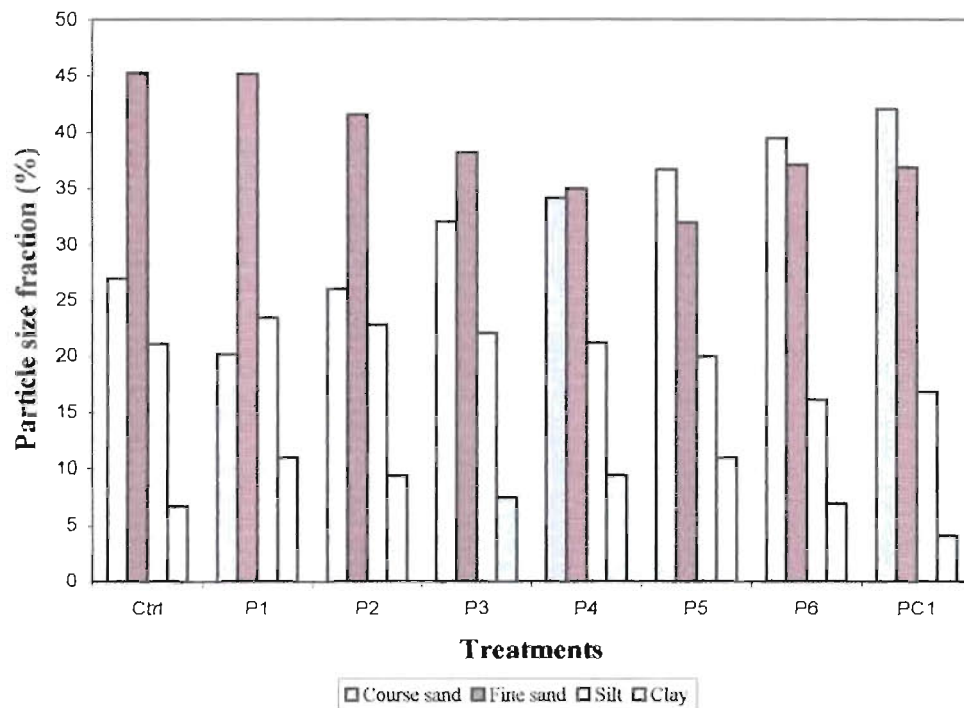


Figure 1: Ratios of particle size distribution for the physically rectified tailings treatments.

Table 4: Results of the microbial heterotrophic plate count evaluation.

Sample	Heterotrophic Plate count (mL ⁻¹) (1 x 10 ³)	Heterotrophic Plate count (mL ⁻¹) (1 x 10 ³)
	March 2002	September 2002
Gold tailings material (Ctrl)	5	1
Topsoil inoculum treatment (M1)	59	20 000
Sewage sludge inoculum treatment (M2)	410	700
Physical and chemically rectified trial (PC1)	75	300

Table 5: Physical and chemical properties of the different ameliorated treatments.

(Clay< 0.002mm, 0.002mm<silt<0.020mm, 0.020< fine sand< 0.2mm, 0.20 < sand <2.00)

	Particle size distribution				Chemical analysis											
	g 100g ⁻¹				mg kg ⁻¹					pH	CEC	EC	Cation ratios			Base saturation
	Coarse sand	Fine sand	Silt	Clay	Ca	Mg	Na	K	P (Bray)	H ₂ O	cmol(+) kg ⁻¹	mS m ⁻¹	Ca:Mg	Mg:K	Ca+Mg/K	%
Ctrl	26.9	45.3	21.1	6.7	451.0	37.9	12.5	16.0	3.81	3.7	1.1	445	11.91	2.4	30.6	1197.8
P1	20.2	45.2	23.4	11.0	922.2	189.7	50.0	155.1	77.1	4.0	3.0	457	4.9	1.2	7.2	260.8
P2	26.0	41.6	22.8	9.4	881.0	201.4	63.6	260.9	108.2	4.8	3.3	516	4.4	0.8	4.2	215.7
P3	32.0	38.2	22.1	7.4	840.5	221.0	77.1	366.7	139.2	5.6	3.0	575	3.8	0.6	2.9	172.0
P4	34.1	35.0	21.2	9.4	800.55	272.5	80.0	382.5	146.6	4.7	3.2	634	2.9	0.7	2.8	194.2
P5	36.7	32.0	20.0	11.0	760.6	323.9	82.9	398.3	154.1	5.7	3.6	693	2.4	0.8	2.7	186.5
P6	39.5	37.1	16.2	6.9	694.0	302.7	77.2	328.7	166.2	6.4	3.5	605	2.3	0.9	3.0	205.7
O1	21.3	47.2	24.2	7.1	2051.0	715.0	206.0	824.0	107.3	8.1	1.2	540	2.9	0.9	3.4	837.8
O2	21.3	47.2	24.2	7.1	2378.0	575.5	60.5	94.0	17.0	7.8	2.7	252	4.1	6.1	31.4	811.4
O3	21.3	47.2	24.2	7.1	2775.5	449.5	49.0	90.0	28.3	7.7	1.6	292	6.2	5.0	35.8	884.4
C1	21.3	47.2	24.2	7.1	3708.0	803.5	170.5	911.5	159.1	7.5	3.4	314	4.6	0.9	5.0	713.9
C2	21.3	47.2	24.2	7.1	3484.0	1088.5	166.5	946.0	132.0	7.5	3.6	286	3.2	1.15	4.8	537.9
C3	21.3	47.2	24.2	7.1	3444.5	736.0	122.5	624.5	161.3	7.7	2.9	350	4.7	1.2	6.7	651.5
C4	21.3	47.2	24.2	7.1	3301.5	726.0	112.0	569.5	105.0	7.7	3.4	381	4.6	1.3	7.1	1582.5
M1	21.3	47.2	24.2	7.1	2337.5	575.0	103.0	454.0	92.3	8.0	3.4	350	4.1	1.3	6.4	636.6
M2	21.3	47.2	24.2	7.1	2478.0	851.5	100.5	471.0	57.2	7.7	3.2	285	2.9	1.8	7.1	1143.2
PC1	42.1	36.9	16.9	4.1	2984.0	476.0	46.5	273.0	73.0	8.3	3.6	178	6.3	1.7	12.7	550.2

Treatments and seedling abundance

The Shapiro-Wilk's W Test was applied to determine the statistical significance of the seedling abundance results for each of the survey weeks. Six of the nine survey dates proved to be significant ($p < 0.044$), with Week 26 being the most significant ($p = 0.000$). The three winter surveys, Weeks 8, 12 and 26 proved not to be statistically significant with p-values of 0.464 (a result of the first frost occurrence), 0.139 and 0.130 (resulting from the persistent cold and dry weather) respectively. The results for week 26, which portrayed the persistence survey results, were used to determine the significant difference between the trials (results presented in Table 7), which will be referred to in further discussion. A summary of the statistical results derived from the seedling and species data is presented in the addendum.

The physically ameliorated treatments had both the highest seedling establishment rate and persistence results overall (Figure 2), and also the highest species diversity (Figure 6). P6 and PC1 show the best performance with constant abundance of species above the 250 mark, where PC 1 almost reached 400 seedlings per square unit on average. P5 shortly followed and reflected the same growth response relative to P6 and PC1, with slightly lower species abundance. P1 – P4 commenced slowly over the first four weeks but seedling abundance increased substantially thereafter, possibly as a result of sufficient moisture retention (moisture took longer to reach the seed as a result of insufficient aeration) and in response to the sudden decrease in rainfall and temperature. These treatments also maintained a constant species abundance through the cold and dry period, contrasting with the high coarse sand fractions, P5, P6 and PC1, where the number of seedlings constantly increased until there was a significant decrease in average temperature and average weekly rainfall in Week 7. From this time onwards the seedling abundance rapidly declined, but remained higher than the low coarse sand fraction treatments, and showed a rebound when the warmer and wetter conditions returned, where P1 – P4 stayed constantly under the 100 mark. PC1 followed a sharp decrease from week 7 onwards presumably as a result of the climatic factors, but the high pH value (8.31) (Table 5) could also have had a stressor effect on seedling persistence in this specific treatment.

Seedlings also persisted for a while on the Control treatment (Ctrl), but growth never accelerated and seedling abundance seldom exceeded 40. The impact of low temperatures and insufficient moisture is also clearly reflected by the species persistence the Ctrl treatment, as not one seedling survived the winter period. It is therefore not an absolute fact that the chemical characteristics are the main limiting factor for vegetation survival on gold tailings dams, but the harsh winters can possibly be the main reason for poor seedling survival. The combination of the physical characteristics and low temperatures might be an underestimated factor limiting secondary succession and long-term restoration success.

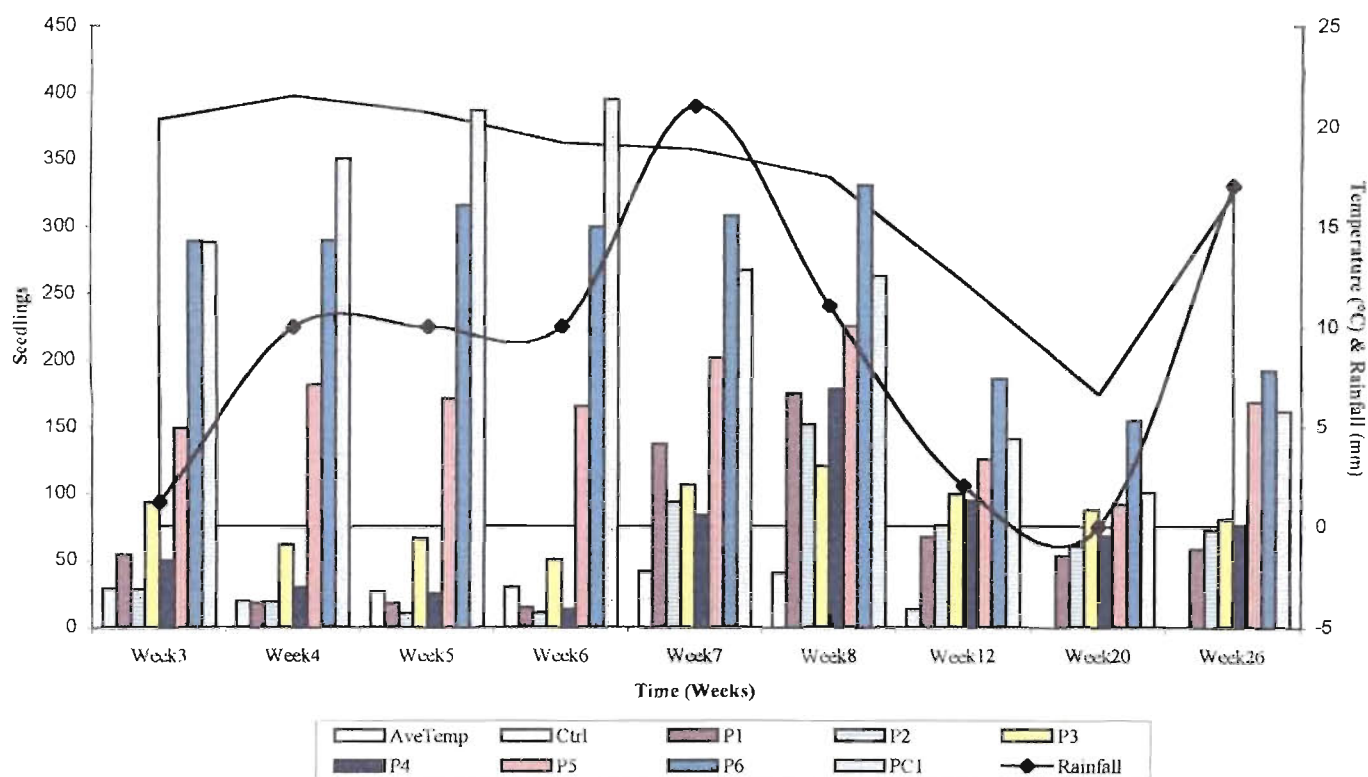


Figure 2: Seedling abundance for the various physical treatments over time.

- When a plant experiences stress, all the nutrients are withdrawn to the roots, where the plant survives until better conditions prevail, to resprout and continue its life cycle. Favourable conditions in the root zone is therefore of extreme importance for a plant to persist. Compacted tailings material pose poor aeration and unfavourable water retention potential as a growth medium and if the physical conditions of the tailings are not enhanced, no plant will be able to survive through its root-defence strategy.

For the Chemically ameliorated group (Figure 3), the microbiologically inoculated trials showed the best results with M2 outperforming the rest, with seedling abundance constantly above the 260 seedling mark before the cold and dry period. The comparative microbiological plate count showed that the microbes in both M1 and M2 increased substantially over the 6 month period (Table 4) but seedling abundance in M1 surprisingly did not keep up with M2 and two of the chemical treatments, C3 and C4, which were ameliorated with amendments of KNO_3 , presented better results. The higher pH of 8.01 in treatment M1 (Table 5) might be the limiting factor. As already mentioned, the chemical variations of C3 and C4 also showed satisfying results, presumably as a result of the nitrogenous nature

(13%N, 38%K) of the amendment, compared to the C1 and C2 variations where KCl (0%N, 50%K) was applied as the potassium source. From Table 5 it seems that these two treatments had a higher K concentration, but despite this advantage, C3 and C4 outperformed the KCl amended trials. The amendment of the two concentrations of superphosphate did also have a significant impact on seedling establishment and persistence. The pattern of influence was equal for both the KCl (C1 & C2) and the KNO_3 (C3 & C4) treatments. For the first 6 weeks of establishment and germination, seedling establishment was better on the 350 kg ha^{-1} application of superphosphate than on the 1000 kg ha^{-1} treatments. From week 7 onwards, seedling persistence was better on the 1000 kg ha^{-1} treatment, which also correlates with the decrease in temperature and moisture. The higher phosphate application could therefore have acted as a persistence stimulator in the stressing conditions. Even after the winter period, more seedlings persisted on the high phosphate treatment.

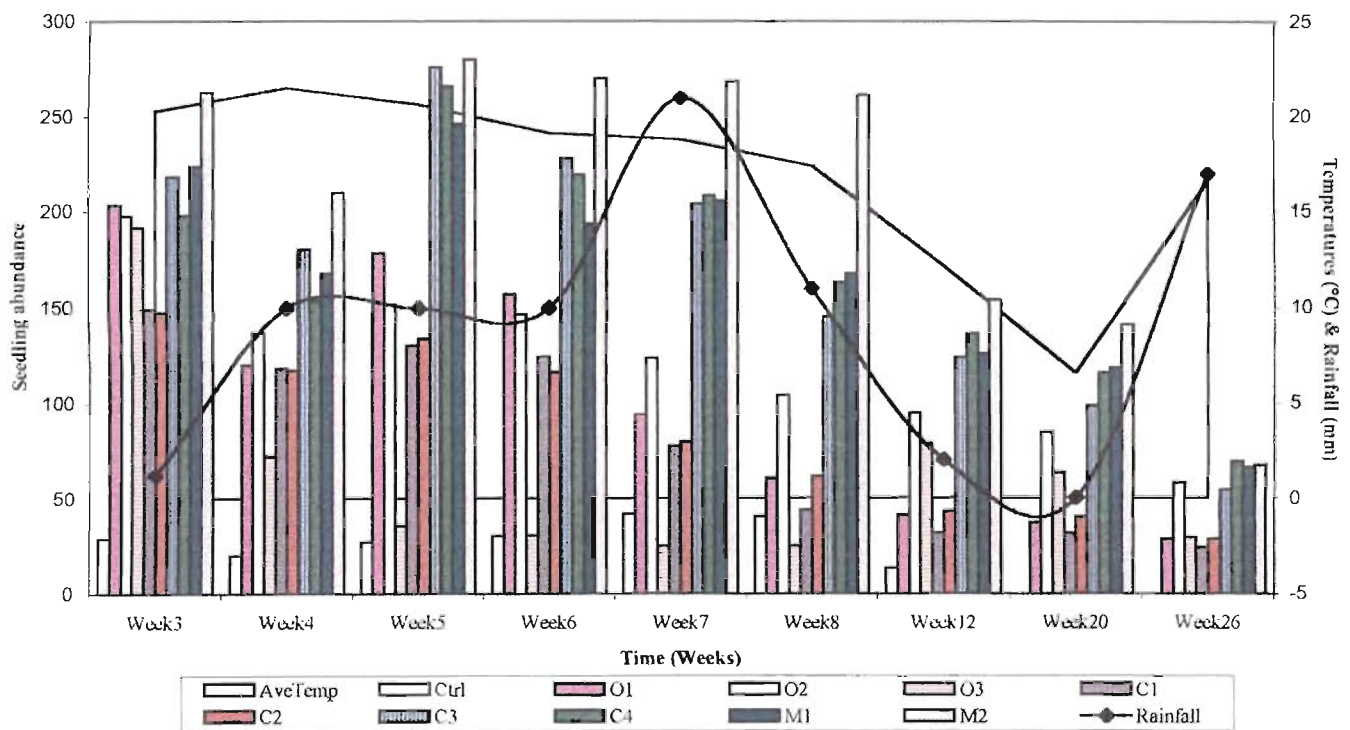


Figure 3: Seedling abundance for the different chemical treatments over time.

The sole organic treatments showed very high establishment results initially and competed very well in terms of seedling abundance, outperforming the KCl treatments. O1 and O2 showed very much the same results in the initial establishment stages, but O2 (10 tons ha^{-1} sewage sludge) outperformed O1 from week six onwards, despite the imbalance in cation ratios. The O3 variation of 20 tons ha^{-1} sewage sludge had disappointing results with a steep

decline in species establishment and persistence, presumably as a result of cation ratio imbalances, very low CEC ($1.57 \text{ cmol}(+) \text{ kg}^{-1}$) and possibly mobile localised heavy metals (despite the measured pH of 7.69) (Brofas *et al.*, 2000). The lower performance of O1 to the end of the trial could be a result of the high pH of 8.05, high Na concentration (206 mg kg^{-1}) and the low CEC of $1.21 \text{ cmol kg}^{-1}$ (Table 5).

Both the physically and chemically ameliorated groups performed similar through the winter period (Week 12 – 20) with seedling abundance ranging between 100 and 150 seedlings for most of the trials. The seedling abundance and therefore germination, however, showed a better recovery after the winter period (enhanced soil texture allows better aeration and faster water penetration), while the chemically ameliorated group posed the lowest results for the time that the experiment was conducted (as a result of crust formation).

The multivariate ordination analysis results are presented in Figures 4 and 5 and explain the associated physical and chemical parameters that determined seedling abundance according to gradients derived from the variation, which is quantified by the Eigenvalue of each axis. Figure 4 depicts the results for the determinant physical characteristics, as well as the cation ratios and selected chemical variables. The first axis, which represents the greatest variation, is a seedling abundance gradient (Eigenvalue = 0.626), while the second axis depicts a physical fraction and chemical dissimilarity gradient (Eigenvalue = 0.118).

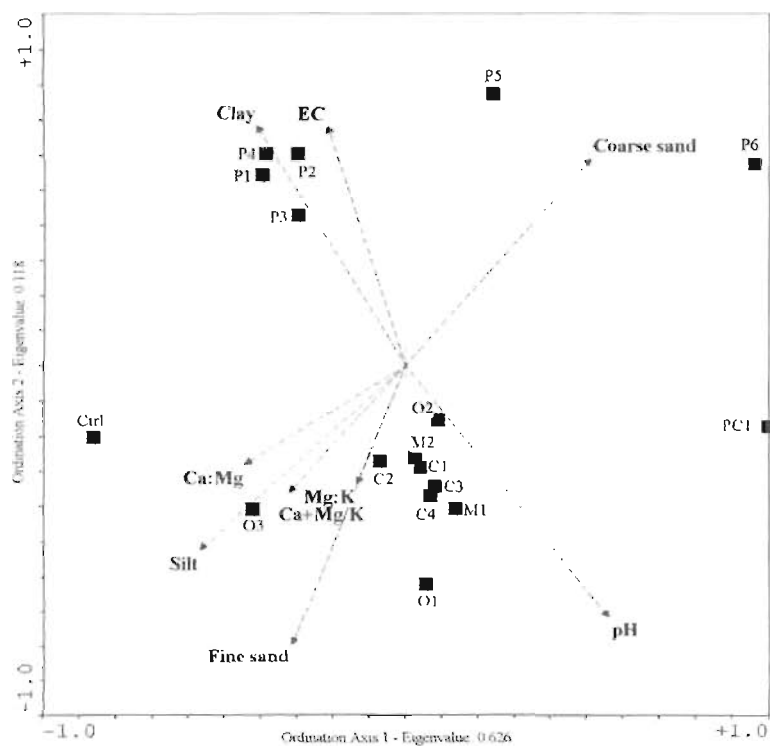


Figure 4: RDA Ordination biplot for seedling abundance, soil physical, and selected soil chemical variables.

Two distinct groups of associations are distinguished, being the physical (Quadrants 1 & 4) and chemical treatments (Quadrants 2 & 3) respectively. From this ordination it is clear that a coarse sand fraction is associated with seedling abundance (associated closely with treatments P5 and P6). The physically and chemically rectified treatment (PC1) and the Control treatment (Ctrl) are also found on the two opposite ends of the ordination, indicating their dissimilarity with the species abundance gradient. It should also be mentioned that PC1 is not yet ideally physically rectified, as it resorts to the chemical associative quadrant of the ordination. Favourable pH is also emphasised as a critical variable for seedling establishment. Factors that limited seedling establishment are pointed out by the ordination figure and include the imbalances of cation ratios, the compositional total of fine sand and silt fractions for the chemical treatments, as well as the high EC values and higher proportional clay percentage for the physical treatments. From the data presented in Figure 2 and Figure 3 it was clear that physical amelioration of the tailings media is indispensable to initiate vegetation development and to ensure long-term revegetation success, as proved by the results presented by Figure 4.

The chemical amelioration approach, however, showed greater average seedling abundance overall (Figure 3) and chemical amelioration for successful revegetation of gold tailings material therefore seems to be inevitable. The association between treatments on a soil chemical basis, related to seedling abundance results of each treatment, is outlined in Figure 5. The highest variation is associated with the seedling abundance gradient (Eigenvalue = 0.724) along the first axis, while the second axis (Eigenvalue = 0.127) depicts a [Ca]/pH gradient. Once again the treatments are separated according to their dissimilarities, in this case mainly as a result of the higher [Ca] in the chemical treatments. Quadrant 1 and 2 are characterised by the treatments that showed the best seedling establishment results for the chemical and physical treatments respectively. According to the results presented in Figure 5, the high base saturation, high EC and also the high [Na] are associated with those treatments that indicate low similarities with high seedling occurrences. It is also pointed out that the treatments that had a higher pH, a higher [P] and a higher CEC showed affinity towards high initial seedling establishment. Once again the Control treatment is isolated with complete physical, chemical, microbiological and seedling abundance dissimilarity.

The results of the Tukey Honest Significant difference test (Table 7) supported the findings of Figures 4 and 5 with regards to the similarity between the treatments. It was clear that P5, P6 and PC1 had the highest statistical dissimilarity, compared to the other treatments ($p = 0.00$ for most of the compared values). This finding explains why these treatments are isolated in the ordination figures. The identified dissimilarity for the dataset could therefore be primarily based on physical differences between the treatments, pointed out by the p-values of the comparison between the Control treatment and P3 and P4 ($p < 0.03$).

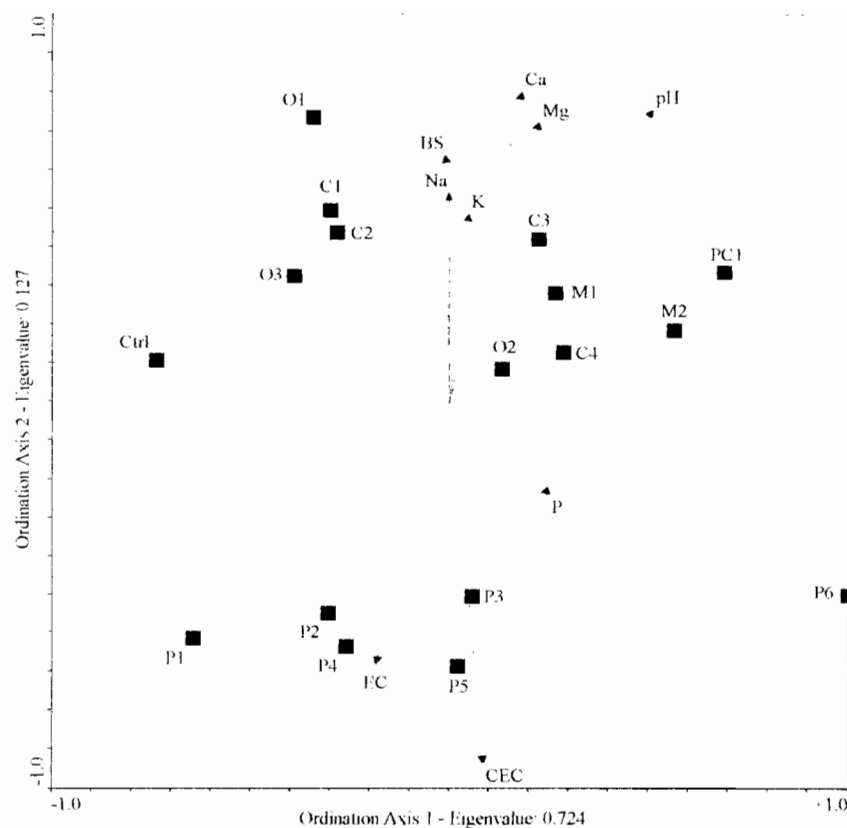


Figure 5: RDA Ordination biplot for seedling abundance and soil chemical variables.

Nine of the treatments could be identified as successful (Figures 4 and 5) in terms of seedling abundance and therefore expected vegetation establishment, and standards for revegetation of gold tailings dams could be characterised by a combination of these treatments' physical, chemical and biological characteristics. These treatments include: P3, P5, P6, O2, C3, C4, M1, M2 and PC1. A summary of the treatments' performance in terms of what could be expected for seedling establishment, persistence and diversity is presented in Table 6.

Treatments and species seedlings

Revegetated gold tailings dams are mainly dominated by monocultures of *C. gayana* and *E. curvula* and grass species from the surrounding grassland seldom occur through natural succession on these dams. By seeding the species selected from the surrounding environment, it was possible to determine what the limiting factors for these species' establishment were, and to establish what soil qualities are necessary for these absent species to persist on tailings material. The survey data for the species abundance in each treatment was also statistically evaluated (Shapiro-Wilk's W Test) and the results for each survey proved to be statistically significant (p-values for each species < 0.001, except for *C. gayana*, $p = 0.06$). The species abundance in each of the different treatment variations, and the diversity of the seeded species are presented in Figure 6.

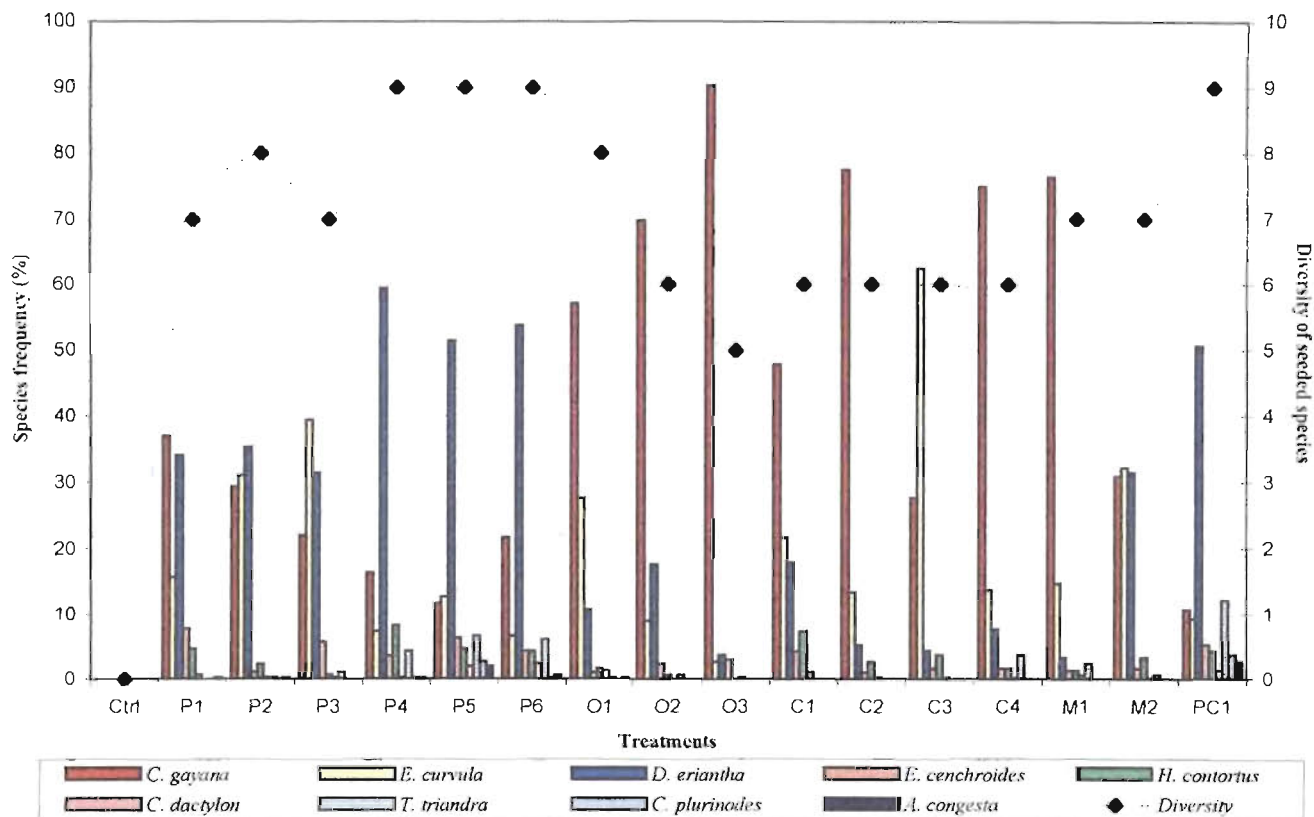


Figure 6: Species seedling frequency and diversity.

One factor that needs to be kept in mind is seed viability, as this factor could determine the outcome of species frequency results. Although *C. gayana* had germinability success of only 2% (Table 3), it was in combination with *E. curvula* (germinability = 42%) the most commonly found species in all the treatments, confirming its suitability for revegetation of gold tailings media. The low seed germinability could therefore not have been a reason for poor establishment (compared to the results of *C. gayana* that had the highest frequency but poor germinability), except if the seed of the absent species have a dormancy period to complete. The highest diversity occurred in four of the treatments, which were all physically rectified, while all the treatments had more than 5 of the seeded species (O3 being the lowest). The physically amended treatments were dominated by *D. eriantha*, which constantly exceeded 30% of the species composition (30% - 60%), while the chemically amended treatments were dominated by *C. gayana* (30% - 90%). There was also a correlation between *C. gayana* dominance and low species diversity, but this phenomenon could be a function of the tolerability of the species, and not necessarily a result of inter-specific competition. PC 1 presented the best ratio of the measured species composition.

Redundancy analysis (RDA) was also applied to soil physical and chemical, and species data.

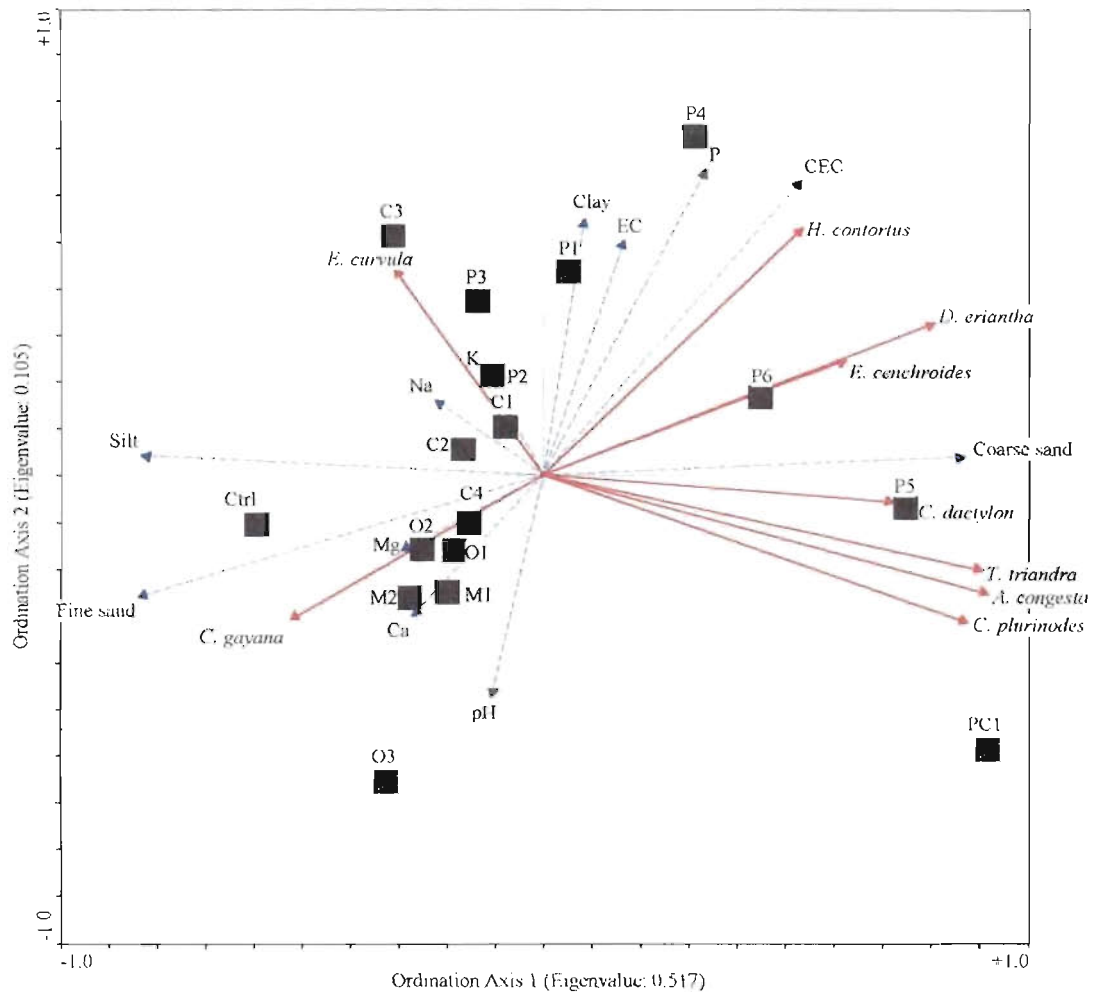


Figure 7: RDA Ordination biplot results determining gradients to which species affinity resorts in terms of its physical and chemical preferences.

The species physical and chemical preferences, based on the species' abundance in the different treatments are evident from the results presented in Figure 7. The first axis presents a soil physical gradient (Eigenvalue = 0.517) while the second axis (Eigenvalue = 0.105) is characterised by a pH gradient. Markedly, seven of the nine species showed affinity towards the coarse sand fraction and as expected, *C. gayana* and *E. curvula* show strong association with the fine sand and silt quadrants. It is also clear that *E. curvula* seems to tolerate the higher [Na] conditions and low pH the best, while *C. gayana* is only abundant when the pH is favourable. This observation confirms the reason why *C. gayana* only survives for seven to nine years under irrigation (Harwood *et al.*, 1999), implying that if the pH decreases through evaporation, and the salts are not constantly leached out, the conditions become intolerable, and *E. curvula* remains as the dominating species.

Furthermore, *C. gayana* shows high affinity towards chemical amelioration and thrives on the artificially rectified media directly after revegetation. No other species can compete or establish a niche for regeneration in the presence of this effective stoloniferous species, which results in monocultural systems that decelerate vegetation dynamics.

Treatment PC1 is once again isolated as an outlier in Figure 7, which is also supported by the results from the statistical Tukey HSD test (Table 7). The combination of the species diversity and physical, chemical and biological characteristics define the treatment as the ideal rectification technique, with high statistical significance ($p < 0.03$). PC1 shows immense dissimilarity compared to all the trials, except P5 and P6, which posed similar species frequency results. This proves that merely the physical characteristics of the tailings material could be enhanced to optimise seedling abundance and species diversity.

The results presented further proves that the only way to establish native species from the surrounding environment, and to expect succession of these species on the tailings material for that matter, vigorous physical rectification will be a prerequisite. Therefore, to expect that *T. triandra*, *C. plurinodes*, *A. congesta*, *H. contortus* and *E. cenchroides* will occur on tailings dams after a few years of natural succession, applying only soil chemical amelioration of the tailings media, is highly unlikely. *C. dactylon*, however, readily occurs on the tailings dams in association with *E. curvula*, but took advantage of the favourable conditions in the treatments and therefore associates with the natural veld species in the graph.

Table 6: Ranking of treatments according to species abundance and performance from highest to lowest average seedling establishment.

Treatment	Total Average	Standard deviation.	5 High Average	5 Low Average	Persistence	Diversity
P6	263	62	375	160	193	9
PC1	261	101	398	92	162	9
M2	213	71	325	86	67	7
C4	170	56	278	79	69	6
C3	170	66	297	51	54	6
M1	168	54	267	71	67	7
P5	164	37	226	89	169	9
O2	122	39	208	51	58	6
O1	102	62	196	31	28	8
C2	85	42	159	21	28	6
P3	85	21	145	15	82	7
C1	81	47	160	22	24	6
P4	69	47	158	13	76	9
P1	66	52	165	10	59	7
O3	61	50	151	17	28	5
P2	58	44	136	10	72	8
Ctrl	22	15	66	0	0	0

Table 7: Statistical results from the Tukey Honest Significant Difference Test performed on the results derived from the seedling abundance survey (Upper half of the table) and the species frequency survey (Lower half of the table) with $p < 0.05$ in bold.

	<i>Ctrl</i>	<i>P1</i>	<i>P2</i>	<i>P3</i>	<i>P4</i>	<i>P5</i>	<i>P6</i>	<i>C1</i>	<i>C2</i>	<i>C3</i>	<i>C4</i>	<i>O1</i>	<i>O2</i>	<i>O3</i>	<i>M1</i>	<i>M2</i>	<i>PC1</i>
<i>Ctrl</i>		0.23	0.06	0.02	0.03	0.00	0.00	1.00	0.99	0.35	0.07	0.99	0.25	0.98	0.10	0.09	0.00
<i>P1</i>	1.00		1.00	1.00	1.00	0.00	0.00	0.92	0.97	1.00	1.00	0.97	1.00	0.98	1.00	1.00	0.00
<i>P2</i>	1.00	1.00		1.00	1.00	0.00	0.00	0.56	0.69	1.00	1.00	0.70	1.00	0.72	1.00	1.00	0.01
<i>P3</i>	1.00	1.00	1.00		1.00	0.01	0.00	0.25	0.35	0.99	1.00	0.36	1.00	0.38	1.00	1.00	0.02
<i>P4</i>	1.00	1.00	1.00	1.00		0.00	0.00	0.41	0.54	1.00	1.00	0.56	1.00	0.58	1.00	1.00	0.01
<i>P5</i>	0.10	0.31	0.31	0.10	0.31		1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
<i>P6</i>	1.00	1.00	1.00	1.00	1.00	0.66		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.96
<i>C1</i>	1.00	1.00	1.00	1.00	1.00	0.31	1.000		1.00	0.98	0.64	1.00	0.93	1.00	0.71	0.70	0.00
<i>C2</i>	1.00	1.00	1.00	1.00	1.00	0.31	1.000	1.00		0.99	0.76	1.00	0.98	1.00	0.83	0.82	0.00
<i>C3</i>	1.00	1.00	1.00	1.00	1.00	0.10	0.999	1.00	1.00		1.00	0.99	1.00	1.00	1.00	1.00	0.00
<i>C4</i>	1.00	1.00	1.00	1.00	1.00	0.10	0.999	1.00	1.00	1.00		0.77	1.00	0.79	1.00	1.00	0.00
<i>O1</i>	1.00	1.00	1.00	1.00	1.00	0.31	1.000	1.00	1.00	1.00	1.00		0.98	1.00	0.84	0.83	0.00
<i>O2</i>	1.00	1.00	1.00	1.00	1.00	0.10	0.999	1.00	1.00	1.00	1.00	1.00		0.98	1.00	1.00	0.00
<i>O3</i>	1.00	1.00	1.00	1.00	1.00	0.10	0.999	1.00	1.00	1.00	1.00	1.00	1.00		0.85	0.85	0.00
<i>M1</i>	1.00	1.00	1.00	1.00	1.00	0.10	0.999	1.00	1.00	1.00	1.00	1.00	1.00	1.00		1.00	0.00
<i>M2</i>	1.00	1.00	1.00	1.00	1.00	0.10	0.999	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00		0.00
<i>PC1</i>	0.01	0.03	0.03	0.01	0.03	1.00	0.100	0.03	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01	

CONCLUSION

Gold mine revegetation practices need to reintroduce native species to succeed in the reinstatement of ecological function on the tailings dams. This could be achieved either through seed mixtures, or by means of spontaneous establishment through natural succession. It was, however, clear from the results presented that the enhancement of the tailings media through physical, chemical and microbiological inputs is the only way to initiate spontaneous ecosystem development. Although the effects of slope gradient and slope length on seedling establishment, vegetation persistence and native species diversity was not included in this study, the results from this experiment could have a substantial impact on restoration objectives and steer it into a new direction in terms of holistic soil profile reconstruction.

Results from the conducted experiment proved that the introduction of a coarse sand fraction into tailings material is critical, not only for seedling establishment, but for native pasture species succession and associated species diversity. Not only did the high seedling abundance show strong affinity towards physical rectification, but seven of the nine seeded species associated very strongly with the physically ameliorated treatments. Vigorous physical rectification will therefore be a prerequisite for native species establishment. The use of a coarse fraction could also limit the erodibility of the tailings media and enhance landform stability. It was however shown that the minimum application for native species establishment expectations was the P3 treatment, which will include at least 40% topsoil amendment, 57% tailings medium at the most, and 120 tons ha⁻¹ compost. It will not be a cost effective option though. This ameliorative approach should, however, be encouraged and could be easily implemented if the coarse sand fraction could be included in the processing phase when the tailings material is transported to the dams.

A combination of the physical, chemical and microbiological amelioration techniques proved to be the most successful for revegetation, as was seen in treatment PC1, which had the highest species diversity, resulting from the favourable growth conditions.

The urgency to test the hypothesis presented by this experiment in a field trial and on a greater scale is ever increasing and further research should concentrate on the effect of slope factors and climate on different combinations of physical, chemical and biological restored soil profiles.

The importance to find a way to succeed in the establishment of native species on gold tailings dams is highly underrated, but sustainable gold tailings restoration will remain a challenge until questions asked by the acceptability of revegetated areas to surrounding ecological systems are thoroughly answered.

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ADDENDUM

Table A: Average and standard deviation of counted seedlings/0.04m² for the different treatments over time

		<i>Ctrl</i>	<i>P1</i>	<i>P2</i>	<i>P3</i>	<i>P4</i>	<i>P5</i>	<i>P6</i>	<i>C1</i>	<i>C2</i>	<i>C3</i>	<i>C4</i>	<i>O1</i>	<i>O2</i>	<i>O3</i>	<i>M1</i>	<i>M2</i>	<i>PC1</i>
Week3	Average	29	54	28	93	50	149	289	149	148	218	198	203	198	192	224	263	288
	Stdev.	24	28	3	86	10	56	42	34	12	61	61	33	17	25	64	35	28
Week4	Average	20	19	19	61	30	182	289	118	117	180	154	120	137	72	168	210	350
	Stdev.	20	13	6	59	20	49	54	26	31	39	22	6	29	9	46	30	32
Week5	Average	27	18	10	66	26	171	315	130	134	276	266	178	152	35	246	280	386
	Stdev.	24	11	8	65	12	24	86	36	43	80	50	22	77	29	33	63	26
Week6	Average	30	15	11	50	14	166	300	124	116	228	219	157	147	30	194	270	395
	Stdev.	26	12	0	50	9	34	93	44	36	94	55	3	75	27	46	66	21
Week7	Average	42	137	93	106	83	201	308	78	80	204	208	94	124	25	206	268	267
	Stdev.	51	38	6	56	4	23	54	37	41	100	64	7	54	22	76	60	37
Week8	Average	40	175	152	120	178	226	330	44	61	146	163	61	104	25	168	261	263
	Stdev.	49	22	26	15	16	34	27	27	49	86	56	6	68	22	68	70	75
Week12	Average	13	68	76	99	94	125	186	31	43	124	136	41	95	79	126	154	141
	Stdev.	21	19	44	27	53	36	31	8	24	37	38	4	32	10	41	59	68
Week20	Average	0	53	61	87	69	91	155	31	40	99	116	37	85	64	118	141	100
	Stdev.	0	21	20	18	52	34	13	7	24	48	22	7	38	21	37	44	46
Week26	Average	0	59	72	82	76	169	193	24	28	54	69	28	58	29	67	67	162
	Stdev.	0	16	18	3	49	34	22	13	11	27	21	2	22	11	18	11	49

Table B: Average and standard deviation of determined species frequencies derived from the different treatments.

		Ctrl	P1	P2	P3	P4	P5	P6	C1	C2	C3	C4	O1	O2	O3	M1	M2	PC1
<i>A. congesta</i>	Avg	0.00	0.33	0.33	0.00	0.33	2.00	0.67	0.33	0.33	0.00	0.00	0.33	0.00	0.00	0.00	0.00	2.67
	Stdv.	0.00	0.58	0.58	0.00	0.58	2.00	0.58	0.58	0.58	0.00	0.00	0.58	0.00	0.00	0.00	0.00	1.53
<i>C. dactylon</i>	Avg	0.00	0.67	0.33	0.33	0.33	2.00	2.33	1.00	0.33	0.33	0.33	1.33	0.00	0.33	0.67	0.33	1.33
	Stdv.	0.00	0.58	0.58	0.58	0.58	2.00	1.53	1.00	0.58	0.58	0.58	1.15	0.00	0.58	1.15	0.58	0.58
<i>C. plurinodes</i>	Avg	0.00	0.00	0.33	0.00	0.33	2.67	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.67
	Stdv.	0.00	0.00	0.58	0.00	0.58	0.58	0.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.08
<i>C. gayana</i>	Avg	0.00	37.00	29.00	22.00	16.33	11.67	21.67	49.00	77.00	27.67	75.00	57.00	69.67	90.33	76.33	30.67	10.67
	Stdv.	0.00	2.65	3.61	3.61	8.02	2.31	4.51	5.29	6.08	2.31	4.36	4.58	3.21	4.04	5.51	4.51	3.06
<i>D. eriantha</i>	Avg	0.00	34.00	35.33	31.33	59.33	51.33	53.67	17.00	5.33	4.33	7.67	10.67	17.67	3.67	3.33	31.33	50.67
	Stdv.	0.00	1.73	4.04	5.13	5.69	5.51	8.96	1.73	4.16	3.06	2.08	5.51	5.13	2.52	3.21	4.04	2.89
<i>E. cenchroides</i>	Avg	0.00	7.67	1.00	5.67	3.33	6.33	4.33	4.33	1.00	1.67	1.00	1.00	2.33	3.00	1.33	1.67	5.33
	Stdv.	0.00	3.51	1.73	2.52	0.58	2.89	1.53	0.58	1.00	0.58	1.00	1.00	1.53	2.65	1.53	1.53	1.53
<i>E. curvula</i>	Avg	0.00	15.67	31.00	39.00	7.33	12.67	6.67	21.67	12.00	62.33	10.67	27.67	9.00	2.67	14.67	32.00	9.00
	Stdv.	0.00	4.51	2.00	6.24	3.06	5.51	4.04	6.81	6.56	4.51	3.51	6.43	5.00	3.06	5.51	4.36	4.00
<i>H. contortus</i>	Avg	0.00	4.67	2.33	0.67	8.33	4.67	4.33	7.33	2.67	3.33	1.67	1.67	0.67	0.00	1.33	3.33	4.33
	Stdv.	0.00	1.53	1.53	1.15	2.08	2.52	3.79	1.53	1.15	2.08	1.53	1.15	0.58	0.00	1.53	1.53	2.31
<i>T. triandra</i>	Avg	0.00	0.00	0.33	1.00	4.33	6.67	6.00	0.00	2.00	0.33	3.67	0.33	0.67	0.00	2.33	0.67	12.33
	Stdv.	0.00	0.00	0.58	1.00	0.58	2.31	4.00	0.00	1.41	0.58	2.08	0.58	0.58	0.00	1.53	0.58	2.89

CHAPTER 5

SOIL AND VEGETATION DYNAMICS ON REVEGETATED GOLD TAILINGS DAMS' SLOPES: GROWTH MEDIA DETERIORATION, MONOCULTURE DOMINATION AND REVERSED SUCCESSION

CHAPTER OVERVIEW

Grass species monocultures are characteristic of the vegetation composition of ecologically restored gold mine tailings dams in South Africa. *Chloris gayana*, which is now the primary grass species used in revegetation seed mixtures, dominates the vegetation composition to a large extent, especially on the northern and eastern aspects, while an equally abundant grass species, *Eragrostis curvula*, is often augmented in the seed mixture for establishment on the southern and western aspects. The species occurring on the tailings dams persist under continual irrigation and as a result of heavily fertilised growth media, which include excessive liming for latent and potential acidity, macro- and microelement deficiency amendments and added sewage sludge for soil physical, organic matter and microbiological optimisation. The extent to which the rectified growth medium will contribute to sustainable nutrient cycling, and its capacity to support a healthy vegetation cover, eventually enabling ecosystem development, is largely unknown. It is therefore necessary to determine what the dynamic trend of species occurrence is in response to the physically restored and chemically amended growth media. Furthermore it should be determined whether soil profile development is evident, and whether the identified dominant species will persist on the rectified growth media while plant community succession is facilitated. The soil chemical status and species occurrence on the four aspects of side slopes of two adjacent revegetated tailings dams were monitored over a five-year period to investigate species fluctuations and early successional patterns. The dynamics of the soil chemistry and the reaction of the vegetation in terms of species composition in response to the soil chemical changes and with respect to macro- or microclimatological exposure were further explored. The regenerative potential of the dominant *C. gayana* from the study sites was also assessed through seed germinability tests, to determine its inherent potential for secondary succession. It was established that current gold tailings restoration still only succeed in terms of its primary objective, which is dust pollution prevention, making use of chemical ameliorative techniques, irrigation and fast growing species to cover the tailings material as quickly as possible. The soil chemical status of the ameliorated media deteriorated to a great extent and soil profile development is questionable. Ecosystem development also tends to be slow and the successional pattern is characterised by an increase in weeds, and a decrease in basal cover, a state known as reversed succession.

SOIL AND VEGETATION DYNAMICS ON REVEGETATED GOLD TAILINGS DAMS' SLOPES: GROWTH MEDIA DETERIORATION, MONOCULTURE DOMINATION AND REVERSED SUCCESSION

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ABSTRACT

Soil and vegetation dynamics of revegetated gold tailings dams are largely unknown. These ecological criteria are of interest to determine the degree of nutrient cycling and vegetation development, which will reveal the sustainability status of the restored areas. The edaphic and biological driving parameters of these restored systems also need to be identified to establish which factors will determine restoration outcomes. This study focussed on the soil chemical dynamics and vegetation compositional trends over a five-year period, on four different slopes of revegetated gold tailings dams. Soil chemical analyses and vegetation assessments were conducted each year on the studied tailings dams, and the climate was also monitored. Seed germinability tests of the dominant *Chloris gayana* were also carried out. The data were statistically and multivariately analysed, and significant results presented clear trends of system development. It was established that the soil profile depleted chemically to a state of severe deficiency, possible as a result of leaching from irrigation, or by the nutrient dissipating monocultures. Cation ratio imbalances were further a constant feature. Floristically, 61% of the species identified in 2002 belonged to the family *Poaceae*, but there was a notable increase in weeds in the last two seasons. The ten most abundant species were used to quantify the dynamics, and although *Chloris gayana* were the most frequent species (>45%), the fluctuation in composition showed clear trends related to edaphic variability. The seed of *Chloris gayana* also proved to have no reproductive potential. The most important factors determining species resemblance included the effect of slope related microclimate, macroclimate, moisture, pH fluctuation, and basal cover. Although the climax species for disturbed areas, *Hyparrhenia hirta*, showed a recent increase, the vegetation is in a state of reversed succession. The revegetated areas are ecologically young though, and vegetation development seemed to be slow. Follow-up fertiliser programs should also be incorporated to accelerate soil profile development.

Keywords:

Soil chemical dynamics; Vegetation dynamics, Gold tailings restoration; *Chloris gayana*; Slope microclimate; Reversed succession.

INTRODUCTION

Mining discard engulfs enormous surfaces of productive land on the South African Highveld, leading to the loss of healthy soils, plant nutrients, vegetation and habitat, and inevitably, functional disruption of ecosystems. These disturbed areas are restored ecologically through the recreation of pasture ecosystems, which are climatically hardened, have a high turnover of root material and restore normal soil function (Mentis, 1999). Initial aggressive pasture vegetation, which is able to tolerate the mitigated extreme conditions, is established on heavily fertilised tailings media (Wali, 1999), acting as a supplier of favourable soil physical and chemical conditions, which will optimise growth conditions and nutrient capacity, enabling colonisation from the adjacent natural veld to reclaim the site over time. The biological sustainability is further enhanced by the constant improvement of the tailings media to be suitable for vegetation establishment and community persistence, enhancement of species diversity, and the creation of favourable microclimate and habitat conditions for voluntary ecosystem establishment (Hatting *et al.*, 2001).

The ecological reintegration of such systems is, however, complex and timely with few sustainable outcomes. Vegetation development is expected to complete the restoration process on its own through primary and secondary succession, which is a practical and cheap reclamation technique, and flowing from logical expectations, the approach seems to be sound. This natural process of ecological capacity replacement, however, rarely occurs on mined land, and it is rather the exception than the rule (Bradshaw, 1997).

The created pasture-based restoration system on gold tailings dams is often dominated by stoloniferous *Chloris gayana* Kunth (Rhodes grass) (Harwood *et al.*, 1999) and the versatile hay and pasture species *Eragrostis curvula* (Schrad.) Nees (Weeping Love-grass) (Rethman & Tanner, 1995), which are commonly used in the revegetation of the side slopes of the plenteous gold mine tailings dams of South Africa. Although able to establish quickly under favourable conditions presented by the fertilised growth media and constant irrigation, neither of these species, nor other exotic introduced species, has proven to either persist or facilitate successional change on the tailings dams over time. Even though fertiliser programs are applied, the effect of this input wears off quickly and the established vegetation becomes moribund (Marrs & Bradshaw, 1993). An explanation for this incomplete system development phenomenon is crucial, as the methodology of sustainable gold tailings revegetation is primarily based on growth media evolution and natural succession, implying that the regenerative capacity of the introduced biological sphere will self-sustain the recreated system.

According to Wiegand & Felinks (2001), natural dynamics should be investigated to establish the evolutionary trend of ecologically restored systems and to determine restoration success.

These natural dynamics relate to abiotic (erosion geomorphology, soil dynamics), biotic (colonisation, migration, succession), and combined processes (land type development, soil formation and plant community dynamics, the base for biological optimisation). The dynamics of the reinstated system will highlight certain limiting or combination of factors responsible for the failure of restoration. The need to quantify the dynamic interactive response between soil and vegetation is evident, as it will characterise the regenerative capacity of the system. Practically, this will in turn determine to what degree the legal requirements are met in terms of the sustainability of the vegetation, and could define the healthiness of the ecological state, predicting when site closure could be expected.

A number of factors may be responsible for successional failure, and the restored site should firstly be analytically quantified to identify possible succession limiting criteria and to evaluate restoration success. Several parameters that could be used to characterise the state of the restored biosphere were identified. According to Brown & Grant (2000) the proportion of the total amount of nutrients in the restored ecosystem that are contained within the recreated soil surface should be monitored over time to establish the success of soil profile development (and the success of the restoration technique). The changing vegetation assemblages also need to be investigated to determine the success and interrelationships of the introduced species in both the applied and greater ecological context. Jochimsen (2001), however, found that neither basal cover nor species diversity seemed to be suited to assess the state of vegetation with respect to succession, but species composition and dominance of certain species represented the vegetational dynamic process in a more precise way. It was also found that weather conditions and soil quality interfered with succession.

Wiegand & Felinks (2001) state that the quantification of the dynamic relation between the soil and vegetation in response to climatological conditions is suitable for ecological research by which restoration success and sustainability could be determined. Furthermore, Marrs and Bradshaw (1993) suggest that man-made waste could even allow us to make significant progress in understanding the dynamics of natural ecosystem development.

In this study, the possibility of using the characteristics of soil and vegetation dynamics of the restored tailings media to determine the stability state and evaluate the sustainability of the regenerative capacity of the ecological sphere is investigated.

STUDY AREA AND STUDY SITES

The tailings dams investigated are situated in the Free State goldfields approximately 10 - 15 km north of Theunissen (Figure 1), and 35 - 40 km to the south of Welkom. The area forms part of the Highveld region, and has an average elevation of 1360 m above mean sea level. A gently undulating surface characterises the area and prominent landmarks are rarely visible. The disposal facilities are located on the Beaufort sediments of the Karoo Supergroup, and drainage in the area is reasonably well developed towards the meandering Sand River (the Bosluis Stream and the Doring River drain the study sites). Avalon sandy soils are typical of the area, with agriculture as the predominant land use surrounding the mining areas. Most of the unploughed land is covered by grass and drought tolerating vegetation, which coincides with the classification as sour grassland (*Cymbopogon-Themeda* veld) by Acocks (1988).

The study area is, however, situated in a semi-arid region with annual rainfall ranging between 400 and 600 mm, the mean annual precipitation being 518 mm (Cogho *et al.*, 1992), which mainly occurs in the form of thunderstorms, peaking in the summer months from October to March (Figure 2). Temperatures show large daily and seasonal variations ranging from 34°C in summer to -2.9°C in winter ($\pm$ 100 frost days from June to August (Cogho *et al.*, 1992)), with a mean temperature of 23°C in the growing season. Winds in the region are usually north-westerly, but strong and gusty south-westerlies are common during rain and dust storms, reaching maximum velocities in the afternoon.

The edaphic extremes posed by the tailings media, which mainly included high salt concentrations and also poor moisture regimes resulting from the low rainfall, necessitated artificial watering of the revegetated areas (to leach the salts out and to permanently supply water). The sites were artificially watered twice daily for 15 minutes since establishment (not on rainy days), from August to March each year, amounting to approximately 2 mm per day. The irrigation was suspended though from January 2002, as the effect of dryland conditions on vegetation persistence were evaluated onwards.

The relations between the soil and vegetation dynamics were studied on the slopes of two adjacent tailings dams in the described area over the period 1998 – 2002, on one of which the northern, eastern and southern slopes have been revegetated (Oryx Gold Mine Tailings Dam), and one of which only the western slope have been revegetated (Beatrix Gold Mine Tailings Dam).

Revegetation was carried out in spring of 1998 (September) and the amelioration included 130 – 160 tons ha⁻¹ dolomitic lime, 50 tons ha⁻¹ treated sewage sludge, 1 ton ha⁻¹ Super Phosphate (10.5%) (P = 105 g kg⁻¹), 300 kg ha⁻¹ 4:3:4 (39kg N ha⁻¹, 29 kg P ha⁻¹, 39 kg K ha⁻¹), 1 ton ha⁻¹ KCl (50,0% K) and 300 kg ha⁻¹ LAN (42 kg N ha⁻¹) (Van Deventer *et al.*, 2001).

The seeded grass species included: *Chloris gayana* Kunth (Rhodes Grass), *Cynodon dactylon* (L.) Pers. var *dactylon* (Couch Grass), *Dactylis glomerata* (L.) (Cocksfoot), *Digitaria eriantha* Steud. (Common Finger Grass), *Eragrostis curvula* (Schrud.) Nees. (Weeping Love Grass), *Eragrostis tef* (Zuccagni) Trotter (Annual teff), *Hyparrhenia hirta* (L.) Stapf. (Common Thatch Grass), *Lolium perenne* (L.) (Rye Grass), *Panicum maximum* Jacq. (Guinea Grass), *Pennisetum clandestinum* (Chiov.) (Kikuyu), and *Polypogon monspeliensis* (L.) Desf. (Rabbit's foot). Other species planted included *Medicago sativa* (L.) (Alfalfa) and *Melilotus alba* (Desr.) (Wild Lucerne) and various hand plants, which included *Cynodon nlemfuensis* (Vanderyst) (Star Grass), *Hyparrhenia tamba* (Steud.) Stapf. (Blue thatching Grass), *Pennisetum macrourum* (Trin.) (River bed Grass), were also introduced.

The studied slopes had average slope gradients of 30° and slope lengths range between 10 - 15 m. The lengths of the footprints of the distinctive tailings dams exceed 500 m, and the dam heights range between 15 - 35 m, with a total surface of approximately 5 ha of restored tailings being studied between the four slopes.

METHODS

Soil Analysis

Three tailings samples were taken randomly at each of the monitored slopes and the composite samples made up for the respective slopes were yearly analysed. Soil chemical analyses were carried out using the Standard Ammonium Acetate Extraction procedure (Handbook of Standard Soil Testing Methods - Method 8: Ammonium acetate [1 mol dm^{-1} ; pH 7]), to determine the cation status of the rectified tailings media. Other selected chemical variables were also either calculated (cation ratios, SAR) or determined (CEC, EC, pH, %C) from the different samples.

- This procedure was carried out directly after the amelioration took place (December 1998), and then every year thereafter, except for the year 2000.

Vegetation analysis

Vegetation surveys were carried out in years 1999, 2001 and 2002 in March. The highest species diversity is evident at this stage of the growing season

- Proportional pasture species composition was established by observing 1000 points (10 transect surveys of 100 points each) on each of the four slopes on the selected tailings dams, using the step-point method (Tidmarsh & Havenga, 1955; Kent & Coker, 1994; Mentis, 1999). Random surveys were conducted parallel to the contours of the slopes, and were limited to the revegetated area on the bottom deposition, with slope lengths of less than 15 m.

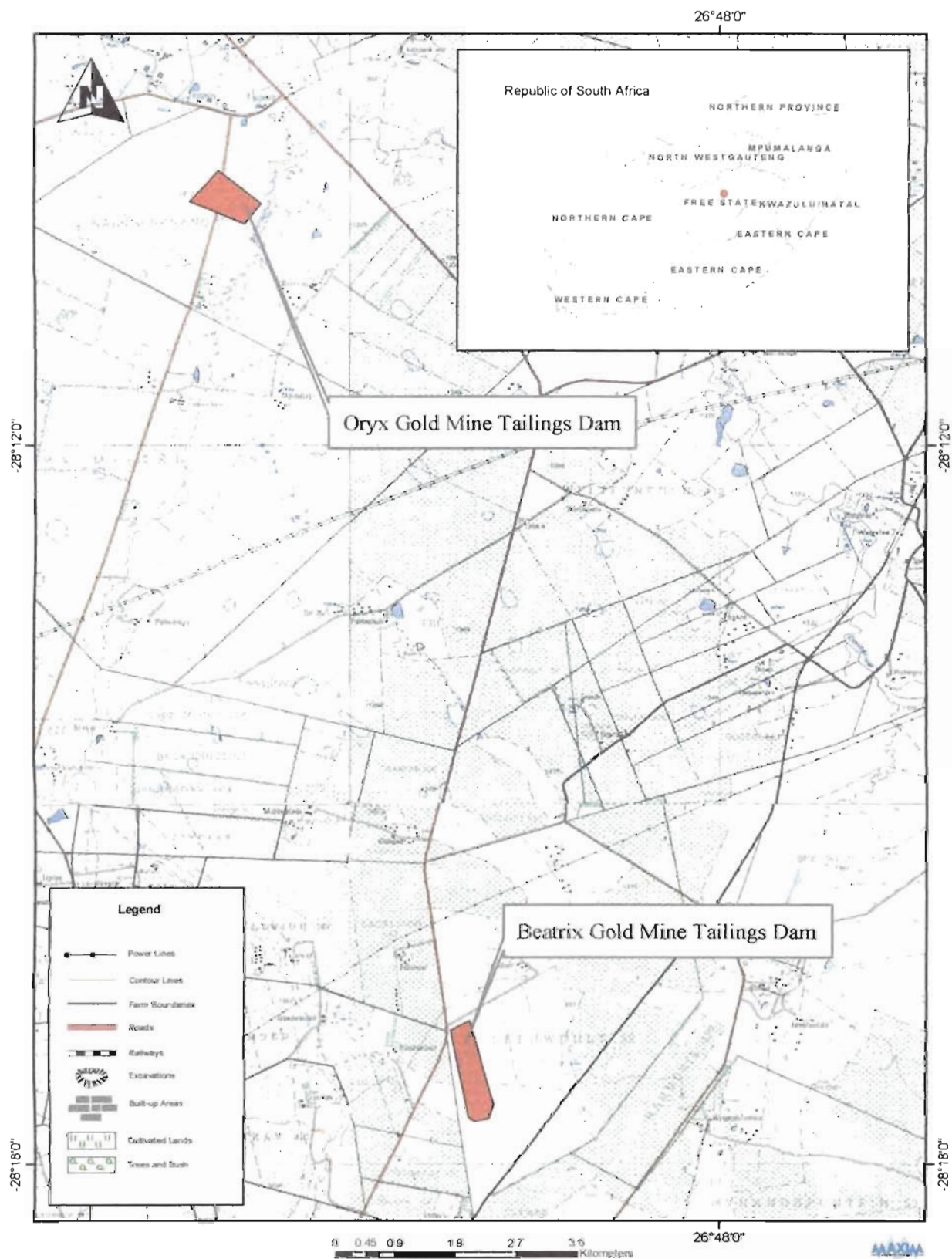


Figure 1: Study area

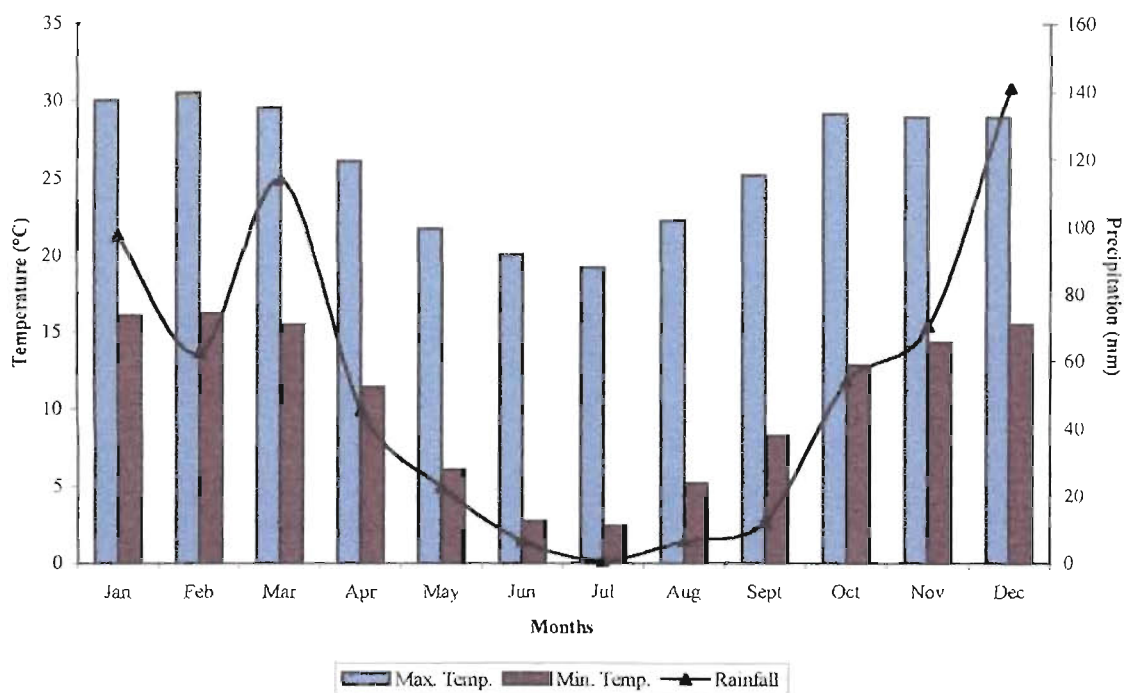


Figure 2: Average maximum and minimum temperatures and precipitation at the study sites for the period 1998 – 2002, measured at the Theunissen weather station.

Starting at the bottom of the slope, 10 points were noted, after which one meter were stepped up and the following 10 points were assessed in the opposite direction. This procedure was followed until 100 points were assessed, which represented one transect survey.

- Plant basal cover was determined by scoring when the point of the dropped rod intersected rooted and living grass forage. The descending point was then scored as a hit and the species was recorded. The total number of hits in 100 descending points provides a measure of basal cover for the specific transect.
- When the point failed to strike plant material, or the plant material struck was not rooted or living, the descending point was scored as a miss and the nearest rooted grass species within the radius of 300 mm was recorded.
- The relative abundance of plant species was determined by the frequency of each species recorded for the 100 points scored within a single transect, expressed as a percentage.

In 2002, a plant species diversity survey was conducted, identifying all the species alongside the transects, and every species that was additionally found on the tailings dams was also noted.

The viability of the dominant species in terms of its resiliency on a revegetated area must be assessed by seed analyses (Brown & Grant, 2000). Therefore, harvested seed of *C. gayana* was tested for the sites by assessing the seed germinability (after Hardwood et al., 1999).

- Seed were pre-chilled (5°C) for seven days. Three hundred pure seeds of harvested *C. gayana* were randomly counted from five separate groups of seed. The seed were germinated on a moistened (10mL of 0,2% KNO₃ and deionised water solution) layer of Carlton towel paper in Tupper® containers (115 mm x 115 mm x 20 mm).

The containers were then marked and randomly placed in a germination incubator (26°C for 24 hours). Germination results were scored after 14 and 28 days. After 28 days, seed that germinated (seeds of which the plumula and radicula were visible) were counted.

Data analysis

- Statistical analysis was performed making use of StatSoft Statistica Release 6.
- Multivariate analysis was applied to the species data, and physical and chemical characteristics respectively, making use of CANOCO (Ter Braak, 1996) (Ver. 4).

Canonical correspondence analysis (CCA), which is a unimodal direct ordination technique, was initially applied to indicate the direct determining gradients.

Redundancy analysis (RDA), which is a refined Principal Component Analysis (PCA) technique and allows for the linear direct ordination of low variation datasets, resulting in short gradient interpretation, was applied to determine the gradients responsible for species' chemical, aspect and climatological preferences.

RESULTS

Soil chemical dynamics of the ameliorated media

The data derived from the soil chemical analysis showed as expected large variations for the soil chemical status over time. Nevertheless, clear trends of the dynamics of the macroelements and the selected chemical parameters were evident (Table 1). Figure 3 depicts the dynamics of the soil chemical parameters over the study period.

The chemical status of the tailings media proved to be optimum in the first year after restoration took place but a steep decline in the macroelemental status is evident in the following years (except for P). The very high quantities of lime amendments, which are applied to neutralise both latent and potential acidity, resulted in an increase in pH. There was also an increase in P from the slow releasing superphosphate, and an increase in Na probably as a result of the effect of capillary rise after irrigation ceased in 2002. The availability of P could, however, be inhibited if the pH decrease any further. The pH did increase substantially after lime amendments, but showed a gradual decrease over the last 3 years. Mg, K and possibly even Ca have declined to unacceptable deficient levels over time as depicted in Figure 3, and follow-up fertiliser is of utmost importance for the survival of the vegetation.

Table 1: Restored gold tailings media chemical characteristics over 5 years

	Year	Ca	Mg	K	Na	P	pH	SAR	EC	CEC	%C
		(mg kg ⁻¹)	(mg kg ⁻¹)	(mg kg ⁻¹)	(mg kg ⁻¹)	(mg kg ⁻¹)	H ₂ O	(%)	(mS m ⁻¹)	(cmol(+) kg ⁻¹)	
North	1998	4308.4	461.7	437.9	250.1	5.02	2.8	1.0	477	1.0	0.0
	1999	581.1	54.7	117.3	67.0	19.0	6.4	1.4	272	3.4	0.2
	2001	158.3	10.0	30.5	17.4	13.1	7.1	1.4	428	3.4	0.2
	2002	352.2	65.3	37.7	39.1	47.2	6.6	0.1	296	3.4	0.4
East	1998	5190.1	328.1	629.9	359.7	11.1	3.7	1.4	273	1.1	0.0
	1999	641.3	53.5	242.4	138.5	22.2	6.7	0.7	327	3.0	0.1
	2001	281.6	15.1	18.0	10.3	24.1	6.5	0.7	399	3.0	0.3
	2002	152.8	7.9	24.7	75.1	16.9	5.0	0.2	439	3.1	0.3
South	1998	2665.2	388.8	914.9	522.5	8.0	3.6	2.6	231	1.0	0.0
	1999	400.8	62.0	109.5	62.5	16.0	7.2	0.8	219	2.7	0.3
	2001	222.4	8.4	15.3	8.7	20.0	6.4	0.8	340	2.7	0.2
	2002	176.8	18.2	70.2	283.3	48.6	5.5	0.5	670	2.7	0.2
West	1998	4909.6	376.7	117.3	225.3	3.0	2.2	1.0	1006	2.3	0.0
	1999	162.3	45.9	19.6	13.8	10.6	5.9	0.7	639	5.8	0.1
	2001	149.2	14.6	27.4	36.7	8.2	5.9	0.7	224	6.1	0.2
	2002	121.4	20.9	43.0	86.9	17.4	4.7	0.2	509	6.0	0.2

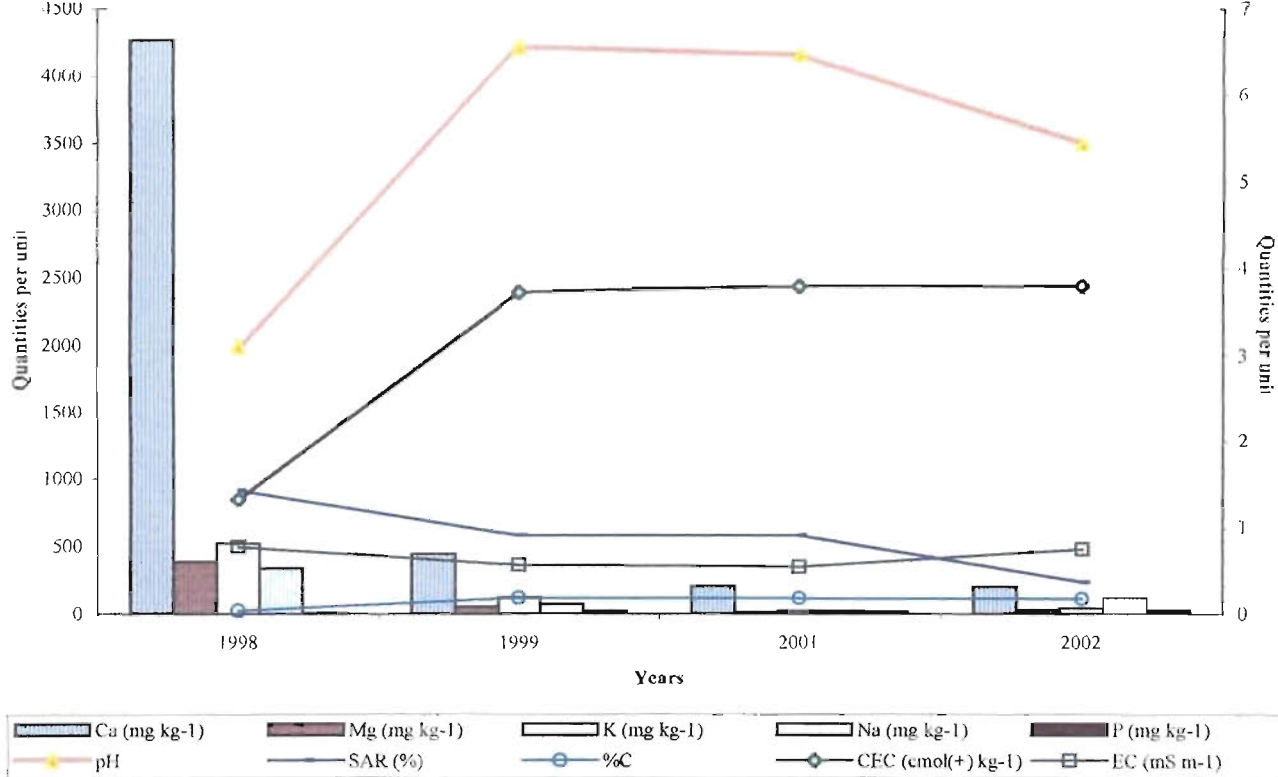


Figure 3: Soil chemical characteristics over time on the four slopes of the studied tailings dams (Yearly averages of composite samples of all four slopes).

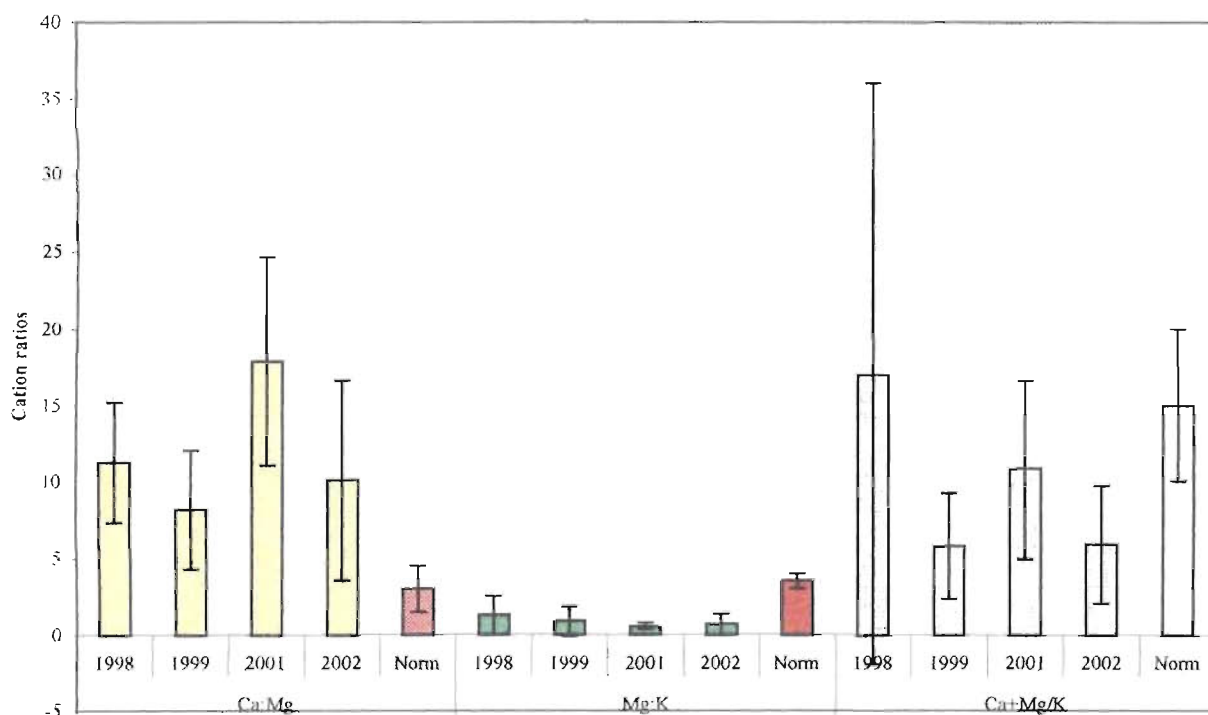


Figure 4: Average cation ratios of the samples taken from the four slopes of the studied tailings dams over time (Norm values from Buys, 1993).

Other chemical variables were also optimised through soil chemical restoration, with an evident increase in the EC and %C, and a decrease in the SAR. The CEC stayed constant for the study period. Cation ratio imbalances were, however, a constant feature of the rectified tailings (Figure 4). The Ca:Mg ratio was consistently higher than the norm while the Mg:K and the Ca+Mg/K was lower than the norm. The high imbalances could be ascribed to the high liming quantities.

Dynamics of the restored vegetation cover

An annotated list of all the species found on the tailings dam and positively identified during the last vegetation survey, is provided in Table 2. A total of 41 species were identified of which 61% (25) belonged to the family *Poaceae*. The method used to quantify the species composition revealed 10 species being the most abundant (each species contributing > 1% of the total species composition). These species include *Chloris gayana*, *Cynodon dactylon*, *Digitaria eriantha*, *Eragrostis curvula*, *Hyparrhenia hirta*, *Pennisetum clandestinum*, *Medicago sativa*, *Melilotus alba*, *Conyza bonariensis* and *Cirsium vulgare*. The relation of each species in terms of the total species composition over time for the 10 species used to evaluate the vegetation dynamics, is presented in Figure 5.

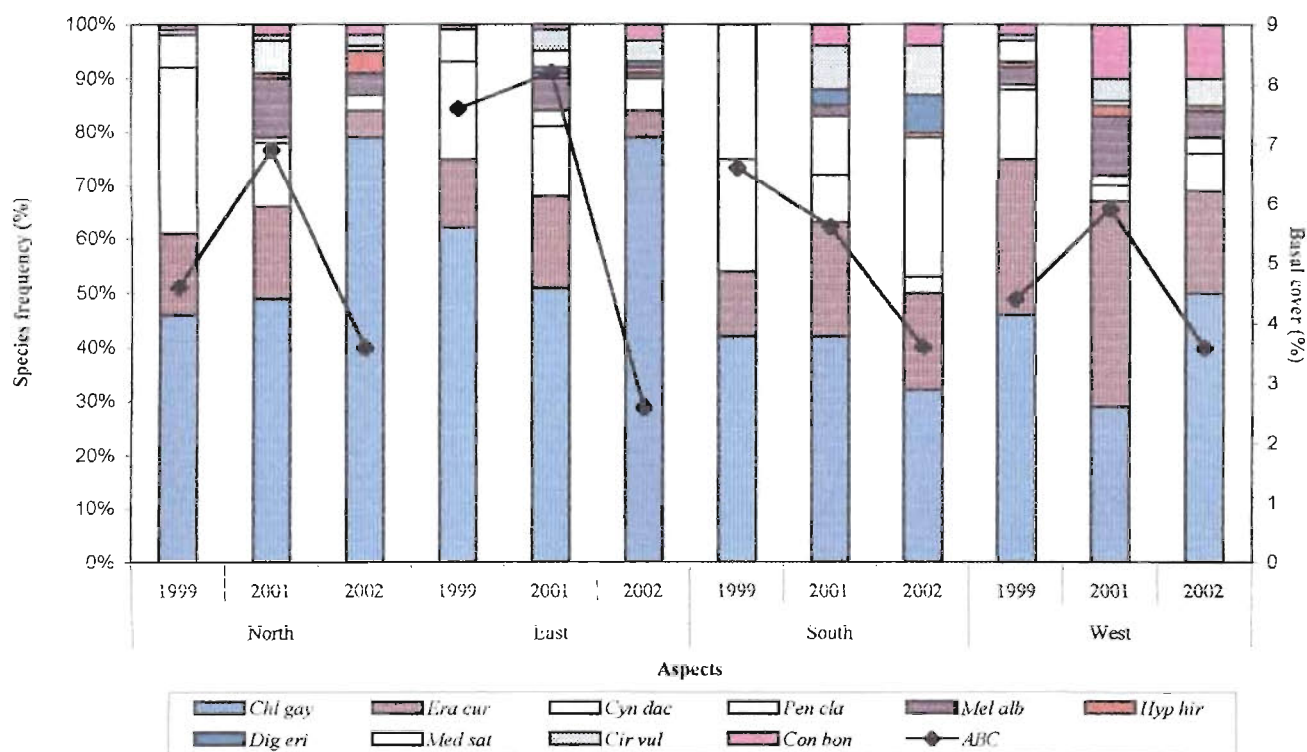


Figure 5: Species frequencies, compositional ratios and dynamics of the most abundant species on the different slopes of the tailings dams over time (Abbreviations explained in Table 2).

Table 2: Plant species identified on the gold tailings dams in 2002 (Exotic species in bold).

Family	Species	Abbreviation	Common name	Description
Poaceae	<i>Aristida congesta</i>		Tassel three-awn	Grass
	<i>Chloris gayana</i> *	<i>Chl gay</i>	Rhodes grass	Grass
	<i>Cortaderia selloana</i>*		Pampas grass	Grass
	<i>Cynodon dactylon</i> *	<i>Cyn dac</i>	Couch grass	Grass
	<i>Cynodon nlemfuensis</i> *		Star grass	Grass
	<i>Dactylis glomerata</i>*		Rough cocksfoot	Grass
	<i>Dactyloctenium australe</i>		LM grass	Grass
	<i>Digitaria eriantha</i> *	<i>Dig eri</i>	Common finger grass	Grass
	<i>Digitaria sanguinalis</i>		Crab finger grass	Grass
	<i>Eleusine coracana</i>		Goose grass	Grass
	<i>Eragrostis curvula</i> *	<i>Era cur</i>	Weeping love grass	Grass
	<i>Eragrostis plana</i>		Tough love grass	Grass
	<i>Hyparrhenia hirta</i>	<i>Hyp hir</i>	Common thatching grass	Grass
	<i>Hyparrhenia tamba</i> *		Blue thatching grass	Grass
	<i>Lolium perenne</i>*		Perennial ryegrass	Grass
	<i>Panicum maximum</i> *		Guinea grass	Grass
	<i>Paspalum dilatatum</i>		Dallis grass	Grass
	<i>Pennisetum clandestinum</i> *	<i>Pen cla</i>	Kikuyu	Grass
	<i>Pennisetum macrourum</i> *		Riverbed grass	Grass
	<i>Phragmites australis</i> *		Common reed	Grass
	<i>Polypogon monspeliensis</i> *		Rabbit's foot grass	Grass
	<i>Setaria sphacelata</i>		Common bristle grass	Grass
	<i>Setaria verticillata</i>		Bur bristle grass	Grass
	<i>Vetiveria zizanioides</i> *		Vetiver	Grass
	<i>Triticum aestivum</i> *		Wheat	Grass
Fabaceae	<i>Acacia melanoxylon</i> *		Blackwood	Tree
	<i>Medicago sativa</i> *	<i>Med sat</i>	Lucerne/Alfalfa	Forb
	<i>Melilotus alba</i>	<i>Mel alb</i>	Sweet lucerne	Weed
Asteraceae	<i>Cirsium vulgare</i>	<i>Cir vul</i>	Scotch thistle	Weed
	<i>Conyza bonariensis</i>	<i>Con bon</i>	Flax-leaf fleabane	Weed
	<i>Lactuca serriola</i>		Wild lettuce	Weed
	<i>Stoebe vulgaris</i>		Bankrupt bush	Weed
	<i>Tagetes minuta</i>		Tall Khaki weed	Weed
Myrtaceae	<i>Eucalyptus camaldulensis</i>*		Blue gum-tree	Tree
Salicaceae	<i>Populus alba</i>*		Common poplar	Tree
	<i>Populus canescens</i>*		Grey poplar	Tree
Chenopodiaceae	<i>Atriplex semibaccata</i> *		Creeping salt bush	Forb
Tamaricaceae	<i>Tamarix gallica</i>*		Tamarix	Tree
Cyperaceae	<i>Cyperus rotundus</i>		Purple nutsedge	Forb
Asclepiadaceae	<i>Asclepias fruticosa</i>		Milkweed	Weed
Asparagaceae	<i>Protasparagus larinicus</i>		Wild asparagus	Weed

* - Species established during restoration

The vegetation data collected were statistically significant for each year ($p < 0.001$), and also for each of the 10 abundant species used for the evaluation of the dynamic vegetational trend ($p < 0.0001$), except for *Chloris gayana* ($p = 0.095$). Basal cover data also proved to be statistically significant ($p < 0.05$)

Chloris gayana is by far the most abundant species, constantly comprising $> 45\%$ on the northern and eastern slopes, and $> 30\%$ on the southern and western slopes. Other observable trends include a decrease of *Medicago sativa* and *Cynodon dactylon* and an increase in weedy species, which include *Cirsium vulgare*, *Conyza bonariensis* and *Melilotus alba*. *Hyparrhenia hirta*, which is known as the climax species for disturbed areas, is also invading the slopes. A sharp decrease in basal cover in the last year of observation is also clearly visible, as is a change in species composition ratios.

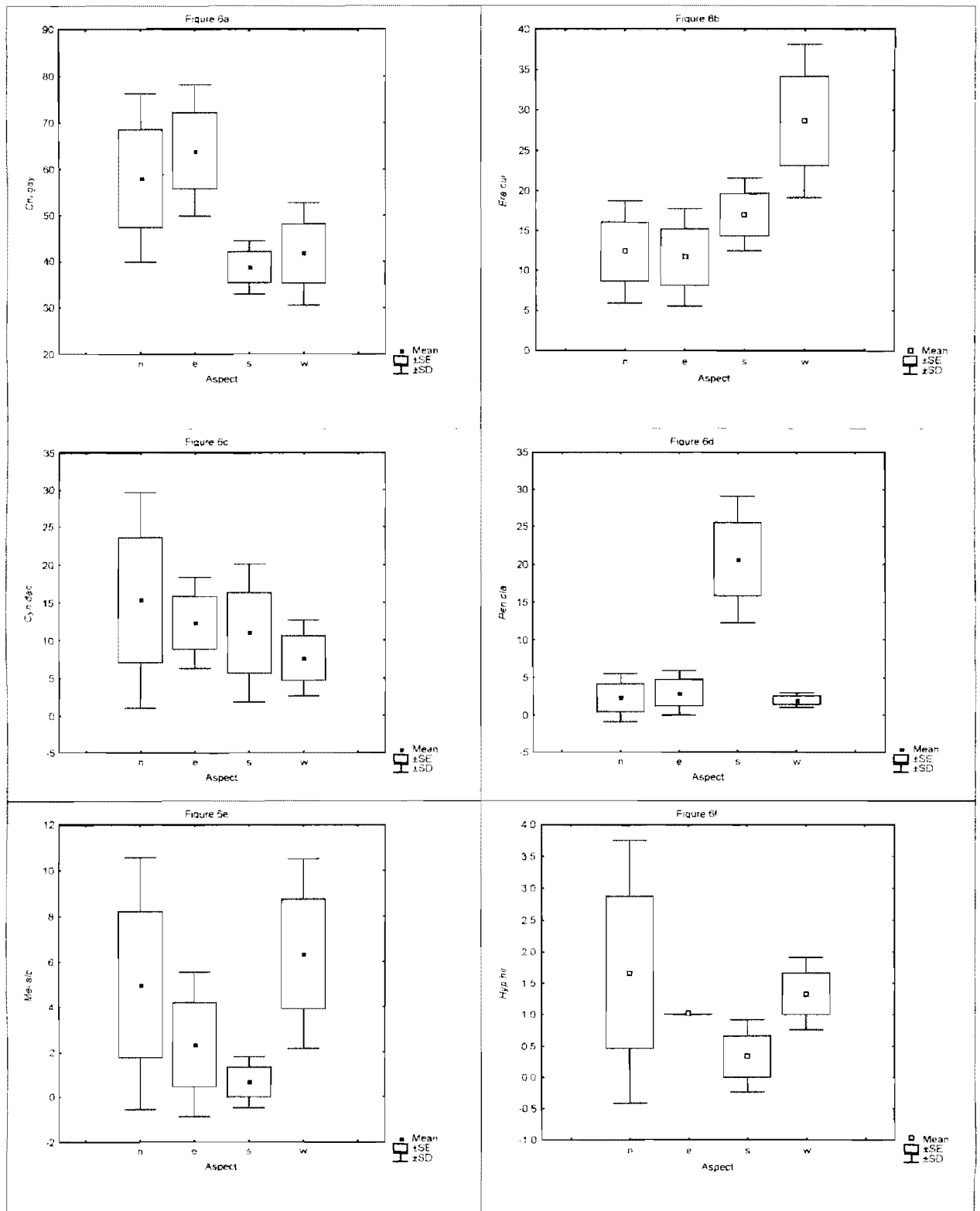
Although *Chloris gayana* was effective in the quick colonisation of the ameliorated tailings material, its ability to persist through time is questionable. Results from germinability tests predict grim expectations for reproductive potential of the dominant *Chloris gayana* (Table 3). Although the quantity of seed tested is only a minute fraction compared to the amount of the seed it is intended to represent, the testing procedure was sound and low variation was encountered ($p < 0.05$). This preliminary seed viability test indicates that *Chloris gayana* established on gold tailings dams has very little reproductive potential.

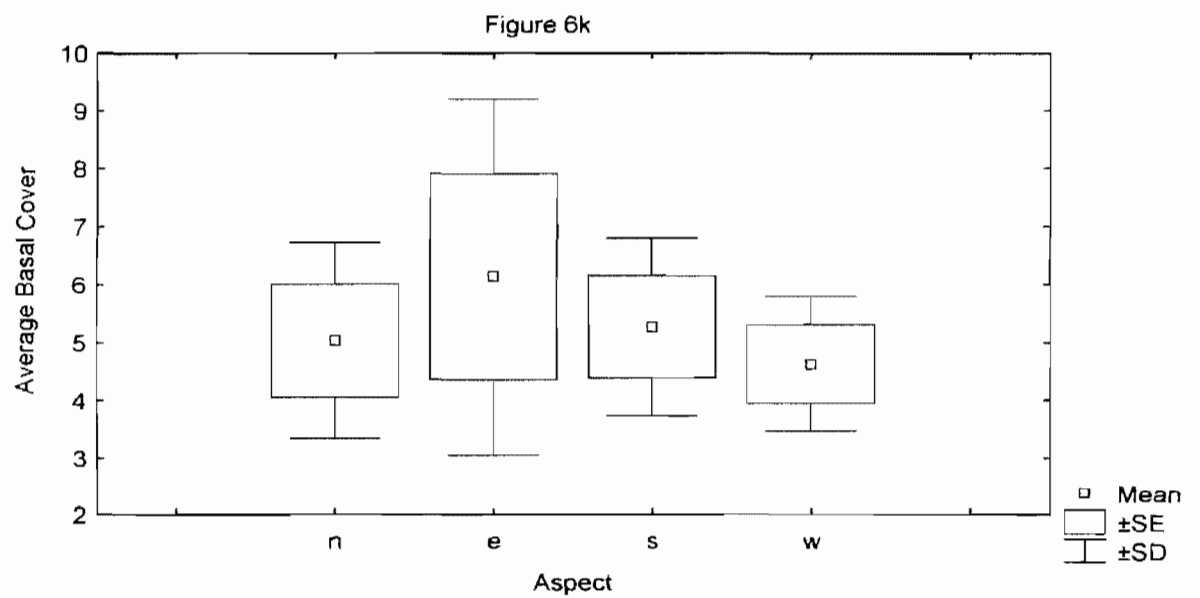
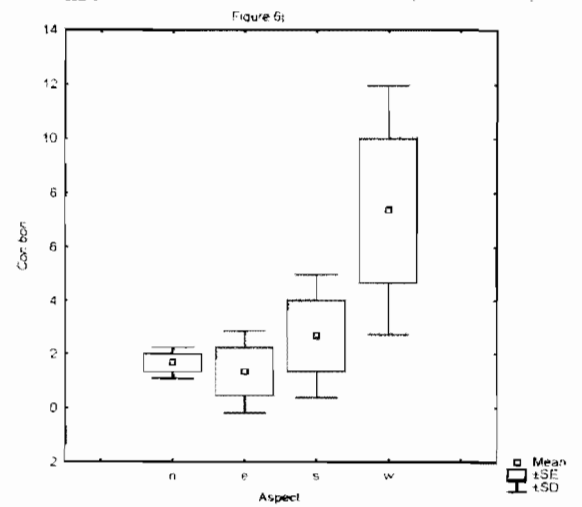
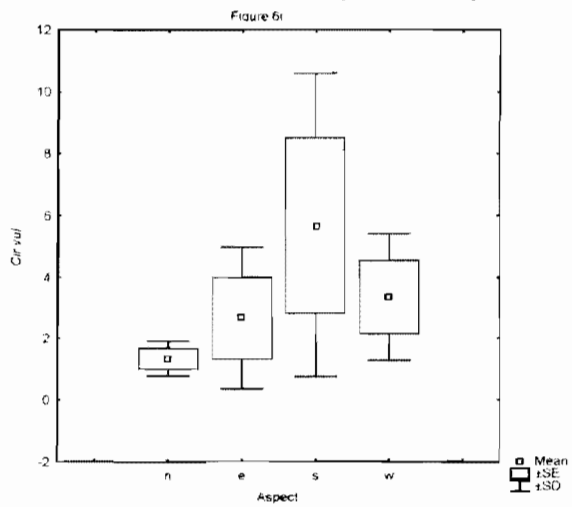
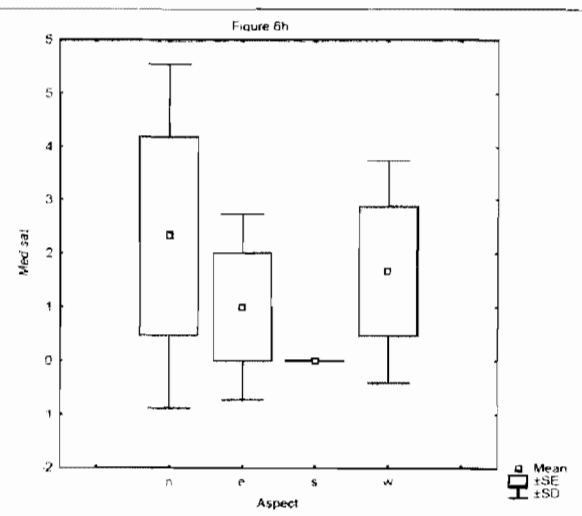
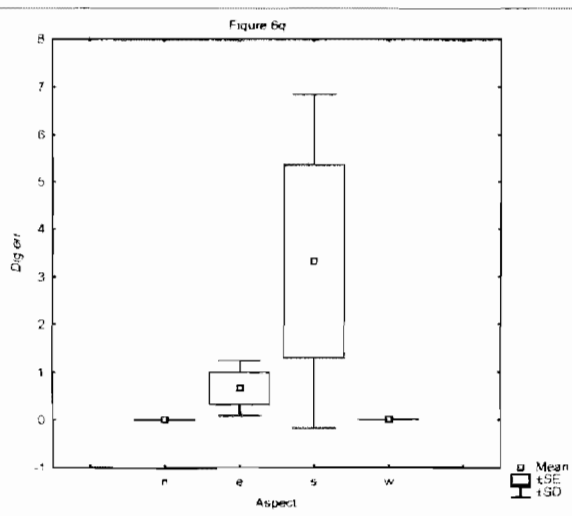
Table 3: Results of the seed germinability tests.

Aspect	Seed germinability (%)			
	Trial 1	Trial 2	Trial 3	Average
North	0	0	0	0
East	0	0	0	0
South	0	0	0	0
West	1	1	0	0.66

The average species frequency found on the different slopes of the tailings dams for the study period is presented in Figure 6a – j, and Figure 6k reflects the average basal cover of the different slopes. From the data presented in these Figures, it is evident that the different species show clear affinities towards certain aspects, which could be a function of either preferential fertilisation stimuli, climatological preferences or simply inter-specific species competition resulting from tolerability and community development.

Figure 6 a-j. Average frequency occurrence of evaluated species on the different slopes of the gold tailings dams for the study period.





Climate

The influence of temperature extremes on restored gold tailings vegetation is a major limiting factor for seedling establishment, and therefore ecosystem development (Versveld *et al.*, 1998). The climatological influence could thus have a considerable and determinant influence on the vegetation dynamics of revegetated tailings dams. Although the restored vegetation cover was irrigated twice daily for 15 minutes in the summer months, the effect of the macroclimate had a significant impact on ecosystem development of the study sites.

The weather data for the study period are depicted in Figure 7 and represents the temperature and rainfall for the 12 months preceding April of the labelled year. In this respect, the weather data are representative for the vegetation analysis, which was conducted in March each year.

The different seasons are each characterised by certain relative features. The 1998/1999 season represented the best climatological average for the sites (Cogho *et al.*, 1992), while the 1999/2000 and 2000/2001 seasons were on average the coldest and hottest seasons respectively. The 2000/2001 season also had the highest average temperature fluctuations, while 2001/2002 was an abnormal wet season. The vegetational composition and cover also significantly reflected this seasonal variation (Figure 5)

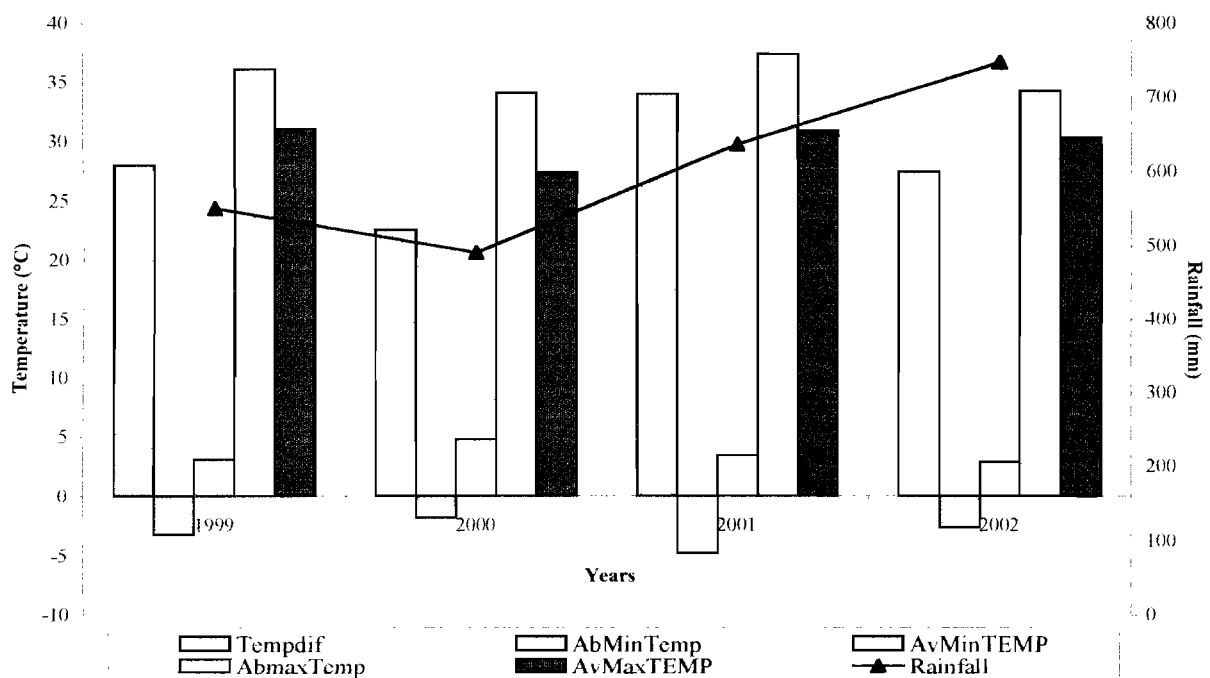


Figure 7: Summary of the average temperature regimes for the different years at the study sites (Theunissen weather station).

Tempdif = Temperature difference; AbMin/MaxTemp = Absolute Minimum/Maximum Temp. average (30 extreme days); AvMin/MaxTemp = Average Minimum/Maximum Temp.

DISCUSSION

Examining relationships between species distributions and the distribution of associated environmental factors and gradients necessitated the use of multivariate ordination techniques. CCA ordination was firstly applied to express the patterns of variation in the floristic data, and to demonstrate the principle relationships between the species and each of the environmental variables. Each of the identified affinities and selected gradients were then indirectly assessed making use of Redundancy analysis (RDA), to establish what influential relationships are determinant for the vegetation development.

The relation of species preference for the study period was assessed on a soil chemical basis, which obviously correlates with the treatments of the different slopes, and the degree of soil profile development. From the CCA ordination biplot (Figure 8), it was clear that the chemical characteristics of the different slopes determined the variation along both axes (Eigenvalues of first and second axes being 0.290 and 0.066 respectively), explaining the association of certain species with the different aspects.

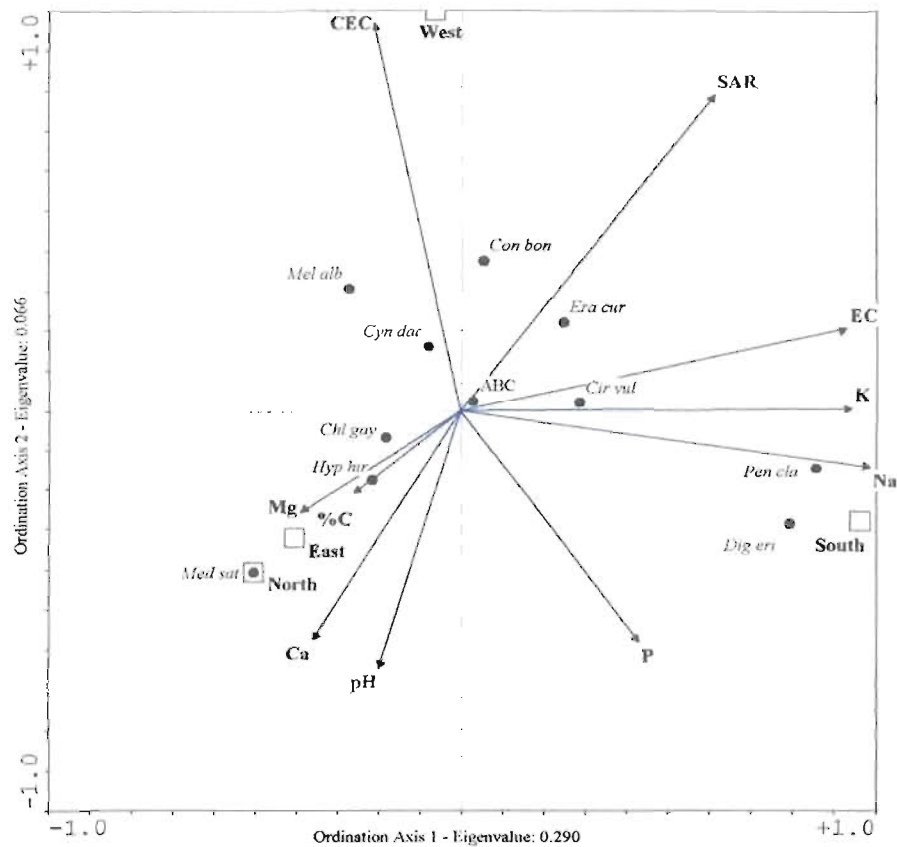


Figure 8: CCA Ordination biplot for soil chemical variables and species frequency on the different aspects over the study period.

The first axis explains the highest variation, but no specific chemical parameter or combination of parameters seems to cause this gradient. It could therefore be speculated that a micro-climatological influence on the different slopes, in combination with the chemical variables, characterises the gradient.

The fact that the northern and eastern slopes associate significantly, though the chemical status differs to a large extent, confirms the presumption that an external factor could be responsible for the gradient along the first axis, which is also reflected by the floristic preferences (the northern/eastern slopes being warmer and drier – and southern/western slopes being wetter/cooler). The second axis, however, resorts to a pH/CEC gradient, differentiating chemically between the western and the other aspects.

The first axis (Eigenvalue = 0.509) explains the highest variation resulting from the differences between the northern/eastern and southern/western aspects.

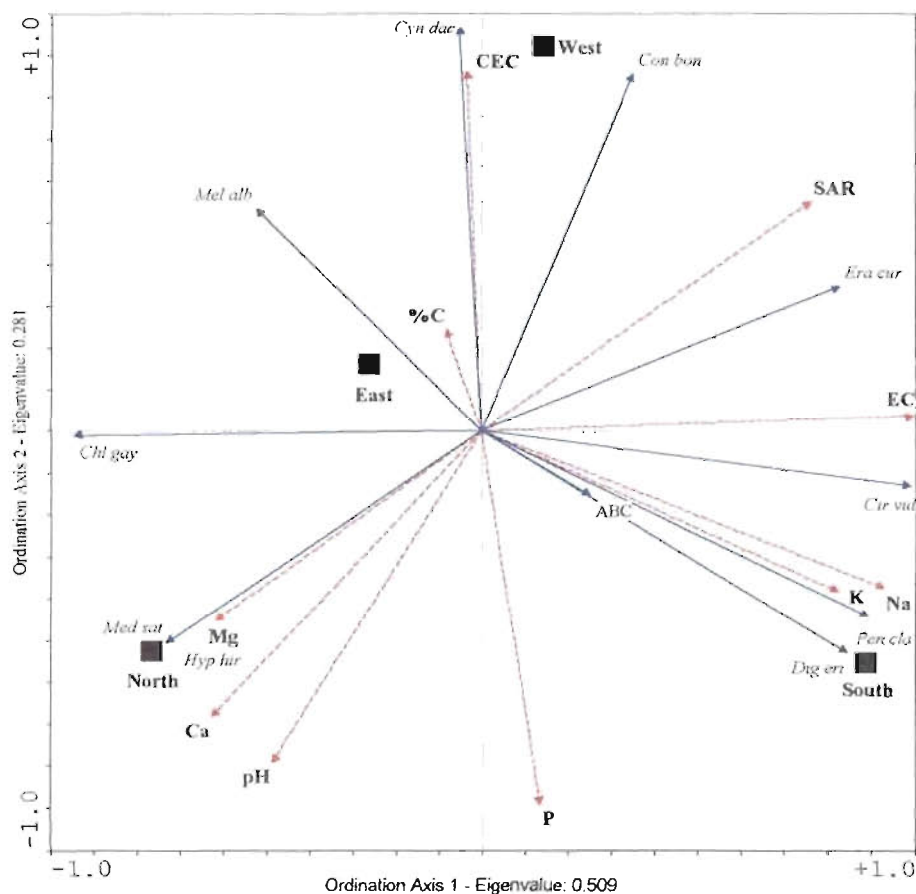


Figure 9: RDA Ordination biplot for the soil chemical variables and the species frequency for the last survey (2001/2002 season). The distinction between the different aspects was for the first time clearly made, not only on soil chemical basis, but also on climatological differences, as revealed by species preference.

A significant gradient (Eigenvalue = 0.281) was also established between the eastern/western (mild differences) and northern/southern aspects (extreme differences), related to inter-aspect similarities and dissimilarities, based on soil chemical variability and microclimatology as resembled by species occurrence.

The RDA biplot for the last survey (2001/2002) (Figure 9) also suggests that vegetation development that occurred on the tailings dams is a function of the aspect conditions, and although there are similarities between slopes, it remains necessary to investigate each slope individually (each of the four slopes being grouped in the four different quadrants).

The species preferences for the respective slopes were now assessed to determine what are the main variables responsible for the vegetation dynamics. Figures 10a – d depicts RDA ordination biplots for the soil chemical and vegetation data over the study period. The Eigenvalues for both the axes were very similar (Averages: 1st axis 0.60 ± 0.036 ; 2nd axis: 0.38 ± 0.031), and were either characterised by seasonal variability or pH related gradients.

RDA ordination biplots were further applied to determine which edaphic variables drive the dynamics on the tailings dams. Figure 11 depicts the species climatological preferences, and each species' soil chemical preferences (with slope and survey dates excluded) are outlined in Figure 12. Although the results from the southern aspect (Figure 10c) consistently differed from the other aspects, it correlated remarkably with the data presented in Figure 12. The following general principles were derived and confirmed from these figures:

The dynamics of *Chloris gayana* are determined by its affinity for moisture/rainfall (Figure 11), which override to some extent low pH and nutrient deficiency tolerance. This species' occurrence correlated very well with the 2001/2002 season on all but the southern aspect (wettest aspect) (Figures 10 a,b,d), where its abundance is independent of the seasonal variation. This phenomenon is also confirmed by the data presented in Figure 5, indicating an increase in the species that correlated with a wetter season. The occurrence of *Chloris gayana* correlated negatively with the presence of *Eragrostis curvula*, Average Basal Cover (ABC) (Figure 5), high Sodium Absorption Ratio (SAR) and high %Carbon (%C) on the different aspects, probably as a result of inter-specific competition, although data presented by Figure 12 indicate pH sensitivity (*Chloris gayana* thrives in alkaline conditions) and basal cover dependence. This confirms the ability of *Chloris gayana* to exploit microclimatological conditions of the different aspects to the detriment of species diversity and community succession. This species also correlated well with high P concentration, associating with the occurrence of *Hyparrhenia hirta*, the climax species for disturbed conditions. Once again the southern aspect was an exception.

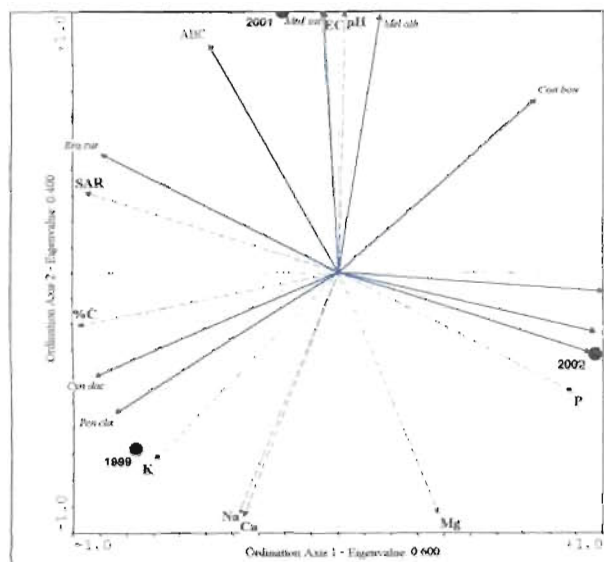


Figure 10a: Northern Aspect

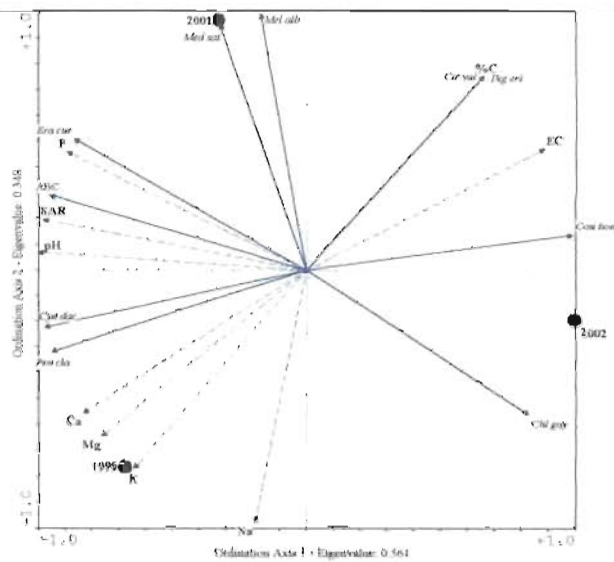


Figure 10b: Eastern Aspect

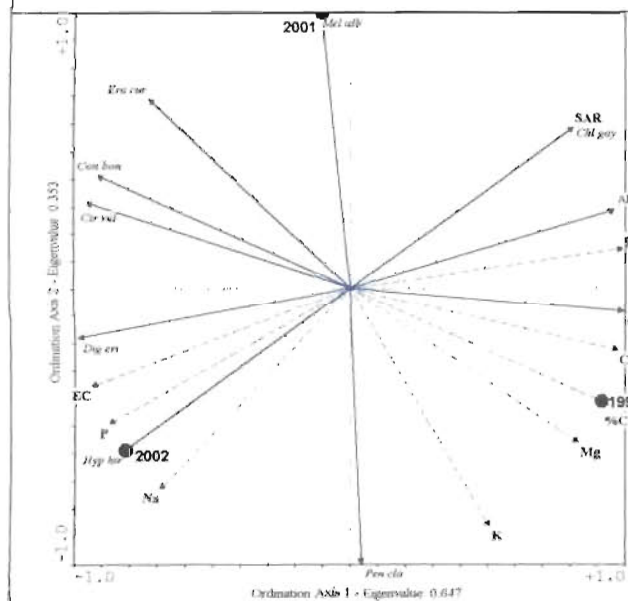


Figure 10c: Southern aspect

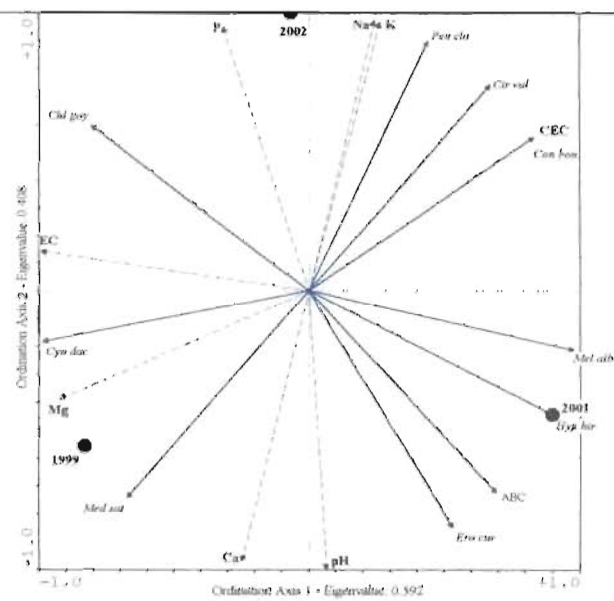


Figure 10d: Western aspect

Figure 10a -d: RDA Ordination biplots for the different aspects.

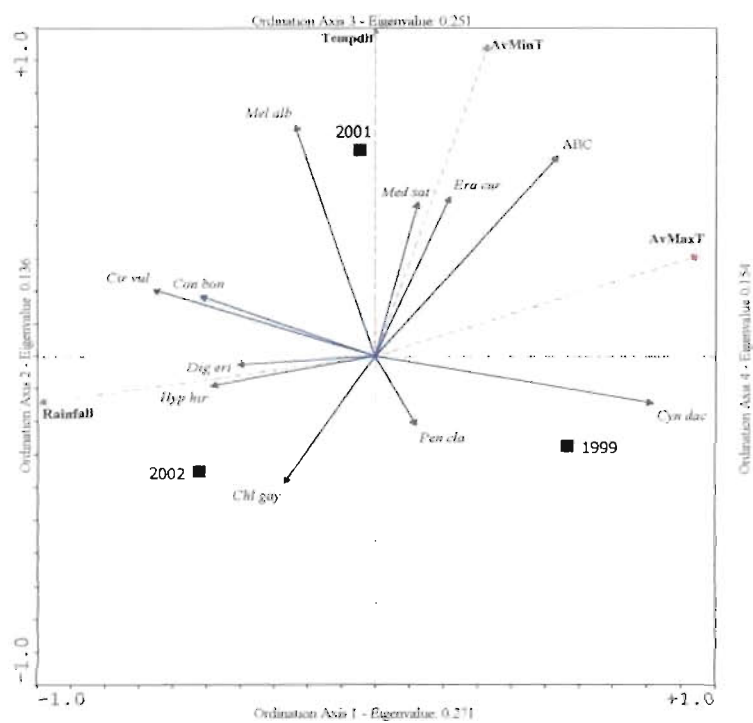


Figure 11: RDA Ordination biplot depicting species affinity in relation with climatological variables on the studied aspects.

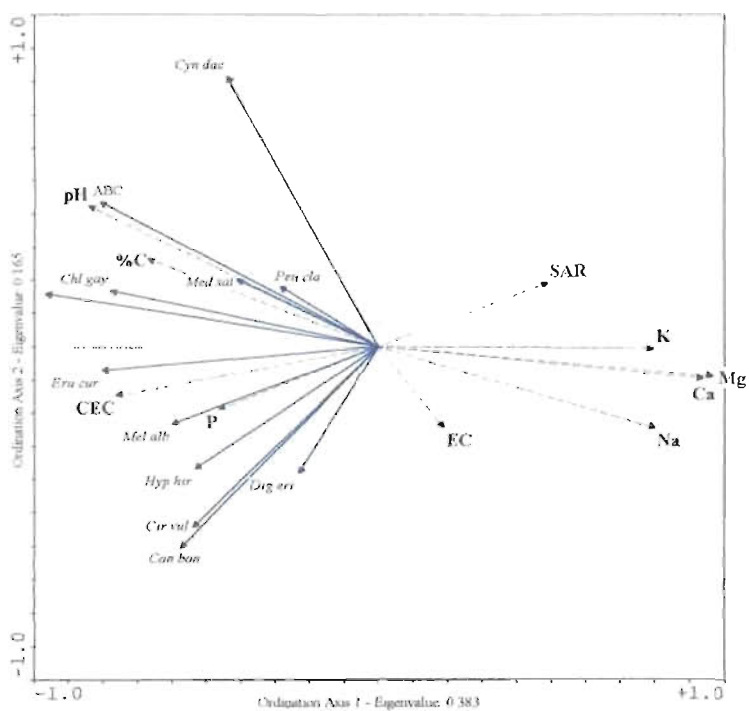


Figure 12: RDA Ordination biplot for soil chemical variables and species resemblance: Neither aspect, nor season were included in this ordination, thus reflecting each species affinity towards chemical association, independent of possible external influences.

Although *C. gayana* is specifically sown on the warmer slopes (Figure 6a), and is also incorporated into the other aspects' seed mixture, it quickly dominated the vegetation composition through its stoloniferous nature. Seemingly this species dominated the vegetation to such a large extent, it does not facilitate ecosystem development, and even more so if its sterile seed (Table 3) is accounted for. It seemed that when the tailings material was constantly leached (to control capillary rise), and if the pH stayed high, *Chloris gayana* persisted. The most persistent species on revegetated gold tailings dams, *E. curvula* (Thatcher, 1979) turned out to be with *Chloris gayana* the most consistent species (Figure 5), tolerating extreme pH, SAR and even low temperatures (Figure 11). This species occurrence also correlated very well with ABC (except for the southern slope), facilitating succession (Figure 10c) as it is positively correlated with r-strategists *Melilotus alba*, *Conyza bonariensis*, *Cirsium vulgare* and the climax species *Hyparrhenia hirta* (Figure 12). The legume species, *Medicago sativa*, correlated as expected very well with pH (Figures 10, 12) and could also be used as an indicator for decreasing pH over time. This species also tolerates low night temperatures (Figure 11), and its relevance is indispensable for its N-fixing characteristics. *Medicago sativa* also correlated with ABC, as a result of the N input. The frequency of the species' presence, however, shows a steep decline (Figure 5) as the recreated profile re-acidified (Figure 3).

The three r-strategist species (opportunistic and weedy pioneer species) correlated well with the season that showed the greatest temperature differences (Figure 11), probably as a result of vegetation dieback from climatological extremes on the tailings dams and opportunities to exploit the low inter-specific competition. These species also correlated well with higher organic matter concentration, and with soil nutrient deterioration. The stoloniferous *Cynodon dactylon*, which occurred mainly on the northern aspect (Figure 6f), associated well with average maximum temperatures (Figure 11), and proved not to be dependant on optimum soil chemical conditions to establish itself, except for the influence of low pH. This species also correlated well with ABC (Figure 10a - d), but its stoloniferous nature is known to inhibit secondary succession. Another pasture species, *Digitaria eriantha*, correlated with more stable soil chemical conditions (Figure 12), and moisture also proved to determine this species occurrence (Figure 11). Although it showed negative affinity for *Chloris gayana*, this species would be ideal for post-landuse purposes, if it could persist.

The ABC correlated extremely well with pH (Figure 12), which is also evident from Figures 3 and 5. With a decrease in pH, a decrease in basal cover could be expected. However, ABC also correlated negatively with rainfall (Figure 11), which could be ascribed to the steep slopes and erosive nature of the gold tailings, leading to the deterioration of vegetation as a result of the incapability of the particles to aggregate. This observation explains why secondary succession does not occur on the tailings dams. Not only might sterile seed, as earlier mentioned, be a limiting factor for succession, but the lack of safe sites for seed

germination and the seed constantly being washed down-slope, are significant inhibiting factors for secondary succession.

Although slow, soil profile development is evident, with a steady contribution of organic matter (%C) by the vegetation over time (Table 1). The CEC was also substantially enhanced through restoration. The cation ratios are, however, not satisfactory yet (Figure 4).

It was also clear that the re-established vegetation is still ecologically highly unstable. Minor fluctuations in either soil chemical or climatological parameters have enormous impacts on species composition (Figures 3,5), which result in an increase in weedy species. According to Jochimsen (2001), revegetated sites go through a phase where reversed succession/development is encountered. This could also be seen as an ecological shock for two reasons: 1) Ecosystem development starts through the introduction of tolerating k-strategists, which are infiltrated by r-strategists, and develops through natural succession to a new ecological state where k-strategists of a new climax state dominate the revegetated area, and 2) The functional traits of the surrounding area do not allow for accelerating colonisation and associated ecosystem development as it is not ecologically equipped to exploit the potential area. It therefore seems that on some level, the surrounding area neither 'recognises', nor 'accepts' the new landtype with its associated characteristics. This phenomenon was also encountered in this study as the data presented in Figure 5 shows a gradual increase in weedy species (*Cirsium vulgare*, *Conyza bonariensis*, *Melilotus alba*), a steep decrease in basal cover and the disappearance of desired species. The climax species for these disturbed areas, *Hyparrhenia hirta*, does, however, invade slowly. It could therefore be postulated that the species dominance shift will occur over time as follows: *Chloris gayana* → r-strategists (weeds) → *Eragrostis curvula* → *Hyparrhenia hirta*, depending on soil chemical and climatological consistency.

CONCLUSION

Sustainable ecosystem development on revegetated gold mine tailings dams relies on secondary succession to self-perpetuate the recreated system. Therefore, the restored system should be empowered to self-regenerate and blend with natural processes of ecosystem evolution. It is, however, necessary to understand the dynamic trends of the soil and vegetation to measure revegetation success of gold tailings dams. The dynamics of the soil chemistry and the reaction of species composition in response to soil changes, as well as the interaction of these parameters with microclimatological exposure, as reflected by vegetation assemblages, were therefore explored in this study.

It was established that both soil profile and vegetation cover development were very slow and the development of the restored systems are still highly unstable.

The vegetation on the tailings dams is dominated by the stoloniferous *Chloris gayana*, which is a fast growing and tolerating grass species, known for its revegetation merits. Serious questions should, however, be asked about the use of this species for future revegetation as it seems through this study that the application of this species might be one of the single most limiting factors for long term gold tailings revegetation success. Not only does *Chloris gayana* fail to persist in the environment, but it had the lowest seedling emergence of all species tested by Harwood *et al.* (1999). It also seemed that this species had no regenerative potential through seed, but could survive through stoloniferous persistence. *Chloris gayana* also correlated negatively with average basal cover, which proved that this species disappears when subjected to inter-specific competition.

The soil chemical characteristics deteriorated to a large extent in the chemically restored tailings material, and it seems that although active nutrient cycling is taking place through the incorporation of organic matter, the growth medium is depleting fast. This overexploitation of the medium could also be ascribed to the use of *Chloris gayana*, as Brown & Grant (2000) proved that the concentration of most micronutrients was highest in the stems of this species, and the roots contained the highest concentrations of most micronutrients in restored tailings material, compared to that of other grass species. It was further established that the dynamics of *Chloris gayana* are driven by moisture, and that a combination of moisture shortages and decreasing pH is responsible for the disappearance of this species.

Species that should rather be used include *Hyparrhenia hirta*, *Eragrostis curvula*, *Digitaria eriantha*, *Medicago sativa* and other indigenous species should further be investigated.

The following significant features of dynamics on gold mine tailings dams were established:

- The vegetation cover is in a state of reversed succession/development.
- The chemical variability of the different aspects determined species composition to a great extent.
- The effects of microclimatological influence were evident, as reflected by the species ordination. Several species associated with different aspects, but the effects were only clearly visible in the last season.
- The fluctuations of *Medicago sativa* could be used as an indicator for pH status, showing a decrease when the pH decreases.
- The ameliorated growth media became depleted to a great extent and a new fertiliser program should be applied to accelerate soil profile development.

This study furthermore brought one question to mind of which the answer could have enormous impact on future revegetation and research: Could the revegetated mine waste be analysed and compared in terms of known ecological principles, or is it a completely new system with its own characteristics for which new principles have to be derived. The dynamics of these revegetated discard systems does shed light on the extent of its sustainability, but the principles of natural systems cannot be used to quantify restoration successes. This does not mean, however, that natural systems cannot be used as reference or to determine its state of ecological stability, but gold tailings restoration needs to be evaluated in terms of its own inert and similar comparative successes.

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CHAPTER 6

THE SELECTION OF FUNCTIONAL AND STABILITY INDICATORS TO QUANTIFY THE CONTRIBUTION OF GOLD TAILINGS REVEGETATION TO RESTORED LANDSCAPE SUCCESS

CHAPTER OVERVIEW

South Africa has the second most gold tailings dams in the world resulting in a mosaic of fragmented natural grassland, with grouped gaps of ecologically sterile patches. It is of utmost importance to return these areas to full productivity in the interest of biological systems that co-developed and are dependent on the interactive and mutual ecological support of these missing areas. Some of these wastelands' ecological capacities are restored through ecological restoration, but the degree to which these revegetated gold tailings contribute to the return of ecological function, measured in terms of the surrounding environment, is still largely unknown. Until recently, little attention was given to the quantification of terrestrial restoration projects' success. Therefore, measurement of the adequacy of restoration of gold tailings dams, and more specific, to what degree the various functions and values of habitats have been recreated and returned, are addressed in this study. Developing indicators of chosen habitat functions, and creating statistical representations of natural, local reference sites for comparison to the functional development of the restored habitat are used to evaluate ecological restoration success. It was clear that the ecological function of the investigated revegetated gold tailings dam was reinstated to some extent, but the biological acceptance of this area to the surrounding environment is questionable, based on the dissimilarity of species reflection, basal cover and grass species diversity. Multivariate analysis results also supported dissimilarity of the sites, but indicated that the investigated site was in a better ecological condition than the pre-evaluated conventional ameliorated sites. Using a statistical approach, two vegetation characteristics and five grass species were identified as indicators of functional return, while seven species were selected as ecological stability indicators. Based on the Success Criteria and the Success Ratio described in the literature, a Functional Success Index is proposed accordingly, based on the similarity of each species on the revegetated area and the reference sites. It is, however, clear that the revegetated area does not fulfil its functional role yet, and that the identified stability indicators are scarce. Either a new holistic physical-chemical ameliorative approach, or the use of native seed mixtures, ideally a combination of both, could initiate ecological function return and achieve ecological stability with ultimately landscape success. Relying on successional sequence to restore landscape success leaves a lot for uncertainty to decide, and restoration success cannot be guaranteed.

THE SELECTION OF FUNCTIONAL AND STABILITY INDICATORS TO QUANTIFY THE CONTRIBUTION OF GOLD TAILINGS REVEGETATION TO RESTORED LANDSCAPE SUCCESS

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ABSTRACT

The degree to which ecological restoration contributes to mitigate the effects of functional disruption of ecosystems by the vast surfaces of revegetated gold tailings dams is evaluated in this study. The challenge to quantify ecological reintegration and to determine the functional efficiency of the revegetated systems is delayed by the fact that no ecological criteria exist to determine restoration success. The objectives of this study were to evaluate the return of functional equivalency on revegetated gold tailings dams, using norms derived from the surrounding environment, and to identify floristic indicators for restoration success. Furthermore, the study attempted to initiate thoughts on possible ways to establish ecological criteria, to measure restoration success objectively. Vegetation assessments were conducted on 9 conventionally revegetated tailings dams, on 1 optimally rectified and diverse dam, and in the veld surrounding this dam. Data were statistically analysed following an approach presented in the literature, and the three vegetation assemblages were multivariately compared. The ecological status of the revegetated tailings dams did resemble that of the surrounding reference areas, except for the main differentiating factor, which is the domination of monocultures on the tailings dams. The statistical comparison of the diverse tailings dam and the surrounding veld revealed 5 functional indicators, of which basal cover and species diversity were prominent, and 7 stability indicators, which mainly included climax species of the surrounding area. There was still high similarity between the optimally revegetated tailings dam and the conventionally revegetated ones, but the dam with the higher diversity showed affinity towards the reference sites. Through the results presented by the proposed Functional Success Index it was clear that the low species diversity were the main factor paralysing ecosystem function. Although the effects of landtype and media characteristics were not included, the results presented clear indications of functional return, based on the vegetation resemblance.

Keywords:

Functional success; Restoration; Gold tailings dams; Ecological indicators.

INTRODUCTION

The South African Highveld is pervaded with mining discard material, which result in the fragmentation and pollution of vast surfaces of the poorly conserved Grassland vegetation type (Acocks, 1988; Low & Rebelo, 1998). The original vegetation is inevitably destroyed by mining activities, and previously healthy soils are buried by tailings wastes (Bradshaw, 1997). Gold mine tailings dams account for more than 400 km² of desolate, unproductive land in the Witwatersrand mining area alone (Winde, 2001) and this ecologically inactive islands need to be rehabilitated, enabling it to co-function sustainably and replenish surrounding ecological systems. To return the sterile surfaces of tailings dams to full productivity, and ultimately to a self-sustaining state will however take time, but the ecological function of the land covered by the tailings dams should at least be restored to some extent, to support critical ecological interactive functions and to supply necessary migration corridors for the maintenance of ecological stability.

The objectives of restoration with regards to biological optimisation therefore include the improvement of the existing growth medium to be suitable for vegetation establishment and community persistence, to engender species diversity and to create favourable microclimate and habitat conditions for voluntary ecosystem establishment (Anon, 2001). Restoration projects, however, often fail to provide the minimum ecological capacity necessary for the site to function properly, resulting from incomplete knowledge (Thom, 1997) and inadequate understanding of the ecosystem being manipulated (Westman, 1991), often leading to poorly planned and non-functional replaced ecosystems (Pastorok *et al.*, 1997). According to Bellairs & Davidson (1999) there is a hierarchy of functional processes that needs to be achieved for spontaneous vegetation establishment and native species succession. Reasonable landform stability, coupled with soil profiles that are in equilibrium with prevailing hydrological and climatological conditions (Olyphant & Harper, 1995), are required for the retention of nutrients, moisture and propagules. Nutrient cycling must be initiated for vegetation establishment to be sustained and the effects of toxic materials should further be mitigated and managed to tolerable levels to maintain future plant growth. The interactions between micro and macro flora and fauna species should further be encouraged through restoration as it is an indispensable part of ecosystem function which is often overlooked (Bellairs & Davidson, 1999). Ultimately, the healthy reinstated ecosystem is characterised by the integrity of nutrient cycles and energy flows, stability, and resilience to environmental or anthropogenic stresses (Van Bruggen & Semenov, 2000).

To be qualified as sustainable, all components of the ecosystem have to be re-established or developed at the site, recruitment needs to occur and the biological community needs to develop resilience to future disturbance, similar to responses of unmined communities.

There is little or no information about the long-term development and sustainability of native ecosystems established on revegetated gold tailings sites (Bellairs & Davidson, 1999; Wali, 1999), and therefore sustainability criteria have not been investigated. Determining whether the goal of re-establishing a self-sustaining vegetation cover has been met is difficult, and accepted criteria for doing so have not been established (Ward, 2000). Therefore, when the aim of restoration is to recreate the pre-disturbance ecosystem, one way in which restoration success can be assessed is to compare the values of a set of parameters or indicators of interest on the restored area with the range of natural variability of these parameters in the pre-disturbance ecosystem (Hobbs & Norton, 1996).

MEASURING RESTORATION SUCCESS

An important challenge confronting us as scientists is how to determine, given the constraints of time and the limits of our knowledge, the ecological value of restoration projects. Determining the success of multiple habitat restoration requires the establishment of criteria that can be used to judge ecosystem development as these habitats replace important functions and values over time (Short *et al.*, 2000). Ongoing research is continually providing information on what has or has not been accomplished through restoration, providing valuable insights on how to correct mistakes, and new approaches for defining success. Ultimately, while many older projects have had limited success in terms of replacing or repairing ecological functions, they have provided an important base of information that can be used to assure that future restoration projects make a positive contribution to new challenging remediative efforts (Kentula, 2000).

Although quantitative information on restoration projects has been rapidly increasing over the past decade, knowledge of restoration and the ability to use information to restore mined lands vary with and are influenced by, the type of tailings/discard, the region of the country, the ecological functions of interest, the type and degree of degradation, the surrounding land uses, and the ability to establish and maintain geotechnical equilibrium of the landform. The unique characteristics of each tailings site make it impossible to use generic references and standards to establish restoration success. Furthermore, baseline studies for the impacted environment were more often than not neglected and the variability of the characteristics of these parameters led to a lack of comparative ecological standards. The remediative outcomes are therefore often based on post-landuse expectations, and not necessarily on ecologically sound goals.

A hierarchical approach to setting performance standards for habitat restoration, which recognises various aspects of the ability of a habitat to support certain target indicator species, should be implemented to evaluate restoration success.

Many different variables have been used as indicators in the past, with measurements of vegetation being the most common, (Mitsch & Wilson, 1996) followed by analysis of soils, fauna and hydrological characteristics. Ecologically there is a need to go beyond the traditional documentation of site attributes such as vegetation cover, and system function must be addressed. Quantitative characterisation of restoration in the context of the properties and variability of the naturally occurring systems in the area is therefore necessary. Characterising surrounding areas, from highly degraded to highly functioning, and from early successional to mature, could serve as baseline for the comparison of the state of the revegetated area. These reference standards could define restoration goals and support post-restoration monitoring and management. There is debate in the literature about the use of reference ecosystems to which restoration projects should be compared (Ward, 2000). Pickett & Parker (1994) considers this comparative approach ambitious and opportunistic, as natural systems are dynamic, rather than static and predictable, and therefore contend that it is futile to try to recreate an ecosystem as it was previous to mining conditions. However, Aronson *et al.* (1995) defined an ecosystem of reference as 'some standard of comparison and evaluation, even if the choice is somewhat arbitrary' and therefore has merit to act as reference. If relevant and scientifically sound success criteria could be derived from the state of surrounding reference sites, it could indeed be applied to monitor restoration success. Success criteria for habitat restoration have historically focused on the occurrence and abundance of species, rather than whether the status of the target species has been sustained or improved for the long term (Kentula, 2000). Such an approach assumes a particular, stable habitat endpoint, when in fact, restored habitats develop and readjust due to both biotic and abiotic processes operating at various scales over time. It is therefore necessary to either monitor the dynamics of ecological attributes over time, or to make use of functional indicators, which are statistically derived from the surrounding environment.

By comparing the populations of naturally occurring, unaffected areas and discard areas within an area, the entire range of conditions and factors important to the function of the local terrestrial ecosystem can be characterised (Bellairs & Davidson, 1999; Kentula, 2000; Short *et al.*, 2000). A standard for comparison is a prerequisite for setting goals and determining the success of restoration projects and initial ecological function minima, which are quantified as indicators, should therefore act as guideline. The current proposed requirement that has to be met is the revegetation of mining discard with 60 per cent (no less than 30 per cent initially) of the original indigenous plant species (De Villiers *et al.*, 1999). Therefore, pre-mining vegetation surveys are necessary to compile a databank on the phytosociology of an area earmarked for deposition (Jochimsen, 1996; De Villiers *et al.*, 1999). These data can then be used for suitable species selection prior to revegetation, and to select functional indicators to monitor afterwards.

The use of these native species is the only criteria that will lead to the establishment of plant communities that are more persistent, require less management inputs, allow for more comparable management strategies and superior landuse options, in line with characteristics of surrounding native communities (Redente & Keammerer, 1999).

Although particular characteristics of projects, such as vegetative cover and production, can resemble those of similar naturally occurring ecosystems, overall functional equivalency has not been demonstrated on restored mine tailings (NRC, 1992). The ultimate test is an evaluation of ecosystem resiliency, which is the system's ability to recover and persist after perturbation and to function successfully under landscape conditions. Functional success therefore needs to be monitored and therefore, relevant ecological success criteria should be developed.

Functional success is determined by evaluating whether the ecological functions of a system have been restored (West *et al.*, 2000) while landscape success is a measure of how restoration (or management in general) has contributed to the ecological integrity of the region or landscape, and the achievement of goals such as the maintenance of biodiversity (NRC, 1992). At landscape level, objectives such as performance curves or the combination of resemblance functions (used to quantify static similarity with a reference site) and resilience indices (used to quantify temporal aspects of recovery) are used to assess the degree of replaced ecological function (Thom, 1997). The successional development through state and transition of an ecosystem to a climax condition, resulting in natural evolutionary response and persistence to environmental stress, will be the optimal point of ecosystem stability gained through the reinstatement of ultimate landscape success. The degree of interactive ecological function reinstatement could thus be measured by a comparative analysis of the dynamics associated with an increase in microbiological diversity, coupled with returned soil function and vegetation structure and diversity that persists over time on the restored discard (Jochimsen, 1996), evaluated on the basis of criteria of the surrounding undisturbed area.

In this study the contribution of revegetation to the return of ecological function of the restored surfaces of gold tailings dams is evaluated, as vegetation is a practical and relative easily measurable parameter reflecting the current ecological state of the ecosystem success. The vegetation structure and diversity established on mining discard reflect the degree of returned ecological function as a measurable index. The use of a statistical norm to objectively evaluate the merits of functional indicator species is also applied.

ECOLOGICAL INDICATORS

Ecosystems consist of a mosaic of habitats that varies in space and time. An understanding of ecosystem structure and function at these various scales is essential to the approach of restoration projects (Wali, 1999). Ecological concepts that should be applied for the selection of ecological success criteria include 1) a landscape perspective of habitats at the site, 2) an understanding of species-substrate interactions, and 3) an assessment of both natural and anthropogenic disturbance processes, frequencies and magnitudes (Pastorok *et al.*, 1997). In addition to these physical habitat factors, the presence of certain organisms and their functional role will drive the outcomes of restoration. Restoration objectives include the enhancement of site or habitat characteristics by restoring abiotic functions, target species and biological communities (Short *et al.*, 2000). Therefore, characteristics for the identification of possible ecological indicators include the following:

- Indicators should be physical, chemical or biological elements of ecosystem structure or function.
- Indicators should be sensitive to various levels of stress, but not overestimate impacts resulting from natural variation (Pastorok *et al.*, 1997).
- Indicators should be clearly connected to environmental values and responsive to individual or cumulative effects of stressors.
- Indicators should require limited sampling effort, be cost effective and preferably have occurred in other successful monitoring projects.
- The monitoring process should be not too complex and obvious indicators should be applied, as scientists are not always assisting in the evaluation of restoration.
- Objectives of the identification of indicators should be as specific as possible, recognising natural variability (Pastorok *et al.*, 1997).

The most obvious quantitative objectives measuring restoration success at site level, relate to achieving desired levels of species abundance, vegetation cover, biomass and species richness (Thom, 1997). Indicator species are therefore selected from these data, which are easily obtainable through low cost surveys. Criteria for the selection of ecological indicators are presented in Table 1.

Indicator species in this study define the current state or condition of the site in regional context using reference sites for comparison, and does not reflect decisive conclusions about the stability of the restored ecosystem. The target species for restoration include foundation or keystone species, which provide the key structural component of habitat for a variety of other species. Stability indicators are identified to quantify ecological stability. These species usually appear when pristine conditions persist and either fade or emerge as ecosystem pressure increase or decrease. If these indicators are found on a restoration site, it could be argued that the restored system is moving towards more ecological stable conditions.

Table 1: Components of a conceptual ecosystem, guiding the selection of indicator species for the evaluation of restored ecological function in disturbed terrestrial systems.

Functions	Conceptual ecosystem function indicators	Values
Ecosystem structure	Foundation and keystone species, successional sequences and soil function.	Ecosystem stability, habitat and refuge, acceptance of the surrounding environment.
Primary production	Biomass, species richness, key resource species and food web structure.	Support of food web, reinstatement of species migration and natural species distribution.
Nutrient sink	Key abiotic processes, nutrient regeneration and recycling, soil physical, chemical and biological characteristics.	Support of primary production, optimisation of vegetation quality and microbiological activity.
Organic matter accumulation	Soil microbial organisms, soil physical, chemical and biological characteristics.	Support food web in the soil. Soil microbial diversity, soil quality and stability improved. Chain of ecological interactivity optimised.
Microhabitat	Biodiversity, distribution patterns, key biotic and abiotic processes.	Disturbed area blends in ecologically, diversity optimised, micro-associations restored. Response to geomorphology optimised, climatological interactions restored (Wind dispersal, oxygen supply etc.).
Seed production	Succession, vegetation dynamics, primary production.	Habitat and support of wildlife.
Self-sustaining ecosystem	Landscape influences that support or inhibit restoration. Spatial and temporal homogeneity/heterogeneity.	Recreation, education and landscape level biodiversity. Sustainable nutrient supply reinstated.

STUDY AREA

The vegetation of both a restored gold tailings dam and selected surrounding reference areas were assessed. The study area is located on the western part of the South African Highveld, more accurately on the Bc land type of the North West Province (Figure 1a). The Hartebeesfontein No. 7 gold tailings dam (26°42' E, 26°54' S) is located $\pm$ 6 km to the southwest of Klerksdorp in the highly active Stilfontein gold mining zone (Figure 1b). Ecologically, the area is situated in the Grassland biome (Low & Rebelo, 1998) and more specifically in the Dry *Cymbopogon-Themedra* grassland (A48) with characteristics of intrusions of the Bankenveld (A61) (Acocks, 1988). The habitat is classified as Low altitude sour grassland and is characterised by 155 syntaxa of plant species, of which 41 are commonly found grass species of the Highveld (Bezuidenhout & Bredenkamp, 1991). The vegetation of the Bc land type and thus the reference areas, are in a state of degradation resulting from erratic rainfall and continual grazing pressure (Bezuidenhout & Bredenkamp, 1991), as well as indirect effects of the ever-increasing infrastructure of mining activities in the study area.

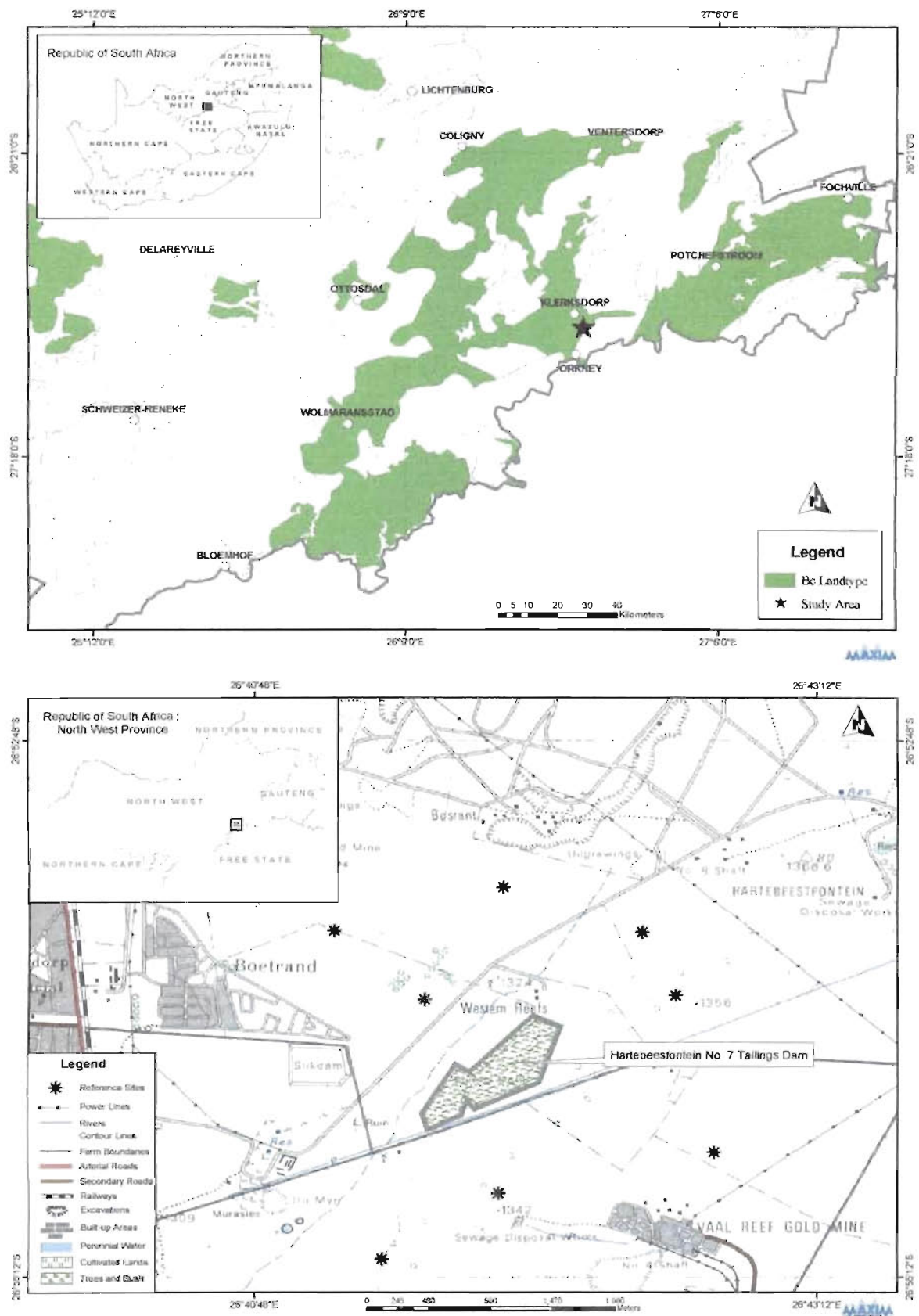


Figure 1: (a) Bc Landtype of the South African Highveld characterising the study area and (b) location of the study site and the reference areas.

The landscape varies from flat to undulating plains, with an altitude of 1370 m above sea level, sometimes dissected by prominent quartzite ridges. The Ventersdorp and Transvaal supergroups mainly represent the geology of the area. The soils are derived from quartzite and shales and sometimes from Ventersdorp lavas, resulting in either red structureless or a catena of ferrallitic soils. The Koekemoerspruit and its tributaries drain the area to the east and the Schoonspruit and its tributaries to the west, both draining towards the Vaal River. The area is situated in the summer rainfall zone where rain mainly occurs as thunderstorms and mean rainfall varies around 600 mm per year. Summer temperatures are high, with an average of 26°C and the mean maximum monthly temperatures exceeding 32°C during October to January. The winter temperatures are low with an average of 15°C, and mean monthly minimum temperatures are below –1°C during the months June to August.

Study site

The Hartebeesfontein No. 7 tailings dam was decommissioned during the 1980's and no restoration took place until 1998 (Anon, 2001). The site was rehabilitated in the dry season of 1998, and after assessing initial vegetation establishment, follow-on revegetation was carried out early in 1999. The restoration occurred with the objective to assess the performance of vegetation on gold tailings subjected to Dryland conditions. For the restoration, landscaping was conducted (slopes not steeper than 25% and, slope lengths not exceeding 15 m), dozing the slopes down, reallocating fugitive tailings, and infilling erosion gullies. The surface of the dam was then paddocked with primary paddock walls (1.2 m high) dressed in rock to provide additional resistance against water and wind erosion. Water is retained on the dam surface and run-off water is contained in the toe paddocks.

The tailings material was ameliorated to address the total acid forming potential of the tailings and the nutrient deficiencies. In addition to liming and fertilisation, other ameliorants in the form of composted material and sewage sludge have been worked into the surface tailings layer to improve both the physical and the chemical status of the medium. The side slopes were marginally dressed with topsoil recovered during cleanup of the toe paddocks, areas of fugitive tailings and the footprints created during past re-working of a portion of the dam. The tailings on the side slopes were also ameliorated prior to soil placement to ensure that deep-rooted plant species would penetrate a favourable growth medium.

Seeding of the ± 8.4 hectares of resculptured tailings dam involved the introduction of 13 grass species comprising of conventionally used pasture species, and 4 tree species. The grass species in the seed mixture included: *Antephora pubescens* Nees. (Wool Grass), *Cenchrus ciliaris* (L.) (Blue Baffalo Grass), *Chloris gayana* Kunth. (Rhodes Grass), *Cynodon dactylon* (L.) Pers. var *dactylon* (Couch/Bermuda Grass), *Digitaria eriantha* Steud. (Common Finger Grass), *Eragrostis curvula* (Schrad.) Nees. (Weeping Love Grass), *Eragrostis tef*

(Zuccagni) Trotter (Annual teff), *Heteropogon contortus* (L.) Roem. & Schult. (Spear Grass), *Hyparrhenia hirta* (L.) Stapf. (Common Thatch Grass), *Melinis repens* (Willd.) Hubb. (Natal Red Top), *Panicum maximum* (Jacq.) (Guinea grass), *Setaria nigrirostris* (Nees.) Dur & Schinz. (Black Seed Bristle Grass), and *Themeda triandra* Forssk. (Red Grass). A number of grass species also originated from seed that was included in the composted material. Several tree species were planted and included: *Acacia hereroensis*, *Olea europea* subsp. *Europea*, *Rhus lancea* and *Tamarix gallica*.

The Hartebeesfontein No. 7 tailings dam is renowned as the flagship for dryland revegetation of gold tailings dams (Anon, 2001). Therefore this specific tailings dam was selected to evaluate the return of ecological function.

METHODS

The vegetation on the dams is mainly characterised by grass and forb species known to tolerate the conditions posed by the growth medium, and also a few planted tree species survived on the tailings material. The parameters assessed for this study include grass species frequency, average basal cover of the grass species, and grass species diversity.

- A preliminary study of the vegetation on 9 gold tailings dams was carried out first to determine if there were substantial differences in ecological status between vegetation on the revegetated gold tailings dams compared to the vegetation of the surrounding environment. The step point method (described in the next method) was used to quantify the species frequencies. Due to the low variation in the comparative vegetation resemblance on the tailings dams, it was possible to use the mean of the tailings' species occurrences and compare it to the mean species occurrence value of the reference sites of the surrounding veld. Only the grass species were assessed. The grasses were grouped in 4 categories namely Increaser 1, 2 and 3, and Decreaser species (Van Oudtshoorn, 1998).
- Proportional pasture species composition was established by observing 1000 points (10 different transects of 100 points each) on each of the tailings dams, using the step-point method (Tidmarsh & Havenga, 1955; Kent & Coker, 1994; Mentis, 1999). Within each transect, a 10 mm rod with a sharpened end was dropped after every step taken. Plant basal cover was determined by scoring when the point of the dropped rod intersected rooted and living grass forage. The descending point was then scored as a hit and the species recorded. When the point failed to strike plant material, or the plant material struck was not rooted or living, the descending point was scored as a miss and the nearest rooted grass species within the radius of 300 mm was recorded. The total number of hits in 100 descending points provides a measure of basal cover for the specific transect. The relative abundance of plant species was determined by the frequency of each species recorded for the 100 points scored within a single transect, expressed as a percentage.

The same method was used to assess the vegetation in the surrounding area, assessing 250 points per reference site (8 reference sites).

The surrounding vegetation analysis was constantly surveyed at a distance further than 400 m from the tailings dams to eliminate the direct boundary effect of the tailings dam.

As the dam was characterised by an undulating landform, no distinction was made between species frequency on the different slopes and on the top of the tailings dam.

- A phytosociological study conducted by Bezuidenhout & Bredenkamp (1991) was also used as supporting baseline data for plant species native to the Bc land type of the *Cymbopogon – Themeda* vegetation type, which is dominant in the area.
- A statistical representation or model of reference sites was used as standard for comparison (after Short *et al.* (2000)). A quantitative characterisation of the restoration, in the context of the properties and the variability of the naturally occurring systems in the area, was developed (Kentula, 2000). Candidate indicators are chosen as measurable representatives of functions and values, and are used to quantitatively judge restoration success. Choosing a range of diverse indicators is important to insure that the various functions of the habitat are well represented and to assure that success is not being judged on similar measures of the same ecological functions. The selected indicators 1) have the lowest Coefficient of Variation (C.V.) (the target is C.V.< 0.2 – the lower the C.V., the higher the rank), 2) are cost effective for implementation and 3) are representative and important measures of ecosystem function. The C.V. is used to identify the number of samples required and the variation within the samples should be less than 20% of the mean, which is a somewhat arbitrary value that is difficult to surpass with regularity in biological field sampling. For this study, variation of the first 30% defined the functional indicators and the last 30% (highest variation) identified the stability indicators.

To meet the definition of success, the success criteria (SC) is calculated based on the mean and standard deviation (S.D.) for all reference sites combined; thus, the threshold for each SC is within the distribution of data for each indicator from the reference locations but above the lowest 16,7% of those values (i.e. 1 S.D.) The success criteria is determined by the following equation (Short *et al.*, 2000):

$$SC = 100 \times \frac{\text{Mean of all reference sites} - 1 \text{ S.D.}}{\text{Mean of all reference sites}} \quad (1)$$

The S.D. measure is the statistical standard of variability that is independent of sample size yet directly related to the C.V. and was therefore chosen to define the SC.

The success ratio (SR) is the measure of how successful each restoration site is compared with the selected reference site for the functional characteristics being judged. The SR is calculated using the following equation (Short *et al.*, 2000):

$$SR = 100 \times \frac{\text{Mean of indicator on restoration site}}{\text{Mean of indicator on reference site(s)}} \quad (2)$$

The SR demonstrates the level of achievement of an indicator of habitat function along a gradient of success that is mathematically derived from the reference sites. Through the comparison of the SR for each restoration site to a set of SC from local and representative reference sites, scientific evaluation of restored habitat success can occur.

When the SR (for a given indicator) equals or exceeds the SC, this aspect of the restoration is deemed a success, even though a given indicator at a restoration site may overshoot the SC and the mean for the reference sites. Overshooting may indicate that the system is out of balance due to unequal development of functional connections with the ecosystem or due to some stress associated with the restoration site. Over time, as the restored habitat develops, subsequent application of the SC will indicate if reference conditions are achieved. Extreme overshooting of an indicator is usually associated with data having large variance and would be excluded as qualifying indicators.

The method of Short *et al.* (2000) is adapted in this study, adding a Functional Success Index (FSI). This index describes the similarity between the restored indicator and the indicator in the reference site. The FSI is determined by the following equation:

$$FSI = \frac{SR}{SC} \quad (3)$$

Increasing similarity will approach 1, with a value of 0.60 being acceptable (De Villiers *et al.*, 1999), and a state of dissimilarity will approach 0. The state of functional indicators, and the similarity of indicators between sites could easily be evaluated using this technique.

The strength of this approach is that it is built around standard tools of statistical analysis. This method however represents an *ad hoc* assessment of the return of ecological function and only gives an indication to what extent the habitat is restored, up until the date of the surveys. The method implies a statistical norm to determine baseline variables and only constant monitoring and reapplication of this method will enable one to evaluate restoration performance and integrated ecosystem dynamics between reference areas and ecologically restored sites over time.

- The multivariate ordination analysis computer program, CANOCO (Ter Braak, 1988 – Kent & Coker, 1994) (Ver.4) was applied to the site data. As a result of the relative high variation in grass species frequency data, Detrended Correspondence Analysis (DCA), (after Hill, 1979) was applied. This ordination technique will place each variable in spatial context according to its determined weight, in relation to one another, to derive the site and species positions, and to point out ecological gradients and affinities between the variables.

RESULTS AND DISCUSSION

From the preliminary study it was evident that the ecological status reflected by the grass species on the gold tailings dams did resemble that of the reference areas (Figure 2a & 2b). The one primary difference noted was the domination of the vegetation by several groups of monocultures.

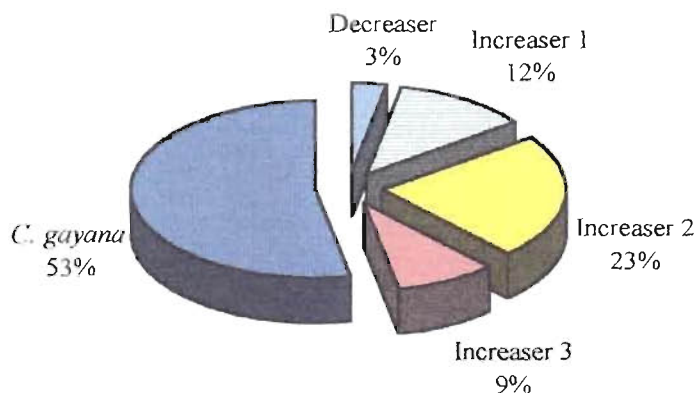


Figure 2a

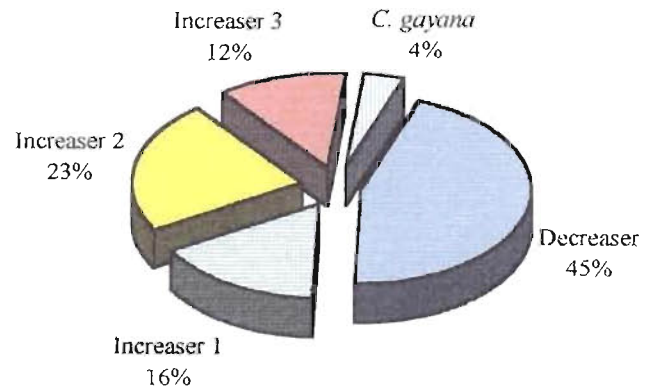


Figure 2b

Figure 2: Ecological status ratio of grass species occurring on gold mine tailings dams (a) and reference sites (b). (*C. gayana* regarded as a Decreaser species.)

The ecological stability offered by these monocultures is limited and the low species diversity also raises questions about the functional role and stability of the biological systems on these dams. It was therefore necessary to determine individual species functional resemblance. The statistical approach described was used to determine whether the diversity factor, the basal cover factor or individual grass species could be regarded as target or keystone indicators of returned ecological function, and which of these indicators could serve as ecological stability references. The results of the statistical analysis are presented in Table 2. Species established on the dam as standard practice, and species that exclusively occur on the tailings dam, were not included in the search for indicators. Species associated with wetland conditions and pioneer species were also excluded in the selection process. Short *et al.* (2000) proposed that species with a coefficient of variance lower (C.V.) than 0.2 should be used as indicators for returned ecological function, that would account for only 10,8% (0.2/1.84) of the variance. Due to the variable nature of grass species frequency data, resulting from site variability in terms of microclimatic influence, soil differences and different land-use practices a C.V. allowing for merits of the site should be applied.

Table 2: Statistical results determining functional indicators and the return of functional success on the evaluated dam.

Functional Indicators	Abr.	Reference Mean	S.D.	C.V.	Dam Mean	SC	SR	FSI
Average Basal Cover	ABC	8.74	2.41	0.03	4.20	72.42	48.07	0.66
Grass Species Diversity	Diversity	38.00	3.00	0.08	14.00	92.11	36.84	0.40
Species of functional return								
<i>Digitaria eriantha</i> **	<i>D. eri</i>	6.24	1.57	0.25	7.68	74.81	n.a.	n.a.
<i>Cynodon dactylon</i> **	<i>C. dac</i>	4.26	1.35	0.32	15.14	68.43	n.a.	n.a.
1. <i>Eragrostis plana</i>	<i>E. pla</i>	4.61	1.74	0.38	0.14	62.17	2.98	0.05
<i>Eragrostis curvula</i> **	<i>E. cur</i>	11.15	4.75	0.43	30.90	57.41	n.a.	n.a.
2. <i>Themeda triandra</i>	<i>T. tri</i>	15.06	7.31	0.49	1.60	51.45	10.62	0.21
3. <i>Panicum maximum</i>	<i>P. max</i>	3.69	1.80	0.49	1.40	51.22	37.97	0.74
4. <i>Eragrostis lehmanniana</i>	<i>E. leh</i>	2.99	1.60	0.54	0.24	46.34	7.95	0.17
5. <i>Cymbopogon plurinodes</i>	<i>C. plu</i>	11.83	6.47	0.55	0.24	45.33	2.01	0.04
Functional diversity species								
<i>Aristida congesta</i> *	<i>A. con</i>	3.03	1.89	0.63	0.88	37.66	28.93	n.a.
<i>Heteropogon contortus</i>	<i>H. con</i>	1.61	1.03	0.64	0.28	36.03	17.05	0.47
<i>Hyparrhenia hirta</i>	<i>H. hir</i>	3.11	2.13	0.68	1.18	31.68	37.75	1.19
<i>Setaria sphacelata</i>	<i>S. sph</i>	10.59	7.92	0.75	0.61	25.18	5.79	0.23
<i>Cymbopogon excavatus</i>	<i>C. exc</i>	1.06	0.80	0.75	0.00	25.05	0.00	0.00
<i>Chloris gayana</i> **	<i>C. gay</i>	2.93	2.37	0.81	28.55	19.14	n.a.	n.a.
<i>Eragrostis gummiiflua</i>	<i>E. gum</i>	1.91	1.72	0.90	0.16	9.85	8.50	0.86
<i>Elionurus muticus</i>	<i>E. mut</i>	3.15	2.92	0.93	0.14	7.26	4.37	0.60
<i>Aristida diffusa</i>	<i>A. dif</i>	1.75	1.74	0.99	1.54	0.75	n.a.	n.a.
<i>Antephora pubescens</i>	<i>A. pub</i>	0.44	0.44	1.01	0.44	-1.44	n.a.	n.a.
<i>Triraphis andropogonoides</i>	<i>T. and</i>	0.70	0.73	1.04	0.00	-3.58	0.00	0.00
<i>Eleusine coracana</i> *	<i>E. cor</i>	0.86	1.00	1.15	0.14	-15.43	n.a.	n.a.
Stability Indicators								
1. <i>Eustachys paspaloides</i>	<i>E. pas</i>	0.56	0.68	1.28	0.00	-21.67	0.00	0.00
2. <i>Urochloa mosambicensis</i>	<i>U. mos</i>	0.85	1.10	1.29	0.21	-29.18	25.00	0.00
<i>Cenchrus ciliaris</i> **	<i>C. cil</i>	0.75	0.98	1.31	1.01	-31.03	n.a.	n.a.
3. <i>Brachiaria serrata</i>	<i>B. ser</i>	0.81	1.08	1.33	0.00	-32.79	0.00	0.00
4. <i>Trachypogon spicatus</i>	<i>T. spi</i>	0.71	1.00	1.40	0.00	-40.24	0.00	0.00
<i>Paspalum dilatatum</i> ***	<i>P. dil</i>	1.16	1.71	1.47	1.61	-47.06	138.71	0.00
5. <i>Andropogon eucomis</i>	<i>A. euc</i>	0.29	0.45	1.57	0.31	-57.14	108.70	0.00
6 <i>Setaria nigrirostris</i>	<i>S. nig</i>	1.30	2.09	1.61	0.76	-60.83	58.65	0.00
<i>Urochloa panicoides</i> *	<i>U. pan</i>	0.78	1.29	1.66	0.46	-65.92	n.a.	n.a.
<i>Melinis repens</i> *	<i>M. rep</i>	0.49	0.81	1.67	0.25	-66.80	n.a.	n.a.
7. <i>Diheteropogon amplexans</i>	<i>D. amp</i>	0.59	1.08	1.84	0.00	-84.32	0.00	0.00
<i>Eragrostis tef</i> *	<i>E. tef</i>	0.16	0.33	2.03	0.64	-1.03	n.a.	n.a.
<i>Ischaemum fasciculatum</i> ***	<i>I. Fas</i>	0.29	0.70	2.43	1.54	0.00	n.a.	n.a.
<i>Polypogon monspeliensis</i> **	<i>P. mon</i>	0.00	0.00	0.00	0.85	0.00	n.a.	n.a.
<i>Cortaderia jubata</i> **	<i>C. jub</i>	0.00	0.00	0.00	1.00	0.00	n.a.	n.a.

* - Pioneer species

** - Grass species sown as standard practice on gold tailings dams

*** - Species associated with wetland conditions

n.a. – not applicable

De Villiers *et al.* (1999) proposed that the return of 30% of the species would be sufficient to maintain ecological function, and therefore, a C.V. value of lower than 0.552 (30% x 1.84) (accounting for 30% of the C.V. values) was regarded as a sufficient indicator of returned functional success. Species that had a C.V. lower than this particular value also characterised the surrounding reference sites and therefore this value seemed appropriate. C.V. values for indicators greater than 1.288 (accounting for the last 30% of the C.V.) were regarded as ecological stability indicators. The remaining intermediate 40% of the C.V. represented the functional diversity between the reference sites and the tailings dams.

From the results presented in Table 2, Basal cover was the best indicator to measure the return of ecological function and is an accurate indicator for restored success (C.V. = 0.03). This parameter is shown to be one of 3 indicators that is satisfying required functional role (FSI > 0.6), the other being *Panicum maximum* (FSI = 0.74) and *Hyparrhenia hirta* (FSI = 1.19). The relative high FSI of basal cover results from the high frequency of stoloniferous species (*C. gayana* & *C. dactylon* are sown on the dam to bind the tailings material and limit dust pollution and water erosion). The basal cover parameter also resorts between the two associations of sites (refer to Figure 4) and indicates the relevancy to be measured in the assessment of returned ecosystem function. The high FSI of *Panicum maximum* results from its affinity for nitrogenous conditions (direct result of fertilisation) and *Hyparrhenia hirta* has an overbalanced FSI as this species is renowned to colonise disturbed and compacted areas, and usually characterise the climax state on the revegetated tailings dams. Grass species diversity was the second most important indicator of functional success (C.V. = 0.08), being the parameter that acts as the centre of long-term ecological stability. The dam still has very low beta diversity, which is acknowledged by the few intermediate species comprising of only 9 grass species, which represent 40% of the total amount of valued grass species occurring on the dam. Measured in terms of the surrounding environment, the functional diversity indicators should add up to between 20 and 25 species (Van Wyk, 1994). The diversity parameter does not have such a low FSI (0.4), but this parameter should be regarded as crucial for successful ecosystem function. The functional indicators comprised of 5 species (C.V.< 0.55) including *E. plana*, *T. triandra*, *P. maximum*, *E. lehmanniana* and *C. plurinodes*. Seven stability indicators were selected (C.V.>1.288) which included *E. paspaloides*, *U. mosambicensis*, *B. serrata*, *T. spicatus*, *A. eucomis*, *S. nigrirostris* and *D. amplexans*. The results presented in Figure 3 show the degree of return of each individual selected parameter, and it is clear that in terms of this analysis, there are still great differences between the monitored parameters of the restored ecosystem and the reference sites. There are a few parameters that resemble acceptable ratios, but the functioning of the whole system is paralysed by the absence of abundant functional indicator species. The stability indicators are also functionally non-existent (Figure 3), which result in very negative SC and high SR values. The stability indicators, however, have variable occurrences and frequencies in the

reference areas as well, but the mere fact that none of these species occurred on the tailings dam underline the highly unstable conditions on the site.

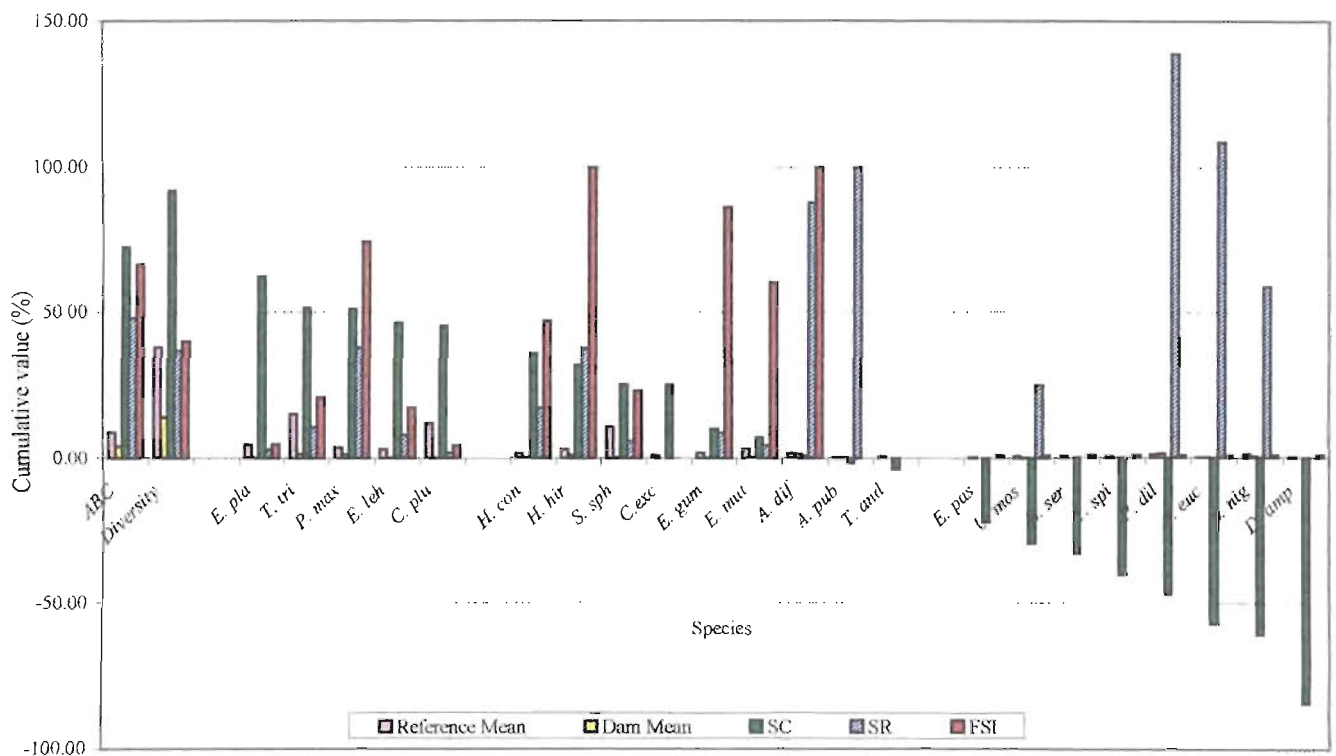


Figure 3: Returned functional success (FSI as %) of species selected statistically on the basis of functional role.

Figure 4 presents data of multivariate ordination results performed on the species that occurred on the three different evaluated sites, which included the reference sites – R, the investigated tailings dam – T (Hartebeesfontein No. 7) and the vegetation occurring on the 9 tailings dams used for the preliminary study (C). Two clear and distinct gradients are evident and characterises either a species diversity or a physical-chemical gradient along the first axis (Eigenvalue of 0.544), and moisture regime (wet to dry) or soil physical fraction (sandy loam to silty) along the second axis (Eigenvalue of 0.106). The high Eigenvalue of the first axis indicates that the diversity/physical-chemical gradient is responsible for the difference between the reference and the tailings sites and that individual species have a significant indirect effect in typifying this gradient. The species diversity, however, does have a strong influence on the gradient and it seems that there is an indirect proportional relation between species diversity and physical-chemical properties of the tailings material. The identified functional indicator species are located in the 3rd and 4th quadrants and associate mainly with the reference sites, as would be expected. The stability indicators are not mainly associated with the reference sites, as these areas may also be in a degraded state, and these indicators are situated at equal parallel distances from the first axis to its preferred ecological position.

The reference sites are arranged along a weaker second axis (less variation), which is characterised by species preference and could be explained by species associations with wetness/clay (4th quadrant) or drier sandy conditions with rocks (3rd quadrant). It is also clear that no species associated significantly with the intermediate conditions between the reference sites and the tailings dams. Ecologically, tailings dams are strongly associated with *C. dactylon*, *C. gayana* (especially the northern and eastern slopes - T6, C1) and *E. curvula* (especially the southern slopes - T3, C3, C4).

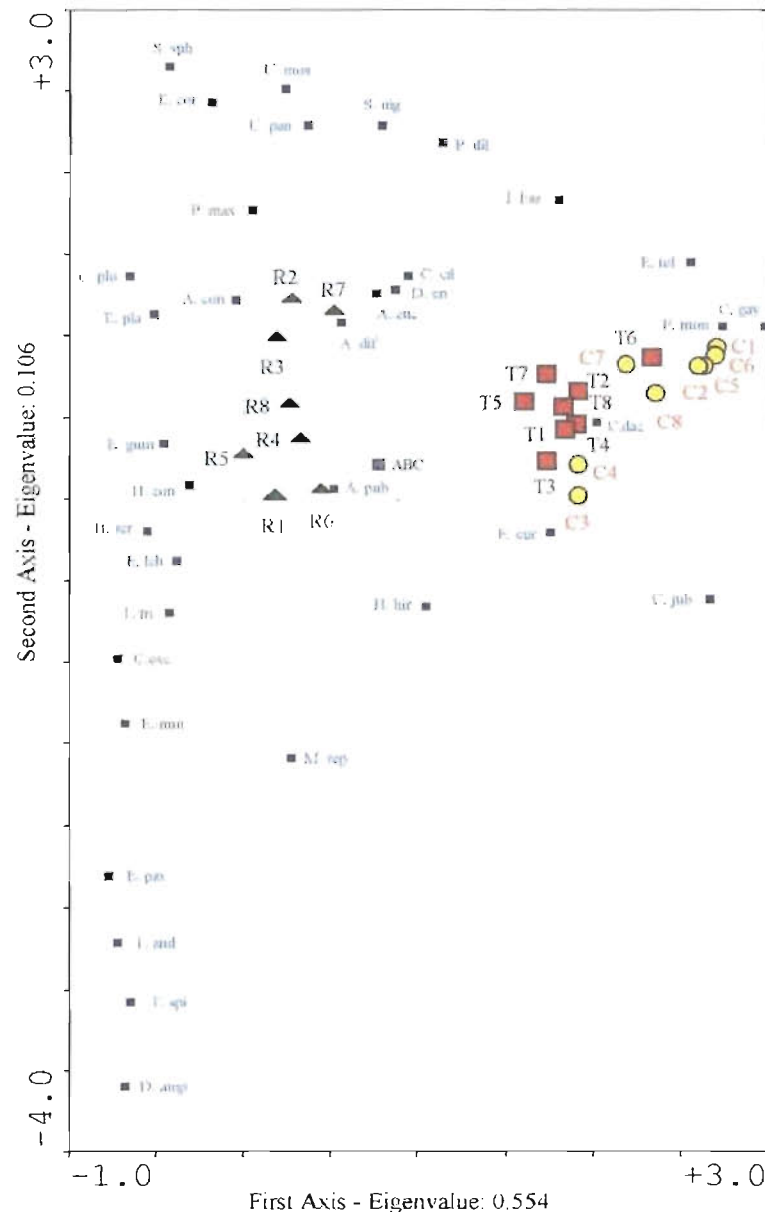


Figure 4: Detrended correspondence analysis (DCA) ordination results for vegetation data obtained from reference sites (R), Hartebeesfontein No. 7 tailings dam (T), and control tailings (C) vegetation surveys.

The Hartebeesfontein No. 7 tailings dam still associates very strongly with the control tailings dams, but does show affinity towards the reference sites. The difference in the spatial position of the evaluated and the control tailings dams in Figure 4, indicates that this tailings dam is regaining some of the lost ecological function, and that the technique used to replace vegetation on this dam did contribute to the return of functional integrity that was missing on the surface of the tailings dam before it was restored. Comparing this tailings dam with the conventionally rehabilitated dams also acknowledges this observation. Hartebeesfontein No. 7 tailings dam is characterised by superior ecological status compared to the other dams, but it is evident that the low species diversity and physical-chemical characteristics still isolate and limit the restored vegetation of this tailings dam to blend ecologically and fulfil its functional role to optimal extent

Of extreme importance of this finding is that it emphasises that tailings material cannot be ameliorated making use of plant species to tolerate the extreme conditions. Only through physical and chemical optimisation of the medium will any native plant species be able to colonise the tailings dams, and persist through natural succession with more sustainable results.

CONCLUSION

The existing gold mine tailings restoration outcomes are ecologically young and a final verdict on our ability to achieve functional equivalency may therefore be premature. The ecological immaturity of the restoration projects also constraints our ability to ultimately determine the success of projects in terms of replacement of lost or damaged ecological functions. We must therefore continue to evaluate the processes of biological optimisation, and use the results in the management of the recreated and affected ecosystems. This study intended to evaluate the return of functional landscape success on restored gold tailings dams by using objective and statistically supported techniques. Through the identification of functional indicator species derived from reference sites, the state of the restored areas could be described, and their contribution to ecological function could be assessed. Stability indicators were non-existent on the tailings dams, implicating ecological instability. By deriving a Functional Success Index, the similarity of functional indicators occurring at the reference sites and on the tailings dams could be quantified. It was evident that the evaluated tailings dam did not resemble the vegetation characteristics of the reference areas, but the ecological function did return to a greater extent on Hartebeesfontein No. 7 tailings dam, compared to that of the conventional restored tailings dams.

We must, however, realise that matching tailings conditions to a naturally occurring reference system may not be appropriate or realistic (Thom, 1997). Situations exist where the naturally occurring systems are either non-existent or in poor condition. In such cases, the goal of the restoration and the overall management strategy should be to improve the current condition, rather than to match it (Kentula, 2000). Any form of ecological optimisation is therefore acceptable, but the quest for sustainable ecosystem recreation should continue and the quantification of restoration must be used to describe ecological acceptability before site closure can be granted. The question should though be asked what role external ecological factors would play in the dynamics of state and transition on revegetated gold tailings dams (Wali, 1999).

As the analysis of restoration sites proceed, more information describing the trajectory of habitat development will become available and provide needed insight on the time course for habitats to re-establish functions and values (Short *et al.*, 2000). The selection of more variables to quantify total ecological restoration is inevitable and microclimatological, soil physical and chemical, microbiological and zoological data should also be pro-actively introduced in the quantification of restoration success criteria.

Furthermore, restoration plans in future will certainly need to incorporate specific, quantitative criteria, as regulatory agencies become more demanding of functional equivalency in restoration.

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Chapter 7

GENERAL DISCUSSION AND CONCLUSION

This study focused analytically on the soil physical and -chemical interaction of gold tailings material with vegetation, as well as the quantification of the ecological response (structurally and functionally) to these variables. Through these assessments, the biophysical factors that were the most limiting factors for gold tailings restoration, and the variables that could be applied as indicators to establish the degree of restoration success, were emphasised. Through multivariate analysis, gradients were derived to identify determinant associations of variables, which were supported by statistical significant correlations.

Although the rapid depletion of the soil chemical amendments inhibited vegetation persistence in the short term, the soil physical characteristics of the tailings media were identified as the most critical inhibiting factor for sustainable gold tailings revegetation, as it opposes the process of secondary succession. As expected, vegetational response clearly indicated the differences in soil physical and chemical traits in various pot and field trials, resembling the instability of the recreated biosphere through the fluctuations of several identified ecological indicators.

Seedling abundance, vegetation frequency and species features were constantly determined by soil physical gradients, but soil chemical interactions also had a considerable influence on the ordination of the various tested parameters in the study. It was further determined that climatological characteristics, either directly (seasonal features) or indirectly (micro-climatological influence through aspect features), did have an impact on vegetation establishment and persistence, but were of the lower priority factors.

However, the soil physical, chemical and biological characteristics of the restored gold tailings material do not yet comply with the norm values derived from the natural environment.

Detailed norm values from the literature are presented in the addendum.

Soil physical characteristics

Gold mine tailings material comprises of fine grained, predominantly SiO_2 particles, of which more than 50% resort under the 0.2 – 0.02 % fraction, and therefore tend to be cohesionless. This media does not resemble any significant similarities with any known soil profiles, resulting from its silty, homogenous and organic absent nature. The material further has a bulk density of approximately 1.7 tons m^{-3} with few physical properties favourable for spontaneous vegetation establishment, especially at unnatural steep slopes. The resulting

features that affect vegetation establishment negatively include extreme compaction, low permeability and thus low aeration, poor soil chemical translocation and high erodibility. The biological incapacity results in poor aggregate formation, non-existent organic incorporation, slow nutrient cycling and evidently static biological and soil physical profile development.

It was found that the comparative relation between mine overburdens, and soils for that matter, on a soil physical basis could best be quantified in terms of the Silt Dispersivity Index (SDI) (Chapter 3). This variable was found not only to accurately describe the susceptibility of a media to erode, but also characterises the seedling establishment success that could be expected from directly and successional introduced vegetation.

Gold tailings material was found to have an extremely high SDI (45,85%, compared to 15.51% for soil), providing new grounds for erodibility application in soil loss equations (Chapter 3). The high SDI explains the enormous erosion losses of gold tailings, despite intensive revegetation efforts, and also characterises the limited germinability capacity of the media.

This finding has enormous implications for the restoration of gold tailings dams, implying that no sustainable vegetation development could be expected if soil physical fractions are not included as standard practice. It was, however, indicated that physical rectification would not be ecologically worthwhile if the reconstructed soil profile comprises of less than 34% coarse and fine sand fractions respectively, and less than 23% silt. Where the SDI was manipulated in a reconstructed soil profile, the coarse sand fraction was the ultimate determinant parameter for seedling establishment, which also proved to have very high positive and negative correlations with the coarse sand fraction and silt fractions respectively (Chapter 3). The highest negative correlation was, however, typified by the SDI factor. The pH of the media, as well as the [P] and [Mg] did also have a significant impact on seedling establishment, but it seemed that a coarse sand fraction component was a prerequisite for successful seedling germination.

The manipulated soil physical treatments also proved to have significant effects on ecological parameters. Not only was high seedling abundance evident on the proportional physically rectified treatments, but there was an increase of species diversity and native species with an increase in the coarse sand fraction (Chapter 4). This result provides evidence that secondary succession of native species onto the tailings dams from the surrounding environment could not be readily expected if the soil physical characteristics of tailings media are not addressed. It was also clearly indicated that seedling abundance and vegetation persistence showed a better recovery after the cold and dry period on the physically ameliorated treatments, compared to the vegetation on the chemically ameliorated profiles (Chapter 4).

Soil chemical characteristics

Gold tailings media is macro- and microelement deficient with high acid forming potential (resulting from the pyritic content of 1,5 – 2,5%). To reach vegetation persistence on the mine spoil, ecological restoration of gold tailings is mainly carried out as a fertilisation process. The methodology includes liming programs and intensive pre- and post fertilisation, amending the growth media for latent and potential acidity, and introducing a long-term nutrient sink. Natural soil profile development should then sustain the growth media through nutrient cycling processes, interacting with the introduced vegetation.

The fertilisation programs could, however, be a limiting factor for vegetation establishment in itself, as initial cation ratio imbalances are evident (Chapter 5), resulting in monoculture domination of the most tolerable species. From the study it was clear that chemical amendments could be successfully applied to establish vegetation initially, but the seedling abundance and species diversity is markedly lower compared to the establishment rate on the physically rectified tailings media (Chapter 4). It was found that Water Treatment Sludge could be successfully applied as an alkalising agent, and that KNO_3 is a better nitrogen source than the conventionally used KCl, resulting in higher established seedling density and eliminating the risk of runoff chlorine pollution (Chapter 4). It was also found that high phosphate applications acted as persistent stimulators through the cold and dry period.

The microbiological inoculated treatments showed remarkable successful results, outperforming all the chemical treatments with regards to seedling establishment and persistence. The amendment of sewage sludge for future restoration could also be strongly recommended. Questions should, however, be asked about the sustainability of the vegetation, as a decrease in seedlings was evident over time, especially after the winter period (Chapter 4). The stress experienced by the vegetation, resulting from the depleting elemental concentrations in the soil profile (Chapter 5) and the effect of climatological seasonal variance (Chapter 4) had a significant impact on vegetation (and soil) dynamics (Chapter 5). The soil chemical status of the rectified media deteriorated to a great extent over the monitored time, especially Mg and K and soil chemical depletion might have been the result of the leaching effect of the supplementary irrigation. The decreasing pH and the capillary rise of salts (high SAR) were further identified as major chemical factors that limit restoration success, while the slow incorporation of organic matter into the soil profile (resulting from the poor physical properties and high runoff from steep slopes), resulted in poor nutrient cycling and inevitably, a decrease in microbiological diversity.

Soil physical and chemical profile development is therefore questionable and vegetation on gold tailings dams can only be sustained by means of irrigation (leaching of salts) and follow-up fertiliser programs (due to leaching of nutrients), except if a new ameliorative approach is considered.

Vegetational response.

Principles of restoration are firmly grounded in the process of natural succession. After introduced revegetation, the restored system will develop over time through several successional phases into a climax state associated with the environmental conditions, which include the physico-chemical, topo-edaphic, climatological and ecological driving pressures. Throughout this study it was evident that the successional processes on gold tailings dams are not clearly observed as would be expected. Secondary succession tends to be slow, and the vegetational pattern is characterised by an increase in weeds, consistency in grass species diversity, and a decrease in basal cover, a state known as reversed succession (Chapter 5). It seemed that except for the weedy r-strategists, no other external grass species invaded the revegetated areas. There were fluctuations in minor species frequencies, and a predominant decrease in most of the species' abundance, which were a result of deteriorating soil chemical conditions, and domination of more aggressive species (Chapter 5). Grass species monocultures were still characteristic of the vegetation composition, and *Chloris gayana* mainly dominated, while *Eragrostis curvula* tended to increase as the growth media deteriorated (Chapter 4; Chapter 5). The microclimatological differences presented by the features of the different aspect were also remarkably reflected by slope conditions and had a significant influence on species distribution (Chapter 5).

Several dynamic trends were noticed and the species response can certainly act as indicators for changing soil chemistry (Chapter 5). *Medicago sativa* decreased substantially with decreasing pH (supported by a remarkable correlation), as did *Chloris gayana*, although the latter could also indicate a decrease in the moisture regime of the growth media. An increase in weeds was associated with an increase in soil organic matter, and a decrease in the dominating grass species. *Eragrostis curvula* reflected an increase with the deterioration of the soil quality (increase in SAR, decrease in pH) although this was only a proportional increase resulting from the intolerance of the other species. It did seem that *Hyparrhenia hirta*, which is the climax species for disturbed areas, was slowly increasing. The vegetation development processes were, however, slow (Chapter 5) and native species from the surrounding area did not invade the revegetated area to any significant extent.

The establishment of native species on tailings dams is certainly the most elusive challenge of restoration. Ecologically it would imply a recreated ecosystem in sound harmony with the ecological functioning of the surrounding environment and thus a sustainable system (Chapter 6). It was found though, that soil physical quality, and native species abundance and diversity, were quantified by a direct proportional relation (Chapter 4). As expected, an indirect proportional relation was resembled by species abundance and diversity, and an increase in the soil dispersivity index (Chapter 3). Therefore, the only way to expect successional development of native species from the surrounding environment, physical

rectification of the tailings material is inevitable. If these native species are encountered on tailings dams, it can also be used to indicate the degree of ecological stability (Chapter 6). The statistical approach followed to identify ecological indicators and associated long term ecological stability, revealed that the recreated systems on gold tailings dams are to a large extent still unstable in terms of the classical ecological theory, which emphasises the relation between diversity and stability. It was clear though, that the ecological function of the investigated revegetated gold tailings dam was reinstated to some extent, but the biological acceptance of this area to the surrounding environment is questionable, based on the dissimilarity of species reflection, basal cover and grass species diversity.

The technique followed presented a scientifically sound method to monitor restoration success. Several indicators were identified which included five stability indicators and seven sensitivity indicators (Chapter 6). To derive ecological restoration closure criteria, more parameters should however be investigated. This trial only indicated the intensity and viability of such an approach. The fluctuation of the indicators could ideally be monitored to rule a decisive answer on the finality of restoration success, and to establish norm values for closure criteria.

A list of criteria that should be assessed is presented in the addendum.

GENERAL CONCLUSION

The extremes posed by the landform of tailings dams, and the poor physical, chemical and biological characteristics of the tailings material combined with the erratic climatological influence, inhibit the initial establishment and colonisation of spontaneous and lasting native vegetation on tailings dams. It is therefore inevitable to revegetate the tailings material. There is, however, nothing natural about tailings material and more than agricultural principles need to be applied to persist vegetation on the spoils. Although the chemical and physical conditions of tailings material are extreme, each of the factors in isolation is not as extreme as those often found in the natural environment. The species established on the tailings dams are usually able to cope with the initial stressors, but the persistent and ever increasing stress of one extremity at a time slowly leads to the detriment of the developing system. The performance of these restored systems is often evaluated and compared to that expected from natural systems, and the results are more often than not disappointing over time. The question does therefore arise whether the discard should be analysed and compared in terms of known ecological principles, or is it a completely new system with its own characteristics and of which new principles has to be derived for.

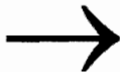
This does however not imply that natural systems cannot be used as reference or to determine ecological stability, but gold tailings restoration needs to be evaluated in terms of its own inert and similar comparative successes.

Current gold tailings restoration still only succeed in terms of its primary objective, which is dust pollution prevention, making use of chemical ameliorative techniques, irrigation and fast growing species to cover the tailings material as quickly as possible. The introduced vegetation is anthropogenically sustained, and is merely more than a glasshouse trial. The sustainability of the revegetation is therefore questionable. Through the study it was evident that there is a possible pattern of restored vegetation degradation over time (Table 1). This pattern could be described as a cycle of mutual ecological rejection, where the vegetation of the surrounding environment is not ecologically equipped to colonise the unnatural landform or media.

A new holistic framework, which addresses the total spectra of topo-edaphic factors, should be phased in. This approach should include both physical and chemical amelioration techniques with the use of native species seed mixtures. A new ecologically sound tailings dam design (Figure 1) will also have a significant influence on restoration success. This ecological reconstruction approach will initiate ecosystem development through the reinstatement of ecological function, and achieve ecological stability with ultimately landscape success. Relying on successional sequences alone to restore landscape success leaves a lot for uncertainty to decide, and restoration success cannot be guaranteed.

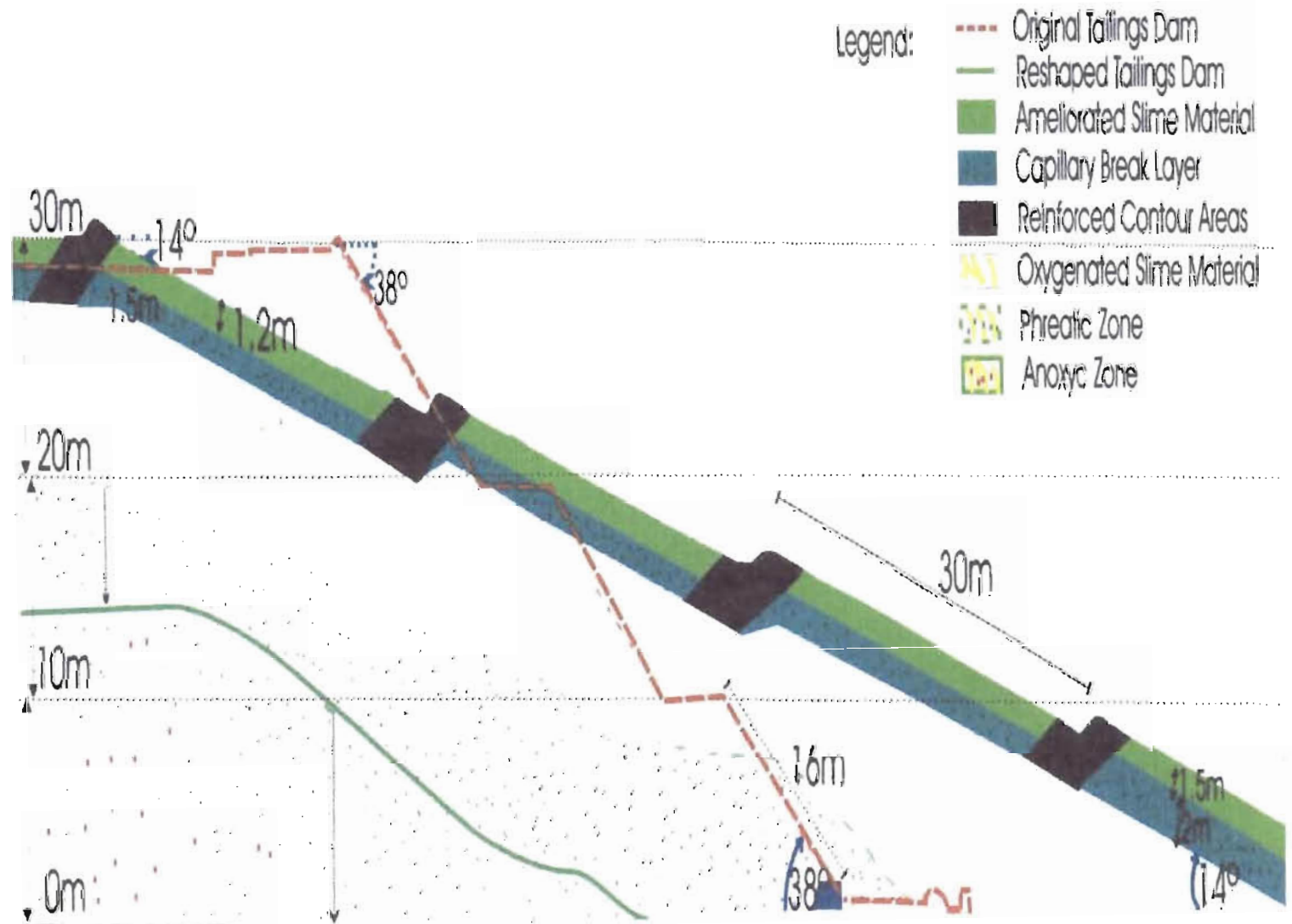
Numerous opportunities for further research were identified during this study, of which the establishment of success criteria for ecological restoration was the most obvious and relevant need. To devise ways of hastening the revegetation and restoration of tailings dams, as well as the understanding of successional processes are also of paramount importance, and could ideally be addressed through ecological modelling. Furthermore, landscape evolution should be investigated, and the proposed dispersivity index technique could be applied to derive new erodibility values for different soils to determine accurate geotechnical stability through more precise equations. The direct and indirect interaction of slope gradient, slope lengths, and media dispersivity on vegetation characteristics of revegetated sites are further to a large extent unclear, and studies to derive ecologically suitable slope criteria for future ecological designs are urgently needed. The need for more successful restoration techniques was also evident, especially to mitigate the effect of the capillary rise of salts.

The strive to achieve sustainable restoration of tailings dams will be an ongoing challenge. The key for ultimate restoration success lies in pro-active ecological designs, which implies to flatten the slopes, to re-introduce a geochemical nutrient sink, to optimise microbiological diversity, to establish native vegetation, and to create micro-niches for system diversity.

<u>Phase IV</u> - Media compacted (resulting from the high SDI) - Organic matter incorporation fails - Secondary succession inhibited - Poor soil-seed contact - Seed sterility - Steep slopes (run-off) <i>Hyparrhenia hirta</i> starts to increase - Basal cover very low	(→)	 Bare Tailings Media	→	<u>Phase I</u> Restoration Input - Cation ratio imbalances <i>Chloris gayana</i> dominates - pH acceptable - Salts consistently leached out - Nutrients leached out - Organic matter high - Basal cover high
↑	Table 1: Pattern of restored gold tailings dams deterioration over time.			↓
Erosion increases				Irrigation suspended
↑				↓
<u>Phase III</u> - pH decreases - Capillary rise of salts - Basal cover decrease <i>Eragrostis curvula</i> dominates - Growth media deteriorates: - Soil physically - cultivated tailings media smoothes up, tailings becomes susceptible for erosion, - Soil chemically - high SAR, low pH. <i>Thiobacillus ferrooxidans</i> dominates	←	Stadium of Reversed Succession.	←	<u>Phase II</u> - Soil chemistry acceptable but elements start to deplete. - Nutrient cycling slow - pH decreases - Basal cover decrease - Weeds increase <i>Thiobacillus ferrooxidans</i> increases

Cross section of the side slope of a new designed ecological stable tailings dam

Figure 1: Cross section of the side slope of a newly designed ecological stable gold tailings dam.



ADDENDUM

Table A: Landform Specifications

<u>Parameters</u>	<u>Current State</u>	<u>Ideal State</u>
Side Gradient	30-40°	14°
Slope Length	40-60m	< 25m
Side area (200ha, 30m high)	15% of footprint	30% of footprint
Footprint	200ha	Increase 10 - 15%
Runoff Control Clean Water	None	1:50 year
Runoff Control Structures Velocity	> 1,5 m.s ⁻¹	< 0,8 m.s ⁻¹
Runoff Control Structures on Sides	Benches and berm walls, as well as drains.	Contour banks with low gradient sides (> 1:3), reinforced chutes
Landform Top Area	Flat, even silted area, better basal cover and species composition on top than on sides	Wetlands (30% of area) with gently sloped impoundment berms on natural contours
Contaminated Water Evaporation Ponds	Toe Paddocks	10% of MAR kept on dam
Microclimate	Evident effects	Mitigated and complementary for surrounding area

(Hannan, 1984)

Table B: Geological Specifications

<u>Parameters</u>	<u>Current State</u>	<u>Ideal State</u>
Erodible Parent Material	None	Available original, secondary and clay minerals
Eroded Primary Minerals	Quarts, Pyrite	Feldspar, Micas, Hornblende, Quarts
Eroded Secondary Minerals	None	Goethite, Hematite, Gibbsite, Calcite, Gypsum, Apatite
Clay Minerals	Some clay	Silicate Clays
Surface Roughness Factor	Smooth silted surface	Cloddy tillage (0.05)
Break layer – Serves as parent material and drainage system; restricts evapotranspiration and re-acidification	None	> 500mm thick

(Brady, 1984)

Table C: Physical Soil Specifications

Parameters	Current State	Ideal State
Medium Type	Crushed rock debris deposited as fine slimes	Avalon Soil Type (Kameelbos Family)
Organic Component	0%	4%
Course Sand	0%	27%
Fine Sand	0%	30%
Silt	65%	20%
Clay	35%	19%
Pore Space	5%	30%
Permeability	2 mm/hour	> 10 mm/hour
Field Capacity	6%	12%

(Brady, 1984)

Table D: Nutrients essential to plant growth

Elements	Critical Level	Sufficient range	Toxicity level
<u>%</u>			
N	< 2.0	2.0 – 5.0	Non Toxic
P	< 0.2	0.2 – 0.5	Non Toxic
K	< 1.0	1.0 – 5.0	Non Toxic
Ca	< 0.1	0.1 – 1.0	Non Toxic
Mg	< 0.1	0.1 – 0.4	Non Toxic
S	< 0.1	0.1 – 0.3	Non Toxic
Na	< 1.0	1.0 – 10	Non Toxic
Si	< 1.0	0.2 – 2.0	Non Toxic
Cl	< 0.2	0.2 – 2.0	> 2.0
<u>mg kg⁻¹</u>			
Fe	< 50	50 – 250	Non Toxic
Zn	15 – 20	20 – 100	> 400
M	10 – 20	20 – 300	> 300
Cu	3 – 5	5 – 20	> 20
B	< 10	10 – 100	> 100
Mo	< 0.1	0.1 – 0.5	> 0.5
Co	< 0.2	0.2 – 0.5	> 0.5
V	< 0.2	0.2 – 0.5	> 1.0

(Bennett, 1996)

Table E: Soil Chemical Specifications

Parameters	Current State	Ideal State
pH (H ₂ O)	3,5 – 6.5	5,5 – 7,2
Exchangeable Sodium % (ESP)	> 10%	< 10%
Sodium Adsorption Ratio (SAR)	> 4	< 4
Cation Exchange Capacity (CEC)	< 5 cmol kg ⁻¹	5 – 20 cmol ₊ kg ⁻¹
Electrical Conductivity (EC)	500 mS m ⁻¹	60 – 100 mS m ⁻¹
Base Saturation (Ca,Mg,K,Na)/CEC (pH 6)	> 100%	< 100 %
Macro Elements		
Nitrogen (NH ₄ ,NO ₃ & NO ₂)	< 20 mg kg ⁻¹	80 – 165 mg kg ⁻¹
Phosphate	0,7 – 1,5 mg kg ⁻¹	1,5 – 2,5 mg kg ⁻¹
Potassium	10 – 17 mg kg ⁻¹	20 – 42 mg kg ⁻¹
Calcium	27 – 54 mg kg ⁻¹	>100 mg kg ⁻¹
Magnesium	5 – 10 mg kg ⁻¹	15 – 35 mg kg ⁻¹
Calcium: Magnesium ratio	> 3,5 cmol ₊ kg ⁻¹	1,5 – 4 cmol ₊ kg ⁻¹
Magnesium : Potassium ratio	1,5 – 2,0 cmol ₊ kg ⁻¹	3 – 4 cmol ₊ kg ⁻¹
Calcium + Magnesium/ Potassium	4 – 6 cmol ₊ kg ⁻¹	10 – 20 cmol ₊ kg ⁻¹
Anions: SO ₄ , NO ₃ ,HCO ₃ , (Cl)	250 – 500 mg kg ⁻¹	36 – 100 mg kg ⁻¹
Micro Elements		
Boron, Zinc, Manganese and Copper	50 – 200 mg kg ⁻¹	18 – 150 mg kg ⁻¹
Iron	200 – 1200 mg kg ⁻¹	200 mg kg ⁻¹
Heavy Metals: Aluminium, Selenium, Arsenic, Chromium, Cadmium, Tin, Molybdenum, Vanadium, Cobalt	5 – 10 mg kg ⁻¹	< 0.1 mg kg ⁻¹

(Abroll *et al*, 1980; Bennet, 1996; Buys, 1993)**Table F: Micro Biological Specifications**

Parameters	Current State	Ideal State
<i>Ferro bacillus oxidance</i>	> 10 ³ units g ⁻¹ silt	< 10 ³ units g ⁻¹ silt
Anoxic bacterial colonies	None	> 10 ⁵ units g ⁻¹ silt
Oxic bacterial colonies	None	> 10 ⁷ units g ⁻¹ silt

(Van Rensburg *et al.*, 1998)

Table G: Botanical Specifications

Parameters	Current State	Ideal State
Desirability	Exotic, invader	Indigenous
Lifecycle	Annual/Perennial	Perennial
Ecological Status	Increaser II / III	Increaser I / II
Basal Cover	3 - 8%	7 - 12%
Species diversity	5 - 10 species/25m ²	30 - 40 species/25m ²
Dispersal ability	Seed, stolons, rhizomes	Seed, stolons, rhizomes fauna
Succession	None or only primary	Primary & Secondary
Nutritional value	Low	Medium to High
Grazing value	Low	High
After Use	None, Discard	Grazing – Game, Wilderness
Habitat	Exotic plant communities, small mammals, birds, amphibians and insects. Sustainability questionable.	Using surrounding environment as reference criteria, indigenous plant communities, small mammals, birds, amphibians and insects. Sustainability more probable

(Van Wyk, 1994)

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CONFERENCE CONTRIBUTIONS

Poster presentations

1. Van Wyk, S.J. & Van Rensburg, L. 2003. Quantifying the effect of the dispersive nature of gold mine tailings on grass species seedling establishment. *Joint International Conference of the South African Association of Botanists and the International Society for Ethnopharmacology held by the University of Pretoria and the National Botanical Institute. 7 – 11 January 2003.*
2. Van Wyk, S.J. & Van Rensburg, L. 2003. The contribution of revegetation to restored landscape success of gold tailings dams. *Joint International Conference of the South African Association of Botanists and the International Society for Ethnopharmacology held by the University of Pretoria and the National Botanical Institute. 7 – 11 January 2003.*

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