The role of vegetation in characterising landscape function on rehabilitating gold tailings

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B.Sc. (Hons)

Dissertation submitted in fulfilment of the requirements for the degree Master of Science at the Potchefstroom campus of the North-West University

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November 2008

Abstract

Gold mine waste poses a significant challenge for rehabilitation practitioners and can negatively impact on soil, air, surface water and groundwater quality. This, in turn, can affect the environmental quality of humans and other biota in nearby settlements and surrounding ecosystems. All mines are required to have a plan in place to impede or mitigate these environmental impacts and to ensure that all legislation is complied with to apply for closure. Site closure is the eventual goal of all mine residue complexes, as it is the stage at which a company becomes released from all legal and financial liability. The South African legislation is comprehensive and essentially requires that all latent and residual environmental impacts are addressed and that an end land-use designation is put in place that conforms to the principles of sustainable development. The Chemwes Tailings Storage Facility complex near Stilfontein was monitored to provide a strategic assessment of the state of the rehabilitation, and to provide recommendations for the successful remediation of problem sites. A combination of vegetation sampling, landscape function assessments and substrate chemical analyses were conducted to gain a predictive understanding of rehabilitation progress. The monitoring was conducted over two years across a chronosequence of rehabilitating sites from tailings dam slopes and an adjacent spillage site. An undisturbed grassland and a starter-wall served as reference sites.

The data were first analysed independently and then by making use of multivariate data ordinations. This allowed for holistic investigations of the relationships between sites, substrate chemistry, vegetation composition and landscape function. The results showed that the tailings dams had a distinctly different suite of vegetation from the reference sites, but had no statistically significant differences in composition across the rehabilitating chronosequence. There were positive correlations between rehabilitation site age and landscape function indices, suggesting that some aspects of ecosystem development were occurring over time. In some sites, deterioration in the substrate quality as a growth medium was observed with increases in acidity and salinity. This was most likely caused by pyrite oxidation in the tailings and the high concentrations of free salts. The increasing acidity and salinity resulted in vegetation senescence and declines in landscape function. However, those sites that possessed higher landscape function appeared to have the ecosystem processes in place that temporarily suppressed negative chemical changes. Whilst this was encouraging, the rehabilitation chronosequence had not yet proven the self-sustainability that it would require for closure purposes. Further monitoring would be required over time. The sustainability of the rehabilitating chronosequence was brought into question by the high acid-forming potential of the tailings growth medium. Concerns were also raised over the ability of the established vegetation cover to persist under conditions of increasing stress and disturbance. Furthermore, the land-use capabilities of the sites are limited by current rehabilitation procedures and various recommendations were made to rectify this. A more streamlined monitoring framework for the tailings complex was also proposed. The contribution of this work lies in its holistic integration of monitoring techniques and the meaningful analysis of ecosystem function, an aspect largely ignored in minesite rehabilitation.

Keywords

Gold mine rehabilitation, Landscape Function Analysis, LFA, Closure, Ecosystem function, EFA.

Opsomming

Die rehabilitering van goudmynafvalprodukte is 'n groot uitdaging vir rehabilitasie-praktisyne. Dié afvalstowwe kan negatiewe invloede op lug, grond, oppervlak- en ondergrondse waterkwaliteit hê. Hierdie afname in kwaliteit kan ook tot besoedeling van omliggende ekostelsels en die menslike omgewing lei. In Suid-Afrika word van myne verwag om 'n omgewingsbestuursplan in werking te stel wat die negatiewe omgewingsimpakte kan beperk of verminder. Hul moet ook kan bewys lewer dat hul aan al die wetlike vereistes voldoen het voordat daar aansoek gedoen kan word vir sluiting. Mynsluiting is die uiteindelike doel van alle mynbedrywighede, aangesien dit die tydstip is wanneer alle finansiele en wetlike aanspreeklikheid afgelos kan word. Die Suid-Afrikaanse wetgewing is geheelomvattend en dit vereis dat alle verborge en oorblywende omgewingsimpakte aangespreek moet word. Daar moet ook n finale landgebruikspatroon wees wat aan die konsep van volhoubare ontwikkeling voldoen. Gedurende dié studie is die rehabiliterende dele van die Chemwes Slikbergingskompleks naby Stilfontein gemonitor om plantegroeidinamika en vooruitgang van die rehabilitasie te ondersoek. Aan die hand van die studie is daar ook aanbevelings gemaak aangaande rehabilitasietegnieke en n voorgestelde moniteringsraamwerk. 'n Kombinasie van plantegroei-opnames, funksionaliteitsanalises van die landskappe en grond-chemiese ontledings is gedoen om 'n voorspellende begrip van slikdamrehabilitasie te ontwikkel. Die monitering het oor twee jaar plaasgevind en het ook gebruik gemaak van verwysingspersele, in die geval 'n onversteurde grasveld en dié slikdamsteunwal.

Die data is eers onafhanklik van mekaar, en later as 'n eenheid geanaliseer deur gebruik te maak van meervoudig-veranderlike analises. Sodoende is kwantifisering van die verhoudings tussen grondchemie, plantegroei, landskapsfunksie en die verskeie transekte gefasiliteer. Die resultate het gewys dat daar 'n unieke plantegroeigemeenskap op die slikdamme groei, wat duidelik onderskei kan word van die omliggende veld, alhoewel daar geen statisties betekenisvolle verskille in die plantegroeisamestelling van die chronologiese reeks rehabilitasie-areas was nie. Daar was wel positiewe korrelasies tussen perseel-ouderdom en die landskapsfunksionaliteitsindekse, wat aandui dat daar aspekte van ekostelselwikkeling mettertyd plaasvind. In sommige persele het die slik, wat as groeimediumgebruik word, verlaag in kwaqliteit as gevolg van versouting en versuring. Dit was bes moontlik as gevolg van piriet-oksidering en die hoë konsentrasies van vrye soute. Die verhoogde suurheidsgraad en braksouttoestande het gelei tot die terugsterwing van plantegroei, en dus'n afname in landskapsfunksionaliteit. Nietemin, die persele met die hoogste landskapsfunksionaliteit het ook al die eksostelseelprosesse getoon wat die negatiewe chemiese wisseling in die grond kan teenwerk. Alhoewel dit baie bemoedigend is, het die reabiliterende chronologiese reeks nog nie voldoende selfonderhouding getoon tot op die vlak wat vir sluitingsdoeleindes veries word nie. Verdere monitering word vereis om 'n beter beeld van rehabilitasie sukses te kan toon.

Die volhoubaarheid van die rehabilitasie is bevraagteken, aangesien die vermoë van die slik groeimedium om sure op te wek so hoog is. Daar is ook kommer dat die huidige plantegroei op die slikdamme nie in staat is om onder stres en versteuringstoestande te kan voortbestaan nie. Verder is die landgebruiksvermoë van die persele beperk deur die huidige rehabilitasietegnieke en daar is aanbevelings gemaak om die situasie te verbeter. Die grootste bydrae wat hierdie werkstuk lewer is dat dit holistiese integrering van verskillende moniteringstegnieke bemoedig en ook landskapsfunksionaliteit bestudeer, 'n aspek wat tradisioneel geïgnoreer is in mynbourehabilitasie.

Sleutelterme

Goudmyn rehabilitasie, Landskapsfunksionaliteitsanalise, LFA, Mynsluiting, Ekostelsel funksionaliteit, EFA.

Acknowledgements

I would like to acknowledge the strong support that I have received throughout the planning and execution of this study. Firstly, my supervisor, Prof. Klaus Kellner, for agreeing to let me take on this significant project, and for his help and experience in the field and in the office. Then, to my co-supervisor Mr. David Tongway who has been instrumental in opening my eyes to the wider field of Landscape Ecology and teaching me the value of ecosystem services as indicators of environmental health. I would also like to thank my wife, Amanda Haggett-Haagner, for moral support and perseverance. Then, to my benefactors from Fraser Alexander Tailings who commissioned this study, especially Mr. Len Reynecke and Mr. Piet van Deventer, I am deeply indebted for the opportunity that has been created for me to pursue my further studies. Thanks must also go to the mining companies, Mine Waste Solutions and later First Uranium, who covered laboratory costs, gave support and assistance and granted access to their property.

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Chapter 1. General Introduction

1.1. Problem statement and substantiation

Repairing landscapes that have been degraded or have suffered loss of productivity through anthropogenic or natural forces has become more central to environmental science and management in recent decades (Cairns, 1996; Cramer and Hobbs, 2007; Aronson *et al.*, 2007). This, together with the burgeoning human population's need for more space, has resulted in a plethora of similarly-focussed ideologies and technologies that, often interchangeably, go by the terms 'rehabilitation', 'restoration', 'reclamation', 'revegetation', 'regeneration' and 'reallocation'. Standardisation of terminology is required for interpretation and meaningful exchange of results between researchers in different countries and also between science, industry, government and social institutions. For the purpose of this introductory chapter, 'rehabilitation' is used as a compromise to encompass all terminology, whilst a detailed review of definitions will follow in the literature review of chapter two.

Whilst large strides have been made in ecosystem rehabilitation, the management information systems that monitor successes and failures have not necessarily kept up (Milton *et al.*, 2007). In South Africa, a widely used, almost generic recipe for monitoring minesite rehabilitation has been in practise for many years and has remained largely unchanged. It has even been revived in the latest Guidelines for the Rehabilitation of Mined Land (Chamber of Mines, 2007). This consists of rapid assessments of species richness and average basal cover, regardless of the nature of species or how the importance of existing vegetation cover is interpreted. This approach is not unique to South Africa and is widely used around the world (Ruiz-Jaen and Aide, 2005; Herrick *et al.*, 2006). However, such investigations are inadequate to accommodate more diverse rehabilitation goals (Aronson *et al.*, 2006) or to keep up with developments in environmental legislation (Bailie, 2006). Without adequate monitoring criteria to justifiably prove rehabilitation success or progression, mines will not be considered for closure under the provisions of the Minerals and Petroleum Resources Development Act (MPRDA), Act no. 28 of 2002.

Establishing robust success criteria for rehabilitation and the ability to demonstrate progress in recovering or improving ecological processes is seen as a vital link to attaining rehabilitation goals (SER Primer, 2004). This essentially entails moving beyond the 'command and control' mindset currently in sway to a more process-oriented approach (Holling and Meefe, 1996). Ecosystem Function Analysis (EFA) has demonstrated recovery of degraded landscapes across a wide diversity of habitat types, including mine sites (Tongway, 1997, 2003). It is a more process-based approach, seeking to define when a rehabilitating landscape has reached self-sustainability, a state characterised by being able to sustain stress and/or disturbance without faltering. This approach has the potential to be incorporated into mine site rehabilitation monitoring in South Africa, with great promise of strengthening the case for closure. A more detailed explanation of EFA will be presented in chapter 2.

Attaining long-term ecosystem stability is a formidable challenge facing rehabilitation managers. Stability is a key goal in the rehabilitation programmes of gold mines (Department of Minerals and Energy, 2005), partly because of its necessity in order to effect closure of a mine and thus to release the mining company from liability. The remaining viable tailings dams at the Chemwes Tailings Storage Facility (TSF) Complex near Stilfontein (North-West Province, South Africa) are currently being re-mined, after which they are aiming to achieve closure. Chemwes has undergone many recent changes in ownership and the environmental policies have differed amongst the mining companies. However, each of the mining companies was legally required to conduct their operations with closure of the facility in mind (attaining closure after the conclusion of re-mining will involve the implementation of procedures that will ensure the safety, environmental stability and aesthetic quality of the site to agreed criteria).

Planning for closure is a progressive attitude to managing the life cycle of a mine. Closure is the final stage that represents the culmination of much capital outlay and robust environmental planning, especially regarding the future of recovering sites. Meticulous records detailing the past performance and short-term trajectories are essential for presenting data and results to the authorities in order to strengthen the case for closure (Chilean Copper Commission/COCHILCO, 2002). Although rehabilitation goals may take many decades or centuries to fully achieve, relevant monitoring data can prove resilience in coping with environmental limitations and stochastic disturbances (De Angelis *et al.*, 1989). On many gold Tailings Storage Facilities (TSF's) in South Africa, the steep slopes (30 to 35 degrees) almost preclude self-sustaining herbaceous vegetation from establishing (van Wyk, 2002). For the successful revegetation of mine discard to become a reality, there needs to be a change in TSF design, construction and rehabilitation practices (Barnhisel and Hower, 1997). Therefore, to achieve closure, South African mines need to consider shaping TSF's to emulate the functioning of local topography (van Wyk, 2002), and modifying rehabilitation practices. Without drastic changes in the way that TSF's are constructed and managed, the required functional vegetation, and thus closure, is unlikely to be achieved.

To achieve this end, the previous mining company had initiated an environmental rehabilitation programme in which they committed to "create a natural environment that sustains indigenous life at a level equivalent to the surrounding natural environment..." (Closure Model Master following workshop of 8th October 2002). In order to measure the progress of the rehabilitation programme, they have established a series of monitoring procedures to track the recovery of the system. It is also designed to serve as an early-warning system to rectify potential deviations from expected trajectories. Monitoring the development and stability of these seral rehabilitating stages or chronosequence was therefore the main theme of this study. The results focused on the resource limitations that hinder sustainable vegetation establishment through the monitoring of applicable indicators and the persistent need for management inputs.

1.2. Research aims and objectives

1.2.1. General aims

During this study, the aim has been to monitor and assess soil development in terms of chemical constituents, long-term stability, and potential for sustainable vegetation establishment. These assessments sought evidence of landscape rehabilitation and to provide an overview of the processes that govern the dynamic nature of this landscape. The focus was therefore to assess the ability of the landscape to sustain the desired vegetative cover. These evaluations were then used to interpret the ecological data so that viable management recommendations could be made regarding first-stage rehabilitation. First-stage rehabilitation was regarded as that initial, active, high intensity stage which includes site design and outlay, substrate preparation, seed selection, irrigation practises and intense baseline monitoring.

1.2.2 Objectives

1. To use Landscape Function Analysis (LFA) indices coupled with vegetation and soil variables to detect and assess aspects of ecosystem development during the course of rehabilitation on gold tailings;
2. To examine the role of the physical and chemical properties of the soil in vegetation establishment on gold tailings dams through regular monitoring;
3. To create a monitoring framework, based on the experimental output, that will provide an economical but effective methodology;
4. To collate the results of the abovementioned objectives into annual performance assessments, thus reporting on the state of the rehabilitation.

The results of this study will bring the resource limitations that hinder sustainable vegetation establishment into focus. These results will provide the basis for recommendations on how to incorporate process-based monitoring of a set of ecological indicators into meaningful and applicable management information.

1.3. Thesis structure

- Chapter 2 provides a summation of the current legislative requirements for rehabilitation, a synopsis of the past and future of monitoring rehabilitating gold mines, and the potential for integrating landscape ecology into rehabilitation planning.
- Chapter 3 reviews the study area in terms of climate, geohydrology, natural vegetation, and the anthropogenic influences on the sites (including construction, management and monitoring histories).

- Chapter 4 outlines the basis for the selection of the monitoring techniques and details the field, laboratory, interpretive and analytical procedures.
- Chapter 5 presents the results and forms the interpretive discussion of the project's findings.
- Chapter 6 collates the information from the preceding chapters and explores the prominence of the difference techniques. It provides a discussion of further research opportunities, the applications of this work and the refinement of the current monitoring programme.
- Chapter 7 provides the full references used in this thesis.

Chapter 2: Literature Review

2.1. Introduction

This chapter serves to summarise and highlight the key issues surrounding rehabilitation monitoring. The flow of thoughts is to first guide the reader through terminology to provide an understanding of the context in which many, often confusing, phrases are used. Then, the following section emphasises the state of South Africa's remaining grasslands and puts perspective on the extent of disturbance imposed by mining. Some of the negative and positive impacts of mining are addressed to illustrate the links between conservation and social and economic development. This is then followed by a synthesis of relevant legislation, as well as the rationale for rehabilitating mined land. Much emphasis is placed on the most influential Act, the MPRDA, and the interpretation of its requirement that 'end-land use designations conform to the principles of sustainable development'.

The chapter then explores the theory of rehabilitation and monitoring and outlines the conventional methods most often used in South Africa. It discusses the shortcomings of conventional monitoring criteria and investigates the use of ecological indicators in moving towards an approach that is based less on monitoring taxa and more on monitoring ecological processes. The chapter then advocates proposes the inclusion of incorporating LFA, a technique based on established principles in landscape ecology, to enhance conventional monitoring and to strengthen the case for mine site closure.

2.2. Semantics

2.2.1. Rehabilitation vs. restoration

The SER International Primer for Ecological Restoration (2004) defines the relationship between rehabilitation and restoration in terms of their similarity and differences. These pursuits both share the focus of using historical or pre-existing ecosystems, with known levels of persistence, as analogue or reference sites (widely called 'benchmarks' in South Africa). Their primary difference is that rehabilitation is geared to repairing damaged ecosystems to recreate processes that contribute to ecosystem services, function and productivity (Jackson *et al.*, 2006). Restoration, on the other hand, aspires to the same goals as rehabilitation, but adds reestablishment of the historical/pre-existing biotic integrity with reference to ecological structure and species composition (Harris *et al.*, 1996). Restoration therefore commits to a long-term relationship of providing resources and managing natural capital once the process of rehabilitation is complete. Therefore, restoration focuses more on longer-term goals and inputs towards maintaining and building natural capital and thus pursuing sustainability, which, by definition, implies persistence over time. Harris *et al.* (1996), is at variance with the SER view on rehabilitation, stating that it pertains only to areas that were previously devoid of structure and function, that are then returned to some level of ecosystem structure or function, after which the rehabilitation process is complete. In these views then, rehabilitated systems are not automatically self-sustaining and have more limited contributions to natural capital and may require intervention to persist over time. Box 2.1 specifies how the oft-confusing restoration/rehabilitation terminologies are used in this study.

Box 2.1. Definitions of restoration, rehabilitation, revegetation and reclamation/reallocation, as used in this study

Restoration: repairing damaged ecosystems to a state conforming to pre-existing levels of structure, function and composition that can form an intrinsic part of the surrounding landscape (SER, 2004).

Rehabilitation: repairing damaged ecosystems to the most functional state as governed by the biogeochemical potential of the landscape matrix. Not necessarily to pre-existing conditions, but can yield self-sustaining ecosystems, perhaps with occasional input (Jackson *et al.*, 2006).

Reallocation/reallocation: repairing damaged ecosystems to a state different to the pre-disturbance state to suit a specific land-use designation. The pre-existing ecological integrity is not considered (Aronson *et al.*, 2007).

Revegetation: replanting selected indigenous or exotic vegetation on degraded/disturbed landscapes in order to effect restoration, rehabilitation or reallocation (Mains *et al.*, 2006).

2.2.2. Restoration of natural capital

The legislation as set out in the MPRDA could be confusing, as illustrated by the various definitions of sustainable development and the failure to differentiate between sustainability and sustainable development. A more appropriate concept, and one that is still in line with the existing legislation, is that of *restoration of natural capital*, a term proposed by Aronson *et al.* (2007). The restoration of natural capital recognises the existence and interconnectedness of the five principal forms of capital (Rees, 1995):

- Financial capital- various forms of money
- Manufactured/physical capital- man-made fixed assets and infrastructure
- Human capital- joint intellectual and physical skills of people
- Social capital- networks, institutions, organisations and groups
- Natural capital- the reserve of biological and physical resources, consisting of non-renewable resources, renewable resources and cultivated resources (Aronson *et al.*, 2006)

Restoration of natural capital has its roots in ecological restoration, but also considers the potential social impacts that restoration may bring about. It therefore incorporates all activities that involve replenishment of depleted or disturbed natural capital to enhance the flows and benefits of ecosystem goods and services, whilst promoting all aspects of human well-being (Aronson *et al.*, 2006). Therefore, restoration of natural capital has much potential in the South African mining industry where the end-land use objectives of rehabilitation must include tangible social benefits.

2.3. Background

The transformed grasslands of the South African highveld are home to some of the greatest concentrations of gold mines in the world (Mucina and Rutherford, 2006) but have potentially devastating environmental legacies (O'Connor and Kuyler, 2006). With large portions of this biome irreversibly degraded (Low and Rebelo, 1996), and its importance as a biodiversity centre and agricultural core, the need for responsible land management has become paramount (Hoffman and Todd, 2000). One area of land management that forms the focus of this study is that of rehabilitation. Whilst many authors consider that grasslands are extremely difficult, if not impossible to restore to full function (Snyman, 2003; van den Berg and Kellner, 2005), grasslands in states of developmental recovery may still be able to offer significant ecosystem goods and services to the surrounding landscapes (Milton *et al.*, 2003).

Mined land, in particular, is legally required to be rehabilitated and industry has the opportunity to manage such rehabilitation according to codes of best practice, such as the triple bottom line (Elkington, 1994). The triple bottom line (sometimes referred to as the three p's) refers to managing projects in such a way that benefits **P**eople, **P**lanet and **P**rofit. (1) 'People' can be addressed by continuous involvement and enrichment of surrounding or affected communities; (2) "Planet" can be addressed in rehabilitated areas' contribution to the conservation of limited natural resources; and (3) "Profit" is addressed by the proven financial liabilities of poorly designed closure plans (Kunanayagam, 2006).

2.4. The state of the South African grasslands

The highveld grasslands of South Africa are characterised by a ubiquitous single-layered herbaceous community, dominated in phytomass by tussocked grasses (Tainton, 1999). Contrary to general opinion, a variety of perennial, non-graminoid herbs make up the majority of species here, (van Wyk and Smith, 2001). In terms of biodiversity, the grasslands are amongst the richest in South Africa with ecologically intact areas harbouring 81 plant species per 1000 m^2 (Huntley, 1989), 53 % of our endemic birds occur here (Barnes, 1996), 14 % of all indigenous, threatened reptiles and amphibians occur here (Passmore and Carruthers, 1995), as well as 44 % of the endemic mammal species (Smithers, 1983). The majority of South Africa's river catchments arise within the grasslands, all adding to the importance of conservation of existing grasslands and the restoration of degraded grasslands. Grasslands tend to occur in some of the most productive agricultural soil and have therefore largely been transformed, stripped bare and cultivated, leading to concerns being raised over whether sufficient source populations and the required mechanisms for dispersal are sufficient for restoration (Cheplick, 1998; Campbell *et al.,* 2003). Without sufficiently large and geographically contiguous source populations, genetic variability could decrease, compromising the ability of ecosystems to resist biological invasions and decreasing their resilience to recovering from disturbances (Holling, 1973, Folke *et al.,* 2004). As remaining habitat patches become smaller and more isolated, the more difficult it becomes for pollination, seed dispersal and colonisation to occur (Cheplick, 1998). It is these concerns that drives the urgency for all industries and activities that impact negatively on the grasslands to be regulated and for complete restoration to be attempted wherever possible.

The highveld grasslands of South Africa have the highest concentration of mines anywhere in the country (Mucina and Rutherford, 2006). Of these grasslands, less than 2.2 % is formally conserved and more than 40 % has been irreversibly transformed by agriculture and forestry (Low and Rebelo, 1996), although van Wyk and Smith (2001) estimate this as high as between 60 and 80 %.

2.5. Some mining impacts in the South African perspective

Estimates of South Africa's land surface directly affected by mining run to 200 000 ha (Fairbanks *et al.*, 2000) and are increasing with many new leases being granted every year. Mining affects terrestrial ecosystems through the disturbance and destruction of vegetation and soil (Milton, 2001) and burial beneath mine waste products at designated sites (Cooke and Johnson, 2002), often called the TSF footprint. Although production from the mining sector has increased in the past four decades, gold mining has decreased in its importance to the national economy (Stilwell *et al.*, 2000). In the North-West Province, which contains the study site, the mining sector is the major contributor to the provincial economy, constituting 42 % of the gross geographic product (GGP) (North-West State of the Environment Report/SOER, 2002). The GGP is an indicator of the total contribution of an individual province's economy to the Gross Domestic Product (GDP). The North-West province's gold mines deliver 25 % of the national production and employ 39 % of the province's active labour force (North-West State of the Environment Report, 2002).

2.5.1. The nature of tailings

Mine tailings, or mill tailings, are a waste product of metalliferous ore extraction (Blight, 1989). Tailings is that waste which remains after beneficiation or mineral extraction and is usually a uniform, silt-sized medium lacking both a wide particle size distribution that natural soils possess and soil structure (Clausen, 1973; van Deventer and van der Nest, 1997). This lack of structure and uniform particle size, in addition to complete lack of organic material, presents a physical growth medium with very poor water retention capacity (Evans, 2000). The poor structure and uniform texture also cause tailings to be prone to physical crust formation (van Deventer and van der Nest, 1997) and compaction with the associated poor aeration (Weiersbye *et al.*, 2006). Furthermore, tailings are often stacked at their natural angle of repose (ca. 35°) and with long slope lengths, further decreasing their infiltration capacity and increasing run-off rate and hence susceptibility to erosion.

Chemically, the tailings contain little or no macronutrients due to lack of clay and/or organic matter and thus have a very low cation exchange capacity (Krzaklewski and Pietrzykowski, 2002). Most tailings, especially gold tailings, have an acidic pH and are associated with high aluminium and manganese concentrations (Winterhalder, 1995). Even though tailings may not be acidic at the time of stacking, most gold tailings contain 1.5-3.5 % pyrite, which oxidises rapidly and can drop pH levels from as high as 8 to as low as 2 within a period of months (van Deventer and van der Nest, 1997). Low pH values (1) increase the solubility of aluminium, manganese and iron, which have the ability to cause toxicity (along with cadmium, arsenic, copper, lead and zinc) (van Deventer and van der Nest, 1997); (2) reduced availability of most essential plant nutrients or plant-assimilable forms thereof (Weiersbye *et al.*, 1999); (3) cause immobilisation of some nutrients, such as phosphorous and potassium; and (4) results in impoverished soil microbial communities with high mortality rates, especially for the beneficial arbuscular mycorrhizal fungi (Straker *et al.*, 2006), and disproportionately high iron and sulphur oxidising bacteria, which have been shown to contribute to poor plant survival (Schippers *et al.*, 2000).

General practice is for tailings material to be deposited within a contained series of elevated embankments, forming high-walled dams known as TSF's, which typically have steep slope angles (Weiersbye *et al.*, 2006). The tailings is pumped as a slurry to the TSF, where it dries out. As mentioned, the elevated positions of TSF's make the tails prone to aeolian dispersion (Gonzalez and Gonzalez-Chavez, 2006). A self-sustaining vegetation community of certain structure is needed to improve dust suppression and to decrease the erosion potential of the structures and the release of contaminants (Weiersbye and Witkowski, 1998).

Due to the chemical nature of most gold tailings being unsuitable for plant growth or microbial habitation, the general practise has become the amelioration of the upper 30-60 cm of tailings strata (Erasmus, 1998). Amelioration is primarily aimed at neutralising excess acidity by the application of agricultural lime (Ca/Mg CO_3) (Envirogreen, 2000), but may also include the application of chemical fertilisers and incorporation of mulch or sewerage sludge (van Wyk, 2002). Most often, no topsoil or cladding is used on gold TSF slopes. A mixture of indigenous and exotic pasture grasses is then sown to achieve dust suppression and for phtyostabilisation of the tailings material (Weiersbye *et al.*, 2006)

2.5.2. Some negative impacts of mining

Mines in the North-West Province are responsible for many environmental hazards. The provincial State of the Environment Report (SOER, 2002) lists particulate matter (mostly airborne tailings dust), asbestos fibres, heavy metals, odours and noise as the mines' role in air pollution. The report also acknowledges the threat that radiation and radioactivity from the uranium deposits associated with gold reefs poses to people and the environment. This uranium is often extracted during mining and may end up in tailings and other waste material, too often ending up in stream and groundwater systems (Winde, 2001; Winde *et al.*, 2004). Mines also negatively impact on water resources through Acid Mine Drainage (AMD), salinisation and effluent discharge (North-West State of the Environment Report, 2002). Soil pollution, too, is a significant problem in areas surrounding TSF's, but it has received less attention than water pollution (The negative impacts of mines can spread far beyond the disposal sites or lease properties (Weiersbye *et al.*, 2006).

Other specific negative environmental impacts of gold mines are (1) acid mine drainage (AMD), (2) salinisation and sodification, (3) erosion and sedimentation, (4) cyanide contamination and (5) air pollution (van Deventer and van der Nest, 1997):

(1) AMD occurs when sulphide-containing moist mine wastes (such as tailings or ore) are exposed to oxygen. The resulting oxidation lowers pH values markedly, causing dissolution of metals, a reaction catalysed by bacteria. AMD's greatest effects are on seepage and surface runoff which may accumulate at the bottom of slopes as much as 50 years after the initial oxidation (Rosner *et al.*, 2000).

(2) Salinisation and sodification are the other major factors influencing water quality and residues on soils or tailings. Gold tailings is handled, transported and stored in slurry form. When the water evaporates, salts precipitating on the soil surface could form a salt crust, but generally they would improve soil friability, structural properties and water and nutrient uptake by plants (by increasing the osmotic potential) (Zhu, 2001). The problems experienced under such saline conditions are exacerbated by high levels of acidity (van Deventer and van der Nest, 1997). These salts are highly mobile and can cause contamination far away from the mine site.

(3) Due to the extreme (30°) slopes of TSF's, a very high ratio of runoff: infiltration exists, with runoff water gaining kinetic energy as the slope lengths increase. Gold tailings material is made up of fine particles that have very low self-coherence and are thus very prone to erosion on these steep slopes. This is evidenced by the formation of alluvial fans (sedimentation) at the toes of TSF slopes. During exceptional rainfall events, the penstocks designed to control storm water sometimes break, resulting in tailings material spilling into adjacent areas and clogging drainage lines (e.g. Merriespruit disaster in 1994 where tailings from a TSF failure engulfed a town and killed many people). The high levels of erosion and sedimentation create a harsh environment for plant establishment and persistence. Exposed tailings are able to be spread over tens of hectares by means of aeolian dispersion and water erosion (Gonzalez and Gonzalez-Chavez, 2006).

(4) Cyanide contamination occurs when crushed or ground ore contains high levels of other metals (Korte and Coulston, 1998). The cyanide that is used to extract and accumulate gold is then passed on to the tailings waste where, when it comes into contact with an acidic environment, it becomes volatile and is released as hydrogen cyanide gas (Korte and Coulston, 1998).

(5) Air pollution is one of the more evident forms of environmental contamination emanating from gold mines and tailings sites. The fine-grained tailings material is very prone to becoming airborne during windy conditions. This is most pronounced where there is no soil organic matter to lend structure to the tailings or vegetative cover to reduce wind speed at ground level. Windborne tailings material can be transported great distances (van As *et al.*, 1992; Mizelle *et al.*, 1995) and deposited anywhere downwind, including undisturbed areas, municipal areas and agricultural areas (Pierzynski *et al.*, 1994).

Chemical flux is an inherent problem in gold-tailings (van Wyk, 2002), partly due to the presence of unstable pyrites, and traces of Uranium (van Wyk, 2002; Londry & Sherriff, 2005, van As *et al.*, 1992). Instability in the chemical constituency of the substrate has obvious effects on vegetation establishment, but it is not the only challenge that faces a recently germinated seedling on a tailings-dam. The effects of slope and aspect (Bennie *et al.*, 2006), irregular rainfall (Tainton & Hardy 1999), and nutrient availability and cycling all play roles that determine the vigour and resilience of colonising plants (Tainton & Hardy, 1999).

2.5.3. Some positive impacts of mining

The negative environmental impacts of mining are often offset against the benefits to the local economy, social development and the potential for restoration of mined land. Since the 1980's, the South African mining sector has contributed an average of 10.64% to the GDP, although since 1990 the figure has varied between 6.5% and 9% (Mabuza, 2006). Gold exports have made up 23% of all primary mineral exports by the mining sector and gold mines employ 36% of the estimated 443 300 people employed by this sector (Mabuza, 2006). South Africa also has 40% of the world's Gold Reserve Base and generates 13% of the world's annual production, making it both the top ranking producer and potential supplier (Mabuza, 2006; Stilwell *et al.*, 2000). In terms of positive social impacts, some mining companies, such as Richards Bay Minerals, have integrated social development and responsibility agendas that actively address the concerns of local communities (Kapelus, 2002). These may include the training and empowering (capacity building) of previously disadvantaged communities, the building and staffing of support infrastructure such as schools, clinics, and also entrepreneurial activities (Hamann, 2003).

Mining often goes hand in hand with research and technological development (Landes, 2003). These lead to advancements that positively influence the everyday lives of people. Although most mining has in the past been portrayed as a greedy industrial concern that seeks development and economic gain without considering environmental and social implications, the global climate is shifting. Increased pressures by conservation and legislative groups and increased internal environmental priorities have resulted in many mines developing biodiversity action plans (Mohr-Swart, 2008). For example, Rio Tinto PLC has mandated having a net positive impact on biodiversity within its sphere of operations (Rio Tinto, 2004). This effectively means that they are committing to leaving a legacy of ecosystems that are ecologically superior to the (most often) degraded conditions prior to mining.

These GDP figures serve to illustrate the importance of the gold mining industry to economic and social development and the future role that it will play in developing South Africa in the global context. Therefore, the surface of land disturbed by mining and the amount of waste generated is likely to increase into the foreseeable future (Fairbanks *et al.*, 2000). This has resulted in the increased need for meaningful rehabilitation and, where possible, full ecological restoration (Aronson *et al.*, 1993; Hobbs, 2003; Mitsch, 2008).

2.6. Rehabilitation policy and theory in South Africa

South Africa has some of the most advanced and comprehensive environmental legislation in the world (Weiersbye *et al.*, 2006). The country's highest legislative script is our Constitution (Act 108 of 1996), which allows for the right of every citizen to live in an environment that is not harmful to their health or well-being, which paves the way for many more Acts. Of these, the overarching National Environmental Management Act (Act 107 of 1998) dictates the application and enforcement of the Minerals and Petroleum Resources Development Act (Act no 28 of 2002). This Act is ultimately of most concern for mines, as it dictates the requirements for closure and serves as a guideline for planning rehabilitation and monitoring in order to demonstrate sustainability. Only then will a closure certificate be granted and the company released from financial and legal responsibility through mine closure.

The rationale for most mines' rehabilitation plans is to achieve closure through legal compliance. The requirements of the Minerals and Petroleum Resources Development Act (Act no. 28 of 2002) for rehabilitation will be discussed later in greater detail but in summary it prescribes how mines are compelled to rehabilitate disturbed lands in order to attain closure and be released from legal liability. Apart from the MPRDA, there are other parts of South African legislation that require the polluter to pay for costs relating to environmental damage (presented here in order of legislative prominence):

- Our Constitution's Bill of Rights (chapter 24; Act 108 of 1996) gives citizens, "The right to an environment that is not harmful to their health or well-being".
- The National Environmental Management Act (NEMA; Act 107 of 1998) embraces the 'polluter pays principle' and stipulates responsibilities for cleanup both on and beyond mining lease areas. It is also intended to ensure that all potential impacts of development are considered before mining or operation permits are granted and that mitigation measures have been put in place.
- The MPRDA, which entails the allocation of mineral rights, specifically to the expansion of opportunities for historically disadvantaged persons, as well as the proviso that mining be conducted in a sustainable fashion by integrating social, economic and environmental factors.
- The Environmental Conservation Act of 1989 provides for 'the effective protection and controlled utilisation o the environment' and requires regular reporting from mines on the state of their impacts.
- The Conservation of Agricultural Resources Act (CARA; Act 43 of 1983) and the National Water Act (Act 36 of 1998) both require that no contamination may flow from mines into rivers or underground aquifers. The CARA also requires the maintenance of the productive potential of land, through combating erosion and the protection of vegetation and combating of weeds and invasive plants.
- The National Environmental Management Air Quality Act (Act 39 of 2004) compels mines to prevent air pollution.
- The Promotion of Access to Information Act (Act 2 of 2002) grants a requester the right to access to records of private bodies, which could be detrimental to the image of mines that do not meet environmental standards.

All of these pieces of legislation pertain to relevant aspects of mining activities and dictate the ways in which mines must go about rehabilitation.

Mines may also achieve recognition for high standards of environmental management by receiving awards of high standards from local media (e.g. Mail and Guardian's Green Awards), non-governmental organisations (NGO's; e.g. BirdLife South Africa's Owl Awards) and international bodies (e.g. ISO 14000 series accreditation). All of these awards mentioned have been conferred upon mines, thus bringing their positive rehabilitation impacts into the public eye.

There is a growing awareness of environmental consciousness and stewardship from the local and international community, NGO's and various government departments, such as Agriculture, Water Affairs and Forestry and Environmental Affairs and Tourism. This places more pressure on mines to rehabilitate and mitigate all potential environmental impacts (Bailie, 2006).

In Australia and New Zealand, the Australia-New Zealand Mining and Energy Council (ANZMEC) has released their Strategic Framework for Mine Closure (2000), in which they outline best practices for rehabilitation. These best practices are not guidelines, but rather specify in general terms the need for adequate planning, financial provision, environmental standards and research. It also calls for an agreed set of indicators that are able to display successful rehabilitation. Most mines in that region use this framework as it strengthens their case for closure. There is no such single document in South Africa that encompasses the cradle to grave concept, although Bailie (2006) presented such a framework in her M.Sc thesis. The South African Chamber of Mines also released their Guidelines for the Rehabilitation of Mined Land (2007), but this is still too new to have been implemented by many local mines.

2.6.1. Rehabilitation and the Minerals and Petroleum Resources Development Act

Fortunately, environmental consciousness and regulations are growing along with the industry and significant progress has been made in legislation under the provisions of the National Environmental Management Act (Act no. 107 of 1998) and the MPRDA (Act no. 28 of 2002). Under the regulations of the MPRDA every mine is required to address latent and residual pollutant impacts (see Box 2.4) on the environment and that an end land-use conforms to principles of sustainable development before their sites can be considered for closure. As mentioned in the previous section, the MPRDA regulates the application for and granting of mineral and prospecting rights, but it also governs the financial provision for rehabilitation, provides the framework in which rehabilitation must take place and, lastly, that monitoring be carried out and performance assessments of the Environmental Management Plan (EMP) be conducted.

Box 2.2: Sustainable development

1. One of the older and best-known definitions of Sustainable Development was supplied in the Brundtland Report (World Commission on Environment and Development, 1987), worded, 'Development that meets the needs of the present without compromising the ability of future generations to meet their own needs'. This definition was largely centred on anthropocentrism, focusing largely on the needs and interests of humans in trying to achieve a global equity by redistributing resources to poorer countries to stimulate economic growth across the globe.
2. 'Sustainable development is a collection of methods to create and sustain development which seeks to relieve poverty, create equitable standards of living, satisfy the basic needs of all peoples, and establish sustainable political practices all while taking the steps necessary to avoid irreversible damages to natural capital in the long term in turn for short term benefits by reconciling development projects with the regenerative capacity of the natural environment' (US Partnership for Education for Sustainable Development, 1995).
3. 'Sustainable development is a continuing process of mediation among social, economic and environmental needs which results in a positive socioeconomic change that does not undermine the ecological and social systems on which it is dependant. Its successful implementation requires integrated policy, planning, and social learning processes; its political viability depends on the full support of the people it affects through their governments, their social interests, and their private activities' (Carly and Christie, 2000).

Many countries' legislation (Australia, U.S.A., Canada, Japan) require that reconstructed TSF's and other waste sites must resemble the surrounding landforms and blend in with the natural topography (COCHILCO, 2002). There are no such requirements in South African legislation. The reconstructed landforms can take any shape or size as long as they align with the predetermined final land-use designation. As mentioned, this land-use designation must contribute to sustainable development. The term 'sustainable development' is often bandied about by regulatory officials and rehabilitation managers alike, but there is often confusion regarding the term 'sustainability'. Appropriate definitions of sustainable development and sustainability are presented in Boxes 2.2 and 2.3 respectively.

Box 2.3: Sustainability

1. "A sustainable process or condition is one that can be maintained indefinitely without progressive diminution of valued qualities inside or outside the system in which the process operates or the condition prevails" (Holdren *et al.*, 1995).

2. "Sustainability is the use of the biophysical environment by humans in such a way that its productive function remains indefinitely." (Matthews, 2003).

Given these widely accepted definitions of sustainability and sustainable development, confusion arises when the phrases are incorrectly and interchangeably used. Sustainability is rather only an essential element of sustainable development. It involves the first successful criteria for sustainable development, that the needs of future generations aren't compromised through our unsustainable practises of resource exploitation. It is inseparable from the development aspect, as the three tiers of sustainable development (economic development, social development and environmental protection) cannot function independently, or without sustainable principles. Sustainability is also only a measure of sustainable development. It is useful for quantifying the status and goals of the development process, and is thus one of the key elements that need to be addressed in rehabilitation planning.

Box 2.4. Latent and residual environmental impacts

Latent impacts: those environmental impacts that may result from natural events or disasters after the issuing of a closure certificate. For instance floods/ intense storm events, fires, disease, insect swarms or acidification.

Residual impacts: the environmental impact that remains after issuing of a closure certificate. For instance heavy metal toxicity, groundwater pollution, radioactivity, acid mine drainage and fugitive dust emissions.

2.6.2. End land-use designations

As part of its Environmental Management Plan (EMP), every mine has to indicate how it is going to rehabilitate affected landscapes, and what their goal is regarding final land use. Different EMP's have different final land-use designations, due to the varying nature of environmental impacts, and thus the potential for restoration and productive use. Whatever the final designation, the MPRDA stipulates that it must conform to the concepts of sustainable development. This means that technology and research must be integrated with policy in order to advance socio-economic benefit whilst maintaining or enhancing ecological integrity. These land-use types must be free of hazards to the environment and to the people who will make use of it (MPRDA, 2002).

Van Deventer (2003) lists the following end land-use possibilities for gold tailings complexes in grassland and mixed grasslands:

1. Wilderness areas (most commonly included in EMP's)
2. Forestry land cover
3. Farming which can include:
    i. Commercial dryland crops
    ii. Irrigation crop production
    iii. Intensive farming (established and scientific plant production)
    iv. Emergent farming (opportunistic or subsistence plant production)
    v. Game/live stock
4. Landfills
5. Construction material
6. Wind/solar power generation
7. Recreation/entertainment
8. Development for:

i. Industrial
ii. Residential
iii. Graveyard

Wilderness areas are most often listed by mines as they pose the least risk with the lowest financial output (Nieman and Merkin, 1995). Agriculture on contaminated land is fraught with health hazards due to the presence of cyanide, mercury, and uranium (Winde, 2001). This is therefore a much higher-rated risk activity and is seldom pursued except where monitoring has proven that all latent environmental hazards have been addressed. Furthermore, urban service-related options (4-8) do have some promise, but supply of contaminated land may outstrip demand and is then, by definition, unsustainable in many circumstances. One of the most important aspects that must be kept in mind during TSF construction and revegetation is that all plans should endeavour to minimise the loss of land capability so that a wider range of end land-use types is available (Limpitlaw *et al.,* 2005).

2.7. Rehabilitation planning, monitoring and closure

2.7.1. Rehabilitation planning

The most important aspect of constructing a rehabilitation plan is to set appropriate goals and end-points for the rehabilitating areas (Pastorok, *et al.*, 1997). Rehabilitation goals are broadly expressed, whilst objectives are more specific and relate to the attainment of said goals. These objectives are important stepping-stones for establishing the successes or failures of various management activities and indicate where adaptive management may be required to reach those goals that were not achieved (Pastorok *et al.*, 1997). These goals must, however, be based on relevant and measurable parameters that can be compared with appropriate reference sites (Hobbs, 2003).

Ehrenfeld (2000) points out that the multitudes of restoration efforts (not limited to mining rehabilitation) in progress across the world often have vastly different goals to achieve. However, he does not advocate that universal goals be set for restoration, but rather that goals be flexible and set out realistically before the onset of operations. The goals that he reviews are restoration of species, restoration of ecosystem function and the restoration of ecosystem services, each of which should be seen as components or subsets in the greater restoration framework. All restoration treatments should strive to regain certain levels of ecosystem structure (species richness, diversity, and evenness), ecosystem function (nutrient cycling, ecosystem services) and aesthetic appeal. The importance of setting out rehabilitation goals stretches beyond the planning and implementation phases as it also dictates the monitoring framework. They specify which biogeochemical parameters must be measured in order to maximise monitoring outputs with the most efficient inputs (Pastorok, 1997; Hobbs, 2003).

Harris *et al.* (1996), distinguish between two groups of restoration endpoints, namely the 'soft' and 'hard' groups. The 'soft' group requires bioengineering and ecosystem re-establishment in which plants are the major component of end-use, dividing this group further into productive soft end-uses (agriculture, forestry, etc.) and amenity soft end-uses (nature reserves, educational/recreational areas, etc.). The link between the two groups is that, as end-points, they both have distinct conservation value. Harris *et al.* (1996) contrast this with the 'hard' end-use group that is strongly engineered and may contain no biotic component (and thus no conservation value), for example reservoirs, industrial development sites, etc. The degree of disturbance on mined sites and the extent to which the substrate has been ameliorated will dictate which end-use group is attainable for a specific site.

Planning for rehabilitation is a vital aspect of any holistic mine closure plan and encompasses the cradle to grave concept (Kunanayagam, 2006). The steps lain out in the rehabilitation plan are crucial, as they guide the type and frequency of monitoring and therefore the designated end land-use options. Cairns (1995) includes the following thirteen basic steps in the compilation of any rehabilitation or restoration plan:

1. Obtain assistance from experts and make use of multi-skilled and interdisciplinary teams. This facilitates comprehensive planning and reduces the chance of omitting critical aspects. Should include ecologists, biologists, engineers, soil scientists and social scientists;
2. Make sure that the goals and objectives are clearly defined and well articulated. Confusion as to what the objectives actually are will doom a restoration plan from the outset;
3. Conduct resource-inventories of all biotic and abiotic components at all the relevant sites. Establishing baseline data is critical for setting specific goals and trajectories for ecosystem

development. These species lists, distributions and densities, as well as physical landscape characteristics such as landforms, and geohydrology are critical in re-establishing ecosystem structure and function;

4. Prioritise goals. Many goals are facilitative to wider objectives, whilst others need to be completed as a sequential process. Success can be an important measure for support from detractors of a restoration effort;
5. Develop an exhaustive site plan. This is a framework plan that delineates areas and describes them based on their characteristics and requirements, and in a graphic form, such as a map;
6. Carefully consider the species selections. After the resource inventories, specific data should be available on the phenotypes and ecotypes most suited to the area. Sources of seed, designation of source areas and corridors must be considered thoroughly;
7. Develop a comprehensive, meticulous design for each delineated community/ecosystem type, which must include a spatial and temporal context. This will be the master plan that will be built on the framework plan mentioned in (5), but detailing more specific information. This information will be regarding ameliorant amounts and seed volumes all within a well-reasoned and realistic timeframe.
8. Prepare the site by means of physical reconstruction and chemical and organic substrate amelioration. This follows on from (7);
9. Administer the project implementation closely to ensure that the plan is followed;
10. Control exotic, encroaching, invasive and unwanted biota. This is to make sure that the integrity of the natural capital is not compromised, and that undue competition from alien species does not compromise the establishment of native vegetation;
11. Make use of ecological economists to enumerate the long-term benefits and costs. This is important to give management/accountants some concrete predictions on long-term benefits of high initial inputs that will ultimately increase the potential for successful restoration;
12. Develop a feedback plan for altering, redoing or correcting completed steps to ensure an effective process. These feedback loops must be operational in order to rectify any

shortcomings throughout the process or during the course of monitoring. The feedbacks must be designed so that alterations can be brought about timeously, before significant negative effects can take hold;

13. Develop a long-term plan for monitoring, management and maintenance. This is an important step that will ultimately dictate the success or failure of the restoration application. If monitoring does not take place, then problems will never be highlighted until they are too late for maintenance to rectify, leading to large capital expenditure and managerial nightmares.

The goals of rehabilitation (and restoration) programmes are often focused primarily on performance targets, such as a specific density or cover of desired species (Hobbs, 2003). However, these performance goals do not always consider their ecological outcomes. If the performance goals are based upon ecological threshold values obtained from appropriate reference sites, then this approach may be suitable, but rehabilitating mine sites are often characterised by lack of suitable reference sites (van Wyk, 2002). Therefore, more suitable measures for calculating whether the desired performance goals have ecological significance would be to monitor the vegetation changes in relation to analogue values and to track decreases in degradative processes (Hobbs, 2003).

Another important facet of a rehabilitation design is scale. The scale of rehabilitation projects relates to the temporal and spatial extent, as well as the levels of ecosystem detail that are pursued. The scale of rehabilitation and monitoring are often limited by financial constraints, but may also be limited by ecosystem complexity and the physical size of areas required to rehabilitate (Pastorok, 1997).

2.7.2. Monitoring planning

The significance of designing a robust, strategic monitoring framework cannot be underestimated, as all rehabilitation activities culminate in the ability of a mine to prove that it has complied with the previously stated legislative requirements to achieve closure. This means that a company can be released from further financial and legal liability. However, rehabilitation may take many decades or even centuries to achieve (De Angelis *et al.*, 1989). Therefore, in order to prove sustainability, good datasets must be presented in such a way, and within such a framework that shows the trajectories of ecosystem development over time and can track the recovery of the degraded system. Although rehabilitation goals may take many decades or centuries to achieve, relevant monitoring data can prove resilience and resistance in coping with environmental limitations and stochastic disturbances (De Angelis *et al.*, 1989). Resilience in recovering from periodic disturbances (such as fire, droughts, overgrazing and anthropogenic disruptions) is essential for sustained ecosystem development and progression or maintenance of ecosystem structure and function (SER, 2004). So too, in terms of resisting biological invasions and aiding facultative interaction between different trophic levels in the microbial community (Straker *et al.*, 2006). The monitoring programme must be structured in such a way that it relates the performance of the rehabilitating landscapes to its biogeochemical potential, and to the potential of surrounding landscapes.

Morgenthal *et al.* (2001) consider that the monitoring of rehabilitating and revegetated areas is a relatively new concept, and that although many of the ecological principles used in agro-ecological systems should apply to rehabilitating mine waste, there may be other attributes that are better able to indicate ecosystem development and rehabilitation success.

2.7.3. Monitoring techniques

Herbaceous layer monitoring

Conventionally in South Africa, a mixture of alien and native pasture grasses are sown in the ameliorated tailings or topsoil covers to act primarily as a stabilisation (combating erosion) and dust suppression (combating air pollution) system (Chamber of Mines, 2007). A recent industry guideline suggests that this type of herbaceous layer will be adequate for TSF closure (Chamber of Mines, 2007), which implies that the pasture grass layer should be able to drive the ecological processes that govern the availability of ecosystem goods and services (Bell, 2001; Aronson *et al.*, 2006). These goods and services are crucial for perpetuating ecosystems in which there are sufficiently organised biotic components to maintain ecosystem development (Aronson and Le

Floc'h, 1996). Conventional criteria for determining that grassing contractual obligations have been met on South African mine tailings in general have focussed mostly on investigations of basal cover and species richness (Chamber of Mines, 2007). This was largely due to the requirement that dust control by a grass sward must be demonstrated at contract handover. Tongway (pers. comm.) considers the vegetation on gold TSF's to be a thin veneer overlying materials with contaminants and other dis-beneficial properties that displays only the current and recent state of the biologically active upper 10-15 cm of tailings strata.

Therefore this biocentric approach, whilst being well-established and reasonably rapid and cheap, is not necessarily sufficient to prove sustainability to regulatory authorities. This does not mean that it is obsolete, but rather that it must form part of the broader ecological framework to include ecological processes and not just transient symptoms. The monitoring of pasture grasses' attributes is however considered insufficient for establishing ecosystem development or indicating changes in landscape function (Herrick *et al.*, 2006). Adding aspects of landscape function to the monitoring regime allows for the conventional monitoring methods of basal cover and species abundance to be supplemented by more informative techniques. One such technique is that of Landscape Function Analysis (LFA) (Tongway *et al.*, 1997), a method developed in Australian rangelands that has shown good application in investigating the recovery of revegetated post-mining landscapes.

Chemically-focussed monitoring

Fortunately at many mines the chemical variation in tailings material is also monitored in addition to monitoring vegetation performance (e.g. van Wyk, 2002; Witkowski and Weiersbye, 1998). Whilst the two are inextricably linked in both agricultural and ecological systems, van Wyk (2002) argues that the perceived link does not necessarily extend to mined land. Whilst he considers that the governing ecological principles are the same, tailings material is so alien a growth medium that the chemical interactions and how these change over time are still poorly understood and vary hugely over space and time. However, performing routine chemical analyses of the tailings material is useful for establishing what ameliorative actions need to be taken to make tailings more hospitable for vegetation establishment. It is also useful for establishing fertiliser and liming requirements, as well as detecting problematic situations, such as the accumulation of toxic compounds or increases in salinity or sodicity (Mitchell *et al.*, 1999). For these reasons, chemical monitoring is an integral part of any rehabilitation monitoring programme, but such data must be incorporated into advancing biological development. However, chemical data remains insufficient in itself, as soil biology is usually omitted from the analyses.

2.7.4. Reference sites

Investigating rehabilitation success is dependent on measuring ecosystem change in relation to values obtained from a predefined reference site (also called benchmark or analogue sites). Reference sites are initially important for rehabilitation planning, but later become essential in evaluating the degree of rehabilitation success (SER, 2004). These reference sites are areas of natural vegetation that have not known to be degraded and that exhibit high levels of ecosystem function for the regulation of goods and services (Herrick *et al.*, 2006). The selection of reference sites is an essential step and in the rehabilitation of mined land they must be linked to the end land-use objectives. For example, if the site is to be restored to full ecological integrity, then a reference site must be identified that corresponds to climatic, geological, chemical, pedological, hydrological, topographical and biological facets of the desired target ecosystem (SER, 2004). Reference databases of biotic community structure (and changes therein) should be kept from the onset of mining operations. In the rehabilitation of uncapped gold tailings, full ecological restoration is seldom realistically possible, due to the severe limitations brought about by the substrate quality (Herrick *et al.*, 2006). In such cases, a desired reference ecosystem should be selected that is both attainable through the goals of the rehabilitation project and relevant to the end land-use objectives. Where no such reference sites that correspond to the biogeochemical setting of the rehabilitated area occur, certain aspects may have to be substituted from the most functional sites available (for example, slope and chemistry) (Cairns, 1993). This is similar in practise to veld condition assessments where, in the absence of suitable reference sites, the site that displays the highest condition values would be selected as a pseudo-reference, with the shortcomings clearly identified (Bothma *et al.*, 2004).

It is also important to understand the site-specific impacts of mechanistic and stochastic disturbances on the rehabilitating ecosystems, so as to guide necessary pre-emptive or reparative management actions. Essentially, this involves the main purpose of monitoring, to serve as an early warning system to indicate potential problems before they get out of hand. It may be useful to quantify active rehabilitating sites and passive or spontaneous rehabilitation sites in relation to reference sites, in order to observe differential rates in developmental trajectories (Redi *et al.*, 2005). There are natural and artificial causes that drive heterogeneity in ecosystems and that thus contribute to the patchy nature of the landscapes (Turner and Chapin, 2005). Natural sources of heterogeneity arise from 1) the physical setting of a patch; 2) the biological agents and 3) the processes of disturbance and stress (Pickett *et al.*, 1997). The physical setting 1) is largely fixed, although in rehabilitating mine sites the potential for disturbances is at a scale which alters even these characters. The primary influential factor here is the substrate, which is one of the most important sources of environmental heterogeneity (Pickett *et al.*, 1997). Substrate dictates plant growth and thus habitat, which are characteristically patchy at all scales (Turner and Chapin, 2005). 2) The biological agents that cause heterogeneity in rehabilitating landscapes are the growth, interactions and legacies of some species (Pickett *et al.*, 1997). This could include the effects of a single organism, such as a big tree that alters microclimatic conditions in a relatively small patch, the effects of sporadic, nomadic groups of organisms, such as locusts or birds, or keystone species. 3) The processes of disturbance and stress in rehabilitating areas have similar effects (although not necessarily similar origins) to those found in natural areas (Archer and Stokes, 2000) and include droughts, fires and floods, whether induced by natural processes (i.e. excessively high rainfall) or human activities (e.g. creation of impervious surfaces, increasing runoff and concentrating storm water runoff leading to flooding during only moderately high levels of rainfall). Humans probably also play a direct role in creating disturbances on fragile rehabilitating sites, as was observed during this study where people and machinery routinely pass.

2.7.5. Ecological Indicators

Rehabilitation managers and minerals and energy regulators often have to deal with complex and deficient environmental data when required to make important ecological decisions that may have lasting effects (Primack, 2002). Much work has been done in recent years on the development of guidelines to measure various aspects of ecosystem health or performance (Westman, 1991; Cairns *et al.*, 1993; Andreasen *et al.*, 2001; Dale and Beyeler, 2001). These performance measures are called ecological indicators or parameters. Indicators are often very specific to types of ecosystem, but some robust, applicable indicators have been found to apply to many different ecological systems (e.g. LFA; Tongway *et al.*, 1997). Using ecological indicators to reveal levels of ecological processes or organisation and the presence or absence of keystone or facultative species is a far more efficient means of monitoring than measuring exact compositional parameters. Whilst indicators of plant composition can be important in monitoring mine rehabilitation, ecological process indicators may yield a more holistic view of rehabilitation progress (Herrick *et al.*, 2006).

An efficient monitoring system making use of ecological indicators should therefore stem from basic measurements that are able to indicate specific ecosystem attributes that, in turn, dictate the levels ecosystem goods and services (Herrick *et al.*, 2006). These indicators can also serve as early warning signals of environmental change and can be specific to different levels of biological organisation (Dale and Beyeler, 2001). In fact, Noon *et al.* (1999), postulate that the main assumption in the use of ecological indicators is that the levels of changes in measured indicators signifies the changes that are happening at different levels of biological organisation. Therefore, the scale of monitoring must be explicitly stated when selecting a set of indicators so that they can be relevant to the performance measures required for evaluating rehabilitation objectives. For monitoring large scale rehabilitation projects, resources are most often limited and therefore monitoring changes in ecological processes at the landscape level may be most appropriate.

Pastorok (1997) lists the following specifications for ecological indicators:

1. Indicators should be physical, biological or chemical elements of ecosystem structure and function;
2. Indicators should be socially relevant, clearly connected to environmental values and responsive to individual or cumulative effects of stressors;
3. Indicators should be sensitive to various levels of stress, but not overestimate impacts resulting from natural levels of variation;
4. Indicators should require limited sampling effort and be cost-effective and have proven results in other monitoring programmes.

Some landscape processes, such as infiltration and runoff, are very slow and expensive to measure but can be evaluated using a combination of indicators (Herrick *et al.*, 2006).

2.7.6. The role of vegetation in landscape ecology

Regarding using landscape function as an indicator of rehabilitation success, and assessing the functional role that vegetation plays in ecosystem reconstruction, Harris *et al.* (1996), list many of the beneficial and adverse effects that vegetation has in restoration applications. The general beneficial effects are that they play an engineering function, increasing stability on disturbed substrates, decontaminate soils and allow other sensitive species to colonise, and lend an aesthetic or visual grace to an area. The beneficial impacts of vegetation are highlighted under hydrological (1-4) and mechanical (5-11) effects:

1. Vegetation cover means increased absorption efficiency and decreased evaporative losses. All organic matter increases the water retention capacity of a soil and thus decreases runoff and erosion.
2. Vegetation cover means reduced kinetic energy of raindrops and thus erodibility. Live plants and litter break the fall of raindrops and decrease the kinetic energy with which soil particles are displaced and erosion is advanced.
3. Litter and low-growing plants lead to increased roughness/complexity of soil surfaces. This creates a more complex microtopography, which reduces the strength of flow of runoff and allows greater soil-contact time to increase infiltration.
4. Decomposing plant material increases suction and soil strength. Organic material in the soil, especially in the rhizosphere, can enhance the movement of water and thus further decrease evaporative loss.
5. Roots bind soil, restraining soil movement and thus reducing erodibility.
6. Roots bind soil, increasing the shear strength of the substrate, an important consideration in restoration sites where soil strength and structure are often lacking and can lead to high erodibility.

7. Roots bind soil, even up to considerable depths, that can bind the substrata and restrain mobility in the substrata that could cause the topsoil to collapse or slide.
8. Roots can anchor in firm strata, even bedrock to enhance substrate stability.
9. Plant stems and buttresses lend uphill stability to the substrate directly up-slope of the plant or plant patch, also increasing stability and decreasing erodibility.
10. Vegetation cover and litter absorb the impact of traffic and retain soil structure and prevent capping or compaction, which would decrease infiltration, and increase runoff and erosion.
11. Vegetation that has been flattened by high-velocity water flows, like in the event of a flood, increases the soil cover and thus lends greater stability to mobile particles and decreases excessive erosion.

2.7.7. Landscape Function Analysis (LFA)

LFA examines how well a landscape is functioning as a biophysical system, using rapidly assessed soil surface indicators. These indicators focus on soil surface processes, rather than the presence, absence or abundance of selected biota, thus making the observed information different from many other monitoring procedures. LFA comprises three modules: a conceptual framework, a field methodology and an interpretational framework. The conceptual framework proposes a scheme looking at the fate of vital resources such as water, topsoil and organic matter, identifying potential accelerated losses and processes that retain those resources. The basis of the field methodology is the identification and description of landscape units that tend to accumulate resources (patches), or permit the loss of resources (inter-patches). The data outputs summarise (a) the organisation of the landscape at hillslope scale (pattern description) and (b) the soil surface condition of the patches and inter-patches recognised in the self-organisation step and a weighted mean representing whole-of-site values. These are expressly designed to be used over time to detect trends in the indicator values that are linked to ecological development, and to see to what extent landscape management objectives have been met. The various indicators that are measured during the soil surface assessments contribute in different ways to the three indices that best describe the functioning of the landscape as a biophysical unit: stability, nutrient cycling and infiltration. The LFA method is fully described in chapter 4

3.5. Site history

This site was originally known as the Stilfontein Gold Mine, and came into operation during June, 1952, once all infrastructure developments had been completed (Marais *et al.*, 2006). The starter walls for the tailings dams had been completed as early as the late 1940's. Mining activities, Gold production and the deposition of tailings material continued until June, 1993, whereupon all Gold production ceased. Uranium was also extracted at the Stilfontein Gold Mine between 1955 and 1970, after which a modernised Uranium production plant ran from 1971 to 1989 (Marais *et al.*, 2006). In the region of 3000 employees were retrenched upon cessation of the mining activities.

Very little surface rehabilitation took place prior to 1993, as was a common occurrence in South Africa at the time, due to poor environmental legislation and enforcement. At the time of cessation of mining activities, several vertical shafts, three rock dumps, four unrehabilitated tailings dams and many abandoned plants and buildings were left behind.

During the year 2000, Mine Waste Solutions intervened and committed to rehabilitate the entire site (with the intention of achieving closure), with proceeds generated from the reprocessing of some of the tailings dams for residual Gold and Uranium. With major technological advances in mining and metallurgy in the past two decades, reprocessing the tailings seemed feasibly lucrative to cover the costs of rehabilitation and generate sufficient profit. Reclamation of all surface infrastructure commenced in July 2003, concurrent with reprocessing, and has been completed in accordance with the closure plan. The rehabilitation of the tailings impoundments, old footprints and a spillage area have been undertaken and all initial work (soil amelioration, seeding) has been completed. A monitoring system was put in place to establish changes in the tailings substrate, vegetation species composition, and surface- and groundwater on the site. Active management of the tailings dams is being undertaken by Fraser Alexander Tailings (FAT), who also execute the necessary maintenance operations, such as reseeding, controlling exotic and invasive plants, and erosion control.

Although there is a fixed monitoring plan, monitoring appears to take place on an ad hoc basis by appointed consultants or researchers. Soil chemical analyses and herbaceous layer monitoring were supposed to take place annually, according to official documents, but in practice did occurred sporadically. Before this study was commissioned, the last herbaceous layer monitoring was

3.2. Climate

The total area of the Chemwes Tailings Complex is 1568 ha. Within this area, the focal zones of the No 5 dam, the No 4 dam (Figure 4.1), and the spillage zone, are 171 ha, 91 ha, and 78 ha respectively.

The area falls within the 400-600 mm rainfall isohyets, and receives 565mm mean annual precipitation and experiences cold, dry winters and hot, wet summers (South African Weather Services) (Figure 3.3). However, the 20-year period containing the present study period was relatively dry, achieving an annual average of only 468 mm. Most precipitation falls in the form of isolated spring and summer thundershowers. The mean annual potential evaporation is 2407mm (Mucina & Rutherford, 2006). During the study period, the two different growth seasons received vastly different patterns and amounts of precipitation. The 2006/2007 growing season received only 340 mm (Figure 3.2), 40% below the long-term average, whilst the 2007/2008 growing season received 642 mm (Figure 3.2), 12% above average.

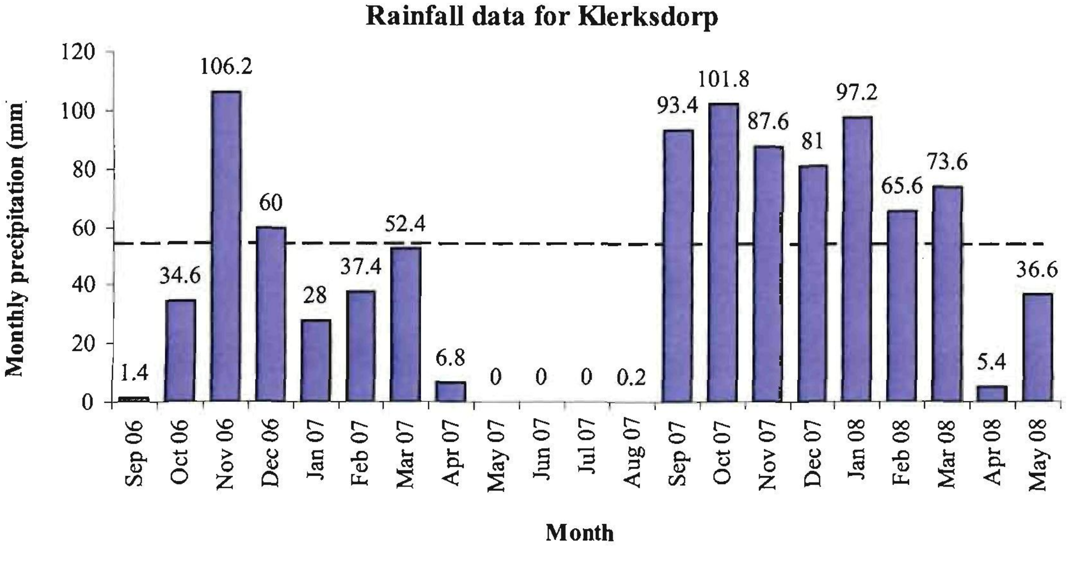

Figure 3.2. Monthly precipitation for the growth seasons of 2006/7 and 2007/8 at Klerksdorp weather station. Klerksdorp was the closest weather station, situated 14 km to the west of the study site. The dashed line indicates the average long-term monthly rainfall.

The mean annual temperature is 16.8°C, with a minimum average temperature of 9°C and a maximum average temperature of 24°C (South African Weather Services) (Figure 3.4). The average maximum temperatures during the study period were lower (22°C) than the long-term mean (24°C), but the average minimum temperatures were similar (9°C) to the long-term mean (9°C) (Figure 3.4 and Figure 3.5). The mean number of days with frost is 34 per annum. The mean annual soil moisture stress is 78%, which indicates the percentage of days in which the evaporative demand is generally more than double the soil moisture supply.

The climate is conducive to agriculture and pastoralism, with sufficient precipitation to sustain summer dryland crop production, as is evident in much of the surrounding landscape.

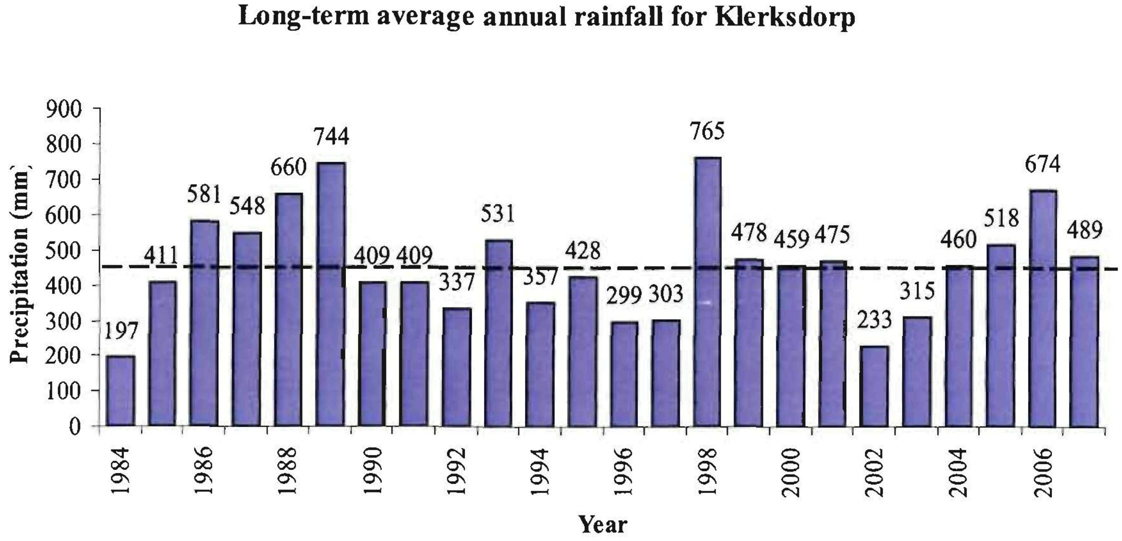

Figure 3.3. Annual precipitation at Klerksdorp weather station from 1984-2007. Klerksdorp was the closest weather station, situated 14 km to the west of the study site. The dashed line indicates the average annual rainfall of 468mm from 1984-2007.

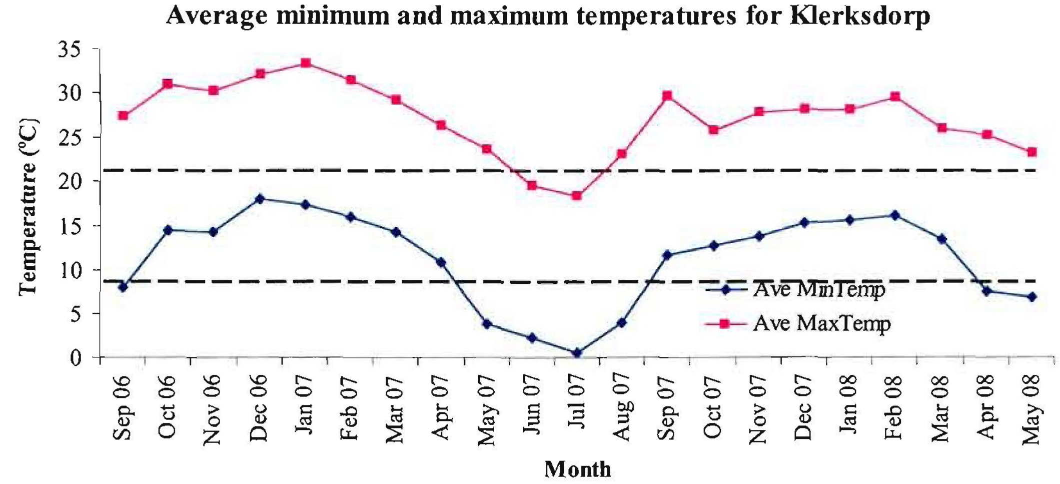

Figure 3.4. The average monthly minimum and maximum temperatures for Klerksdorp weather station during the 2006/07 and 2007/08 seasons. Klerksdorp was the closest weather station, situated 14 km to the west of the study site. The dashed lines indicate the average long-term monthly minimum and maximum.

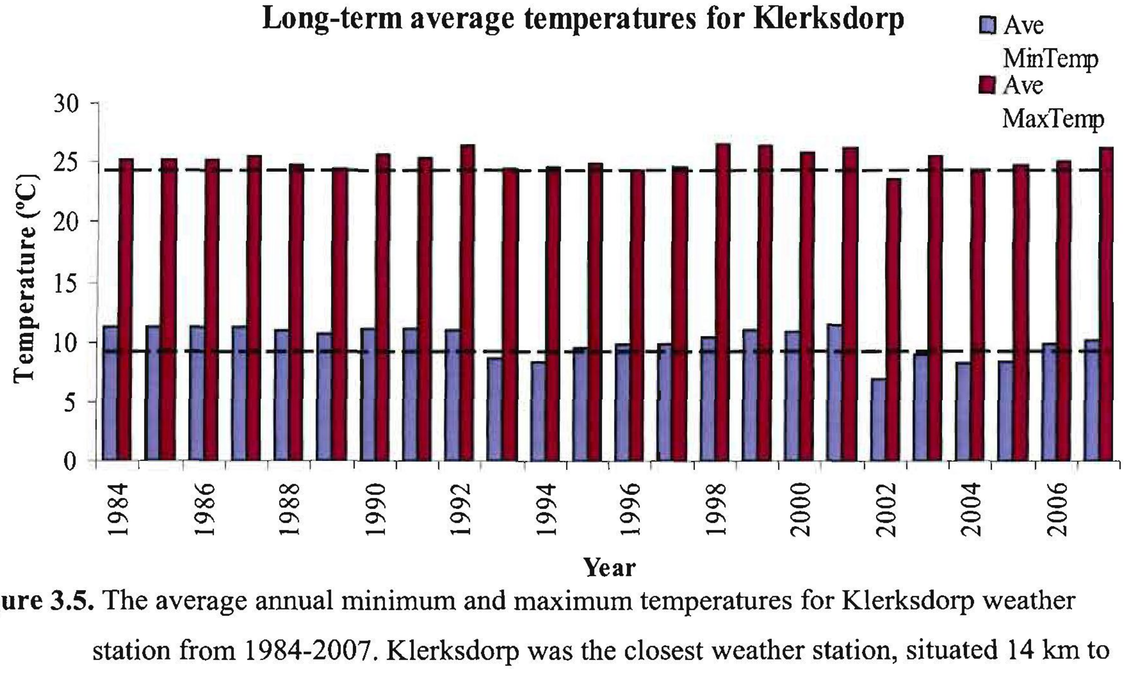

Figure 3.5. The average annual minimum and maximum temperatures for Klerksdorp weather station from 1984-2007. Klerksdorp was the closest weather station, situated 14 km to the west of the study site. The dashed lines indicate the average annual minimum and maximum from 1984 to 2007.

3.3. Geohydrology

The geology of the site is complex given the relatively small area. The underlying bedrock comprises the aquifer-rich dolomites of the Chuniespoort Group of the Transvaal Supergroup (van Deventer, 2003). There are also two intrusions in the form of a Kimberlite dyke, and a Pilanesberg dyke, the latter of which acts as a natural aquitard, dividing the site into two halves; an east-draining and a south-west-draining half. The soil forms are dominated by Glenrosa and Hutton types, with soil depth being a major limiting factor due to dolomite outcrops occurring throughout the upper horizons (van Deventer, 2003). The landscape is variable and not natural due to recent and current mining activities. The underlying geology is prone to sinkhole formation, and the aquifer-rich dolomites are potential avenues for groundwater pollution from mine waste. Penstocks have been constructed around the TSF's to contain any spillages or alluvial sediment deposition on the TSF toes as a result of erosion.

A seasonal stream, the Koekemoerspruit, flows in a north-south direction, approximately 2.5 km east of the tailings complex (see insert, Figure 3.1). This stream is a tributary of the perennial Vaal River, and yields very low runoff volumes, although this is supplemented by groundwater that is pumped from the old Stilfontein Mine to prevent flooding of the adjacent Buffelsfontein Mine (Winde, 2001). The Chemwes TSF facility falls within the catchment area of the Koekemoerspruit, making it prone to seepage-related contamination through dissolved contaminants, particularly uranium (Winde, 2001).

3.4. Vegetation

3.4.1. Natural vegetation

The vegetation of the tailings complex consists of a mosaic of rehabilitating, tailings dams, relatively undisturbed natural veld, and other areas disturbed by mining and related activities. The natural vegetation of the greater area is classified as belonging to the Gh12 Vaal Reefs Dolomite Sinkhole Woodland vegetation type of the Dry Highveld Grassland vegetation unit (Mucina & Rutherford, 2006) (Figure 3.1) at the fine scale; as *Cymbopogon-Themeda* veld (Acocks Veld Type

48) at the intermediate scale; and as fire-climax grassland of potential savanna areas (Tainton, 1999) at a broader scale. The natural grass sward composition here should be dominated by *Themeda triandra*, but is often unstable due to erratic rainfall and proneness to overutilisation, which has led to wide-scale changes in the structure of these grasslands. This results in the formation of bare soil patches in years of below-average rainfall and leads to invasion of these patches by *Eragrostis curvula, E. plana, Cynodon dactylon, Sporobolus africanus,* and *Aristida junciformis* (Mucina & Rutherford, 2006). The exclusion of fire here also leads to changes in the grass sward composition and *T. triandra* is replaced by unpalatable, perennial grasses such as *Hyparrhenia hirta* and *Cymbopogon plurinodis* (Tainton, 1999).

The tree component of this vegetation type is sparse and consists mostly of *Acacia erioloba, A. robusta, A. caffra, Diospyros lyciodes, Rhus lancea, R. pyroides* and *Celtis africana* (Mucina & Rutherford, 2006). These trees are mostly established along water drainage lines or where the effects of frost are less severe, such as at rocky outcrops (Mucina & Rutherford, 2006).

3.4.2. Revegetation

The dominant grasses occurring on the tailings dams are *E. curvula, Chloris gayana, C. dactylon,* and *Digitaria eriantha*, as these are the most common species used during the revegetation programme. Small numbers of other species have either been hand-planted, or have colonised naturally from the surrounding areas. *Cortaderia jubata*, a naturally-colonising grass, forms large tufts but is actively controlled through the use of herbicides.

Trees are reasonably sparse on the tailings dams, although alien species such as *Schinus molle, Melia azedarach, Eucalyptus sp.* and *Tamarix sp* proliferate. Smaller numbers of indigenous *Rhus lancea* and *R. pyroides* naturally colonise the slopes and are joined, on the lower slopes, by woody shrubs such as *Asparagus suaveolens* and *Stoebe vulgaris.*

3.5. Site history

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Although there is a fixed monitoring plan, monitoring appears to take place on an ad hoc basis by appointed consultants or researchers. Soil chemical analyses and herbaceous layer monitoring were supposed to take place annually, according to official documents, but in practice did occurred sporadically. Before this study was commissioned, the last herbaceous layer monitoring was undertaken during 2002. This study was commissioned as part of a performance assessment of the rehabilitating TSF's, as required by the EMP.

Chapter 4. Materials and Methods

4.1. Introduction

In order to accurately establish the current state and developmental patterns emerging throughout the different rehabilitating units, a synthesis of different procedures were necessary. The components of this monitoring procedure consisted of two interconnected components, namely the field procedures and analytical procedures. Due to the perceived link between vegetation cover and the ability of a landscape to function as a biophysical unit, the main focus of investigation was on the vegetation composition and the surface processes that influenced resource-flow in the landscape. Substrate chemistry on gold tailings can be unstable (Londry and Sherriff, 2005) and analyses were thus carried out to establish whether links existed with the observed landscape or vegetation performance.

There were thus four basic components of the field procedures. The first involved the stratification of the study site into discrete units based on their aspect, post-rehabilitation age, and site management history (anthropogenic influences). Unfortunately, some sites were destroyed between the two sampling efforts due to unplanned reprocessing of a section of one of the TSF's. The second component involved using Landscape Function Analysis (LFA) to characterise aspects of the stratified units in terms of their landscape organisation, soil function and soil erosion status. The third component involved the description of vegetation characteristics associated with each site. The fourth component consisted of collection of soil samples for chemical analyses of the soil profiles in each of the stratified units.

The analytical procedures differed slightly between LFA, vegetation and soil chemical analyses and are therefore treated separately under each heading.

4.2. Experimental design

4.2.1. Chronosequence stratification

As mentioned, the study area needed to be stratified into distinct, meaningful units. This guided the monitoring process, especially with regards to the development or retrogression of geochemical properties of the different unit types over time (Figure 4.1 and Table 4.1). Linking the monitoring data to comparable sites resulted in a clear trajectory of site characteristics.

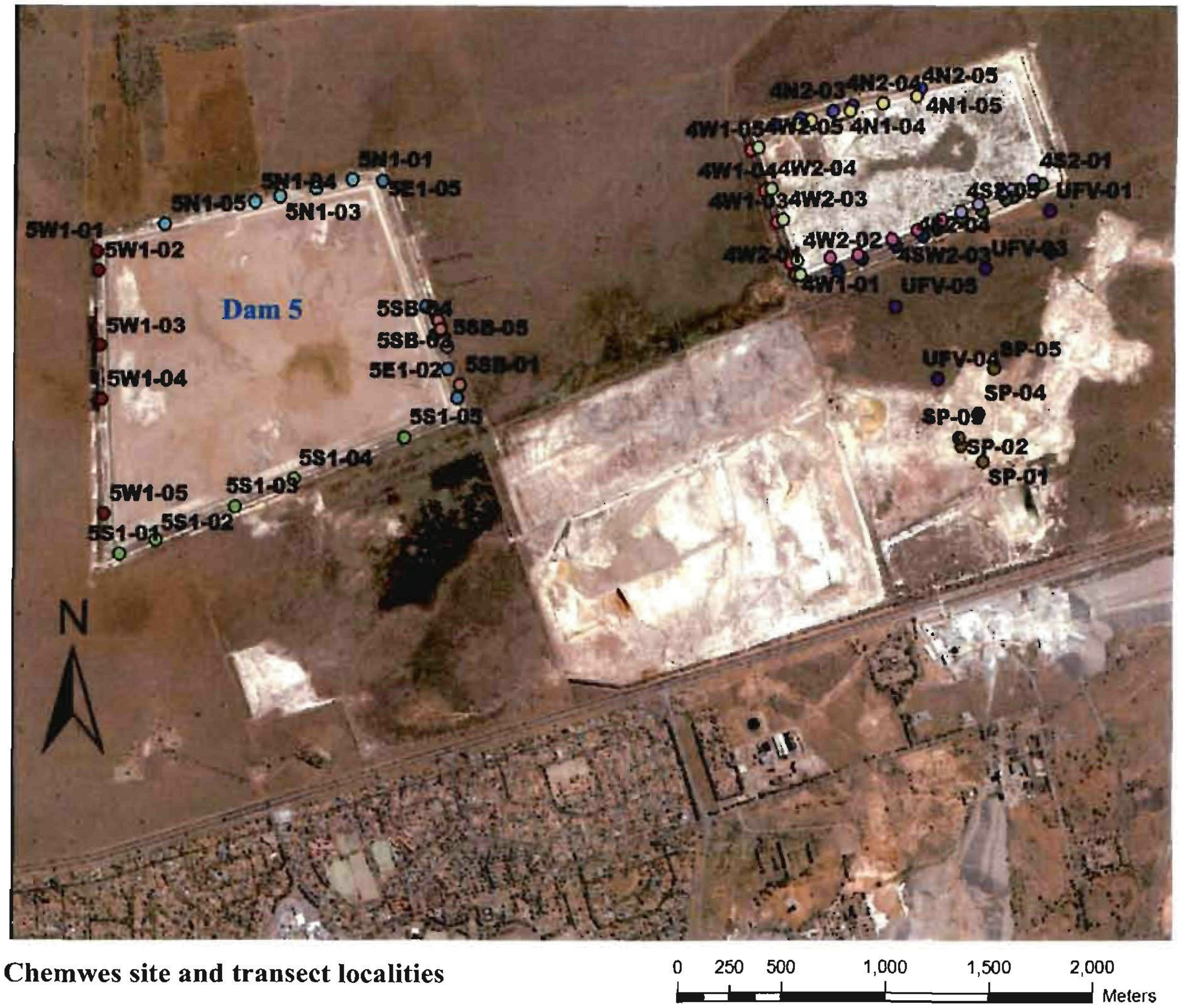

Figure 4.1. Quickbird ™ aerial photograph of the Chemwes Tailings Complex, showing the relative location of sample sites. Site names and abbreviations re explained in Appendix A.

The focal areas within the Chemwes tailings complex were the no 4 and no 5 tailings dams, and the spillage area to the east of tailings dam no 2 (Figure 4.1). For selection of study sites, the first level of stratification was aspect. Due to the southerly latitude, the inclination of the sun, abiotic characteristics such as temperature insulation, photoperiod and moisture relations were expected to vary markedly between aspects (Bennie *et al.*, 2006; Kawule, 2007). These variations then had direct influences on the vegetation associated with these different aspects (Bennie *et al.*, 2006). At the coarser scale (i.e. larger areas) there are differences in plant cover and often species composition, whilst the finer scale (i.e. more detailed) differences may be more subtle, altering phenological responses (Barbour *et al.*, 1998). The second level of stratification was based on the different age-units on the different aspects. The length of time that a unit has had to be subject to resource competition, soil processes and environmental factors post-rehabilitation will have an effect on the basic soil characteristics and vegetation responses. If plant succession does take place on these rehabilitating tailings, then we can expect to see different substrate-associated plant communities with some degree of likeness in similarly aged sites on corresponding aspects (but only if substrate chemistry is similar) . This likeness can be expressed in terms of species structure and the functional role of the vegetation community. The third level of unit stratification was based on the site management history, which described the anthropological influences to the site. This involved a further level of stratifying the already partitioned units into smaller subdivisions based on whether they were rehabilitated in different ways or at different times. Factors that were considered here were irrigation, the use of fertilisers, original tailings material (some of the tailings materials had pyrite extracted), the addition of Mycorrhyzae, areas that were reworked or reseeded, and soil ameliorants (as per Table 4.1).

The levels of stratification yielded a chronosequence of comparable units (Figure 4.2) that were similar enough to test their landscape function and compare vegetation composition. These units guided the sampling procedures, based on their locations and extent. Further analytical methods are applied to the data based on the chronosequence, indicating the associations between substrate-related and vegetation-related characteristics. Differentiation was made between sampling units and sample sites: a sampling unit comprised of several sample sites; i.e. 4N1-01 and 4N1-02 and 4N1-03 were all sampling sites within the sampling unit 4N1. In each instance, the sites were labelled with the tailings dam number first, followed by the aspect and slope number (from bottom up), and then the site/transect number. Thus 4SE2-05 was the 5th site/transect surveyed on the 2nd (upper) slope of the south-easterly section of tailings Dam 4. A full description of all site labels is given in Appendix A.

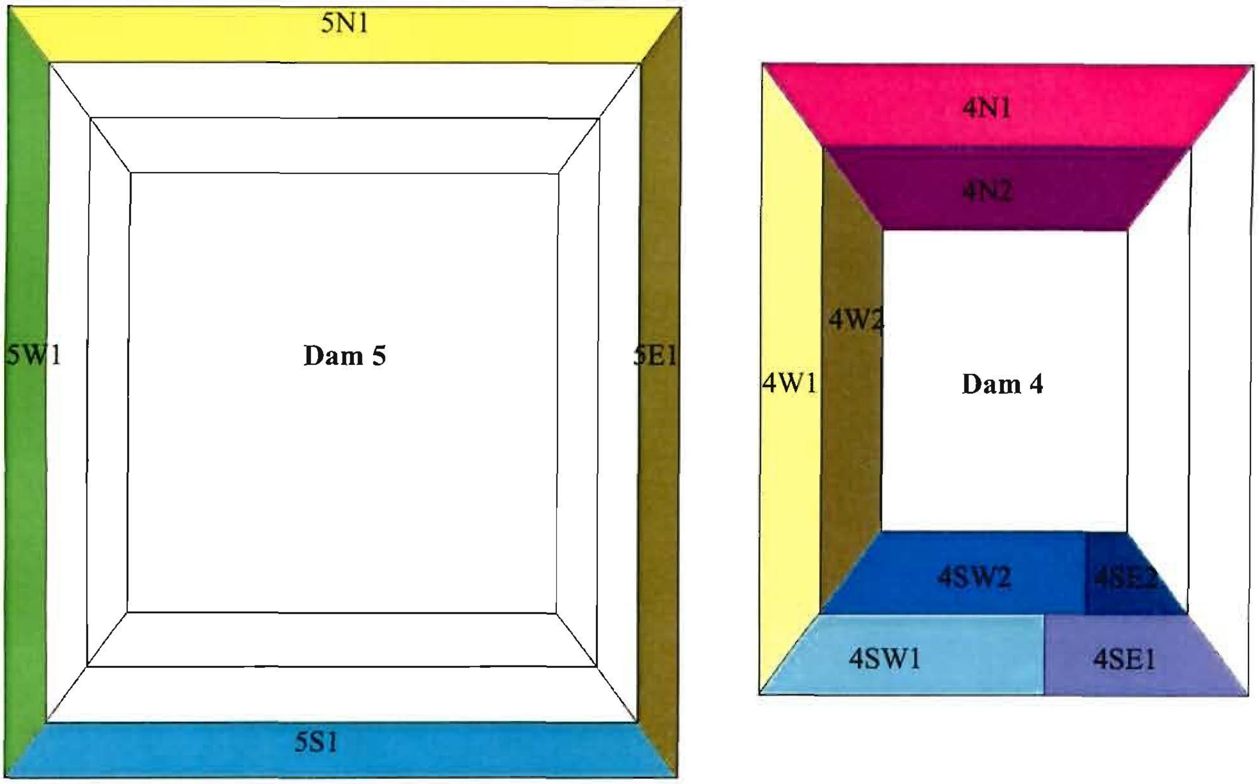

Figure 4.2. A schematic representation of the two tailings dams, Dam4 and Dam 5, depicting the different sampling units into which the dams were stratified (consult in conjunction with Figure 4.1 and Table 4.1). Site codes correspond to Appendix A.

TSF Dam 5

On Dam 5, the substrate was relatively homogeneous within the sampling units, as all tailings materials came from the same parent material and were deposited at roughly the same time. Only the lower tailings slope of Dam 5 was surveyed, as the upper slopes were either still being seeded, or were entirely unrehabilitated. The eastern portion of the starter wall of Dam 5 was also surveyed to test the proposition that this would be able to be used as an analogue site representing landscape function on appropriate landform, as the slope was identical to that of the tailings dams (35°). The homogenous nature of the tailings facilitated progressive rehabilitation of this dam, resulting in a narrow chronosequence of rehabilitating areas that were between 12.5 and 13 years old (Table 4.1). Identical amounts of calcitic lime ($Ca(Mg)CO_3$) had been added to all aspects of the lower slope of Dam 5 as an ameliorant to rectify acidity. Applications were done by hand, due to the extreme slopes, which may have resulted in less precision in terms of coverage, depth and extent of mixing. This may also have had knock-on effects through having unincorporated, concentrations of lime in the tailings profile and may have contributed to the inconsistencies experienced in soil sampling (see section 5.5). Similarly, identical amounts of fertiliser were applied, and identical seed mixtures were sown and irrigated with the same amount of water for the same length of time. Therefore, the only stratification criterion for Dam 5 was aspect and the dam was divided into northern, eastern, southern and western sampling units.

TSF Dam 4

Dam 4 was rather more complex, with a variety of parent material making up the tailings material. This had resulted in some of the areas needing to be reworked after problems with seedling establishment (Table 4.1) emerged in early monitoring. This was most evident on the north-eastern, eastern and south-eastern slopes of Dam 4 (Figure 4.1 and Figure 4.2). The eastern slope, for example, undergoing multiple rehabilitation attempts and experiments. Unfortunately, many of the protocols and experiments were not recorded and the history of the eastern slope of Dam 4 has therefore been left out of the surveys. The southern section of Dam 4 was reworked once and re-rehabilitated, requiring far greater amounts of ameliorants than other sample units, but with different amounts being applied to south-eastern and south-western sections. Similarly, different fertiliser quantities were applied to different sections of the rehabilitating sites, requiring a more detailed stratification. Dam 4 stood unrehabilitated for many years until rehabilitation started in earnest during 1996. All initial rehabilitation efforts on Dam 4 started within about one and a half years of each other, and both slopes of each aspect were rehabilitated simultaneously, although the reworking of some slopes resulted in a rehabilitation age-cere structure varying between four and twelve years (Table 4.1). However, the chemical composition of the tailings materials varied considerably between upper and lower slopes, forcing a further division of sites on the basis of slope. To summarise, Dam 4 was stratified on the basis of aspect, slope level (1 or 2), age and chemical amelioration. This yielded the sampling unit stratification seen in Figure 4.2.

Reference sites

As mentioned, two further units were sampled to compare landscape function values. These were the spillage site, indicated on the right of Figure 4, where tailings material spilled from Dam 2 and covered a large section of adjacent grassland (code SP). The other additional site was the undisturbed, flat veld (code UFV) between the spillage site and Dam 4. These sites were chosen to exemplify a highly dysfunctional and a highly functional landscape, respectively and to facilitate the comparison of sample sites on the tailings dams based on their position relative to these two landscapes. Neither had been mined, but the SP unit possessed very little vegetation cover that had regrown following the removal of the tailings material (mid-2006), whilst the UFV had a rich diversity of vegetation and landscape patch types. These were not meant to serve as analogues, as both of these units were flat and displayed vastly different chemical characteristics, but merely as a frame of reference for easier, meaningful visualisation of the results, and representing the "biogeochemical" potential of landscapes in this region.

4.2.2. Sampling design

Each of the stratified sampling units was demarcated using ArcView GIS software (version 9.2), and five random points were located as the starting positions for the five permanent transects in each site. The locations were uploaded to a handheld Geographical Positioning System (GPS) and located in the field where a 1.2 m long steel peg was hammered into the soil. Another peg was affixed at the end of the slope (which were mostly in the vicinity of 20 m in length), or, on the flat areas, at 20 m distance to mark the end of vegetation and LFA survey transects. The guideline for transect length is that it should be long enough to contain about six patch/interpatch sequences. Marking fixed transects facilitated the reliable comparison of data over time, where distance measurements reflect landscape organisation in terms of patch and inter-patch size.

Table 4.1. Site characteristics (age, amount of soil ameliorants applied, compost volumes and irrigation details) of the stratified units, giving the differentiating factors for each sample site on Dam4, Dam 5, Dam 5's starter wall, the spillage area and the undisturbed veld. Site names and abbreviations are explained in appendix A.

Site	**Rehabilitation date**	**Rehabilitation age**	**Chemical ameliorant**	**Compost**	**Irrigation duration**
		Years	Lime t/Ha	t/Ha	Years
Dam 4					
4N1	Sep 1996	12	70	45	2
4N2	Sep 1996	12	70	45	2
4SE1*	Nov 2004*	4*	30*	0*	2*
4SE2*	Nov 2004*	4*	30*	0*	2*
4SW1	Mar 1997	11.5	65	40	2
4SW2	Mar 1997	11.5	65	40	2
4W1	Sep 1998	11	65	40	2
4W2	Sep 1998	11	65	40	2
Dam 5					
5N1	1995	13	30	30	2
5N2	1995	13	30	30	2
5E1	1995	13	30	30	2
5E2	1995	13	30	30	2
5S1	1996	12.5	30	30	2
5S2	1996	12.5	30	30	2
5W1	1996	12.5	30	30	2
5W2	1996	12.5	30	30	2
Other					
5SB	1940	68	0	0	0
UFV	n\a	100+	0	0	0
SP	Mar 06	2.5	0	0	0

* indicates the two sites in which rehabilitation failed and that had to be reworked

4.3. Vegetation sampling

4.3.1. Theoretical basis

The LFA technique can also address issues of botanical composition, adding vegetation structure and composition to the assessment of landscape function and is then called Ecosystem Function Analysis (EFA). This was achieved by conducting the Point-Centred Quarter (PCQ) method (Mueller-Dombois and Ellenberg, 1974) of vegetation survey at the LFA site, and linking the data to landscape organisation criteria through a composite spreadsheet model. The PCQ method is a plotless, distance-measuring technique that used the mean distances between plants to determine density. Thus, the parameters that could be gleaned from this data were plant species composition, density, basal area (and thus dominance), and frequency. The assumptions underlying the PCQ method are that the same plant is never sampled twice, and that the distribution of plants are random and not regular, as in a plantation, where the density would then be overestimated.

Previous vegetation studies at this site were limited to species composition, frequency and estimated cover. It was hypothesised that although less time-consuming than the PCQ, the method of measuring these variables by using the Descending-Point method (Roux, 1963) would be insufficient for reliably indicating vegetation performance.

Woody vegetation was sampled during the first year by means of 10 m wide belt-transects in which the total height, basal diameter, canopy width and -breadth were recorded for each woody plant. Analysis of the woody data could not denote any chemical or functional explanations for the random distribution of woody plants and they were omitted from further surveys. Therefore the herbaceous vegetation consisted largely of grasses and forbs, with occasional woody plants where these were recorded as the nearest plant in a quarter-circle. A spreadsheet calculated the number of plants per ha, basal cover and species identity.

4.3.2. Field procedure

Vegetation sampling started in March of 2007 and repeat sampling of all sites was undertaken during March of 2008. This represented the end of the growing season when most herbaceous plants would be in flower, allowing for ready identification of especially difficult grasses (family *Poaceae*) and annual plants. This also allowed for plants to be measured at the point at which they had attained the greatest biomass (height in the growing season), which also served as an indication of rain use efficiency (le Houerou 1984).

To determine the optimal number of transects, several pilot transects were surveyed. The relationship between number of species and number of transects (in an adapted species-area curve) resulted in four replicates being selected for each site.

The method involved setting out transects with regular point intervals (in this case, every meter), each of which was divided into four quarters (as per Figure 4.3). The distance to the nearest living plant in each quarter was then measured, along with dimensions of canopy width, -breadth, -height, -density, plant total height and basal diameter. A minimum of 20 points, with four measured plants per point were needed for statistical validity.

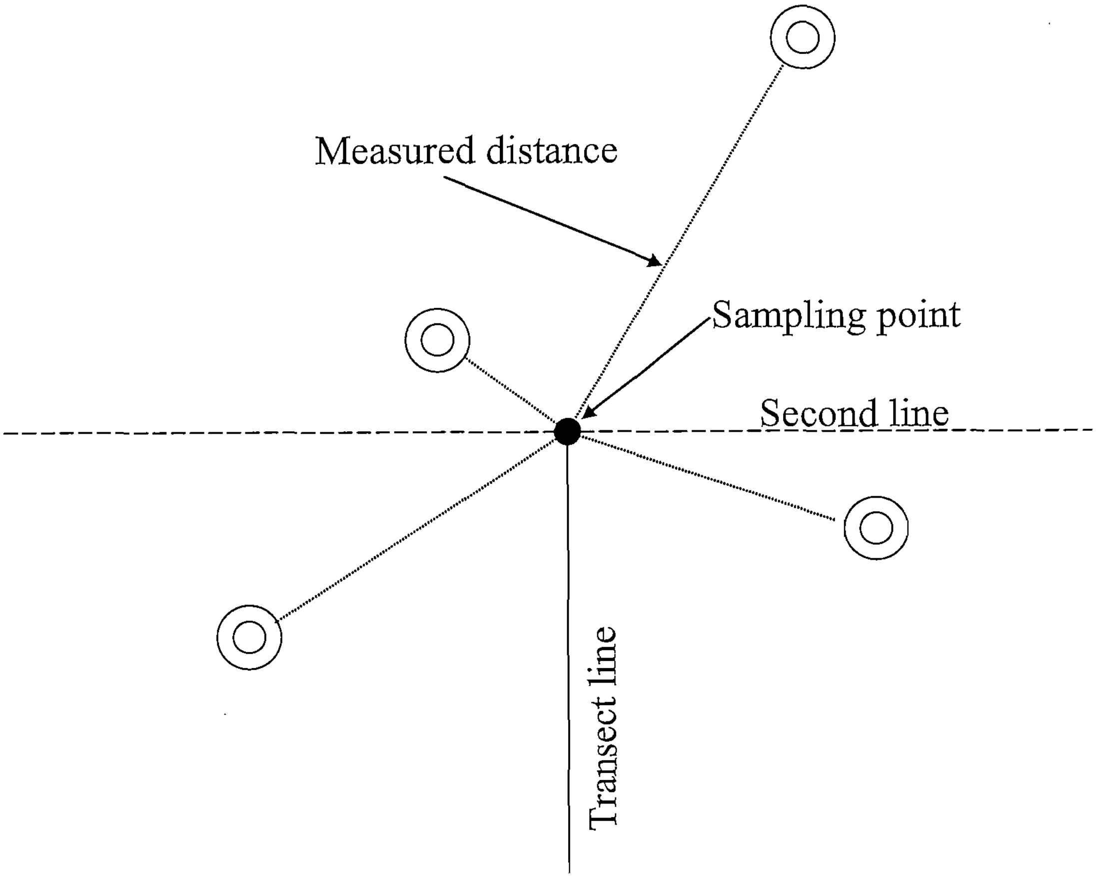

Figure 4.3. A schematic representation of the Point-Centred Quarter method (From Tongway and Hindley, 2004).

4.3.3. Data analyses

The EFA extension software includes an option for assessing up to four vegetation height classes, but this capacity was irrelevant in the present study, as no grazing took place and the vegetation mostly consisted of a single, herbaceous layer.

Specific analyses involved first creating abundance matrices of data for all sites, which were then imported into version 5 of PRIMER (Plymouth Routines in Multivariate Ecological Research) where similarity matrices were computed based on Bray-Curtis distance as a measure of how similar or dissimilar sites were to one another. This then allowed for hierarchical cluster analysis to depict the strength of composition-oriented relationships between sites, followed by non-metric MDS to graphically represent the relationship between sites in multivariate space. These analyses allowed for the robust comparison of species similarities between sites and how great compositional differences were. Data were first analysed between sites, and then between sampling seasons to ascertain whether both spatial and temporal changes took place.

Statistical analyses were similar to those performed for LFA, but differed slightly due to the non-Gaussian distribution of mean values excluding parametric tests. The normality tests were done using the Shapiro-Wilks normality test in GraphPad Prism (version 5) software, after which the non-Gaussian distribution of means dictated the use of a suitable non-parametric test to replace the one-way ANOVA using STATISTICA. The robust Kruskal-Wallis test was selected to test for significant differences between the means of the sampling units and their replicates and then followed by Dunn's post-hoc multiple comparison test to establish between which sites the differences occurred. These analyses were combined with the complementary non-metric MDS and cluster analyses to best represent the differences between sites and sampling units.

Vegetation composition data were also used in indirect multivariate ordination analysis to examine the relationship between sites and species. Detrended Correspondence Analysis (DCA) was selected as it is able to depict the associations of sites based on their species composition whilst also depicting the relative influence of each species.

4.4. Landscape Function Analysis

4.4.1. Theoretical basis

Resource availability and its spatial dynamics followed the LFA methods as devised by Tongway and Hindley (2004), which are based on their extensive work in the fields of landscape degradation assessment and rehabilitation design. This method was developed to objectively assess landscape degradation brought about by human settlement and its associated activities. An original design feature was that of not needing vegetation to be present to reach an assessment.

LFA examines how well a landscape is functioning as a biophysical system, using rapidly assessed soil surface indicators. These indicators focus on soil surface processes, rather than the presence, absence or abundance of selected biota, thus making the observed information different from many other monitoring procedures. LFA is comprised of three modules: a conceptual framework, a field methodology and an interpretational framework. The conceptual framework examines how scarce vital resources move and are used in or lost to the landscape, in a sequence of processes mainly played out at the soil surface. The basis of the field methodology is the stratification of landscape into units (Figure 4.4) that either accumulate resources (patches), or promote the loss of resources (inter-patches). These patches and interpatches define the "landscape organisation", which forms the coarse-scale basis of the analysis procedure. Data collection on a gradient-oriented transect facilitates identifying "cause and effect" sequences of run-off and run-on processes.

Typically, five replicates of LFA transects should be laid out in each habitat type to contend with naturally occurring variation. The transect, or more properly, the gradsect (a **grad**ient-oriented tran**sect** is located in an upslope/downslope position. The length of each transect will vary, as it should include six sequences of the patch/inter-patch pattern. On gold TSF's, the transects are usually similar in length due to the angular, engineered structure of most SA TSF's.

4.4.2. Field procedure

The LFA fieldwork was conducted between March and April of 2007, with repeat sampling in March of 2008. The surveys were conducted towards the end of the growing season when plant production should be at peak, as canopy cover and biomass do influence some of the indicators.

At all sites, a measuring tape was laid out between two fixed stakes, each permanently marking the upslope and downslope limits of the transect. The transect tape (observation line) and the nature of the landscape unit directly below it were of greatest concern when determining the landscape organisation. The entire length of the transect was divided up, or mapped, into a series of patches and interpatches (Figure 4.4). The patches and inter-patches were given names characterising the nature of the soil surface. Additionally the width of each patch was measured on the contour, and each patch was measured for length. To assist monitoring at later dates, the names and images of each type would form part of the meta-data set (as per 4.4.4.).

After the landscape organisation step was complete, five replicates of each of the categories of patches and interpatches were randomly selected, recorded and then a soil surface assessment (SSA), comprised of 11 indicators done in each (as per Tongway and Hindley, 2004). Table 4.2 names the eleven indicators that are assessed to perform the SSA, together with the soil surface process the indicator provides information about. Each indicator is assigned a class value according to the protocol in Tongway and Hindley 2004. Each indicator does not need to be assessed with precision, as each class has rapidly assessed limits.

The eleven SSA indicators were measured rapidly through a series of verified field procedures, as set out in the LFA training manual (vs. 3.5). All of the indicators have been verified by correlating field measurements with laboratory analyses from a very wide range of habitat types (Tongway and Hindley 2003). All data was then input into a spreadsheet (LFA software Version 2.2) designed by Tongway and Hindley (2004), which automatically calculates the emergent index values and tabulates the output.

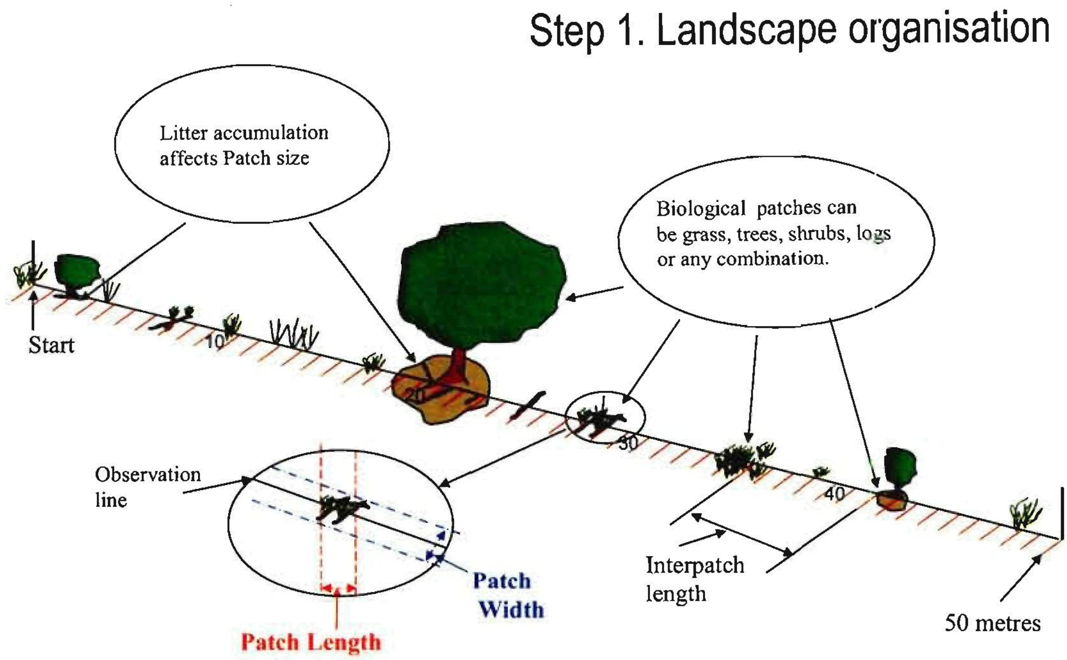

Figure 4.4. Landscape organisation, the first step of LFA, showing the transect set out in the direction of resource flow and the various measurements required (from Tongway and Hindley, 2004).

The data outputs summarised (a) six indices reflecting landscape organisation and (b) the soil surface assessment indices for stability, infiltration/runoff and nutrient cycling for the individual patches and inter-patches recognised in the landscape organisation step as well as a weighted mean representing whole-of-site values. These were expressly designed to be deployed over time (serial monitoring) to detect trends and to see to what extent landscape management objectives have been met. The various indicators that were measured during the soil surface assessments (Figure 4.5) contributed in different ways to the three indices that best describe the functioning of the landscape as a biophysical unit: stability, nutrient cycling and infiltration. An additional, structural index, the Landscape Organisation Index (LOI), was also selected as a variable as it expressed the proportion of a landscape that was covered by patches and thus its 'leakiness (Ludwig *et al.*, 2005).

Table 4.2. Indices of measurement for the Soil Surface Assessment (SSA) method, with the soil surface process for each indicator identified. Note that the indicators include biological and physical processes.

Indicator	**Objective**
Rainsplash Protection	Assess how surface cover and perennial veg ameliorate effects of raindrops
Perennial Veg Cover	Estimate basal cover of perennial grasses and canopy cover of trees/shrubs
Litter	Assess the amount, origin and degree of decomposing plant litter
Cryptogram Cover	Assess the cover of cryptograms (algae, fungi etc.) visible on soil surface
Crust Brokenness	Assess extent to which crust is broken, leaving loose, erodible soil material
Erosion Type & Severity	Assess the type and severity of recent/current soil erosion
Deposited Materials	Assess the nature and amount of alluvium transported and deposited
Soil Surface Roughness	Assess surface roughness for ability to retain & capture mobile resources
Surface Nature	Assess ease with which soil is mechanically disturbed for erodible material
Slake Test	Assess stability of natural soil fragments to rapid wetting
Texture	Classify the texture of surface soil, and relate this to permeability

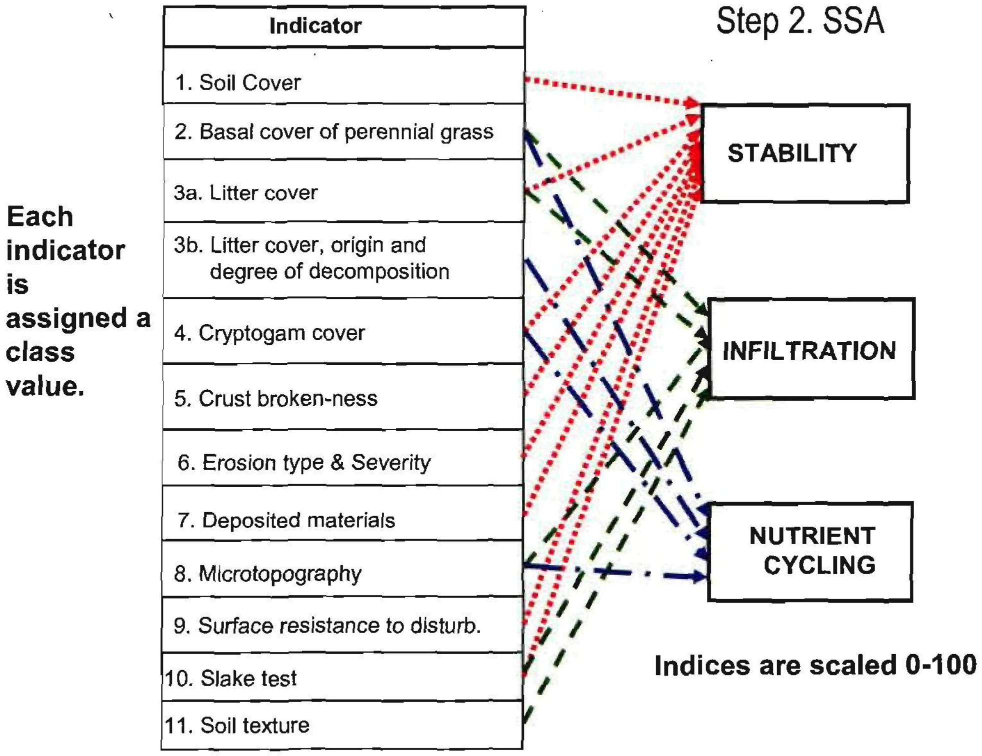

Figure 4.5. The Soil Surface Assessment (SSA) indicators recorded as the second step of LFA, showing how each measured indicator contributes to the functional indices (from Tongway & Hindley 2004)

4.4.3. Data analyses

The LFA software includes some elementary analysis of the indices calculated both at the individual patch scale and the set of patches scale, with their standard error values. These are the values compared over time for a given transect type (e.g. Dam 5, north side), but do not provide an absolute assessment of function. The three indices used were Stability, Infiltration and Nutrient cycling.

Once the indices were computed, data were collated and compared firstly using PRIMER (Plymouth Routines in Multivariate Ecological Research) software version 5.2.9 (Primer-E, 2002). This allowed for the computation of similarity matrices, using Bray-Curtis distance as a measurement of similarity and the resultant cluster analyses and non-metric multidimensional scaling (MDS). These analyses were performed to best illustrate the relationships between sites based on how similarly they functioned as biophysical units, both across space and between seasons.

Data were then tested for normality (Gaussian distribution of means) using GraphPad Prism software version 5, by means of Shapiro-Wilks normality test. This was followed by a one-way Analysis of Variance (ANOVA) with Tukey's post-hoc test to establish between which means the most significant differences occurred. These statistical tests were performed to enumerate the difference observed using MDS. Parametric statistical tests were used where the data distribution allowed it.

LFA data were also analysed using multivariate data analyses. Principal Component Analysis (PCA), an indirect ordination analysis, was selected to examine the strength of relationships between the LFA variables at the different sites. The LFA variables that were selected for the ordinations were a combination of structural and functional parameters. These include:

- Stability: the index of susceptibility to erosion.
- Infiltration: the index of runoff:runon ratio.
- Nutrient Cycling: the index of litter breakdown, mineralisation and microbial activity.
- LOI: the ratio of patches:interpatches, to indicate importance of LFA indices.
- Interpatch Length: average distance between patches, to enumerate bare soil/tailings.
- Patch Area: average patch size (m^2), to illustrate width and efficiency of patches.
- Number of patches: physical number of patches on a gradsect, to illustrate patchiness.
- Density of patches: expressed as number of patches per 10m of gradsect, to illustrate

4.4.4. LFA patch descriptions

Landscape Function Analyses were carried out on all sites during April and May of 2007. Results from each LFA transect were entered into an analytical model (Tongway & Hindley, 2004).

The field procedure required the representation of each site by describing the landscape organisation. The various landscapes were each made up of series of patches and interpatches, each of which is described here. This description was done for the sake of quality assurance, so that data between survey years would be more consistent and reliable, and also to provide for consistency amongst multiple surveyors. A typical record would comprise the name of the patch, a brief description, a vertical photograph of the 1-m mini transect and a set of data selected to be typical. In order for data to be meaningfully compared between different survey years, definitive patch and interpatch types must be identified and described, so that individual patch types can be measured and compared over time. This gives an indication of the recovery or degradation of landscape organisation over time, which then directly influences the ability of the landscape to regulate ecosystem goods and services.

The patch and interpatch types were consistent across the different landscapes, although they presented with some degree of variations between landscapes. For example, a Grass patch (GP) on a TSF slope often consisted of multiple, overlapping perennial grass plants, whereas on the low-density spillage zone, a GP often consisted of a single plant. The key here is that whilst patch/interpatch types may have subtle differences in appearances, they are homogeneously functional units, separable from other patch/interpatch types on the basis of function.

Below follows a short description of each patch and interpatch type, in rank order of prevalence (as per Table 5.2 in the next chapter):

1. Grass patch (GP)

GP's were the most frequently encountered patch types and showed considerable variation in appearance. Figure 4.6 shows the basic GP unit of a single plant, but often overlapping individuals or swards formed larger distinctly functional units (especially for stoloniferous grasses such as *Chloris gayana*). GP's were always made up of living, perennial grass plants and had strong root tufts, which broke physical crusts. GP's contributed greatly to all LFA indices, both as individual patches and in terms of their prevalence in most landscapes.

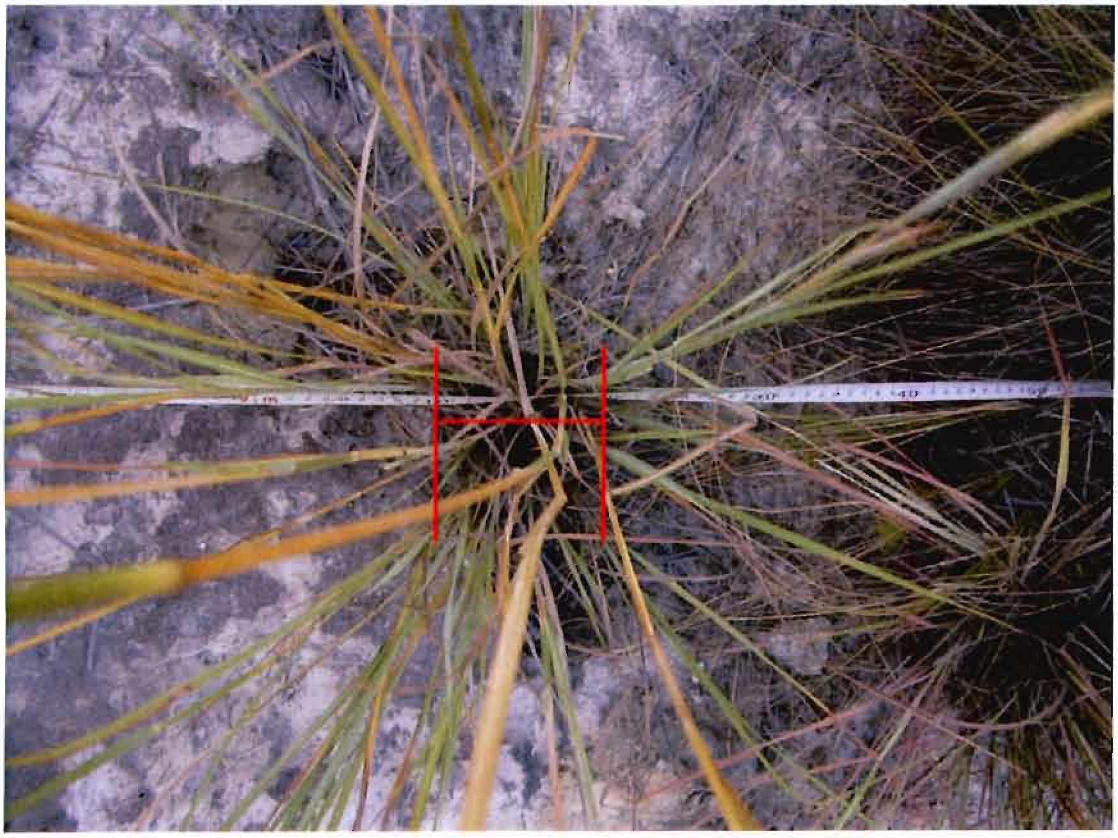

Figure 4.6. A Grass patch on the line transect, with dimensions shown to distinguish from surrounding interpatch.

2. Sparse Grass patch (SGP)

SGP's were the second most frequently encountered patch type, after GP's (Figure 4.7). SGP's are similar to GP's in many ways, but were differentiated primarily on the basis of botanical composition.

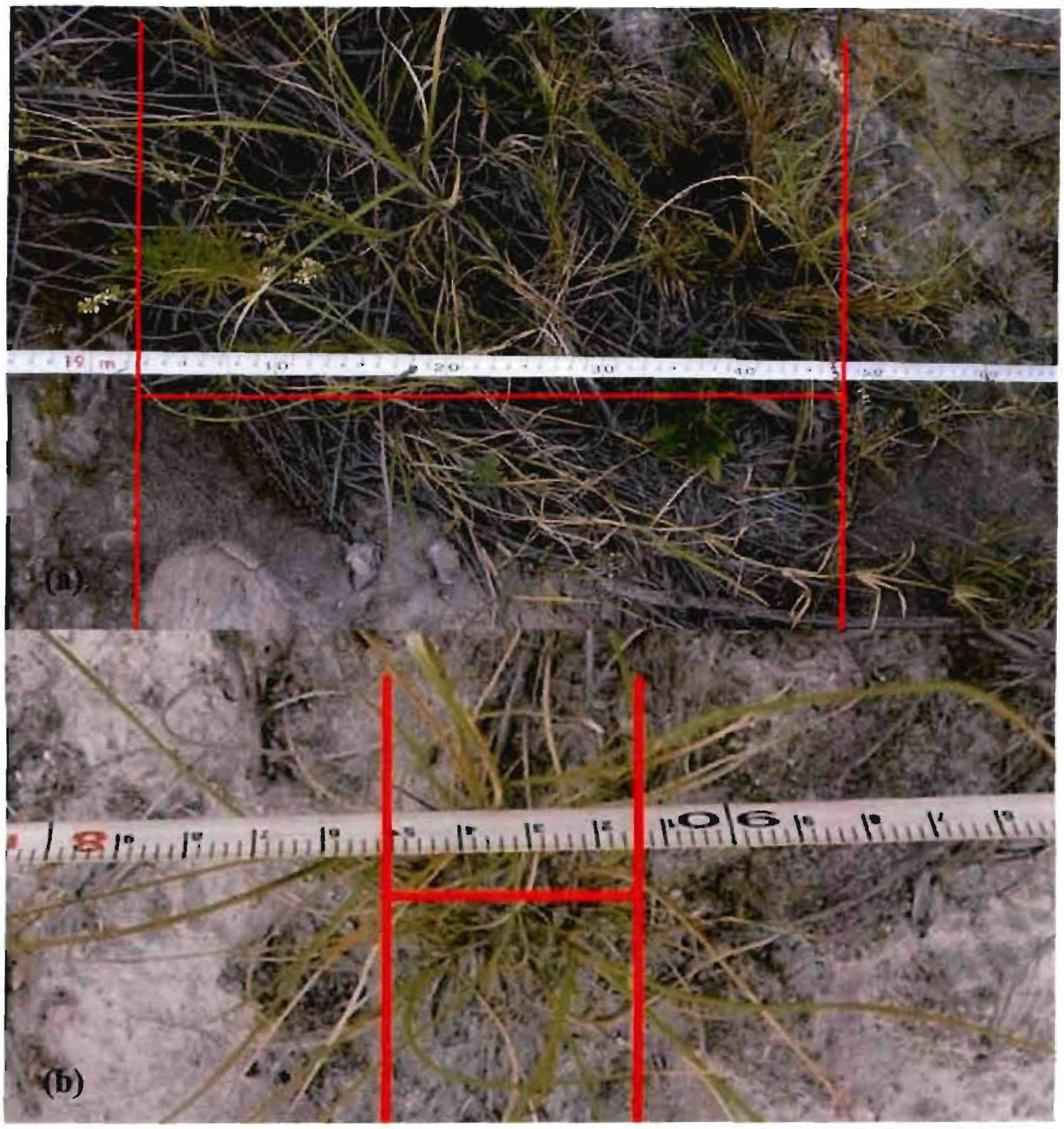

Figure 4.7. Example of Sparse Grass patches on the line transects with dimensions indicating the extent of the patch and separating it from the surrounding interpatch. (a) represents the composite tuft form (here a stoloniferous *Cynodon dactylon*), whilst (b) illustrates the freestanding form.

Whereas GP's always consisted of living, perennial grasses, SGP's always comprised annual grasses (such as *Aristida* species) and semi-annuals (such as *Cynodon dactylon*). The reason for this differentiation was that GP's remained structurally similar throughout the year, especially on the TSF slopes where grazing and fire are limited, whilst SGP's were transient and often only lasted a single season. Those SGP's that consisted of *Cynodon dactylon* were more likely to persist across seasons, but were still likely to show morphometric variations between seasons. SGP's were also separated from Grassy Litter patches (GLP's) on the basis of annual vegetation composition, and also on the extent of litter cover. The litter cover in SGP's was comprised of transported litter that had been accumulated by the patch, whereas GLP's litter was produced in the patch in question. SGP's were characterised by high frequency in less functional areas, low biomass, low resource retention capacity, and soils with increased erosion and crusting. Figure 4.7 shows the two forms of SGP that are most often observed. The first image (Figure 4.7a) is of the typical *Cynodon dactylon* form, whilst the second image (Figure 4.7b) is of the freestanding annual grass form.

3. Grassy Litter patch (GLP)

GLP's (Figure 4.8) were also very prevalent across most landscapes, especially where moribund perennial grasses were shedding dead leaves. This patch type was characterised by a mixture of above-surface litter, some subsurface litter in various degrees of decomposition, and live perennial grasses in between. Care was taken to establish that the litter actually came into contact with the soil and plants, indicating that all were part of a single unit that effectively controlled the cycling and flow of mobile resources. Litter cover varied in extent, but covered at least 90% of the soil surface and with no gaps large enough for runoff to cause litter or sediment movement. This patch type had large amounts of litter cover that were in contact with the soil, which (1) facilitated improved moisture absorption and infiltration; (2) reduced the erosive percussive impacts of raindrops; (3) added organic matter to the carbon-poor soil (which promotes soil aggregation and microbiological nutrient cycling); (4) created a habitat for microorganisms; and (5) created a "physical sieve" that collected mobile resources such as plant litter and seeds. All of these factors resulted in a highly functional patch type, albeit one that was not found in any of the least functional landscapes on the continuum. The live vegetation too, added greatly to the functionality of this patch type by recycling nutrient resources and maintaining production for further litter deposition. There are, however, concerns regarding the persistence of GLP's due to the negative effects of unremoved moribund growth (by e.g. fire) (Tainton, 1999).

Figure 4.8. Example of a Grassy Litter patch on the line transect.

4. Litter patch (LP)

LP's (Figure 4.9) occurred at lower frequencies than GP, SGP or GLP, but were more common than the other patch types. LP's were characterised by a high proportion of above-ground litter cover, whilst being devoid of living perennial vegetation, thus making them easy to identify consistently. LP's were most often encountered as extensive, dead vegetation swathes where some material had not yet been transported downslope. LP's frequently occurred in the vicinity of

Pampas patches (PP's), where ongoing herbicidal applications are used in an attempt to curb the spread and regeneration of the exotic Pampas grass (*Cortaderia jubata*/*Cortaderia selloana* complex). It is conceivable that the herbicides also affect the surrounding herbaceous vegetation, resulting in die-off and formation of bare patches (interpatches). The high litter volumes were indicative of high functionality, especially for infiltration and nutrient cycling, but there were concerns about the stability of such patches and susceptibility to fire which removes all the organic matter without a replacement process.

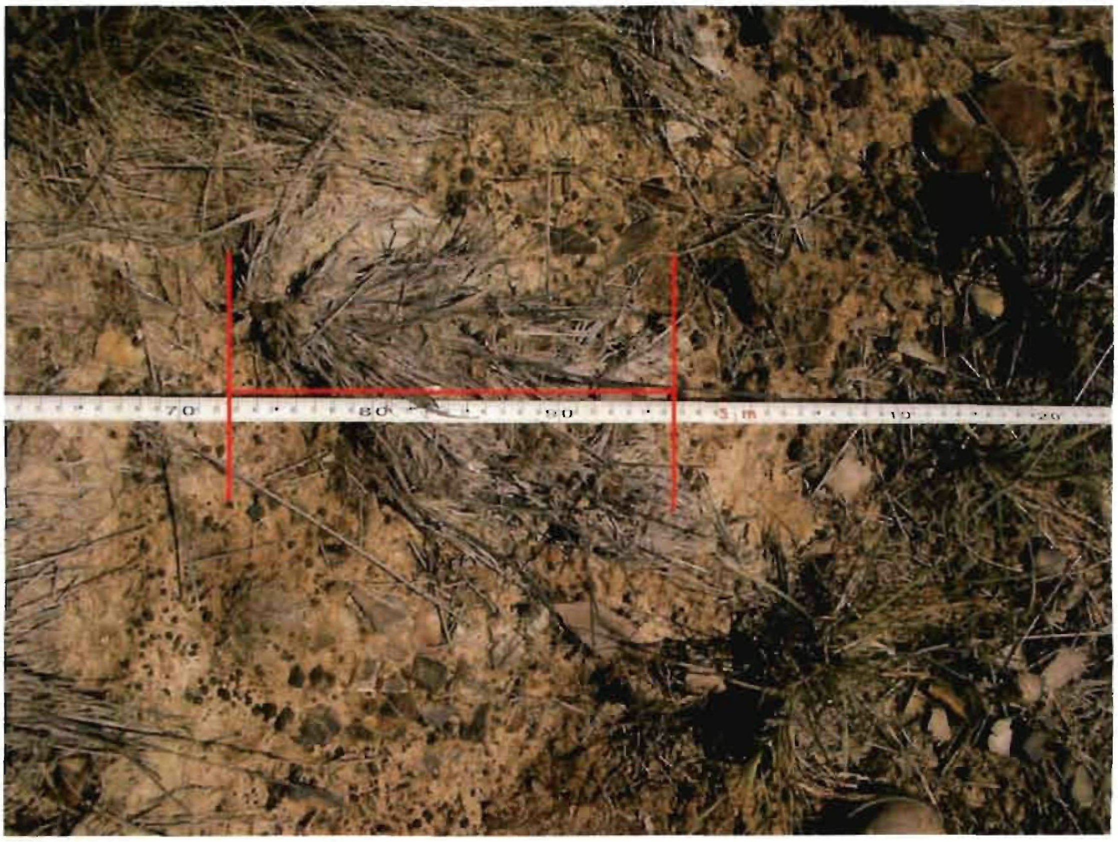

Figure 4.9. Example of a Litter patch on the line transect with dimensions indicating the extent of the patch and separating it from the surrounding interpatch.

5. Shrub patch (SP)

SP's (Figure 4.10) were the sixth most frequently observed patch types and consisted of low-growing perennial woody plants. The main criterion for delineation of SP's was that plant foliage must either come into contact with or be very close to the soil surface, so as to act as a "resource trap" for wind or water-born resources. The foliage created a microclimate different from other patch types, and the indicator signifying litter incorporation into the soil here was highest for all patch types. SP's most often consisted of individuals or clumps of species such as *Stoebe vulgaris, Asparagus laricinus, Rhus lancea* or *Rhus pyroides*. Another, exotic shrub, *Tamarix chinensis,* also occurred on the TSF slopes but never occurred with sufficient foliage biomass or at sufficient densities to be included as SP's.

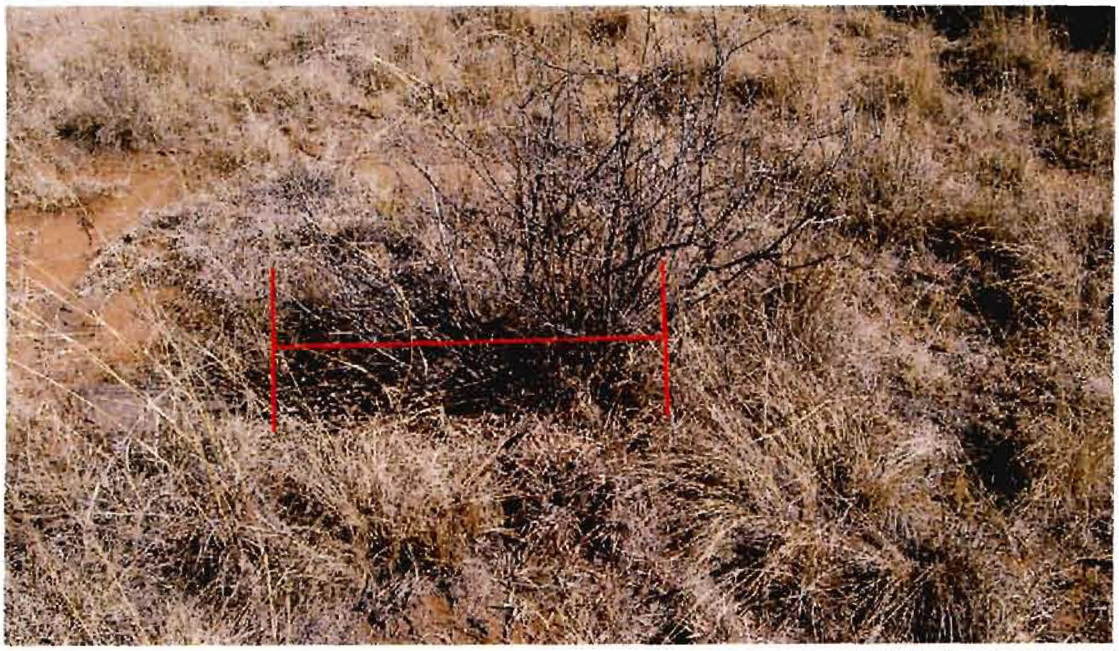

Figure 4.10. Example of a Shrub patch with dimensions indicating the extent of the patch and separating it from the surrounding Grass patches.

6. Rock patch (RP)

RP's (Figure 4.11) were never encountered on the TSF slopes, but were frequent on the starter walls, and in the spillage area and undisturbed grasslands. Overall, it was the eighth most frequently encountered patch type. RP's consisted of rocks, unbroken by soil or vegetation. Although RP's added somewhat to the stability of landscapes, they had no direct effects here on their infiltration or nutrient cycling capacity. A rocky surface can often minimise the formation of physical crusts which slow infiltration. There were, however, potential indirect effects on nutrient cycling such as the provision of shelter for macroinvertebrates that played highly functional roles ("ecosystem engineers", Lavelle *et al.,* 1997; Wright and Jones, 2006) themselves in aeration and contribution to soil structural development.

Figure 4.11. Example of a Rock patch, not on the line transect, with dimensions indicating the extent of the patch and separating it from the surrounding interpatch.

7. Tree patch (TP)

TP's (Figure 4.12) were the seventh most commonly observed patch types. They were characterised by the presence of individuals or clumps of large woody plants. Most TP's were very easy to identify and to isolate from the surrounding, mostly herbaceous, vegetation. TP's showed deep accumulations of litter, mostly produced within the patches themselves, with high levels of decomposition visible. This decomposing litter layer vastly improved nutrient cycling and infiltration indices. The roots of trees also added greatly to the stability of the substrate.

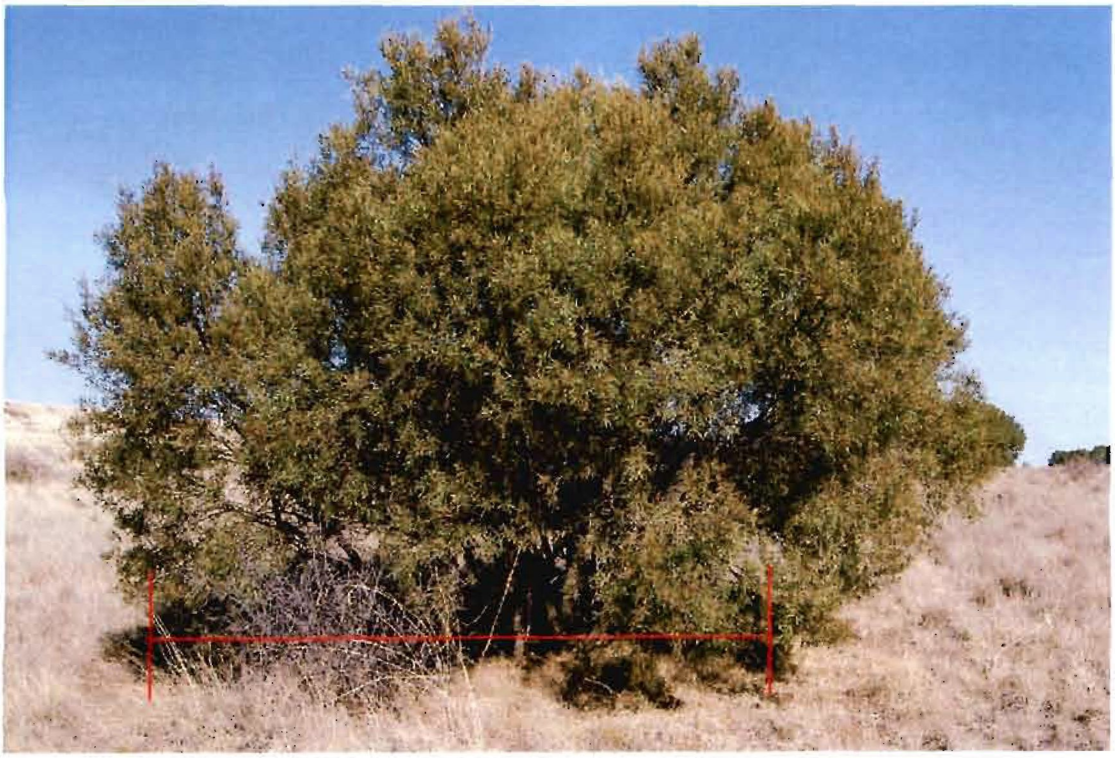

Figure 4.12. Example of a Tree patch with dimensions indicating the extent of the patch and separating it from the surrounding Grass patch

8. Pampas patch (PP)

PP's were the fifth most common patch types observed. They consisted of individual or (rarely) clumps of *Cortaderia jubata* (Pampas grass) (Figure 4.13), an alien plant that was well adapted to the high salinity and acidity conditions found on many gold TSF's. It was initially introduced for dust suppression, as it has a very large basal cover spread (typically 2m²) and is quick to grow and colonise. Unfortunately, it is a declared weed and invasive species under the CARA (Act 43 of 1983 and subsequent amendments in 2001) and it is therefore legally required to be eradicated. The PP's functioned similarly to GP's, but differed mainly in litter production. PP's produced masses of litter and the lower leaves came into contact with the soil surface and thus prevented crust formation or cryptogam activity. During the second survey season, many individual plants had been successfully killed by herbicidal applications but others had not. Both live and dead plants were lumped together in PP's as their structural dimensions persisted long after death, giving similar functional attributes.

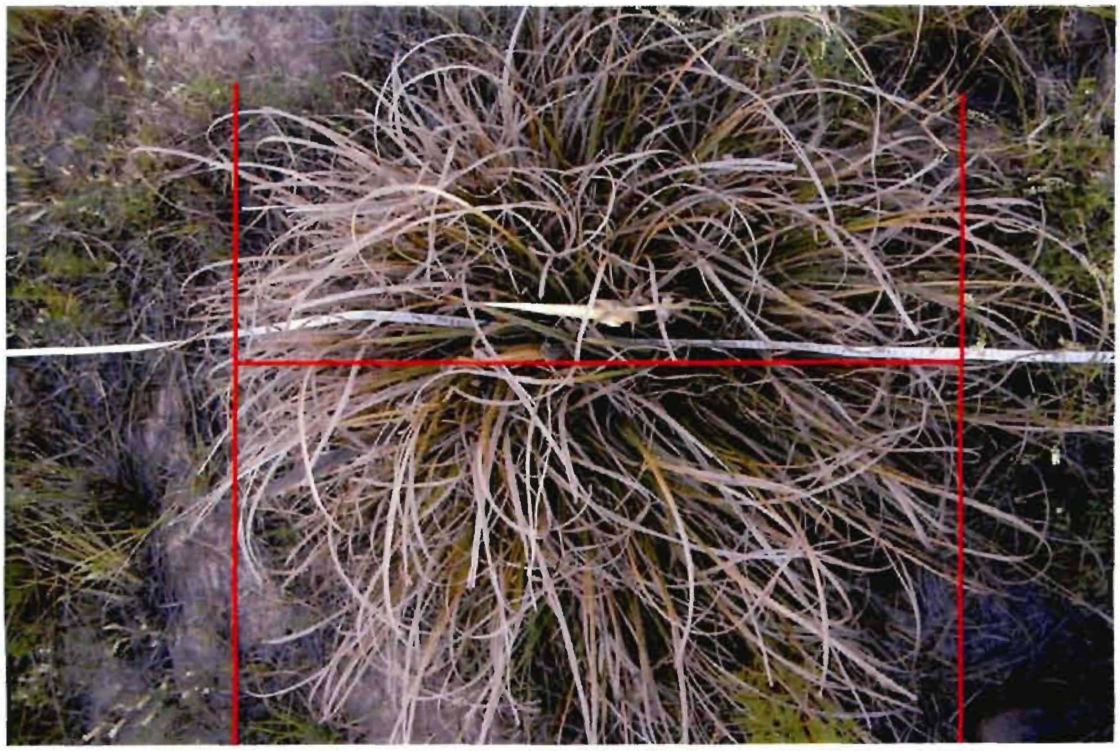

Figure 4.13. Example of a Pampas patch on the line transect with dimensions indicating the extent of the patch and separating it from the surrounding interpatch.

9. Herb patch (HP)

HP's (Figure 4.14) were seldom observed on the TSF slopes and were only the ninth most common patches of thirteen types. These consisted of live, often perennial and low-growing/prostrate herbaceous plants that had sufficient structure and foliage at ground level to aid in the accumulation of mobile resources, such as water, soil particles and seeds. Single-stemmed, erect herbaceous plants were omitted from this category as they did not possess sufficient basal cover to contribute to resource retention. Whilst these were moderately functional patch types that contributed to the functional diversity of the landscapes, there occurrence was erratic and their overall importance was low.

Figure 4.14. Example of a Herb patch with dimensions indicating the extent of the patch and separating it from the surrounding interpatch.

10. Dead Forb patch (DFP)

DFP's (Figure 4.15) were amongst the least common patch types, occurring in less than three percent of all transects (Table 5.2). These occurred where erect, dead, annual herbaceous plants were still standing from the previous season. Their roots and stems were sufficient to form patches of contiguous resource regulation that separated them from the surrounding patches and interpatches. They were not very functional patches, aiding more in stability than for the other indices.

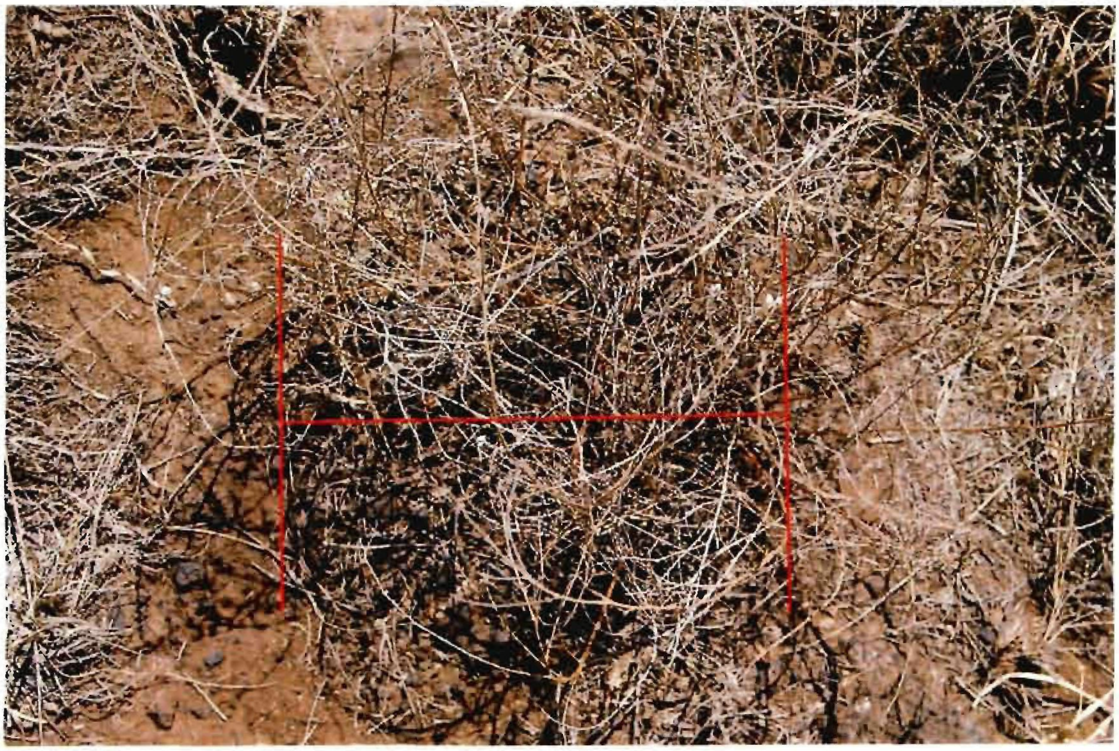

Figure 4.15. Example of a Dead Forb patch with dimensions indicating the extent of the patch and separating it from the surrounding interpatch.

11. Root patch (RTP)

RP's (Figure 4.16) were recorded only on three transects (Table 5.2) of one site. Upon closer inspection of photographs, these patches should in future be lumped together with LP's. The RTP's occurred where all above-ground biomass of perennial grass tufts had been removed, and their roots exposed. This may have resulted from the grazing activities of Common duiker (*Sylvicapra grimmia*), Steenbok (*Raphicerus campestris*), Porcupine (*Hystrix africaustralis)*, Scrub hare or Warthog (*Phachochoerus aethiopicus*), all of which were observed on the TSF slopes.

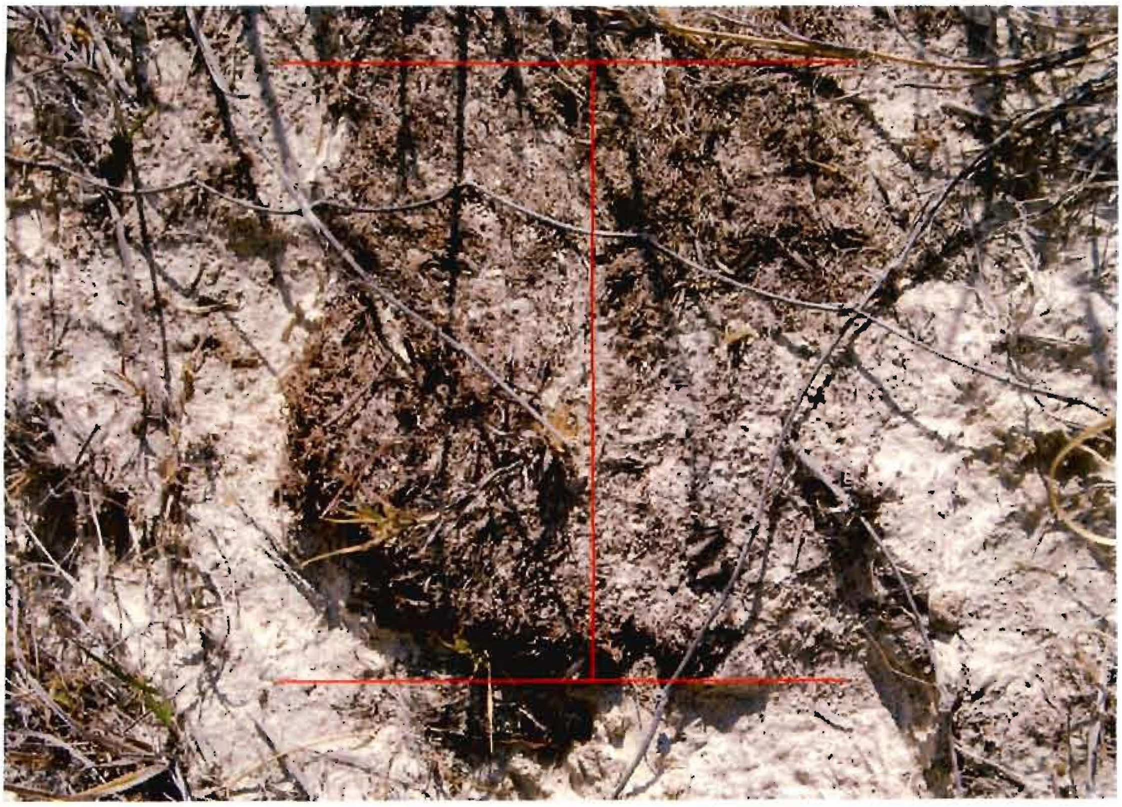

Figure 4.16. Example of a Root patch with dimensions indicating the extent of the patch and separating it from the surrounding interpatch.

12. Cryptogam patch (CP)

CP's (Figure 4.17) were encountered in less than 1.5% of transects and only occurred on one TSF site during the first survey year. Upon inspection of the resultant data, it was decided that this patch type should heretofore be included as an interpatch, rather than a patch, and that it be lumped together with the Bare Tailings interpatch category. Although the CP's scored slightly higher for stability values, the infiltration and nutrient cycling values were very similar. The CP's were essentially areas of the landscape between significant vegetation patches that consisted of 80% or more cryptogams.

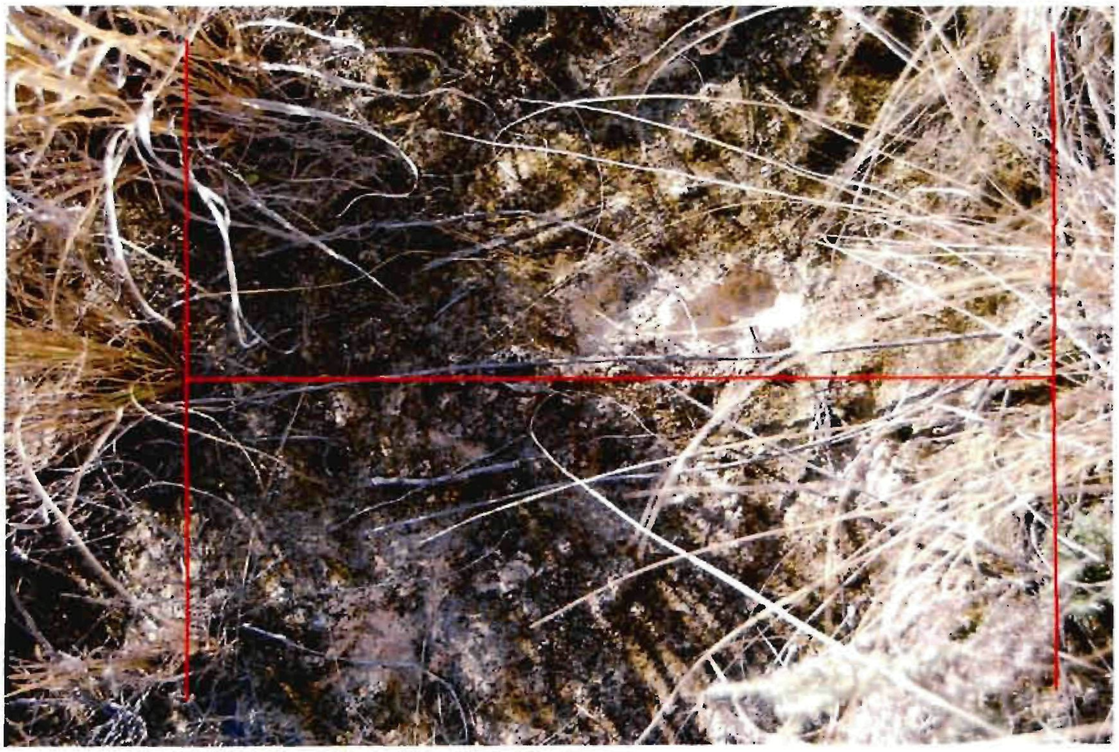

Figure 4.17. Example of a Cryptogam patch with dimensions indicating the extent of the patch and separating it from the surrounding Sparse Grass patches.

13. Woody Litter patch (WLP)

WLP's (Figure 4.18) were limited to a single patch, occurring in only one transect and observed in both survey years. It was an atypical patch type, although readily identifiable. The patch consisted of broken tree trunks and roots, interspersed with accumulated plant litter that were, in all likelihood, disturbed and deposited by vehicular activity. The WLP was highly functional in terms of structure, and the indices of stability, nutrient cycling and infiltration. This was as a result of the enduring nature of the structure, the accumulation of organic material, and the habitat creation for macroinvertebrates.

Figure 4.18. Example of a Woody Litter patch with dimensions indicating the extent of the patch and separating it from the surrounding Grass patches.

The three types of **interpatches** (Table 5.2) were (also in order of prevalence):

1. Bare Tailings (BT)

BT's (Figure 4.19) were encountered in 83% of all transects, being absent only in the undisturbed grasslands, the starter wall, and two TSF transects where the entire transects consisted of patches. BT's were easily characterised as those sections of the tailings-clad landscape that were devoid of visible living vegetation or significant litter accumulations, and in which mobile resources were most able to be lost from the landscape. BT areas had (1) lower stability, enabling soil loss and erosion; (2) lower infiltration, due to crust formation; and (3) lower nutrient cycling, due to poor litter retention, soil loss and poor infiltration.

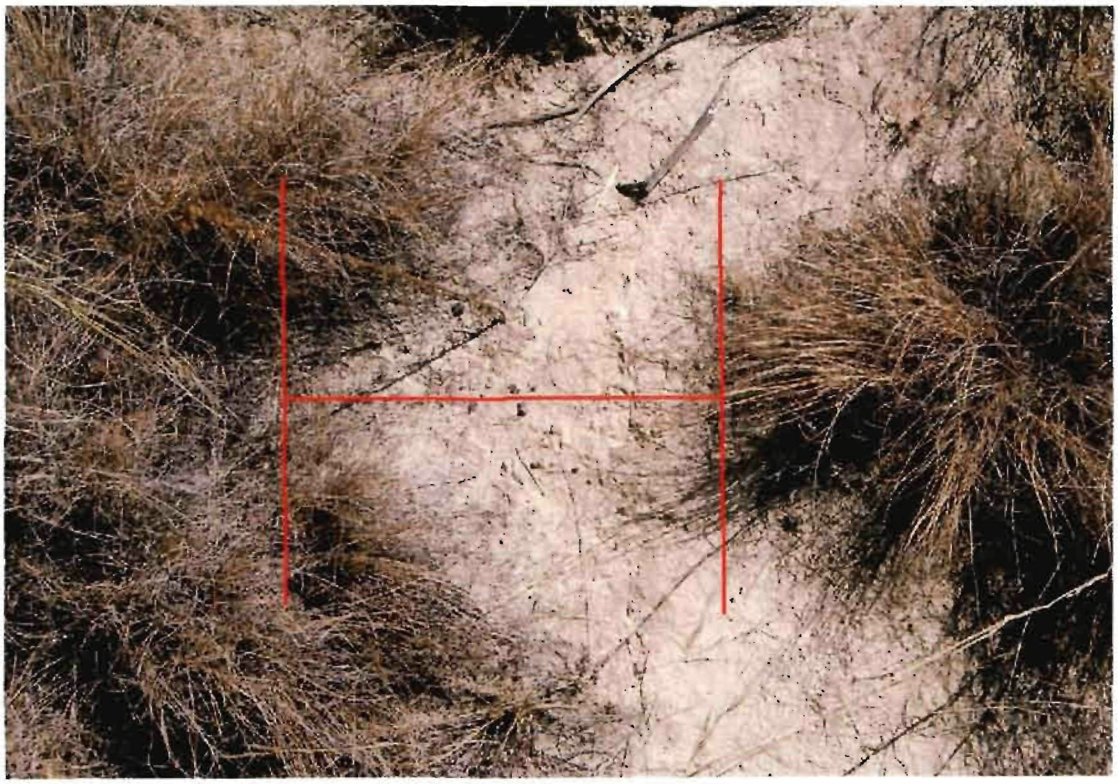

Figure 4.19. Example of a Bare Tailings interpatch with dimensions indicating the extent of the patch and separating it from the surrounding patches.

2. Gravel Interpatch (GRI)

GRI's (Figure 4.20) occurred in only 8% of transects (Table 5.2) and in two sites, the starter wall and the undisturbed grassland. GRI's were characterised by a modicum of gravel-sized stone particles (>2 mm), overlying bare soil. The gravel enhanced the functional attributes of this interpatch type by adding structural dimensions and therefore aiding in topsoil retention. However, resources were still lost from these patches, hence their interpatch classification.

Figure 4.20. Example of a Gravel interpatch with dimensions indicating the extent of the patch and separating it from the surrounding patches.

3. Bare Soil (BS)

Unlike GRI, BS (Figure 4.21) occurred in both the spillage site and the undisturbed grassland. In the undisturbed grassland, they were the main interpatch type that separated patches from one another, whilst in the spillage area, they were exposed where tailings material had been removed. BS interpatches typically consisted of bare soil patches. Although BS only occurred on the two flat landscapes (as opposed to the 35° slope TSF's and starter wall), it was classified as less functional than the tailings material. BS had greater stability values than BT, but had lower capacity for infiltration (as controlled by texture) and nutrient cycling, largely due to its structure and slightly lower dispersivity.

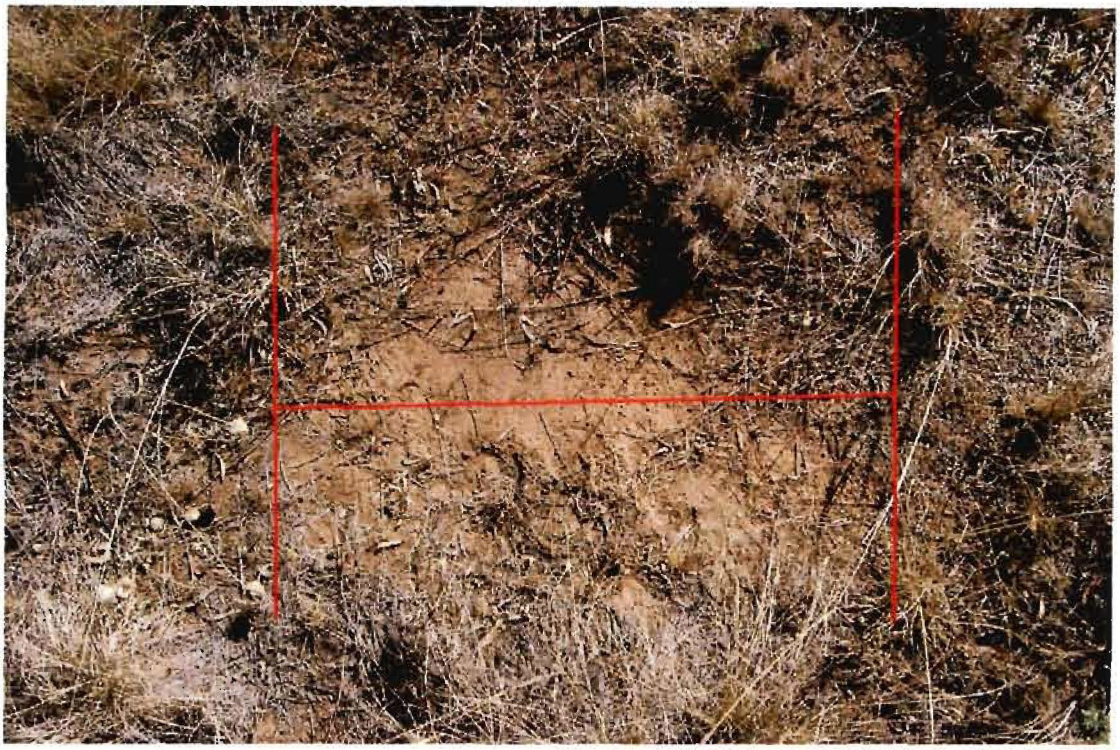

Figure 4.21. Example of a Bare Soil interpatch with dimensions indicating the extent of the patch and separating it from the surrounding patches

4.5. Soil chemical analysis

The soil sampling design was unfortunately not consistent between 2007 and 2008. During 2007, the mining company insisted on collection and analysis of samples according to their design. Access was then granted to the data and the use thereof in analyses. However, not all sites were sampled and not all chemical parameters were analysed in all sites. This resulted in a confusing set of results that were not sufficient for the present study. Dam 5 was previously thought to be entirely homogeneous in tailings chemistry as a result of homogeneous parent material. This

Lastly, the undisturbed grassland sites (UFV) remained largely unchanged, barring the influx of *Conyza bonariensis*, an annual pioneer, into one site that had previously had some bare soil patches.

Overall, the annual pioneer species following the good 2008 rainy season were only able to invade those areas that had had the lowest species richness and cover in 2007. There were, however, three sites that displayed deterioration of species richness values (Figure 5.1). These were the eastern slope of Dam 5 (5E1) (loss of 8 species), the western slope of Dam 4 (4W1) (loss of 5 species), and the starter wall (5SB) (loss of 3 species). These decreases were driven by habitat limitations and changing substrate chemistry, which will be explained in the multivariate data analyses of section 5.6.2.

Whilst the descriptive statistics did indicate that there were differences both between and amongst sites, and was successful in enumerating those composition-related differences, it did not indicate which species were responsible for the differences. To that end, a Detrended Correspondence Analysis (DCA) was performed on both years' datasets simultaneously (Figure 5.2). In the DCA, the Eigenvalue for the first ordination axis was 0.858 and thus only explained 8.9% of the cumulative variance in the species data. The second ordination axis had an Eigenvalue of 0.556 and together with the first axis cumulatively explained 14.7% of the variance in the species data. The ordination was therefore not highly successful in displaying the differences between sites, but was able to indicate which species were characteristic of each site and transect. The differences between the sites are fully investigated in sections 5.2.2.1-5.2.2.4., making use of Bray-Curtis similarity indices in the Hierarchical Cluster Analyses (HCA) and non-metric multidimensional scaling (MDS) diagrams.

In Figures 5.3 and 5.5, HCA were performed in PRIMER (Primer-E version 5.2, 2002), using square-root transformations of Bray-Curtis similarity values of the 2007 and 2008 vegetation data respectively. For ease of interpretation, 40 % similarity was selected as the best compromise between level of detail and interpretability. This also represented the most logical patterns at which to distinguish between sites in terms of their phytosociological associations. The very first division in species composition in 2007 occurred at 0 % similarity, separating the site SP-04, which was had no plant cover, from all other sites, which did have at least some vegetation cover. In 2008 the first level of discrimination occurred at 4 % similarity, splitting two of the spillage (SP) sites from all of the others. The second level of division for 2007 occurred at 4 % for 2007 and 5% for 2008, separating the TSF and spillage (SP) sites from the undisturbed grassland (UFV) and starter wall (5SB) sites. The remainder of the spillage (SP) sites were separated from the TSF sites at 25 % similarity for both years, whilst the reference sites (UFV and 5SB) were separating from one another at 17 % and 16 % for 2007 and 2008 respectively.

At 40 % Bray-Curtis similarity, 12 groups of sites from 2007 and 2008 that had similar species composition had clustered apart from the others. The 12 groups for 2007 are indicated and numbered in Figure 5.3 and correspond with the MDS diagram presented in Figure 5.4, whilst for 2008 they are indicated in Figure 5.5 and correspond with the MDS diagram in Figure 5.6. The position of each site in the MDS diagram relative to one another is dictated by their Bray-Curtis similarity.

These relationships between the two year's data sets in years that experienced dissimilar climatic patterns indicated that they were able to cope with some natural variation and that it would probably require climatic extremes or stochastic disturbance events, such as fire, to alter species composition in the short-term.

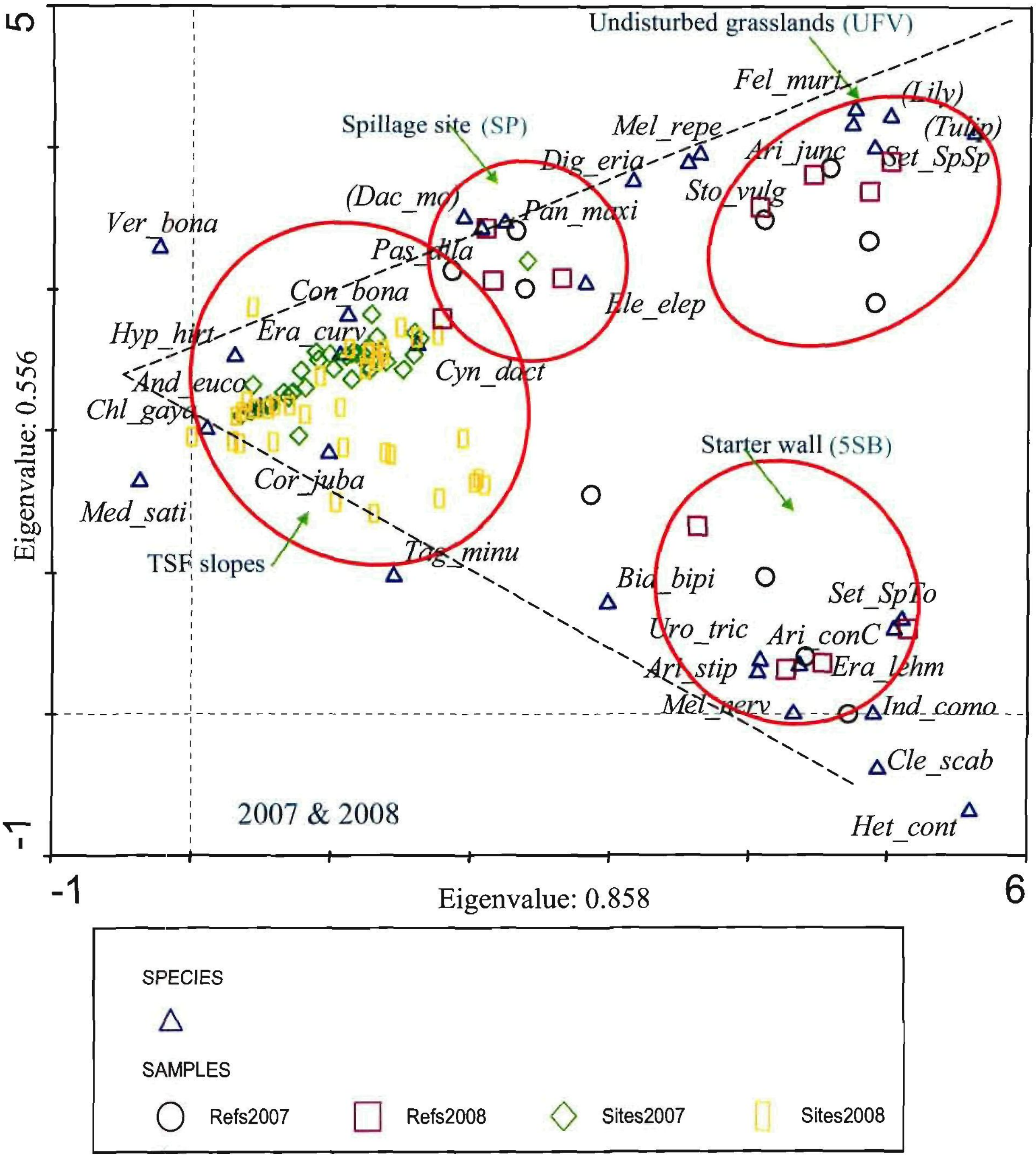

Figure 5.2. Detrended Correspondence Analysis (DCA) of the vegetation data for 2007 and 2008 across all sites. The reference sites (indicated as "Refs 2007" and Refs 2008") are the SP, UFV and 5SB sites, whilst the rest make up the TSF sites (indicated as "Sites" 2007 and 2008). Abbreviations are given in Appendix A and species codes are explained in Appendix C.

5.2.2.1. Spillage site

The first three groups (1-3) on Figures 5.3 and 5.4 and (1, 2 and 5) in Figures 5.5 and 5.6 were the **spillage site (SP)** transects, showing how dissimilar they were from other sites, which is supported by the ANOVA (as reported earlier). Figure 5.2 shows that the species most responsible for the differentiation are *Paspalum dilatatum, Dactyloctenium mossambicense, Panicum maximum* and *Elephanthoriza elephantina*. However, the distortion/wedge-effect observed in the 2007 and 2008 DCA ordination (Figure 5.2) indicate that the species composition of the spillage site (SP) place it between the TSF's and the reference sites (5SB and UFV). This means that the species composition is likely to change over time to become more like either the starter wall (5SB) or the grassland (UFV). The grassland is the more likely of the two eventualities, as it completely surrounds the spillage site (SP) and has soil and topographical parallels (both sites contain relatively intact soils and both sites are flat). There are also three species that occur in both the spillage site (SP) and the undisturbed grassland (UFV) in similar abundance, but not enough to be characteristic of either site: *Melinis repens, Digitaria eriantha* and *Stoebe vulgaris*. Monitoring the abundance of the key species of both reference sites (as per Figure 5.2) and in the spillage site may indicate the patterns of ecological progression. Currently, it appears that the spillage site may resemble the undisturbed grassland more closely in species composition as time progresses. More monitoring data will be required over a longer period of time to establish at what rate the convergence with reference site values has been taking place.

SP-02 (group 3 in 2007 and group 5 in 2008; Figures 5.3/4 and 5.5/6 respectively), was always more related to the TSF sites than to the other spillage sites. This is indicated by it being 30 % similar to the TSF's in 2007, and only 14 % similar to the other spillage sites. The pattern was repeated in 2008, with SP-02 being 25 % similar to the TSF's, but only 4% similar to the other spillage sites. Upon closer inspection of this transect, it was closer to the edge of the spillage site (and thus closer to potential source areas for dispersal and colonisation) and therefore had higher species richness. The similarity was, however, largely driven by large abundance of *C. dactylon*, which was able to creep out over the edges of the spillage site from the unaffected grasslands due to its stoloniferous growth form.

5.2.2.2. TSF sites

Groups 4 and 5 of 2007 (Figure 5.3 and Figure 5.4) and 3, 4, 6, 7 and 8 of 2008 (Figure 5.5 and Figure 5.6) consisted of all of the sites and transects on **TSF slopes** and showed their composition-related associations (Figure 5.2). Figures 5.3 and 5.5 indicate that they had very high compositional similarity, as was indicated by their Bray-Curtis distance, which changed only slightly between 2007 and 2008 (Figure 5.2). As mentioned, the TSF slopes were an artificial biophysical system and consisted largely of introduced, perennial pasture-grass species, which have proven unlikely to change significantly in abundance over the short-term. From Figure 5.2 it is evident that, for both years, the characteristic species of the TSF slopes were *C. dactylon, C. gayana, E. curvula, H. hirta, M. sativa, C. jubata* (all initially planted), *A. eucomus, C. bonariensis* and *V. bonariensis* (all spontaneously colonised). Some species, such as *Tagetes minuta*, were shared with the starter wall (5SB), but were not predominant in either group of sites. The TSF clusters are unlikely to progress along the aforementioned 'wedge' in Figure 5.2, either toward the starter wall (5SB) or the undisturbed grassland (UFV). The biogeochemical and topographical limitations are likely to hinder convergence with reference communities in terms of species composition, but a unique, stable ecosystem may develop over time. As with the spillage site (SP), further monitoring over time is required to fully understand the rates of species change within the TSF's, and the ecological significance of the observed changes.

Whilst the TSF complex consisted of more groups in 2008 than in 2007, this was not necessarily as a result of increased complexity in the vegetation composition. The level of cut-off for interpretation at 40 % Bray-Curtis similarity was responsible for the perceived differences. In ecological terms, the TSF sites for 2007 only split from one another at 36 %, dividing the sites into two related groups (5S transects and 4SE2-01: group 4 on the one hand and all of the other TSF sites on the other; Figures 5.3 and 5.5). This distinction was as a result of a fire that had passed through sections of the 5S site two years before the first sampling, and was most likely exacerbated by indiscriminatory herbicidal applications to control the exotic *C. jubata*, which also killed perennial grasses within the radius of the spray-zone. This then created a vacant niche that was filled by a more complex suite of ruderal species that was different from the spillage site (SP). The second distinction between TSF sites in 2007 occurred very soon after, at 42 % Bray-Curtis similarity, showing that whilst different groups existed within the TSF's, the differences were not enormous. However, the differences were ecologically significant, as was shown by those sites that were altered by stochastic disturbances. In this instance a fire followed by herbicides, brought the stability and resilience of those sites into question. The functional significance of the changes in species composition will be investigated further in the multivariate data analyses (see section 5.6.1).

Looking at the patterns in the 2008 data for the TSF slopes, similar trends emerged as for 2007 (Figures 5.5 and 5.6). The first split in TSF sites occurred at 25 % and again included the 5S transects in which the vegetation had been subject to fire and herbicides, whilst the second split occurred at 40 %. Interestingly, two transects were burnt days before the 2007 survey (5W1-03 and 5W1-04), but these sites did not have any of the exotic *C. jubata* present and were therefore not sprayed with herbicides. Therefore no change in species composition, as is shown by their association with intact TSF sites in 2008 (Figures 5.5 and 5.6) are shown. This may indicate that most of the vegetation on the TSF slopes was able to handle certain levels of disturbance, but not that created by multiple stressors.

5.2.2.3. Starter wall sites

Transects on the 67-year old **starter wall (5SB)** site were also similar between years, but showed greater internal compositional heterogeneity. The transects were represented by groups 9, 10, 11 and 12 in the 2007 dataset (Figure 5.3 and Figure 5.4), and by groups 9 and 10 in 2008 (Figure 5.5 and Figure 5.6). In 2007, the starter wall (5SB) sites separated at 27 % Bray-Curtis similarity into 5SB-01 in cluster 9 and the rest in cluster 10. The differentiating species here was *C. dactylon*, which occurred in greater relative abundance in 2007 than in 2008 (31 % vs. 4 %; Table 5.1). In 2008 the starter wall transects first split at 37 % similarity, indicating greater internal homogeneity as a result of the decreased importance of the common species, *C. dactylon*, and increased importance of the characteristic species, *Heteropogon contortus, Clematopsis scabiosifolia, Indigofera comosa, Eragrostis lehmanniana, Melinis nerviglumis, Setaria sphacelata* var. *torta, Aristida stipitata, A. congesta* subsp. c*ongesta, Urochloa trichopus* and *Bidens bipinnata* (Figure 5.2). The starter wall varied in length (depending on the position within the greater landscape topography), in material composition and in the amount of tailings material that had covered the soil, resulting in sections of reasonably disturbed habitat as well as areas that had been spontaneously colonising unhindered for the last 67 years. This was reflected by the mixture between the ecological statuses of key species, with *B. bipinnata* and *A. congesta* being ruderal pioneers, *H. contortus* being a subclimax species and *S. sphacelata* var. *torta* being a stable, climax species (Tainton, 1999).

The unique species composition of the starter wall (5SB) was most likely as a result of it offering different plant growth habitat variables when compared to the other sites. It consisted of a variety of soils and rock-fragments (as it was created by bulldozing the natural soils from varying depths into walls of the correct shapes and sizes) that made it similar to the undisturbed grassland (UFV) sites but its 35° slope created conditions analogous to the TSF slopes (see Figure 4.1). This resulted in the unique species composition that was sufficiently different from all of the other sites to deviate from the gradient observed in Figure 5.2, finishing the wedge-effect of alternative stable states. This means that the species composition of the spillage site (SP) and TSF sites could theoretically converge with either the undisturbed grassland (UFV) or starter wall (5SB) site over time, although this is unlikely for the TSF's due to physical and chemical substrate limitations. As mentioned, the main driving factors here appeared to be slope and substrate, but that will be more closely examined in the multivariate data analyses (see section 5.6.3).

5.2.2.4. Undisturbed, flat grassland site

The **undisturbed, flat grassland (UFV)** site contained the transects that changed the least in species composition over the two years. In 2007, the undisturbed grassland (UFV) transects split from the starter wall (5SB) at 17 % Bray-Curtis similarity (Figure 5.3), whilst the split occurred at 15 % in 2008 (Figure 5.5). The undisturbed grassland (UFV) was relatively similar in composition to the starter wall (5SB), as is also shown in Figures 5.4 and 5.6 by the close proximity of these sites to one another. This is likely because of the greater number of species that occurred in this site (and in 5SB), and the relative abundances of the key species *Setaria sphacelata* var. *sphacelata, Felicia muricata, Liliaceae* sp. (indicated as "Lily" due to character string length constraints of the ordination software), *Amaryillidaceae* sp. (indicated as "Tulip" due to character string length constraints of the ordination software), *Aristida junciformis* and *Stoebe vulgaris*. As mentioned whilst discussing the starter wall (5SB), the undisturbed grassland (UFV) made up one of the potential alternative stable sites for the rehabilitating spillage site (SP) (more likely) and the rehabilitating TSF slopes (less likely). The vegetation cover was fairly high and the system appeared to be relatively stable, although no grazing by large herbivores had taken place and the area had not been subjected to fire in at least the past six years. However, as the site had not undergone drastic disturbances and the species composition was similar to that characteristic of the area (as per Mucina and Rutherford, 2006; see section 3.4.1), it was assumed to represent a regional reference site. This was supported by the high species richness, the large component of perennial climax species and the prevalence of geophytes and other dispersal-limited species. The resilience of this apparently intact system was also displayed, at least in the short-term, when only one ruderal species was able to invade the system during the above-average rainfall season, whereas sites that had undergone recent disturbances were less able to resist invasion.

The term 'community' was not used here, as the species-associations on mine waste are often transient and show the ability to differ greatly between seasons (van Wyk, 2002). Whilst the vegetation of the UFV site was likely to remain relatively stable, in the absence of grazing and fire, other sampling units such as the SP area were mostly bare and were being colonised from adjacent source areas with relatively high species richness.

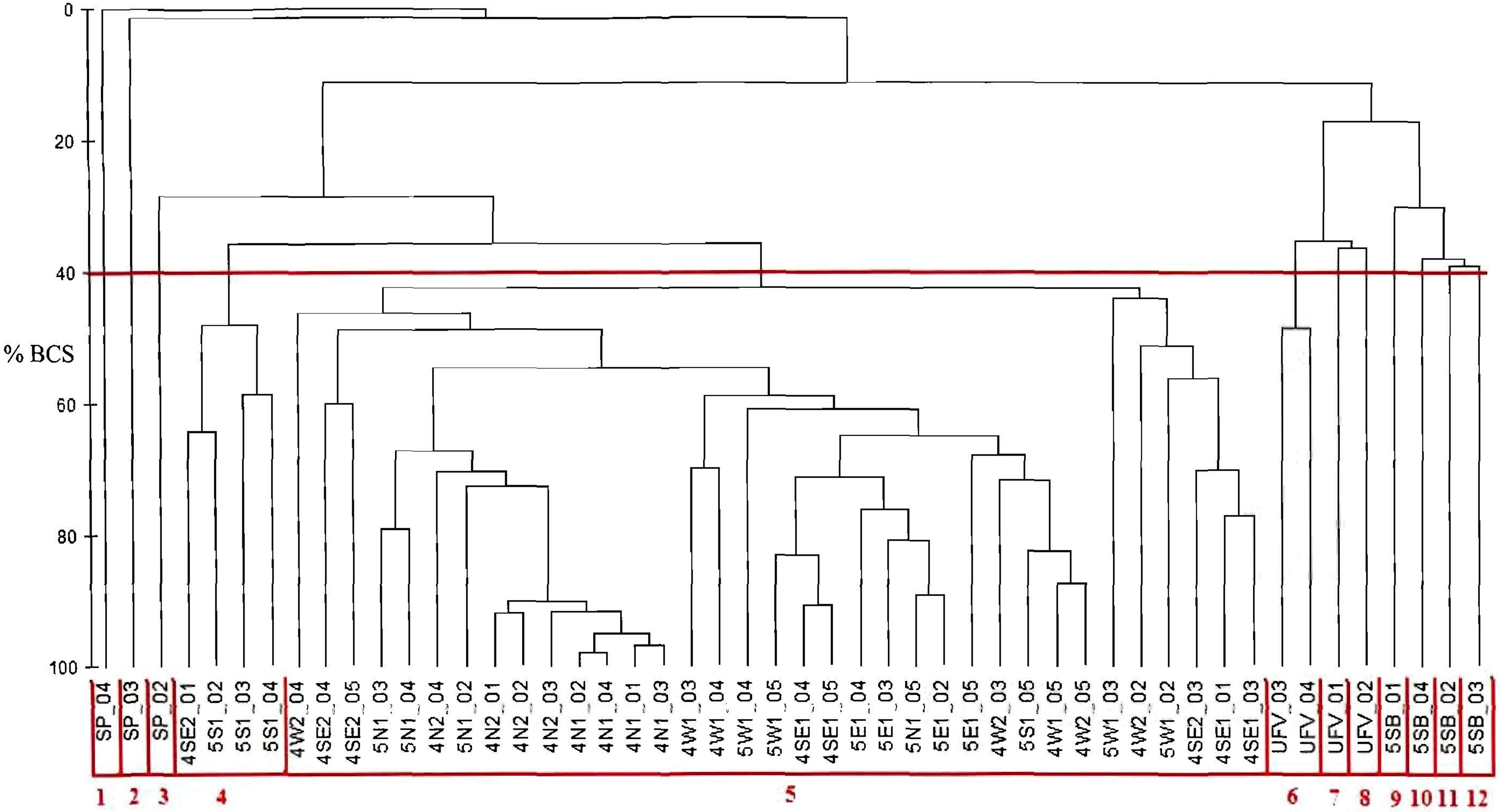

Figure 5.3. Hierarchical Cluster Analysis diagram of the 2007 vegetation composition-related site associations. Cut off at 40% similarity using Bray-Curtis Similarity with square-root transformation. Site clusters are indicated by group numbers and correspond with Figure 5.4 for 2007 and Figures 5.5 and 5.6 for 2008. Site names are further explained in Appendix A.

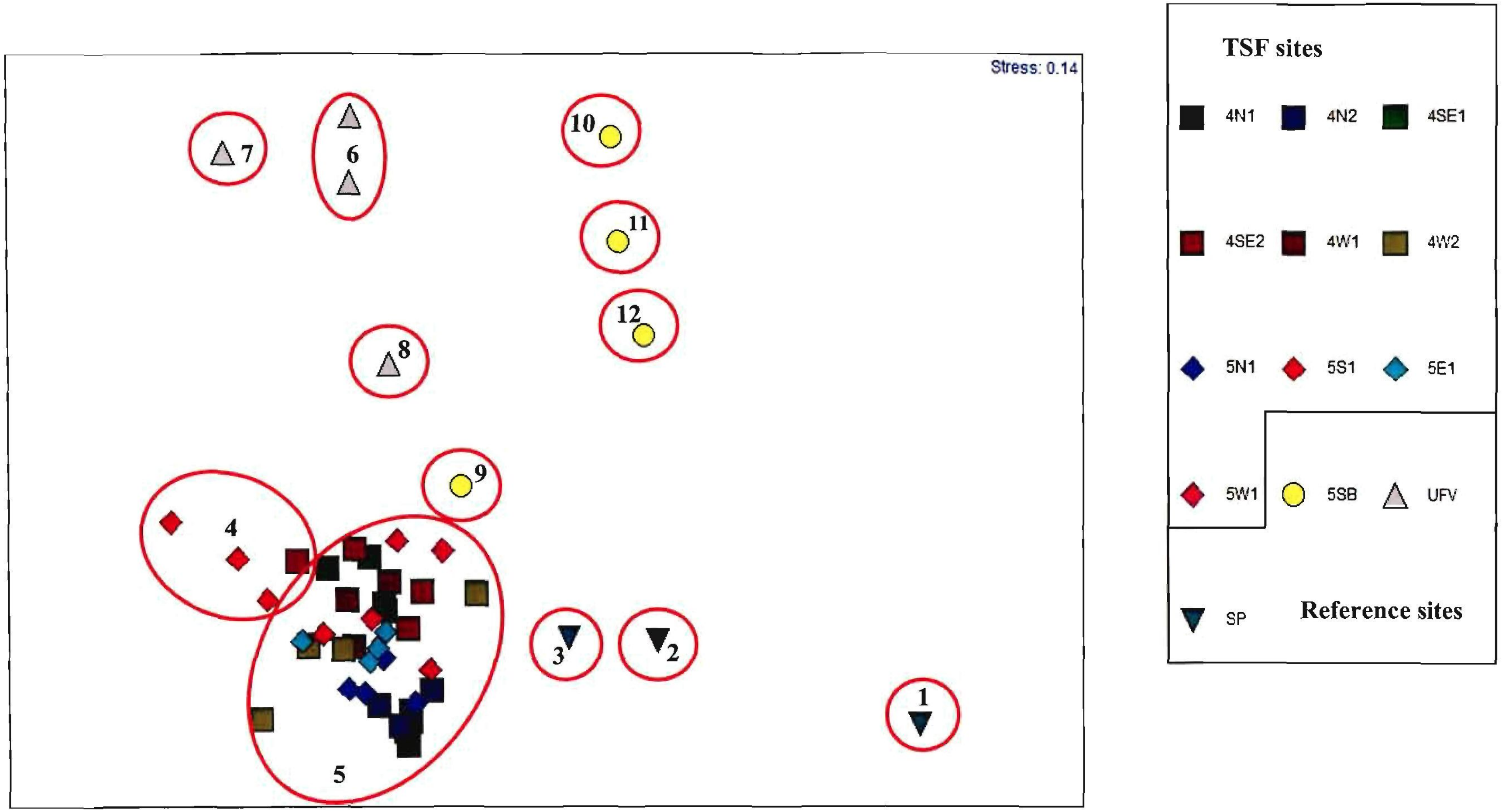

Figure 5.4. Non-Metric Multidimensional Scaling diagram of the 2007 vegetation composition -related site-associations. The red ovals indicate the clusters of sites with similar species composition. The group numbers (1-12) stem from the cluster analysis in Figure 5.3 and are carried over into the 2008 analyses in Figure 5.5 and 5.6. Site names and abbreviations are explained in Appendix A.

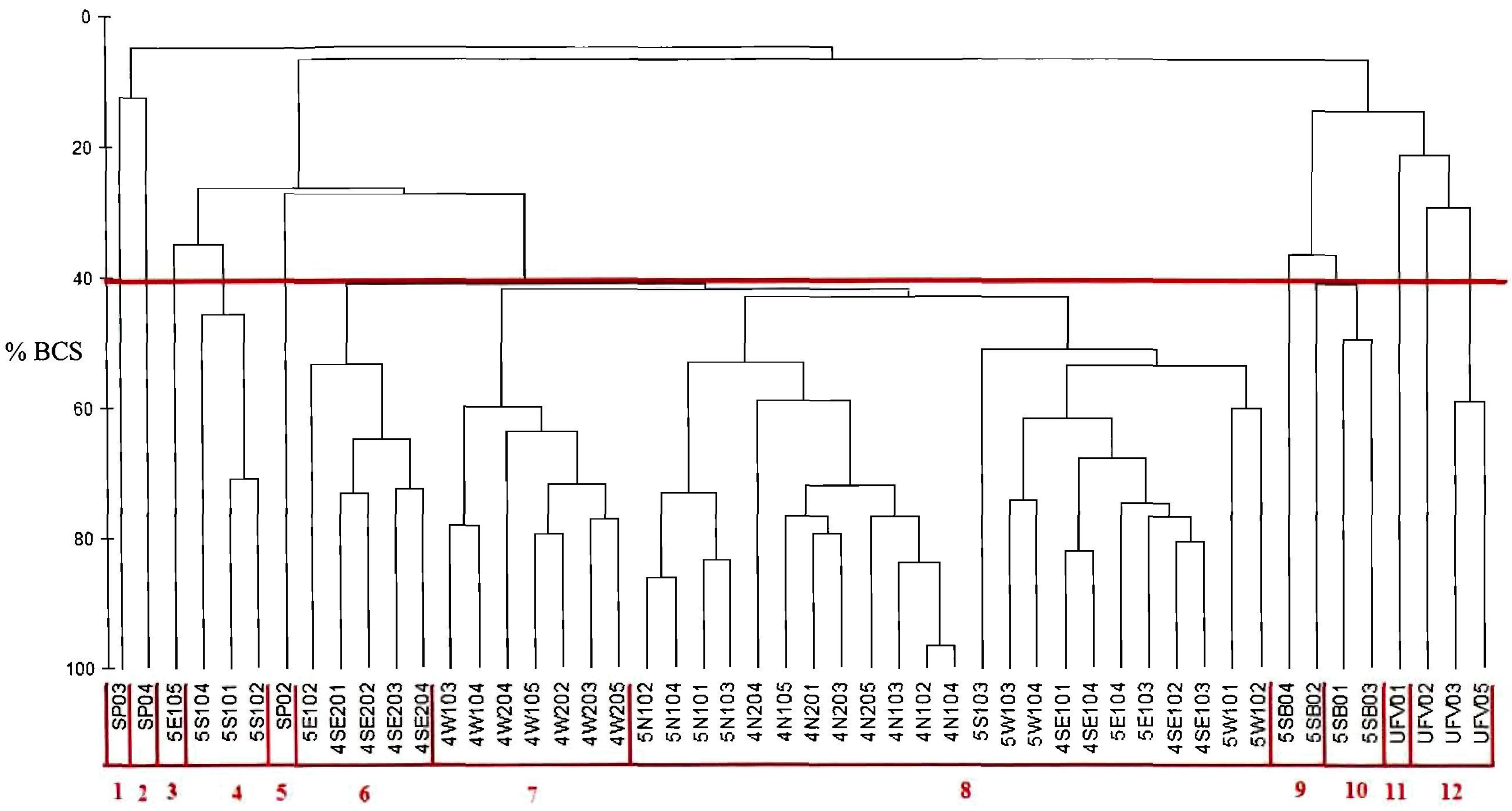

Figure 5.5. Hierarchical Cluster Analysis diagram of the 2008 vegetation composition -related site associations. Cut off at 40% similarity using Bray-Curtis Similarity with square-root transformation. Site clusters are indicated by group numbers, which correspond to Figures 5.3 and 5.4 for 2007 and Figure 5.6 for 2008 and are further explained in the text. Site names and abbreviations are explained in Appendix A.

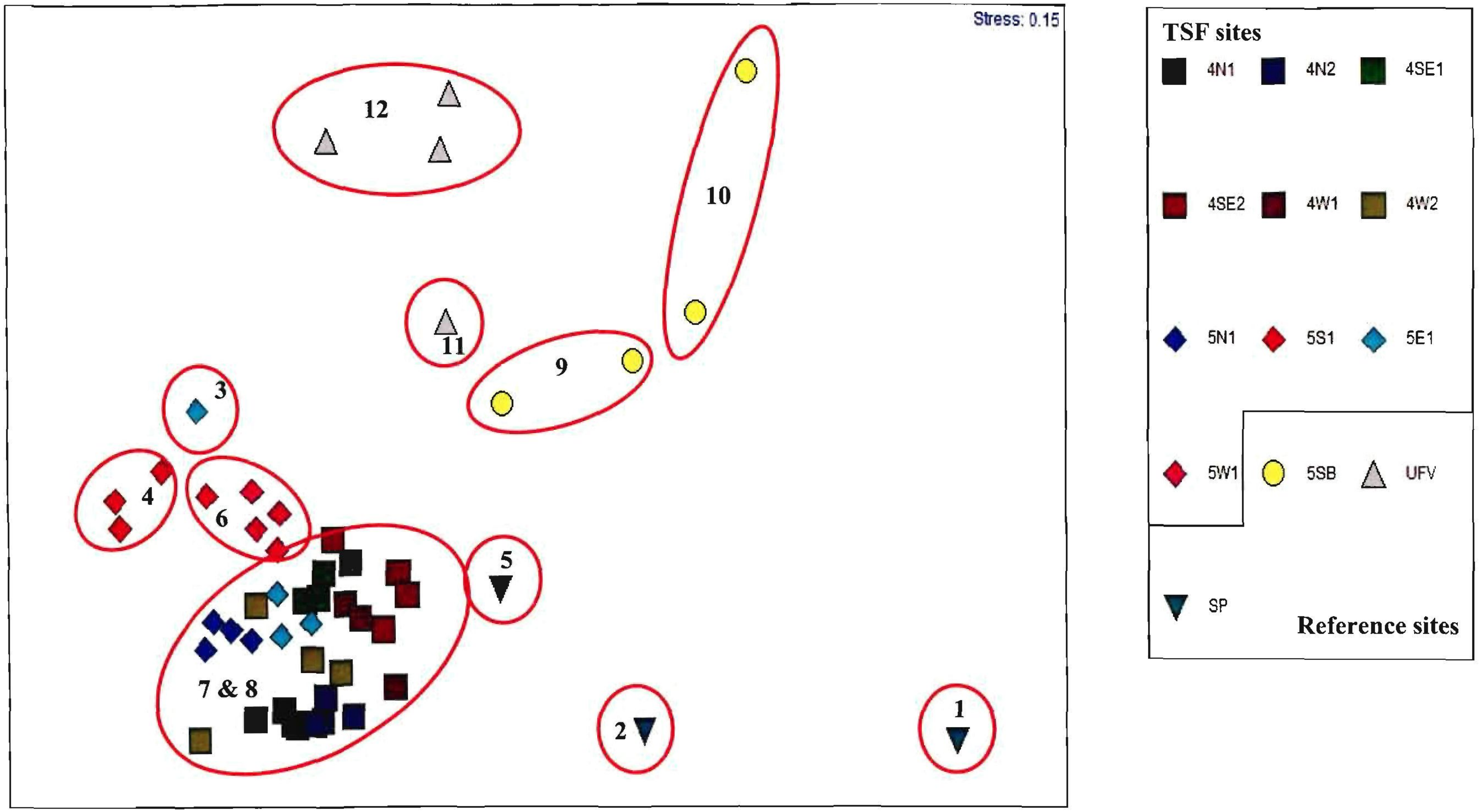

Figure 5.6. Non-Metric Multidimensional Scaling diagram of the 2008 vegetation composition -related site-associations. The red ovals indicate the site clusters of sites with similar species composition. The group numbers (1-12) stem from the cluster analysis in Figure 5.5 that were carried over into the 2007 analyses in Figures 5.3 and 5.4. Site names and abbreviations are explained in Appendix A.

5.3. Landscape function

The LFA data collection also took place in March/April of 2007 and March of 2008. The timing of repeat-sampling in 2008 was important, as inter-seasonal variation can occur for some indicators (Tongway *et al.*, 2004). Five replicate transects (often called gradient-oriented transects, or 'gradsects') were considered to be sufficient to test for variability within each site, based on expert opinion. This was confirmed by the very small standard error margins displayed for each LFA index in Figure 5.7. The data were initially analysed making use of the standard LFA spreadsheet package which computed the various indices of landscape function. These indices were the outputs that made up the basis for further analyses.

5.3.1. Patch/interpatch descriptions

The first step in analysis was describing each patch and interpatch type in terms of their similarity and function. Although this would not affect the overall function of the sites, it was intended to establish whether indicator values of specific patch types differed substantially across all sites. If there were no real differences, or only differences between certain patch types, then it could suggest only landscape organisation need be measured annually (with SSA measured every second or third year). It would also indicate what 'ideal' patch/interpatch composition could be pursued for effective resource regulation on the TSF slopes.

Table 5.2 gives the total number of times that each patch/interpatch type was recorded, with the frequency at which each patch type was recorded (i.e. the percentage of transects in which that patch/interpatch type occurred). These are the patches and interpatches as presented in section 4.4.4. Table 5.2 also gives the average values (across both years), standard deviations and standard error margins for each LFA index (Stability, Nutrient Cycling and Infiltration). Those standard error margins that fell below 1.96 should not be statistically significant (as confidence limits were set at 95%), and would indicate that they were alike enough to not require multiple assessments in future. The Lilliefors and Kolmogorov-Smirnov tests were run to test the distribution of each patch/interpatch type, which was normally distributed in each instance. A one-tailed t-test for single means was then conducted for each LFA index in every patch/interpatch type to test for significance.

The internal differences between patches and interpatches were only significant ($p < 0.05$) for Stability in the Woody Litter Patch (WLP) and Cryptogam Patch (CP), which also had the only standard error margins higher than 1.96. There were no significant differences in Stability for any other patch/interpatch type, nor at all for Infiltration or Nutrient cycling. This meant that, for example, all Grass Patches (GP's) were essentially alike in function, and only WLP and CP need be individually assessed.

WLP's were the most functional patch types (seen by adding Stability, Infiltration and Nutrient cycling average values in Table 5.2), but occurred with the lowest frequency. Tree Patches (TP's) and Shrub Patches (SP's) were next most functional, and interestingly showed almost identical functionality values, but were also relatively scarce, with frequencies of 7.4% and 17.04% respectively. These woody-related patch types possessed the greatest amounts of litter deposition and accumulation, the most efficient rainsplash protection and the greatest individual cover values, which were reflected in high levels of Infiltration and Nutrient cycling. The next three most functional patch types were Grassy Litter Patch (GLP), Grass Patch (GP) and Litter Patch (LP), all of which occurred in relatively high frequencies on the TSF slopes (Table 5.2) and had similar, but slightly lower indicator values than the woody-related patch types. Pampas Patch (PP) was also a highly functional patch type with large volumetric area and exceptional litter production. However, most individuals had been treated with herbicide during the survey period and were unlikely to persist if control was maintained. Sparse Grass Patch (SGP), which was the second most frequent patch type overall (51.85%), was one of the less functional patch types, as it had low aerial cover, low rainsplash protection, higher levels of erosion, lower levels of deposition (alluvial accumulation) and lower levels of litter production, accumulation and incorporation. These factors helped in the creation of the streamlined future monitoring framework as proposed in section 6.6.

Of the interpatches, Bare Soil (BS) was slightly more functional than Bare Tailings (BT) and Gravel Interpatch (GRI) due to the higher Stability values, as would be expected from a more 'natural' and composite substrate. BT, however, did have higher Infiltration values, as would be expected due to the sandy-loam texture (silt-sized particles).

Table 5.2. Patch and interpatch types of the Chemwes Tailings Complex, in order of abundance and with explanatory codes used in the text. The table also gives the total number of patches and interpatches encountered, the frequency with which each patch/interpatch occurred and a summary of values for each LFA index (Stability, Nutrient cycling and Infiltration).

Rank	**Patch name**	**Code**	**Total**	**Frequency**	**Stability**			**Infiltration**			**Nutrient cycling**		
	Patches				*Average*	*Standard deviation*	*SEM*	*Average*	*Standard deviation*	*SEM*	*Average*	*Standard deviation*	*SEM*
1	Grass patch	GP	123	91.11	66.50	8.11	0.07	49.35	7.30	0.15	36.84	6.72	0.18
2	Sparse grass patch	SGP	70	51.85	54.05	5.59	0.08	37.67	4.28	0.11	23.03	3.89	0.17
3	Grassy litter patch	GLP	51	37.78	67.53	6.19	0.12	52.71	5.69	0.11	40.12	5.74	0.14
4	Litter patch	LP	51	37.78	63.50	7.67	0.15	51.82	5.67	0.11	37.20	7.09	0.19
5	Shrub patch	SP	23	17.04	69.03	5.70	0.25	56.03	8.88	0.16	42.45	9.03	0.21
6	Rock patch	RP	17	12.59	48.28	2.50	0.15	9.20	1.14	0.12	9.30	1.38	0.15
7	Tree patch	TP	10	7.41	69.97	6.96	0.70	56.30	8.25	0.15	45.67	8.09	0.18
8	Pampas patch	PP	10	7.41	66.12	6.43	0.64	46.78	7.07	0.15	35.82	14.10	0.39
9	Herb patch	HP	4	2.96	55.27	5.53	1.38	42.64	3.32	0.08	25.27	3.35	0.13
10	Dead forb patch	DFP	4	2.96	53.33	3.14	0.79	34.79	0.57	0.02	23.14	3.12	0.14
11	Root patch	RTP	3	2.22	66.28	4.75	1.58	42.73	1.10	0.03	27.57	1.59	0.06
12	Cryptogam patch	CP	3	2.22	63.35	7.39	2.46	39.28	4.58	0.12	24.72	3.82	0.15
13	Woody litter patch	WLP	2	1.48	79.69	6.63	3.31	70.51	15.43	0.22	59.46	22.55	0.38
	Interpatches												
1	Bare taiings	BT	113	83.70	50.29	5.53	0.05	29.48	4.39	0.15	15.29	3.35	0.22
2	Gravel interpatch	GRI	11	8.15	44.35	5.18	0.47	30.73	3.13	0.10	14.84	2.47	0.17
3	Bare soil	BS	11	8.15	54.04	4.55	0.41	29.55	2.13	0.07	13.69	2.57	0.19

* 'Total' refers to the total number of transects in which patch/interpatch type observed

** 'Frequency' refers to the number of observations out of 135 transects, expressed as a percentage

5.3.2. LFA values

Table 5.3 shows the complete LFA index values for both survey years. It was evident that Stability values on the tailings dams were relatively high across all sites and in both 2007 and 2008, making up the highest scores, followed by Infiltration and Nutrient cycling. This indicated that Nutrient cycling contributed less to landscape function in these landscapes than Infiltration, which contributed less than Stability. Similar results are seen in Figure 5.7, where the sampling units were ranked in sequence of landscape function. The landscape organisation index (LOI) was a useful index that expressed the complexity of a landscape in terms of its patch: interpatch structure. The closer the value was to 1, the greater the proportion of the landscape was covered in patches. Therefore a landscape with a LOI of 1 (such as 4N1-04) consisted of one big patch, whilst a LOI of 0 indicated no patches within a landscape (Table 5.3). The data in Table 5.3 showed that three sites, 4SW1, 4SW2 and 4W1 were surveyed in 2007 but not in 2008. This was unavoidable, as unplanned reprocessing (on the mining company's part) destroyed the majority of the survey transects on these sites. They will henceforth be omitted from analyses, due to lack of comparative data for 2008 and are presented here merely as reference values. These three sites were, coincidentally the three most functional sites with Infiltration scores all above 40 points and often above 50 points, compared to the most functional remaining site that only had Infiltration values from 38-43 (Table 5.3). Similarly, the lowest Nutrient cycling score in the destroyed sites was 32 points, which represented amongst the highest values for the remaining sites.

Table 5.3 will continually be referred to in a later section of this chapter (5.3.4) and is used in cross-referencing the groupings that result from the HCA and MDS analyses.

Table 5.3. Results of the LFA transects, showing the cumulative scores of all landscape patches and interpatches for the LFA indices (Stability, Infiltration and nutrient cycling). LOI is to the Landscape Organisation Index, indicating the proportion of the transect covered by patches (max 1). Sites with XXX values were destroyed between sampling efforts. Site abbreviations are explained in Appendix A.

Sample	LOI 2007	LOI 2008	Stability 2007	Stability 2008	Infiltration 2007	Infiltration 2008	Nutrient cycling 2007	Nutrient cycling 2008
4N101	0.94	0.71	73.66	69.36	43.74	49.58	35.33	35.86
4N102	0.96	0.98	72.10	73.11	42.40	53.93	32.71	42.50
4N103	0.97	0.86	70.31	70.81	38.75	53.29	29.67	43.98
4N104	1.00	1.00	73.50	76.39	40.49	53.00	32.98	45.21
4N105	0.96	0.93	70.06	77.02	40.42	53.03	30.36	44.20
4N201	0.69	0.58	67.13	55.97	31.57	38.72	22.59	25.19
4N202	0.52	0.55	60.94	55.33	30.42	39.90	18.07	24.25
4N203	0.77	0.74	62.51	60.90	33.19	46.44	23.19	30.93
4N204	0.35	0.55	47.87	48.77	25.84	35.45	14.24	17.67
4N205	0.75	0.73	63.84	59.89	40.69	46.44	27.01	30.99
4SE101	0.73	0.37	61.59	50.04	30.34	34.15	21.37	18.46
4SE102	0.42	0.45	56.54	51.27	33.69	36.94	20.61	22.49
4SE103	0.54	0.38	52.87	52.98	34.94	33.20	18.13	20.80
4SE104	0.23	0.25	46.70	46.36	31.58	31.11	12.87	14.53
4SE105	0.37	0.33	51.97	52.71	31.58	33.73	16.70	20.46
4SE201	0.58	0.53	54.82	51.33	43.05	39.91	28.42	24.14
4SE202	0.69	0.51	63.25	55.78	37.63	37.11	29.40	24.04
4SE203	0.38	0.29	55.38	52.53	35.33	35.16	24.16	22.48
4SE204	0.40	0.26	52.11	48.06	30.90	33.84	19.24	17.56
4SE205	0.77	0.77	64.67	62.47	44.49	51.89	34.30	37.43
4SW101	0.77	XXX	65.27	XXX	48.17	XXX	35.41	XXX
4SW102	0.80	XXX	66.54	XXX	51.05	XXX	38.73	XXX
4SW103	0.86	XXX	67.35	XXX	49.89	XXX	38.64	XXX
4SW104	0.83	XXX	61.59	XXX	48.66	XXX	35.02	XXX
4SW105	0.63	XXX	62.50	XXX	46.89	XXX	34.42	XXX
4SW201	0.82	XXX	66.37	XXX	44.62	XXX	34.89	XXX
4SW202	0.83	XXX	60.63	XXX	49.91	XXX	33.17	XXX
4SW203	0.92	XXX	65.87	XXX	50.47	XXX	35.79	XXX
4SW204	0.94	XXX	60.26	XXX	48.63	XXX	34.08	XXX
4SW205	0.84	XXX	59.99	XXX	45.95	XXX	32.35	XXX
4W101	0.91	XXX	61.25	XXX	51.97	XXX	35.80	XXX
4W102	0.98	XXX	62.95	XXX	50.58	XXX	34.04	XXX
4W103	0.91	XXX	64.52	XXX	53.69	XXX	35.59	XXX
4W104	0.94	XXX	66.93	XXX	51.32	XXX	37.05	XXX
4W105	0.51	XXX	58.97	XXX	39.71	XXX	24.94	XXX

Table 5.3 (continued).

Sample	LOI 2007	LOI 2008	Stability 2007	Stability 2008	Infiltration 2007	Infiltration 2008	Nutrient cycling 2007	Nutrient cycling 2008
4W201	0.66	0.61	64.67	61.44	40.64	37.82	28.70	29.51
4W202	0.69	0.52	62.03	59.35	40.07	37.43	28.45	26.60
4W203	0.71	0.62	62.49	53.65	41.53	41.80	29.29	26.75
4W204	0.47	0.70	59.19	52.96	36.85	45.23	23.55	27.30
4W205	0.77	0.69	64.92	56.49	42.77	44.86	28.82	30.41
5N101	0.78	0.73	61.03	62.87	45.21	52.63	34.24	37.80
5N102	0.78	0.68	58.27	62.95	41.08	50.05	31.44	35.90
5N103	0.81	0.75	58.77	61.72	43.33	50.21	30.45	34.29
5N104	0.55	0.50	57.34	53.23	37.96	41.16	25.82	24.55
5N105	0.61	0.53	54.64	52.61	43.13	44.51	28.37	24.92
5E101	0.72	0.71	61.90	65.01	42.49	52.22	32.71	39.46
5E102	0.59	0.38	62.84	58.55	42.99	41.29	30.18	30.10
5E103	0.76	0.72	62.40	66.08	48.87	52.29	34.42	38.75
5E104	0.78	0.76	61.70	67.69	47.74	53.89	33.23	40.35
5E105	0.74	0.56	59.87	61.06	43.97	47.47	31.76	35.96
5S101	0.43	0.60	51.73	56.22	42.37	44.50	25.09	29.13
5S102	0.54	0.50	52.70	57.17	42.39	41.86	27.68	26.64
5S103	0.26	0.16	50.83	42.36	34.80	35.91	20.94	13.67
5S105	0.55	0.61	57.25	64.86	42.52	44.53	28.90	31.49
5W101	0.83	0.79	66.01	60.88	49.65	52.65	36.37	35.71
5W102	0.99	0.94	73.07	73.93	52.65	63.24	41.78	49.39
5W103	0.27	0.54	56.70	50.56	30.44	33.27	20.30	20.58
5W104	0.38	0.49	57.78	54.17	31.65	34.13	21.86	20.56
5W105	0.85	0.78	67.83	63.19	46.01	52.70	38.07	36.21
5SB1	0.68	0.63	58.18	59.77	44.91	47.37	30.48	32.46
5SB2	0.66	0.40	62.94	54.78	38.71	43.94	33.03	24.24
5SB3	0.82	0.69	64.90	60.81	44.22	47.95	35.29	29.89
5SB4	0.66	0.35	60.26	51.43	41.64	40.00	31.36	24.17
5SB5	0.42	0.38	51.14	45.10	33.33	38.98	23.25	21.56
UFV01	0.57	0.73	66.49	61.43	41.16	40.39	29.88	25.27
UFV02	0.76	0.68	66.07	63.82	43.77	40.66	31.52	27.92
UFV03	0.82	0.75	66.42	64.06	48.45	48.93	35.56	30.86
UFV04	0.74	0.74	67.59	64.73	43.81	44.33	32.94	28.74
UFV05	0.72	0.67	64.63	62.01	40.60	37.59	29.08	27.20
SP01	0.24	0.13	50.91	56.46	23.84	21.98	9.47	8.57
SP02	0.09	0.08	53.95	52.30	23.32	28.80	9.15	9.46
SP03	0.26	0.24	52.41	53.39	22.29	21.23	8.89	9.69
SP04	0.12	0.12	49.79	54.47	31.91	23.08	9.11	9.95
SP05	0.10	0.51	54.29	52.00	22.38	24.62	9.27	11.57

5.3.3. Statistical analyses and comparisons of landscape function data

For analyses and comparisons, four indices were selected on the basis of their contribution to functional and structural aspects of the landscapes. These were: (1) Landscape Organisation Index (LOI), which was an index that measured what proportion of the measured transect was covered by patches (those biophysical units that promote resource accumulation in a landscape) and expressed with a maximum value of 1 (Table 5.3); (2) Stability index, which was made up of a combination of biological and physical indicators and that expressed a landscape's resistance to erosion and soil loss, expressed out of 100 possible points. High Stability values (as per Table 5.3) indicated the presence of organic matter that was becoming incorporated into the soil, thus improving soil structure, and the presence of plant roots, which bind the soil; (3) Infiltration index, which was also expressed out of 100 points, (Table 5.3) represented the capacity of a substrate, including the above-ground components, to absorb water at a rate faster than it accumulates, and to thus decrease runoff and erosion susceptibility. Substrate texture, litter cover and plant roots, especially, enhanced Infiltration; (4) Nutrient cycling index, also expressed out of 100 (Table 5.3), which was largely a biological index (but was influenced by landscape and soil physical properties) that indicated to what extent litter was being accumulated, broken down and incorporated into the soil matrix for pedogenesis and cycling of nutrients. Soil compaction and the formation of soil crusts hinder cycling.

Data from the aforementioned four LFA indices were statistically analysed by first testing the means for Gaussian distribution. Unlike the vegetation data, the LFA indices did pass the Shapiro-Wilks normality test ($P > 0.05$). Therefore a parametric test, the One-Way Analysis of Variance (ANOVA) could be used to establish whether significant differences occurred between the sites. This was followed by Tukey's post-hoc test to indicate between which of the sample sites the differences, if any, occurred. The statistical analyses found significant differences only between the spillage sites (SP) and every other sites, but not between any of the other sites. For LOI, the spillage area (SP) differed significantly from all but the sites with lowest index values (ANOVA, $P < 0.05$), 4SE1 and 4N2. For Stability, the spillage area (SP) was least stable and differed significantly only from the most stable site, 4N1 (ANOVA, $P < 0.05$) (Figure 5.7), but interestingly not from the undisturbed grassland (UFV). A similar pattern emerged for both Infiltration and Nutrient cycling, in which the crusted and nutrient-poor spillage area (SP) differed significantly from all sites (ANOVA, $P < 0.05$) other than two TSF sites, 4SE1 and 4N2, that had very low Infiltration and Nutrient cycling values. These similarities between and amongst sites were supported by the tight groupings in the MDS diagrams (Figures 5.15 and 5.17), as well as the very high levels of Bray-Curtis similarities (Figures 5.14 and 5.16), which will be discussed at length. Although there may not have been statistical significance, there certainly was ecological significance. Tongway and Hindley (2004) consider that a shift in five index points in any of the LFA indices between surveys is always ecologically significant. This applies particularly to their critical threshold analyses in which sites that are either five points above or five points below a calculated threshold are ecologically significant (this will be discussed later under section 5.4).

Direct comparisons of the soil surface assessment and landscape organisation indicators showed that, at first glance, little change had taken place during the two survey periods, but that some specific indicators were becoming more important in maintaining landscape function. There were too many transect values for each indicator to realistically be portrayed in this thesis, so the index values were used in reporting as summaries to represent the processes occurring at each site and where inconsistencies or changes in trends were observed, the data were then scrutinised to establish the root cause of variation.

Figure 5.7 illustrated the continuum for Stability, Infiltration and Nutrient cycling as components of landscape function for all sample sites over the two-year sampling period (2007 to 2008). The sites to the left of the graph possessed the least Stability and therefore had the greatest susceptibility to erosion as a result of poor vegetation cover. Those sites to the left of the graph also possessed the lowest Infiltration scores, resulting in increased runoff volumes and thus increased net loss of resources such as topsoil, organic matter and seeds. Those sites to the left of the graph also had the lowest Nutrient cycling index, a direct function of the low amount of vegetation cover, resulting in minimal litter accumulation within the soil, the formation of crusts, and inferred poor soil biology (due in part to lack of readily available Carbon food sources (Ashman and Puri, 2002)). Figure 5.7 is also presented as a cross-reference and will be referred to again in section 5.3.4. The specific indicators that comprised the index values, as well as why they changed between years, will be fully investigated in section 5.3.4.

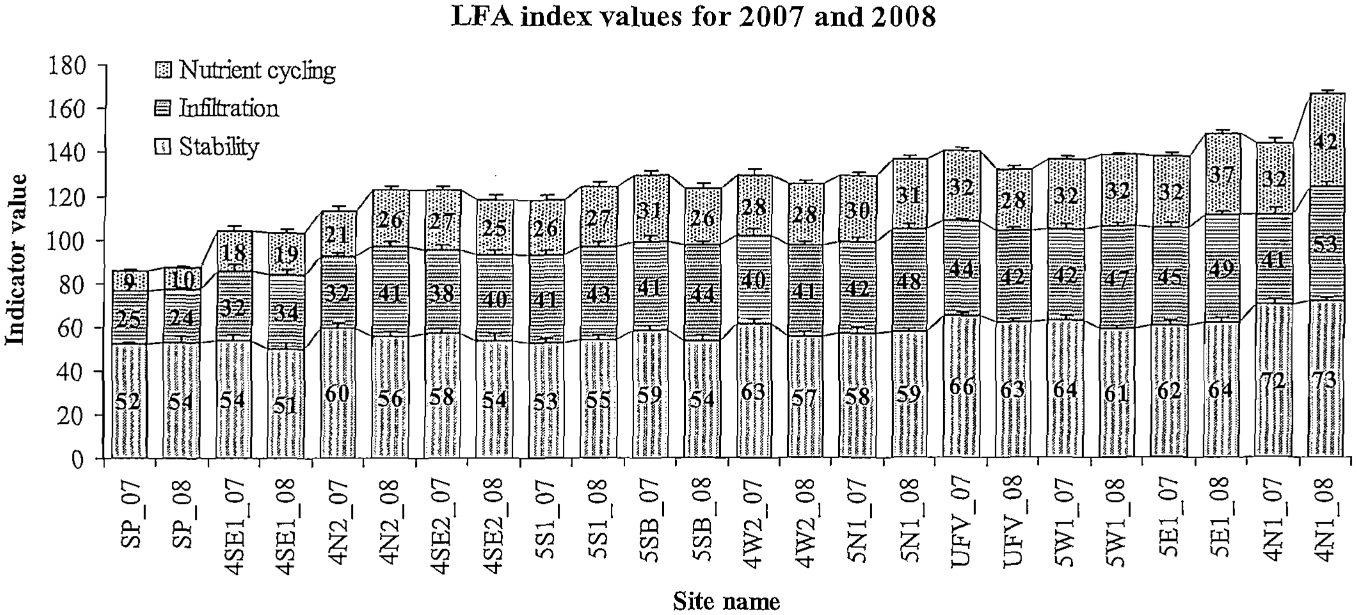

Figure 5.7. Average landscape function index scores (individual transect scores in Table 5.3) for each site, presented here as a sigmoidal curve ordered by the ranking of total values for each site. This presents the data on a continuum from least to most functional sites.

5.3.4. Graphical descriptions and analyses of function

When considering the ecological significance of changes in the LFA index values, the site differentiation that resulted from the ANOVA matched well with the cluster diagrams drawn in PRIMER 5 (Figure 5.8 for 2007 and Figure 5.10 for 2008). The data were then regrouped using CANOCO 4.5 (Ter Braak and Smilauer, 2002) on that basis to discern the principal components accounting for the differences observed between groups. This allowed for initial analyses to establish differences between the sites and then a finer-scale investigation of the indicators that made up those differences. PRIMER creates similarity matrices from standard data tables, which then allows pair-wise comparisons between sites based on the input data.

Similarity was based on Bray-Curtis distance as a measure of relative similarity between sites. This allowed for the graphic illustration of similarities between sites making use of MDS (Figures 5.9 and 5.11), similar to the vegetation analyses. As in the vegetation analyses, consistent patterns emerged between the successive survey years. In Figures 5.9 and 5.11, a functionality gradient was evident, with the least functional sites grouping at the bottom left of the graphs (SP) and the most functional grouping at the top right (4N1). Most sites showed similar relative positions to one another in 2007 and 2008 except for the spillage site (SP), which increased in organisation over time but not in functionality. In 2008, most sites displayed improved landscape organisation, whilst functionality either improved or declined slightly.

Figures 5.8 and 5.10 did not present the data organised along a restoration gradient, as did Figures 5.9 and 5.11, but rather the spread of functionality scores for each individual sample. This was an indicator of the internal variation within sites based on the combined LFA indices. When not split into sampling units, it became evident that some transects could have grouped with transects from other sampling units and different aspects, even different tailings dams, based on the indicator scores that comprised their landscape function.

The 2007 LFA data were split into five distinct groups (Figures 5.8 and 5.9), based on their internal compositional similarity (as measured by Bray-Curtis similarity or BCS), which were repeated in 2008 (Figures 5.10 and 5.11) and represented the functional status of these sites.

The five groups were ranked from 1-5 in terms of their functionality, with group 1 being highly dysfunctional sites, group 2 being the moderately dysfunctional sites, group 3 being moderately functional, group 4 being functional, and group 5 being the highly functional sites. This served, as has been explained, to overcome the lack of suitable reference sites for the TSF slopes in an attempt to characterize all sites on the continuum of highly dysfunctional to highly functional values. The composition of the groups did not differ substantially between the two survey years, although some sites did improve in function (i.e. from group 2 in 2007 to group 3 in 2008), whilst others declined in function (i.e. from group 4 in 2007 to group 3 in 2008). However, these levels of function were expressed on the relative scale, and actual values can be correlated with Table 5.3. The first level of separation between sites occurred at 77% BCS in 2007, separating group 1, 2 and 3 (more dysfunctional) from groups 4 and 5 (more functional), but this split occurred at 71% BCS in 2008. This is largely due to the split being slightly different in 2008, with groups 1 and 2 (more dysfunctional) clustering separately from groups 3, 4 and 5 (more functional). Therefore, the functional status of sites occurring in group 3 were promoted into a more functional general grouping in 2008 than in 2007, as will be explained in full detail below.

As Figure 5.7 showed, there were few major changes amongst sites between the two survey years. However, exploring the finer-scale changes in the indicators, and how these in turn affected the soil surface processes, were important in gaining insight into how these artificial biophysical systems function and to aid in developing a predictive understanding of how flux in these processes alters the economy of vital resources.

Looking more closely at the spatial and temporal variation in groups of sites (1-5), it became evident that finer-scale changes in processes may have been driven by natural factors (climatic, competition, succession), anthropogenic factors (burning, herbicide applications, physical disturbance of substrate), or combinations of these factors.

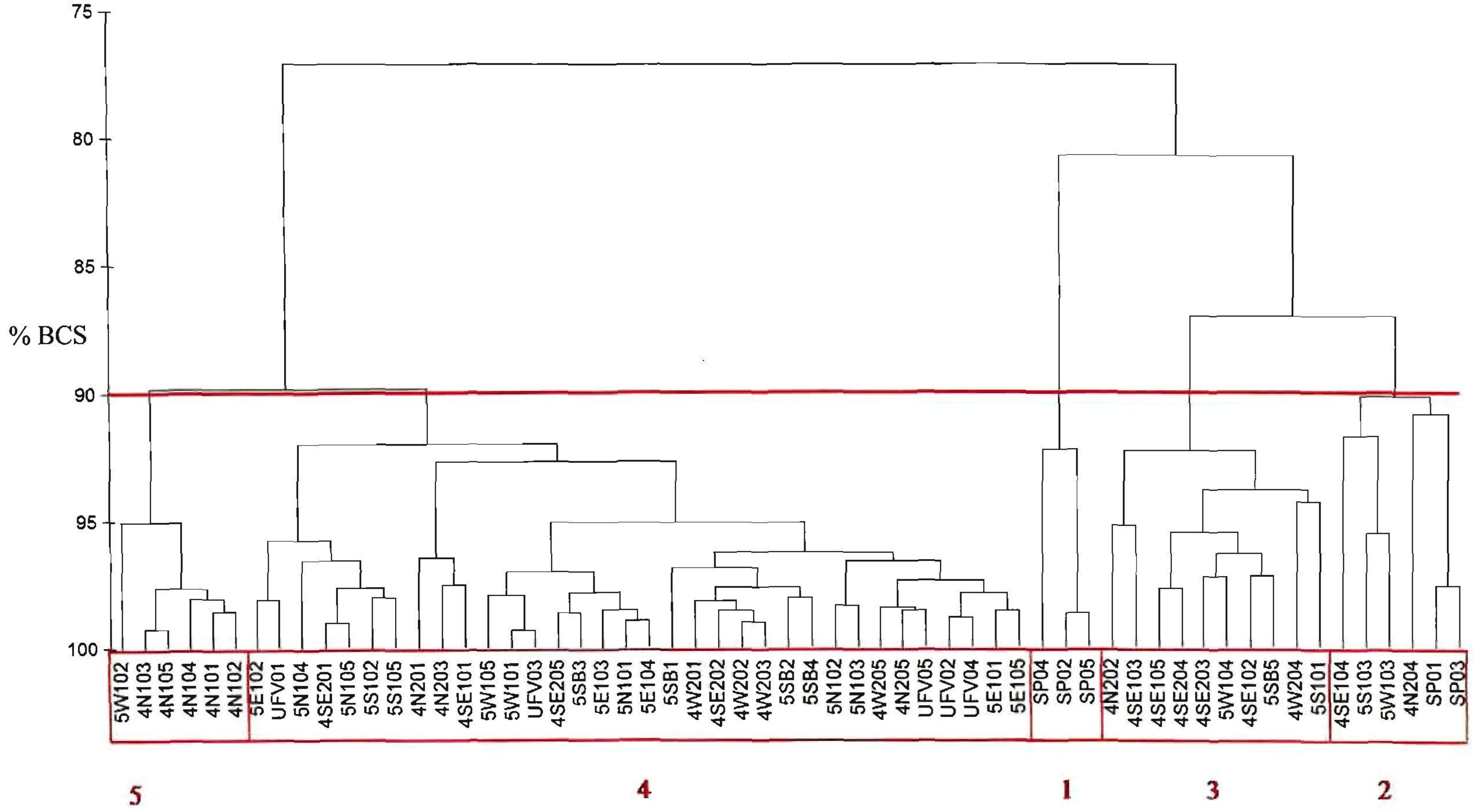

Figure 5.8. Hierarchical Cluster Analysis diagram of the 2007 LFA index-related site associations to denote relationships between sites. The cut-off for groupings was at 90% similarity using Bray-Curtis Similarity with no transformation. Site clusters are indicated by group numbers, which relate to Figure 5.9 and are repeated for the 2008 analyses in Figures 5.10 and 5.11. The site names and abbreviations are further explained in Appendix A.

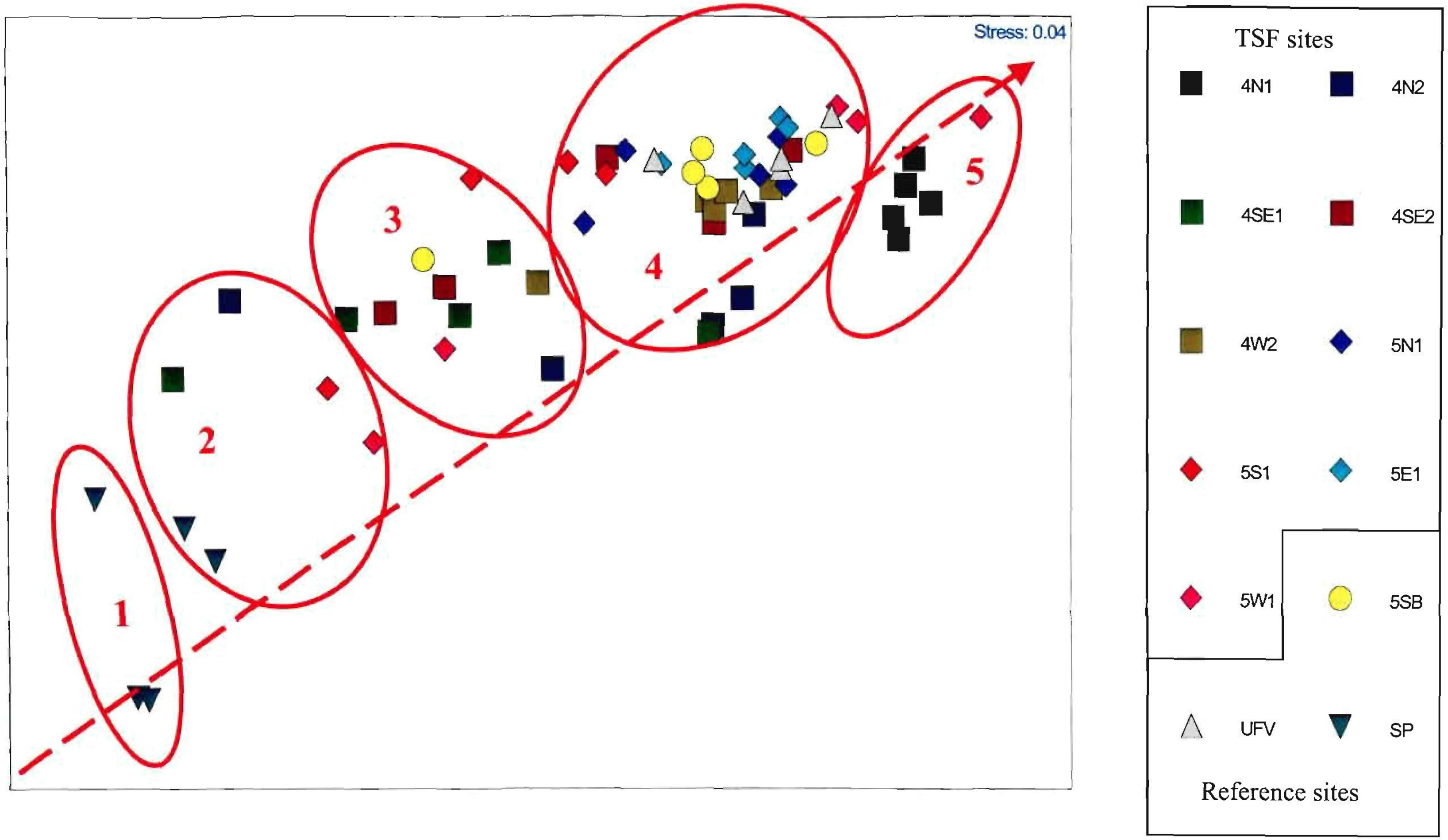

Figure 5.9. Non-Metric Multidimensional Scaling diagram of the 2007 LFA index -related site-associations. The red ovals indicate the site groupings and have numbers derived from Figure 5.8. The groupings are repeated in Figures 5.10 and5.11 for 2008. Site names and abbreviations are explained in Appendix A.

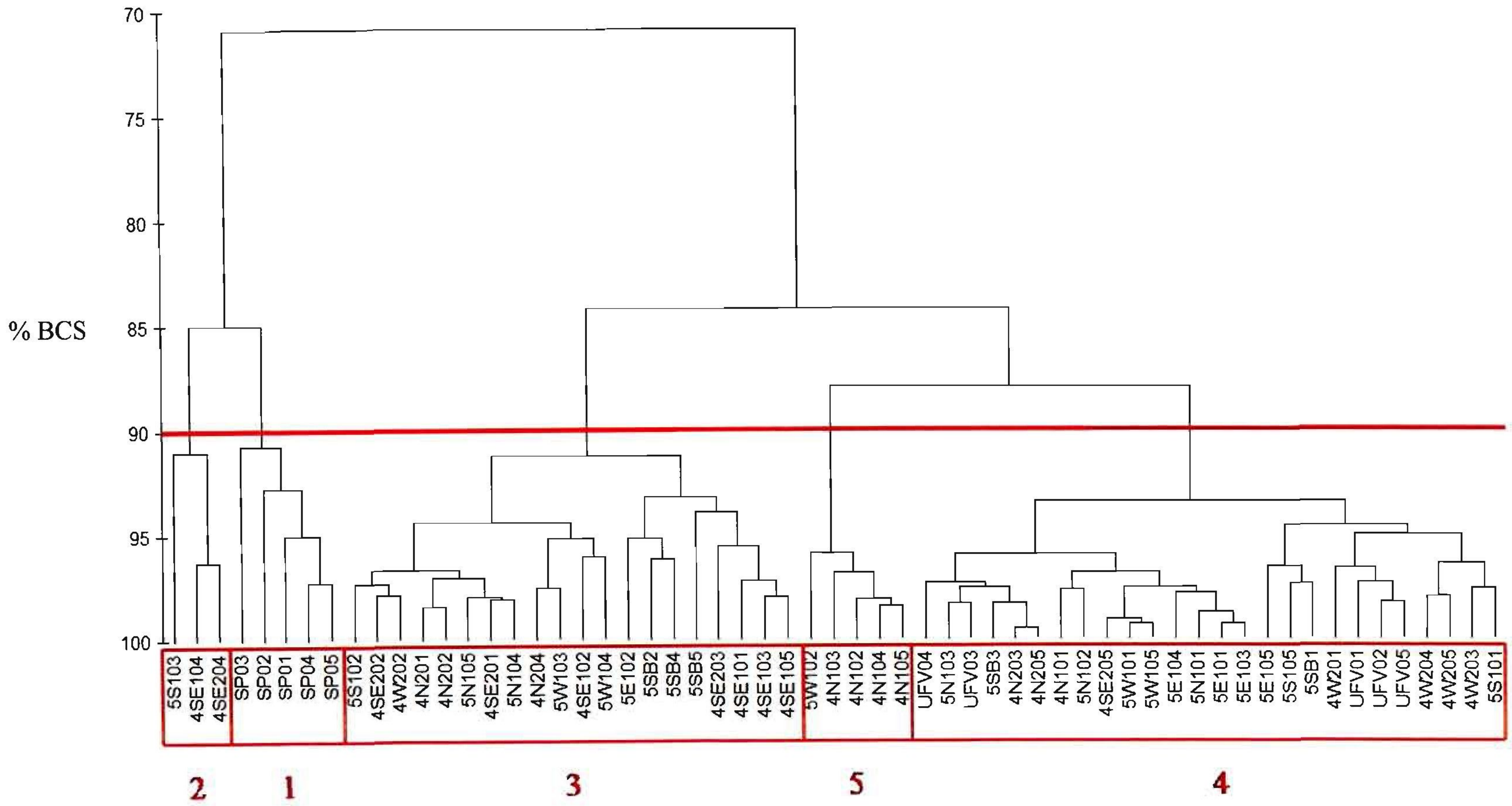

Figure 5.10. Hierarchical Cluster Analysis diagram of the 2008 LFA index-related site-associations. The cut-off is at 90% similarity using Bray-Curtis Similarity with no transformation. Site groupings are indicated by numbers, which originate from the 2007 analysis in Figure 5.8 and corresponds to Figure 5.11. Site names and abbreviations are explained in Appendix A.

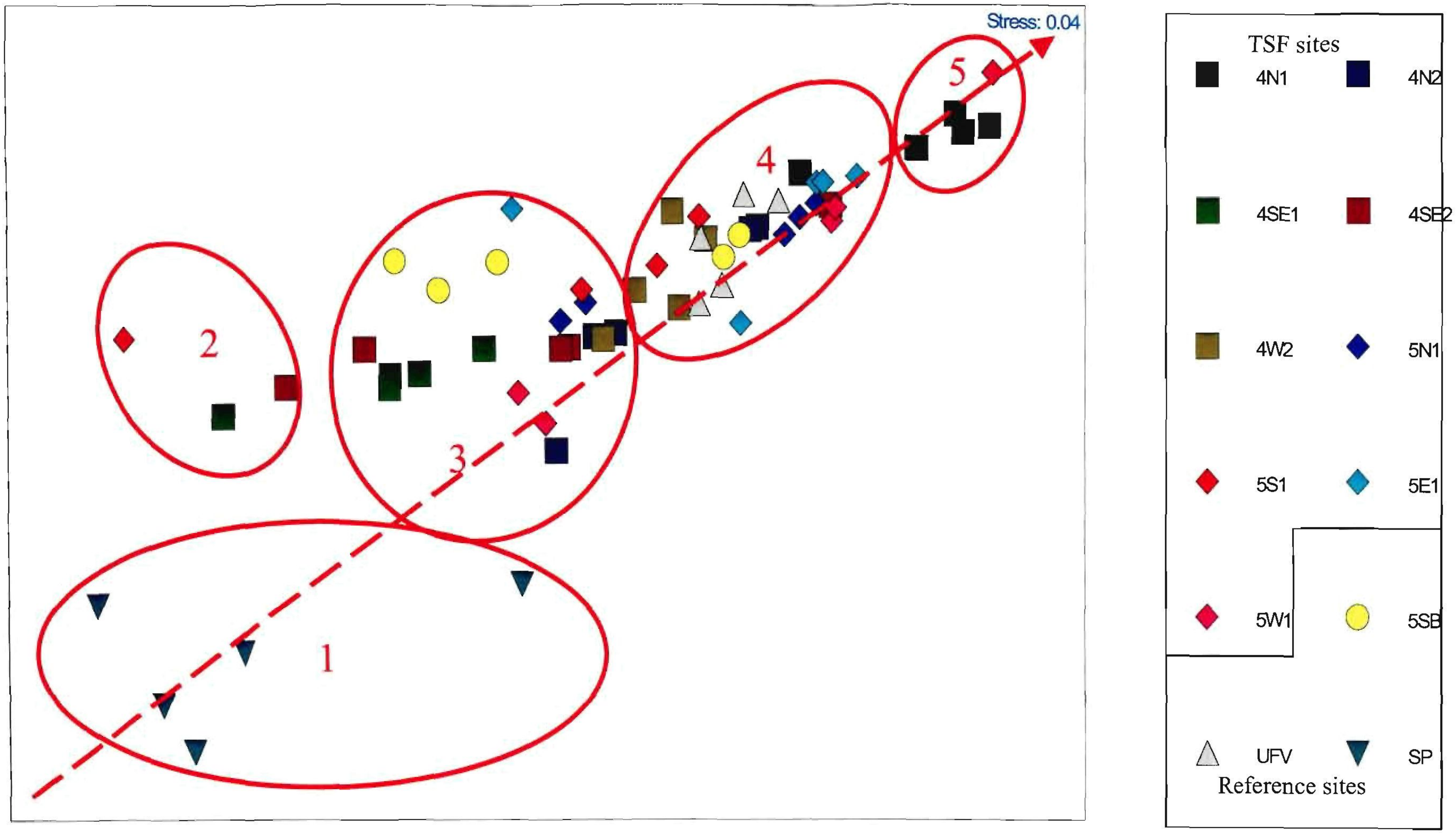

Figure 5.11. Non-Metric Multidimensional Scaling diagram of the 2008 LFA index -related site-associations. The red ovals indicate the site groupings and correspond to the cluster analysis in Figure 5.10 and to the 2007 analysis in Figure 5.9. Site names and abbreviations are explained in Appendix A.

CANOCO Principal Component Analysis (PCA) (Figure 5.12) showed that there were specific structural variables that were either directly or inversely related to the LFA indices. The size of the dataset resulted in a highly cluttered diagram and precluded an intelligible interpretation. Therefore, the data were later presented in a series of PCA ordination diagrams (Figures 5.13-5.17), each showing just those sites/transects corresponding with each functional group, as defined by the HCA and MDS analyses. The Eigenvalues are therefore identical in each PCA ordination, as they are, in essence, all the same ordination but with selected sites 'switched off' to allow interpretation. All sites were included in the analysis, but only selected sites were displayed in each instance for ease of interpretation.

The first ordination axis (Figures 5.12, 5.13, 5.14, 5.15, 5.16 and 5.17) had an Eigenvalue of 0.454 and thus accounted for 46.2% of the variance in the dataset. The LFA indices (Stability, Infiltration and Nutrient cycling), LOI and Interpatch length all had positive correlations with the first ordination axis and therefore explained most data variance. The positive correlations of the LFA indices and LOI with the first ordination axis are coupled together with their strongly positive correlation with one another. In the opposite direction, Interpatch length has a positive correlation with the first ordination axis but this is combined with Interpatch length having strongly negative correlations with LOI and the LFA indices. This indicates that, in general, there is a gradient of increasing functionality from the right to the left of the ordination diagram that correlates with the first ordination axis. This gradient was also weakly positively correlated with site age, a variable that was influenced by both ordination axes. Therefore the tendency of LFA indices and LOI to increase with decreasing Interpatch length correlated positively with increasing site age (although the correlation was not 100%, as indicated by the ca. 45° angle between site age and LFA variables and LOI). This significant result was also found in the later analyses in section 5.6.1.2. The second ordination axis (Figures 5.12, 5.13, 5.14, 5.15, 5.16 and 5.17) had an Eigenvalue of 0.245 and, together with the first axis, accounted for 71.2% of the total variance in the LFA dataset for both 2007 and 2008. Patch area, Number of patches and Number of patches/10m (patch density) correlated positively with the second ordination axis. However, Patch area correlated negatively with Number of patches and Number of patches/10m. This meant that sites with large patches tended to have fewer of these and that sites with many patches more often had smaller patches. The intuitive relationships between the variables indicate that the selected variables were adequate to elicit the inherent differences between sites and thus facilitated meaningful interpretation.

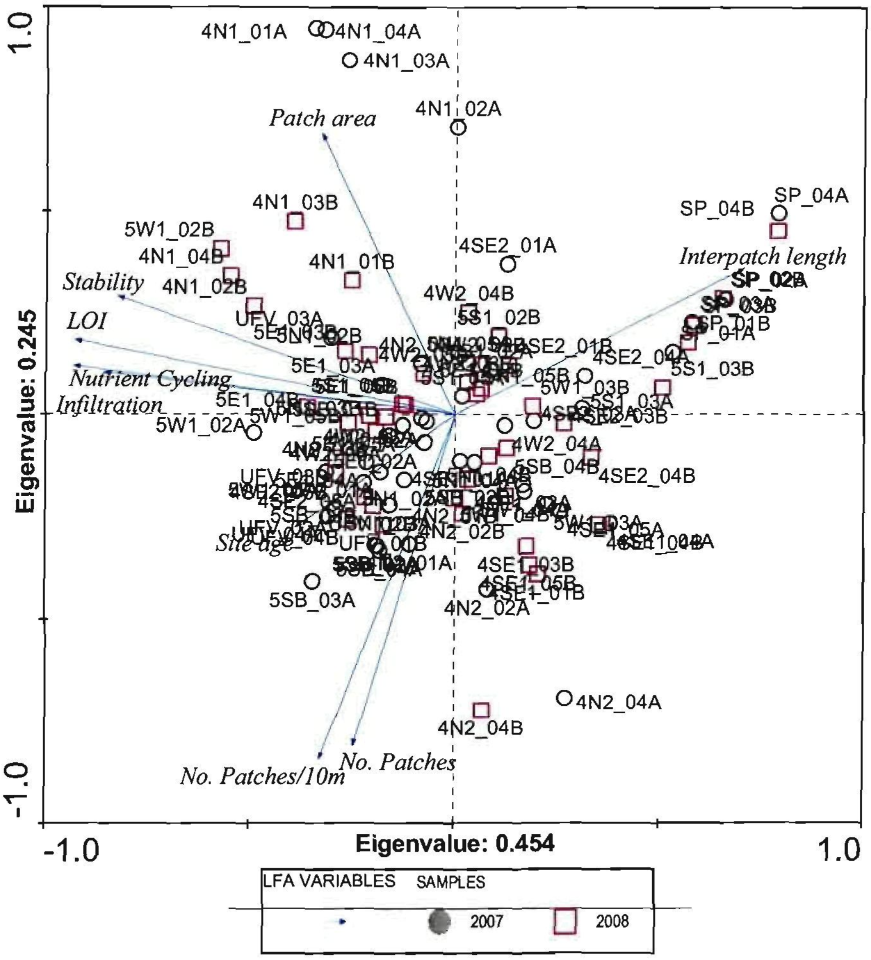

Figure 5.12. Principal Component Analysis (PCA) of the LFA indices and structural variables to investigate relationships between function and structure. The circles represent the transects falling within this group in 2007 (annotated with "A"), whilst the squares indicate transects in this group in 2008 (annotated with "B"). Site names and abbreviations are explained in Appendix A.

5.3.4.1. Functional Group 1

Group 1, the transects with the lowest function, comprised three of the spillage sites (SP), SP-02, SP-04 and SP-05 (not illustrated due to high inflation factor), in 2007 (Figure 5.13). These transects shared similar LFA index values, but had lower LOI values, generally around 0.15 (range 0.08-0.26) (Table 5.3), indicating that a very small proportion of each transect was made up of patches and that interpatches played a greater role in controlling what little resources may have flowed through the sites. Stability was reasonable, with an average of 53 (range 49-56), Infiltration was poor at average 24 (range 21-31) and Nutrient cycling was very, very low at average 9 (range 8-11) (Table 5.3).

These transects typically consisted of:

1. Very little or no perennial vegetation cover and thus no mentionable rainsplash protection;
2. Little or no litter deposition or breakdown;
3. Negligible microtopographical variation for resource capture;
4. Evident soil physical crusts, which were devoid of cryptogams;
5. But fortunately did not possess dispersive soils (although none of the tailings materials sampled on any transect were dispersive).

These indicator classes resulted in sites that were (corresponding to above numbers):

1. Prone to A-horizon capping, disturbance and displacement by the impact of raindrops due to poor perennial vegetation and litter cover, which effectively decreased soil aeration and Infiltration and also therefore the capacity to exchange gases and provide habitat for microbial organisms, which then led to very poor Nutrient cycling;
2. Very low in soil organic matter, due to all litter being transported and largely transient in the sites and not achieving any levels of incorporation into the soil. This then decreased the physical Infiltration and water retention capacity and also the carbon food-source for potential microbes and thus inferred decreased nutrient mineralisation and cycling;
3. Very flat and unable to accumulate any mobile resources such as seeds, topsoil, water or organic matter, which then directly decreased all LFA index values;

4. Soils that were prone to water and wind erosion, nearly impervious, with high levels of runoff and thus low Infiltration and low Nutrient cycling and mineralisation due to hostile conditions for microbial persistence;
5. Reasonably stable due to non-slaking substrates and the presence of rocks and gravel that offered at least some degree of spatial pattern.

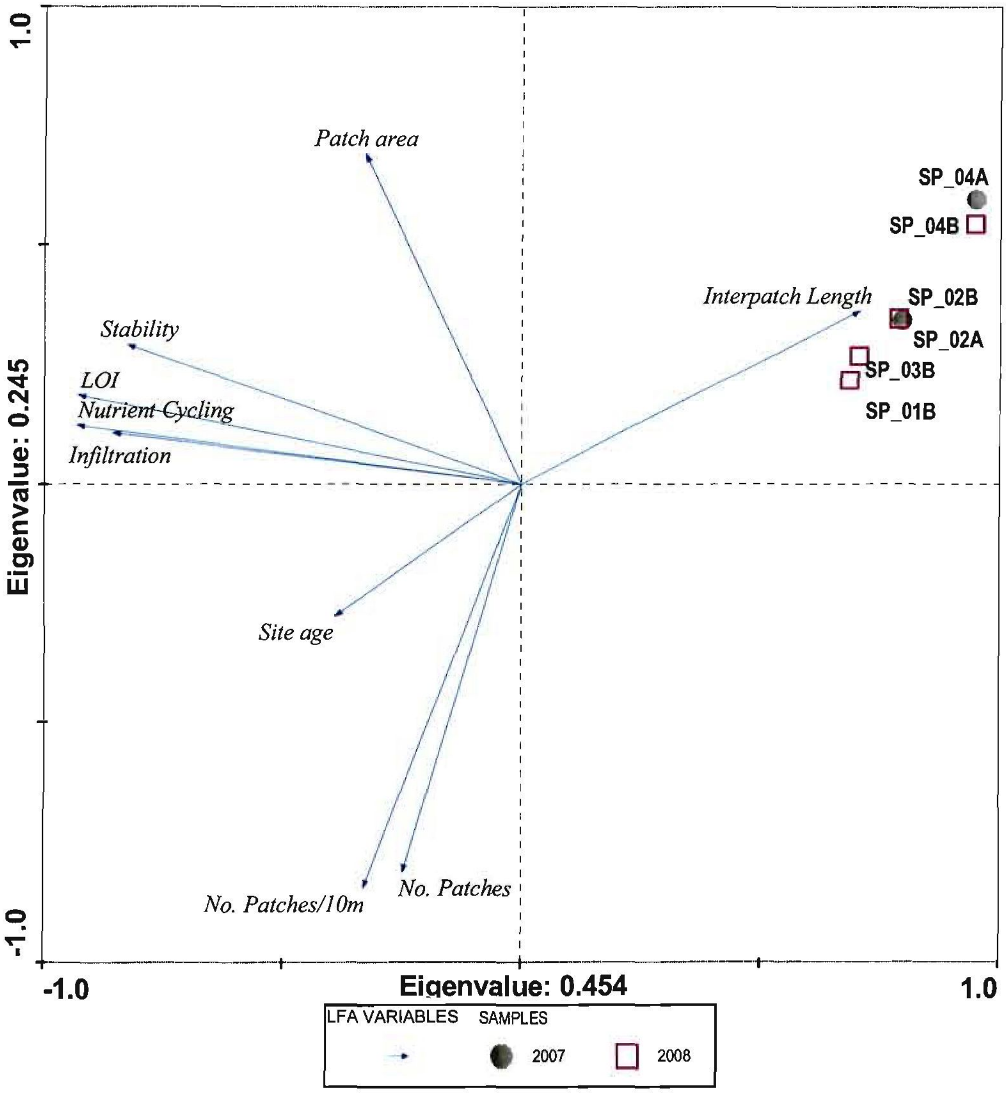

Figure 5.13. Principal Component Analysis for the LFA functional and structural parameters of group 1 for 2007 and 2008. The circles represent the transects falling within this group in 2007 (annotated with "A"), whilst the squares indicate transects in this group in 2008 (annotated with "B"). Site names and abbreviations are explained in Appendix A.

Figure 5.13 confirmed the relationship between the transects of group 1 and interpatch length (and thus inverse relationship with LOI) on the first ordination axis, which indicated that the poorly functional interpatches that made up these transects were also lacking in function and that secondary variables, such as patch area and number of patches were less important for differentiation (supported by their associating with the second ordination axis). The PCA ordination also showed that the sites from group 1 were negatively correlated to site age, which was the case, as the spillage area possessed the youngest rehabilitating sites.

The patterns observed in 2008 were similar to 2007, although the other two spillage sites (SP), SP-01 and SP-03, also clustered into group 1, unlike in 2007 (thus decreased in functional association from group 2 to group 1). Looking at the specific values in Table 5.3, very little important change occurred over time in the LFA index values but looking at the specific indicators that were responsible for the changes, it could be ascertained that the transported litter present on SP-01 in 2007 was lost in 2008 (most likely blown away as it had not become incorporated into the soil), patchiness had decreased and Infiltration and Nutrient Cycling had therefore decreased as well. This resulted in a proportional increase in Bare Soil and Rock Patch that had underlain the Litter Patches, which although being more stable made them less like the TSF slopes, on which these two patch and interpatch types did not occur. Therefore SP-01 was more closely associated with the other spillage sites (SP02-SP05) in 2008. SP-05 underwent very little change in the LFA index values but the LOI values did change due to the addition of a new interpatch type, *Gravel* Interpatch, which had possibly become exposed due to aeolian or water erosion of the overlying topsoil, which also made it less like the TSF slopes, with which it had clustered in 2007. SP-05 was not displayed in Figure 5.13, as it was an outlier, owing to its high inflation values.

The relative similarities between Group 1 sites were further illustrated by their BCS values. Group 1 split from the other poorly functional transects at 82% BCS in 2007 (Figure 5.8) and at 85% in 2008 (Figure 5.10). However, these differences were largely compositional, as Figures 5.7, 5.9 and 5.11 showed that the functionality changed very little. The functionality gradients that were indicated by the dashed arrows in Figures 5.9 and 5.11 run from the bottom left to the top right of the diagrams, with all of the spillage (SP) sites being comprising the least functional transects in both years.

5.3.4.2. Functional group 2

In 2007, group 2 consisted of the least functional TSF slope transects that, as has been mentioned and discussed, grouped the two spillage (SP) sites (SP-01 and SP-03) with the same compositional attributes (Figure 5.8). Therefore the focus here was on the poorly functional TSF sites that made up the remainder of this poorly functioning group. These sites were 4SE1-04, 4N2-04, 5S1-03 and 5W1-03. However, in 2008 the composition changed in some of the TSF transects as well (Figure 5.10), with 5W1-03 no longer being in group 2 (improved in function to become part group 3) and 4SE2-04 being added to group 2 from group 3. The decline in function of 4SE2-04 was also reflected in Table 5.3, as was the recovery of 5W1-03. The LOI values for group 2 were very low at average 0.25 (range 0.16-0.38), Stability was relatively poor at average 48 (range 42-58), Infiltration was also relatively poor at average 32 (range 26-36), and Nutrient cycling was very poor at average 16 (range 13-22) (Table 5.3).

The characteristics common to the group 2 transects were:

1. Relatively low LOI values, indicating that interpatches were more prominent than patches;
2. Interpatches were often crusted and also often eroded (terracettes);
3. Most frequent patch type were Sparse Grass Patch (SGP), consisting almost exclusively of *C. dactylon*, most often with low biomass and thus no mentionable rainsplash protection;
4. Little or no litter deposition or breakdown.

These characteristics resulted in (corresponding with the numbers above):

1. Low overall functionality of interpatches reduced functionality, as bare tailings patches made up the majority of all transects and were only clad in cryptogams (to slightly enhance Infiltration and Nutrient cycling) on the southern and south-eastern slopes;
2. Crusting and erosion of interpatch zones indicated poor Stability, which were then exacerbated by poor perennial vegetation and litter cover to reduce raindrop impacts and made worse by the sparse nature of patch types;
3. SGP's had very small basal cover and very little local litter production, which decreased Nutrient cycling and Infiltration;

4. Poor levels of litter production, accumulation and integration with the soil directly reduced Infiltration and water retention capacity, and indirectly affected Nutrient cycling and mineralisation through unsuitable habitat for microbial decomposers.

The PCA ordination for group 2 is presented in Figure 5.14. This diagram confirmed the poor levels of landscape function, but showed that LOI was slightly higher and interpatch lengths slightly shorter. This implied less 'leaky' landscapes with slightly better resource retention capabilities than group 1. It also showed that these transects bore the characteristics of the younger rehabilitating sites, which suggests that all was not well with those transects, and that further investigation or management intervention may be required to halt further degradation.

The group 2 transects collectively split from the slightly more functional group 3 at 88% BCS in 2007 (Figure 5.8). The picture was rather different in 2008, with group 2 associating more with the more dysfunctional transects of group 1 and first splitting from them at 85% BCS (Figure 5.10). Only LOI had ecologically significant negative changes, showing the potential for further functional decline.

Interestingly, 5W1-03 increased in function, whereas the other transects either decreased insignificantly or remained the same. 5W1-03 was one of the sites that burnt immediately prior to surveying in 2007 and it was encouraging to see some recovery that should ultimately aid it in returning to the high function of the other 5W1 transects that were not burnt (5W101, 5W102 and 5W105). It appeared as if most of the 5S1 transects had also been burned in the past, as root clumps showed evidence of blackening, and that herbicidal applications aimed at eradicating exotic *C. jubata* may have also negatively affected the herbaceous vegetation (especially 5S1-03). 5W1-03, which was showing recovery post burning, was a positive sign that the site may be resilient enough to self-regenerate after such levels of stress and disturbance, whilst 5S1-03 underwent multiple stressors (herbicide and fire), which it may not be able to recover from, as is indicated by slight decline in landscape function. Once sites reach certain critical threshold values for self-sustainability (as will later be discussed in detail), fire may play a more positive role in creating and maintaining both specific and functional diversity, although this requires further study.

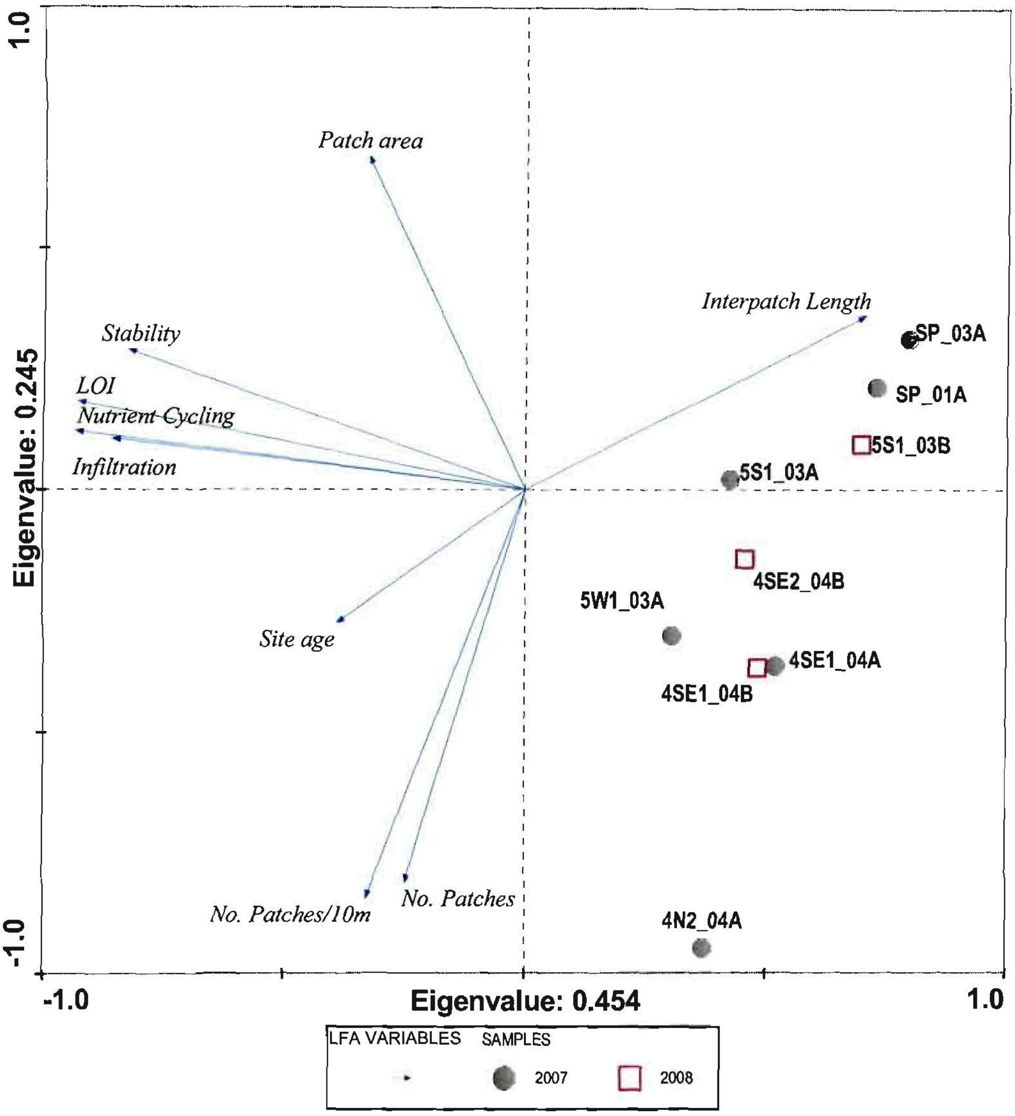

Figure 5.14. Principal Component Analysis for the LFA functional and structural parameters of group 2 for 2007 and 2008. The circles represent the transects falling within this group in 2007 (annotated with "A"), whilst the squares indicate transects in this group in 2008 (annotated with "B"). Site names and abbreviations are explained in Appendix A.

5.3.4.3. Functional group 3

Although Group 3 was intermediate in function, it contained those transects that were still lacking in some crucial aspects, such as retentive spatial patterns and Stability. These factors then impeded the performance and development of the Infiltration and Nutrient cycling indicators, as they cannot increase if Stability and spatial organisation are poor. In 2007, group 3 was associated with the more dysfunctional groups 1 and 2, only splitting from them at 88% BCS (Figure 5.8). The pattern was different in 2008 where group 3 had a greater association with the more functional groups 4 and 5, already splitting from the more dysfunctional groups 1 and 2 at 71% BCS and only split from groups 4 and 5 at 84% BCS (Figure 5.10). However, when looking at the relative position of group 2 transects along the functionality gradients observed in the MDS diagrams (Figures 5.9 and 5.11), it was evident that group 3 was largely intermediate between the two disparate functional groupings 2 and 4, and could represent those transects or sites that were either increasing in function from group 2 towards 4, or decreasing in function from group 4 towards 2, all depending on the site-specific change in indicator contributions. The position along the functionality gradient and differential grouping indicated that there was a high level of functional similarity, but that there may have been differences in compositional similarity.

Figure 5.15 showed the PCA ordination for the transects in group 3. Most transects clustered towards the centre of the diagram, indicating that, for the most part, the values for each LFA index and structural parameter were quite even and occurred midway in the functionality continuum. However, there was some degree in variation, with those sites possessing lower landscape function separating out further from the centre. These were the 4SE1 and 4N2 sites, where their negative correlations with patch area were important explanatory variables, showing that, overall, they had smaller patches, which contributed to poor functionality.

Grass Patch, Sparse Grass Patch, and Bare Tailings were the most prevalent patch/interpatch types in group 3 and contributed differently to overall landscape function depending on their prevalence in each transect (Table 5.2). Interpatches made up the majority of each transect, as was reflected by the LOI values (52% interpatches: 48% patches), indicating that these landscapes were still "leaky", which was further supported by the presence of alluvial fans at the toe of each slope.

Group 3 consisted of relatively few transects (10 from 8 sites) in 2007, whilst in 2008 consisted of many more transects (20 from 9 sites) (see Figure 5.8 for full composition). The same transects occurring in Group 3 in 2007 were repeated in 2008, but ten additional transects were also included, as they no longer associated with group 4. These additional transects were more functional than the original composition from 2007, but their BCS % values were similar enough to merit their grouping. The functional (as opposed to compositional) similarities between sites across both years indicated that transects from group 3 did not require immediate management intervention, but that the specific indicators responsible for the compositional changes must be elicited in order to understand how further changes may affect functionality.

The transects comprising group 3 in 2007 and 2008 had a number of important indicator values in common. These were:

1. LOI was lower than 0.50 in almost every instance (Table 5.3). This meant that interpatch ratios were high and consisted of crusted Bare Tailings with poor microtopography, slight erosion and lower litter values, most of which was not incorporated into the soil;
2. Stability was relatively poor, with values ranging from 40-55 in 2007 but from 50-60 in 2008 (Table 5.3). This was also a function of high interpatch lengths and low perennial basal cover with concordant low rainsplash protection;
3. Infiltration was poor, with values ranging from 25-35 in 2007 but from 30-40 in 2008 (Table 5.3). This was due to crust formation (slightly alleviated by cryptogam cover on the southern and south-eastern slopes) that thus increased runoff, which, coupled with relatively low litter accumulation and microtopographical variation, decreased Infiltration and slightly increased erosion susceptibility between years. However, low levels of surface erosion were observed on most transects in this group ;
4. Nutrient cycling was very poor, with values always below 20 in 2007, with some minor increases or decreases in 2008 (Table 5.3). This was also due to more interpatches than patches that were often crusted, low litter deposition and low to moderate incorporation that decreased the efficiency of any soil microbes present.

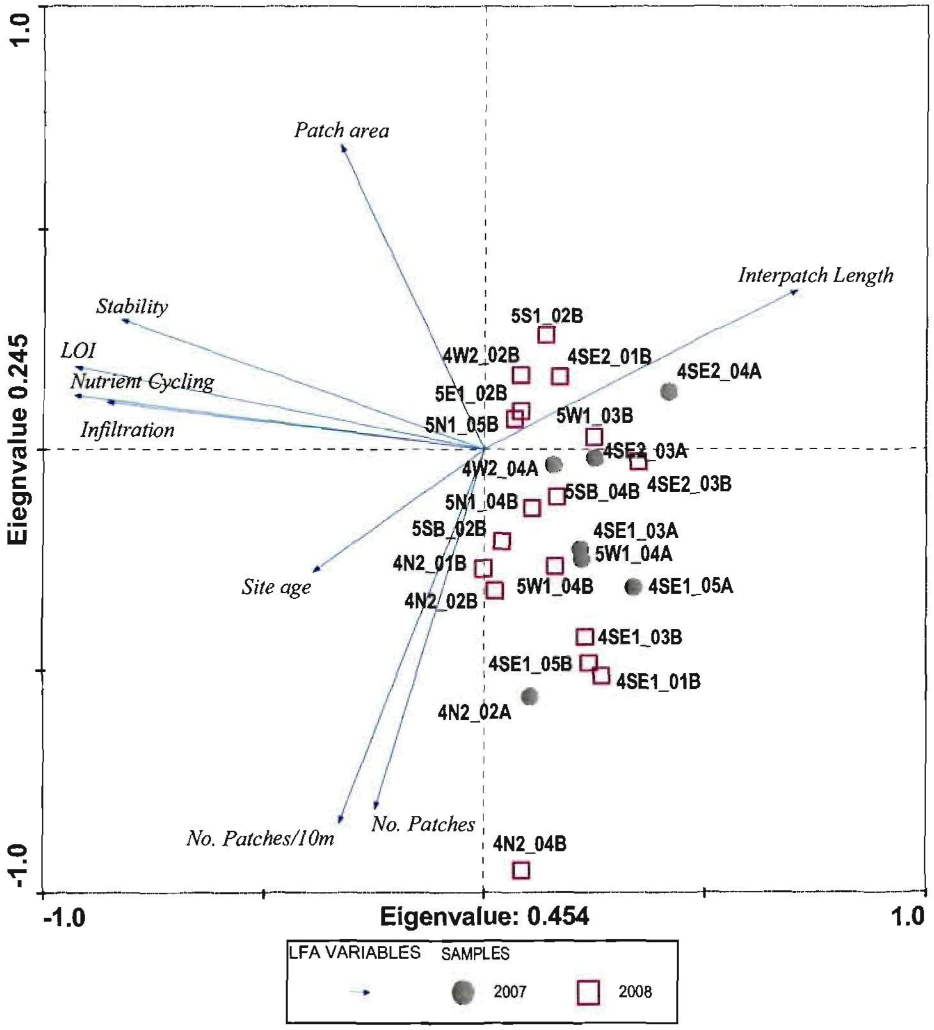

Figure 5.15. Principal Component Analysis (PCA) of the structural and functional parameters of group 3 for 2007 and 2008. The circles represent the transects falling within this group in 2007 (annotated with "A"), whilst the squares indicate transects in this group in 2008 (annotated with "B"). Site names and abbreviations are explained in Appendix A.

However, the increase in functional association of this group was also due to increased physical and biological activity, most likely driven by the increased precipitation during the 2008 growth season. Litter fall and incorporation into the soil was higher in 2008 and there was an improved aerial cover of opportunistic annual plants (that are not assessed for rainsplash protection), which also contribute seasonally to Stability. Many of the physical crusts on the interpatches were less severe, improving the potential Infiltration and Nutrient cycling as also reflected by increases in cryptogam cover on some transects. Lastly, there was increased litter drop in some transects that had previously moribund perennial growth, which was important in some sites to increase Infiltration and Nutrient cycling. This was, however, combined with slight increases in erosion as a result of increased runoff due to the higher rainfall.

5.3.4.4. Functional group 4

Group 4 was, as mentioned, largely linked to group 3 in terms of the transect composition. It contained the majority of the TSF sites in 2007 (Figure 5.8), some of which had decreased in function between survey years and therefore associated with group 3 in 2008 (Figure 5.10). However, as mentioned in section 5.3.4.3, those differences were compositional rather than functional (i.e. some functional difference, but different factors making up the levels of functionality), and those differences have already been explored under Group 3. Therefore this discussion focuses mainly on those sites that had similar composition and function in both years. The most prominent patches were the highly functional Grass Patch, Grassy Litter Patch and Litter Patch types. This group then consisted of all of the undisturbed grassland (UFV) sites, some of the starter wall (5SB) sites, most of the transects (55%) from Dam 5 (all but one from 5E1, two from 5W1, two from 5S1and three from 5N1), four transects from 4W2, the two most functional 4N2 transects and the least functional 4N1 transect (Figure 5.8 and Figure 5.10). Notably absent were three of the least functional sites: SP, 4SE1 and 4SE2. In 2007 and 2008, group 4 clustered together with group 5 (the most functional sites), separating from them at 90% BCS and 88% BCS respectively, whilst splitting from the less functional groups at 77% BCS and 71% BCS respectively (Figure 5.8 and Figure 5.10).

The most prominent result emanating from Figure 5.16 was that the transects were all positively associated with higher levels of functionality (apart from 4W2-04 in 2007, but it recovered in 2008). These transects were also negatively correlated with interpatch length and positively correlated with LOI, indicating that their spatial patterns were more conducive to capturing and retaining resources than preceding groups. Although only of secondary importance, all of these transects also had more patches and larger patches, leading to improved overall landscape function.

The characteristics that were shared amongst these transects and sites did not change with either statistical or ecological significance and were:

1. High LOI values of >60 from most transects, indicating that fertile patches were proportionately greater than interpatches (Table 5.3). Therefore, there was less Bare Tailings with lower proportions of physical crusts, often with cryptogams present;
2. Relatively high Stability values of at least 55 (most were above 60), which included the persistent 100+ year-old UFV grassland site and the 67 year-old starter wall (5SB) site (Table 5.3). This was largely due to high perennial plant basal and aerial cover to intercept raindrops, far less erosion and higher microtopographical variation than in the other sites. The high Stability values were supported by the absence of alluvial fans at the toes of the slopes, indicating that there was little resource loss from these more functional landscapes;
3. Moderate Infiltration values, with most above 40 (Table 5.3). This was due to greater plant basal cover, high levels of litter deposition and retention with slight decomposition evident, all increasing Infiltration and water retention capacity whilst simultaneously decreasing the potential for runoff. High cryptogam cover of the interpatches and short interpatch length also increased the Infiltration rates;
4. Poor to moderate Nutrient cycling with all values >25 and some being as high as 40 (Table 5.3). This was also largely driven by the good litter accumulations and decomposition values, as well as the retentive spatial pattern afforded by the high proportion of patches. These transects were more likely to have higher levels of fungal or microbial activity and thus higher rates of nutrient mineralisation, although this requires further study.

Those sites that were clustered into group 4 in 2007 but were moved to group 3 in 2008 showed slight variance from these common indicator values mentioned above, increasing slightly in some indices (especially Infiltration), but then decreasing slightly in others (such as Stability) (Table 5.3). However, these sites maintained their overall levels of function but for slightly different reasons (often related to the seasonal amount of decomposing litter present), perhaps indicating a dynamic equilibrium and thus some level of self-regulation within these more functional sites. This will be discussed later under the critical thresholds section of this chapter.

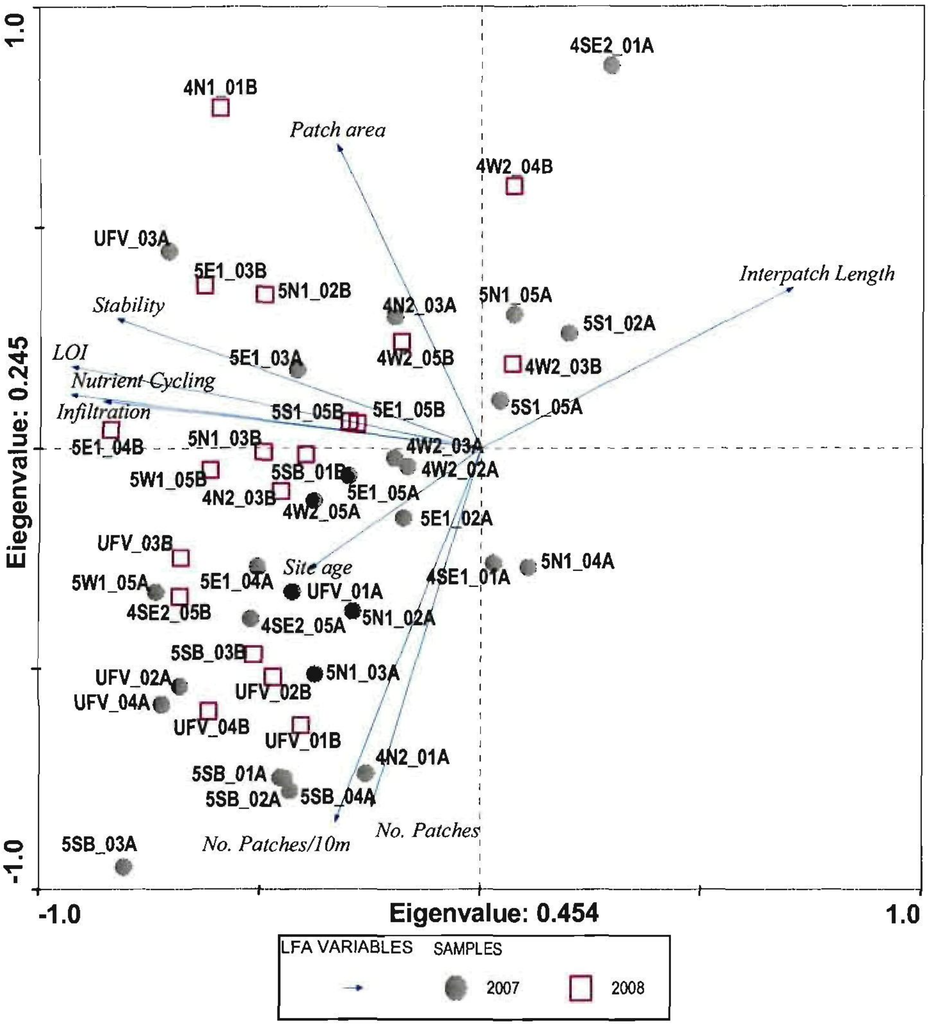

Figure 5.16. Principal Component Analysis of the 2007 and 2008 LFA index and structural parameters of group 4. The circles represent the transects falling within this group in 2007 (annotated with "A"), whilst the squares indicate transects in this group in 2008 (annotated with "B"). Site names and abbreviations are explained in Appendix A.

5.3.4.5. Functional group 5

Group 5 was virtually identical in composition for both years, consisting of all of the 4N1 transects and 5W102 in 2007, whilst 4N102 was moved to group 4 in 2008 as it did not increase in function as much as the other sites. Although these sites were more functional than group 4, they were, as mentioned, only 10% dissimilar in composition in 2007 (Figure 5.8) and 12 percent dissimilar in 2008 (Figure 5.10).

Figure 5.17 showed strong positive correlations between the transects of group 5, with high LOI, Stability, Nutrient cycling and Infiltration, and low interpatch lengths. This meant that the transects had a very retentive spatial pattern with very few areas that resources could be lost from. The 4N1 sites also had very strong positive correlations with patch area, but negative correlations with number of patches. This indicated, together with high LOI, that the landscape consisted of highly functional and very wide patches that stretched almost from the very top to the very bottom of the slope.

The compositional similarities between transects were considerable, but the increase in function between years was even more so. 4N1 increased in overall function with ecological significance for LFA indices after a slight decline in LOI values. This site consisted of a very dense, almost monoculture of *C. gayana*, which had increased in density to the point of becoming moribund. Between 2007 and 2008, large amounts of above-ground biomass dropped, and because of the high LOI and retentive spatial pattern, all or most of the litter was captured within the site and started decomposition and incorporation into the tailings. This was reflected in that although the LOI decreased between the two survey years, Stability remained high (±70) and largely unchanged; Infiltration increased massively by between 6 and 20 index points (from average of 40 in 2007 to 52 in 2008); and Nutrient cycling also substantially increased by up to 14 index points (average of 32 in 2007 to 42 in 2008) (Table 5.3). Whilst this site was highly functional due to the active soil surface processes, it remains to be seen whether the high levels of biomass production will be sustained over time. It is unlikely though, and it is predicted that the 4N1 sites (and indeed group 5) will soon rejoin the level of functionality experienced by the pseudo-analogue sites. There are furthermore reservations about the sustainability of the near-monoculture in terms of resistance to biological agents such as pathogens or environmental disturbances, such as fire. The one site that had decreased in function between survey years to associate to group 4 in 2008, 4N1-01, experienced a slight drop in Stability (not ecologically significant), and Nutrient cycling did not increase as much as the other 4N1 transects (as a result of slightly lower cover and higher density of *C. dactylon*), perhaps indicating the future path that the other 4N1 transects will follow over the short-term (Table 5.3).

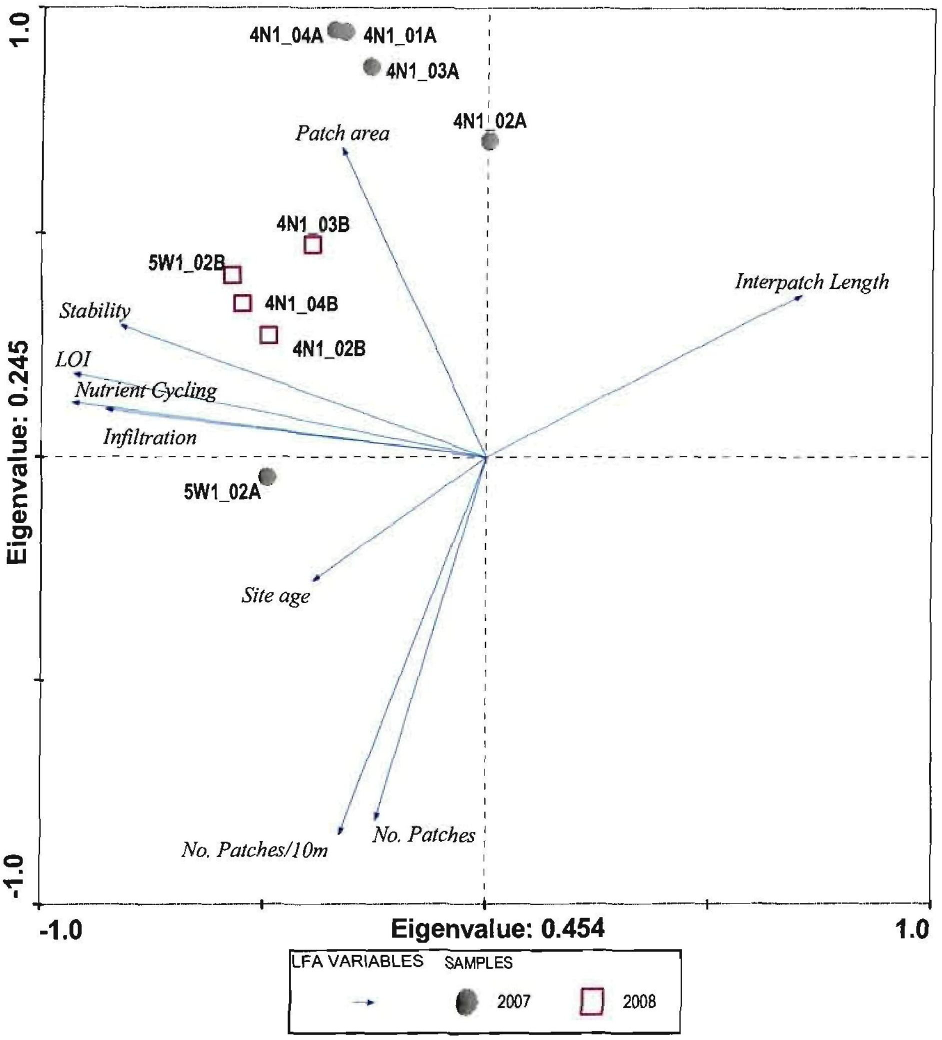

Figure 5.17. Principal Component Analysis of the 2007 and 2008 LFA structural and functional parameters of group 5. The circles represent the transects falling within this group in 2007 (annotated with "A"), whilst the squares indicate transects in this group in 2008 (annotated with "B"). Site names and abbreviations are explained in Appendix A.

5W1-02 was a fairly unique site, as it contained the only representative of an atypical patch type, the Woody Litter Patch (WLP). This patch type consisted of an accumulation of dead branches from a tree that had senesced, causing build-up of large woody biomass and creating a sheltered environment for perennial grasses to proliferate due to high resource accumulation. Higher levels of litter incorporation into the tailings were observed than for most other patch types (excluding living Tree Patch and Shrub patch types, which were also rare), and Infiltration and Nutrient cycling values were accordingly very high (69 and 43 respectively; Table 5.3). Other than this highly productive patch type, the landscape organisation and function varied little from the other 5W1 sites that had not burnt (5W1-01 and 5W1-05) and were clustered in group 4. This serves to illustrate the importance of spatial patterns for resource regulation and also how brush-packs (branch-mounds), which is what this WLP patch type essentially was, could be applied to great advantage in stabilising slopes and promoting the development of soil surface processes.

Also of note were the two sites that were burnt just before the surveys took place in 2007 (5W103 and 5W104). In 2007 they were split into groups 2 and 3 (Figure 5.8), whilst both clustered in group 3 in 2008 (Figure 5.10). Their LOI had both increased a year after the burn (Table 5.3). Stability had slightly decreased as a result of the large interpatches, but the regeneration of vegetation and cryptogams had already increased Infiltration rates and Nutrient cycling will hopefully follow suit (Table 5.3).

The possibility exists that other variables that were not measured by LFA such as subsoil chemistry (periodic Pyrite oxidation, acidification and acid mine drainage) may alter or even prevent procession along the developmental pathways.

5.4. Critical Threshold values of LFA indices

Sigmoidal curves have been in use for the interpretation of monitoring data for some time, including data from degraded or resource-limited landscapes (Noy-Meir, 1981; Bastin *et al.*, 1991). More recently, Tongway and Hindley (2000) have used the sigmoidal model to assess both rehabilitation success and retrogression. The sigmoidal curve fits landscape function data very well, as all landscapes must have upper and lower biogeochemical limits, with a range of values in between, representing the continuum of most to least functional units (Tongway and Hindley, 2000). However, a substantial time-series of data is required to obtain accurate results, more than are available in the current study. Fortunately, Tongway and Hindley (2000) have devised and substantiated an adaptation of the sigmoidal model that is based on the principles that arise therein. By using values from sites that range from highly functional to highly dysfunctional (which represent asymptote values), they were able to rapidly assess critical threshold (C/T) values for the landscape function indices (Stability, Infiltration and Nutrient Cycling). These critical threshold values were calculated individually for each index by the formula:

C/T= (top value – lowest value) / 2 + lowest value

Tongway and Hindley (2000) suggest that the critical threshold indicates that point where the indicators making up the index values are sufficiently developed for "self-sustainability" to commence. These values then denote the minimum point at which ecosystem resilience is sufficient to cope with stress and disturbance without significant loss of landscape function.

The data collected for this study (as described in section 4) were well suited to this form of interpretation, as they represented a range of sites, from highly functional (UFV, the undisturbed flat grassland) to highly dysfunctional (SP, the spillage site), with landscapes in between that portrayed a variety of functional stages (the TSF sites) (Figure 5.7). Although the SP site was the most dysfunctional site for most LFA indices, it was decided to rather use the values from the most dysfunctional sites from the TSF's in each instance, as the topographical differences between SP and the TSF sites was too great. The one drawback of this analysis is that the rate of change within the landscapes cannot be ascertained. However, the rapid assessment of critical threshold values can be used until enough data points from successive years of survey are available to construct a time-series sigmoidal curve.

5.4.1. Stability critical thresholds

Due to the steep slope angle, uniform texture and poor cohesiveness of the tailings material and relatively large LOI in many of the sites, there were a number of TSF sites that fell below the critical threshold value for Stability in 2007. Figure 5.18 showed the position of all sites (average values across all repetitions) relative to the critical threshold value that was calculated at 59.68 (Table 5.4). Table 5.4 summarised the sites with problematic Stability (below C/T) and gave the values that were used in the calculation. Half (6 of 12) of all of the sites surveyed had Stability problems in 2007. This may have been as a result of using a flat, natural landscape for analogue values, but this would not appear to be valid, as one TSF site, 4N1 was assessed as being more stable, at least in the short-term, than the flat, undisturbed grassland (UFV).

Table 5.4. Critical threshold (C/T) values for Stability in 2007, showing how the C/T values were calculated, based on the reference site (UFV) value for Stability and the lowest TSF value for Stability (also indicating which TSF site had the lowest value). Site names and abbreviations are explained in Appendix A.

Stability			
Reference value 2007	**Minimum TSF Value 2007**	**C/T**	**Sites falling below C/T**
66.23919221	53.1275065	59.6833	SP_07
UFV	5S1		5S1_07
			4SE1_07
			5N1_07
			4SE2_07
			5SB_07

The spillage site (SP) was expected to be amongst the least stable sites, due to the poor vegetation cover and evidence of sheet erosion due to runoff and aeolian erosion. This was reflected in the data (SP 52.3, Figure 5.18). 4SE1 (53.9, Figure 5.18) and 4SE2 (58.0, Figure 5.18) were sites that had been reworked (re-ameliorated, composted, re-seeded and irrigated) relatively recently, but it seemed as though the efforts were insufficient to stem erosion. This was reflected by their high erosion indicator values in the SSA. 5S1 (53.1, Figure 5.18) was, as mentioned, negatively impacted due to removal and die-off of plant material during a recent fire and exacerbated by the eradication of *C. jubata* (as discussed earlier in section 5.2.2.2). 5N1 (58.0, Figure 5.18) was just below the critical threshold. All of these sites had, as mentioned, unmistakable alluvial fans at the toe of each slope, indicating nett outflow of resources, whereas nett retention of resources was required for Stability. However, it was interesting to note that the starter wall (5SB) (59.5, Figure 5.18) was amongst the sites with problematic Stability (below the C/T). Even though it consisted of real soil (and had a mixture of gravel and shale materials), had a spontaneously regenerated vegetation cover and had persisted for the past 67 years, it was not yet perceived to be self-sustaining over time. Again, this may have been as a result of using a highly stable, flat grassland for analogue values, but it did serve to illustrate how important slope angle was for future rehabilitation projects.

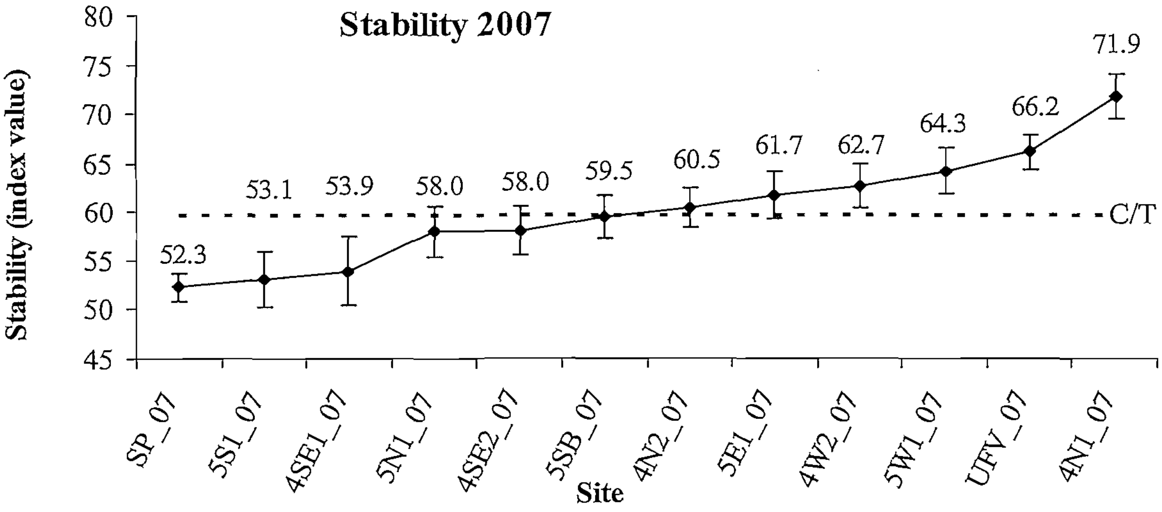

Figure 5.18. Critical threshold values for Stability across all sites, ranked by their average values from the 2007 data. Values are out of a maximum of 100 index points. The threshold (C/T) was calculated as per Table 5.4. Site names and abbreviations are explained in Appendix A.

It is important to remember that those sites that just fell above the critical threshold (4N2, 5E1 and 4W2; Figure 5.18) were not necessarily highly functional and of no concern for management. The critical threshold represents the state at which the landscapes **start** to become self-sustaining and that things may change over time, hence the need for long-term monitoring.

This was reflected by the change in sites below the C/T increasing from six to seven sites in 2008 with the addition of 4N2 (Table 5.5), a site that had previously just fallen above the threshold. This was because of the critical threshold dropping, due to lower Stability in the analogue sites (Figure 5.19). The lower Stability in the undisturbed grassland was due to increased amounts of deposited materials, showing evidence of resource mobility in the above-average rainfall season of 2008. It is also perhaps important to mention that some of the rain fell in exceptionally heavy thunderstorms during February of 2008, but unfortunately the rate of rainfall per hour could not be assessed. These extraordinarily heavy showers were a good test of how stable the TSF slopes were, and some sites proved it by increasing in Stability (4N1) whilst others decreased in Stability (4SE1). The more functional sites were able to retain resources such as soil, seed and water due to the better landscape organisation and higher Infiltration capacity, whereas the less functional sites did not have the spatial pattern to control the outflow and suffered erosion, vegetation and litter losses.

Table 5.5. Critical threshold (C/T) values for Stability in 2008, showing how the C/T values were calculated, based on the reference site (UFV) value for Stability and the lowest TSF value for Stability (also indicating which TSF site had the lowest value). Site names and abbreviations are explained in Appendix A.

Stability **Reference value 2007**	**Minimum TSF Value 2007**	**C/T**	**Sites falling below C/T**
63.21015382	50.67096418	56.9406	4SE1_08
UFV	4SE1		SP_08
			4SE2_08
			5SB_08
			5S1_08
			4N2_08
			4W2_08

Most of the sites falling below the critical threshold value of 56.94 had actually decreased in Stability between the two survey years, also perhaps due to the increased and heavy rainfall. It is also noteworthy that the two most functional TSF sites, 4N1 and 5E1 actually increased in measured function, boding well for their self-sustainability in terms of physical Stability.

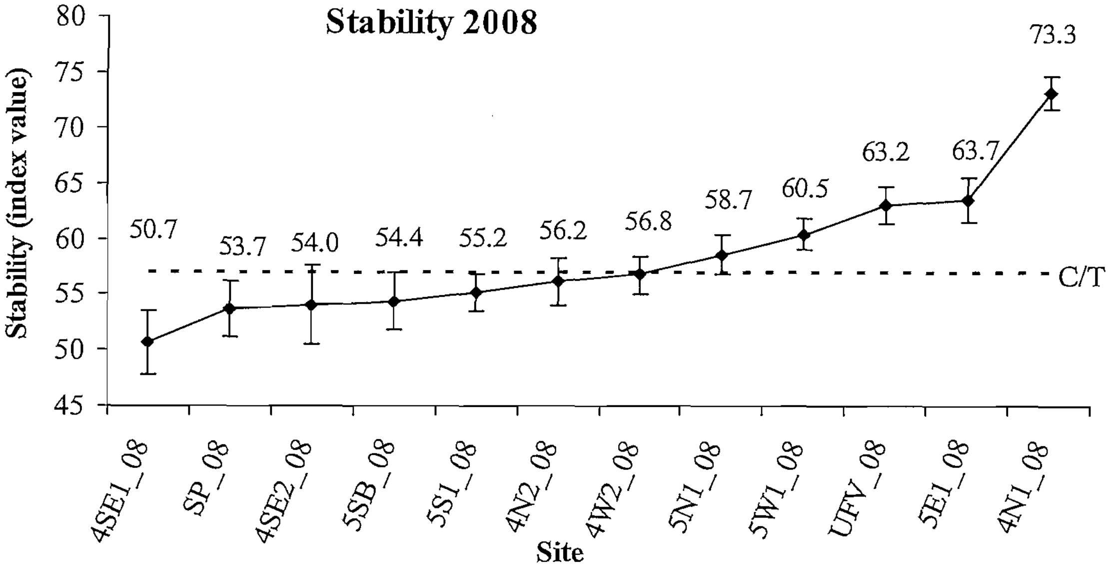

Figure 5.19. Critical threshold values for Stability across all sites, ranked by their average values from the 2008 data. Values are out of a maximum of 100 index points. The threshold (C/T) was calculated as per Table 5.5. Site names and abbreviations are explained in Appendix A.

5.4.2. Infiltration critical thresholds

For Infiltration, fewer sites were expected to fall below the critical threshold levels, as the tailings material was reasonably porous, due to its homogeneous sandy-loam texture. Only three sites fell below the critical threshold of 37.95 (Table 5.6) for 2007. The first of these was the spillage site (SP) (24.7, Figure 5.20), which had values far below the critical threshold (Figure 5.20) largely due to physical crust formation and wind-scour. The other two sites, 4N2 (32.3, Figure 5.20) and 4SE1 (32.4, Figure 5.20) also fell well below the C/T, with the differences being ecologically significant (due to being 5 index points lower than the threshold). 4SE2 (38.3, Figure 5.20) was just above threshold and thus warranted close monitoring.

Table 5.6. Critical threshold (C/T) values for Infiltration in 2007, showing how the C/T values were calculated, based on the reference site (UFV) value for Infiltration and the lowest TSF value for Infiltration (also indicating which TSF site had the lowest value). Site names and abbreviations are explained in Appendix A.

Infiltration Reference value 2007	Minimum TSF Value 2007	C/T	Sites falling below C/T
43.55686852	32.34057076	37.9487	SP_07
UFV	4N2		4N2_07
			4SE1_07

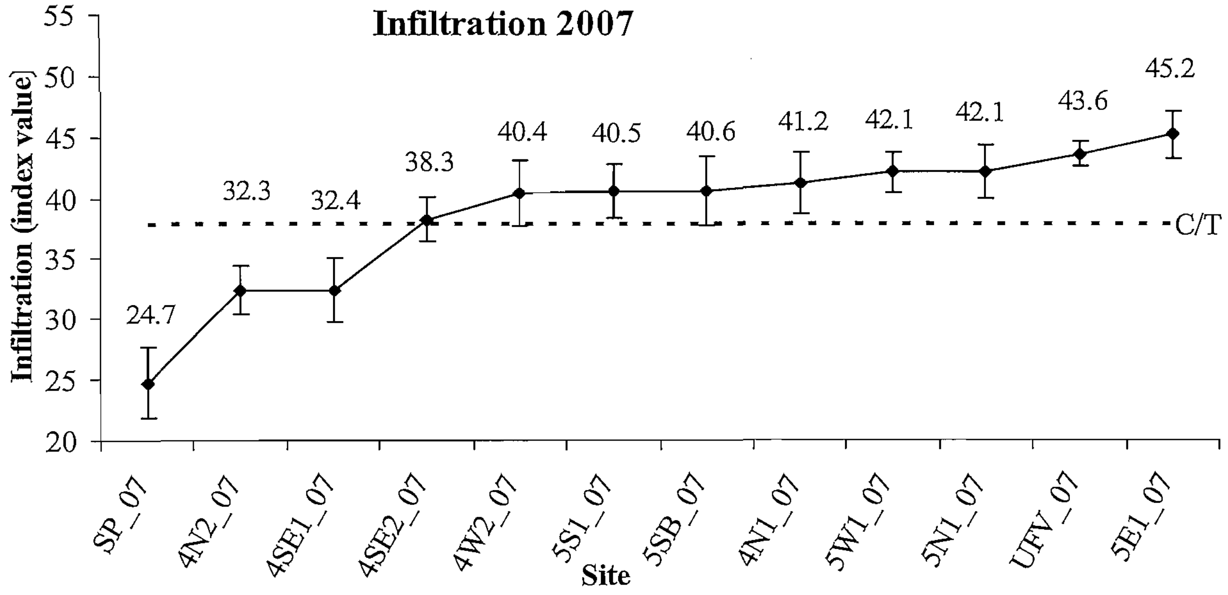

Figure 5.20. Critical threshold values for Infiltration, ranked by their average values from the 2007 data. Values are out of a maximum of 100 index points. The threshold (C/T) was calculated as per Table 5.6. Site names and abbreviations are explained in Appendix A.

The low Infiltration of the three problem sites indicated that soil respiration may also have been modest and that the effective precipitation (precipitation less runoff losses) would have been lower, further increasing the challenges for both plant growth and microbial community development on the TSF slopes (as per Straker *et al.,* 2006). Low Infiltration and associated increased runoff increased the potential erosion, as was reflected by the decrease in Stability for 4SE1 from 2007 (53.9, Figure 5.18) to 2008 (50.7, Figure 5.19).

The TSF sites that fell above the critical threshold were then just starting to become self-sustaining, relative to a flat grassland, but, except for 5E1 (45.2, Figure 5.20) were still all within five index points of the threshold. This indicated that they too, had not yet developed their Infiltration to the extent that they could be judged as entirely elf-sustaining.

2008 saw a 0.05 increase in critical threshold value for Infiltration (Table 5.7), not because the upper (analogue) value had increased slightly, but because of the slight increase in the lowest TSF value. As previously mentioned, many of the more functional sites had experienced increases in litter accumulation after the above-average rainy season, which may have driven their increases in Infiltration. Certainly, those sites that had the largest increase in Infiltration were those that had experienced the most litter interception, 4N1 (41.2 in 2007, Figure 5.20, to 52.6 in 2008, Figure 5.21) and 5E1 (45.2, Figure 5.20, to 49.4, Figure 5.21).

4N2 had managed to increase Infiltration levels to above the critical threshold (Figure 5.21), increasing by 8 points which, as mentioned, was ecologically significant. Although some structural parameters changed, such as a slight decrease in LOI, the number of patches and patch area, of especially Sparse Grass Patch (SGP), increased, causing the indicator classes for physical crust formation to decrease, which then increased overall Infiltration. However, the increased Infiltration due to increase in SGP was associated with a decrease in Grass Patch (GP) due to senescence. Fortunately, much of the litter was accumulated in these SGP's and further increased the Infiltration. If further senescence occurred, the Infiltration, and overall functionality, of 4N2 (41.4, Figure 5.21) was likely to diminish and it is recommended that this then be a site that merits close future monitoring.

Table 5.7. Critical threshold (C/T) values for Infiltration in 2008, showing how the C/T values were calculated, based on the reference site (UFV) value for Infiltration and the lowest TSF value for Infiltration (also indicating which TSF site had the lowest value). Site names and abbreviations are explained in Appendix A.

Infiltration			
Reference value 2008	**Minimum TSF Value 2008**	**C/T**	**Sites falling below C/T**
42.37773889	33.82727734	38.1025	SP_08
UFV	4SE1		4SE1_08

Unlike in 2007, those sites that had values higher than the starter wall (5SB) were more than five index points above the critical threshold, indicating that their vegetative cover was sufficient to mitigate the impact of raindrops and prevent physical crust formation. The increased Infiltration levels in these more functional sites were also accompanied by decreased physical crusting, but this was then associated with a decrease in the available habitat for beneficial cryptogams.

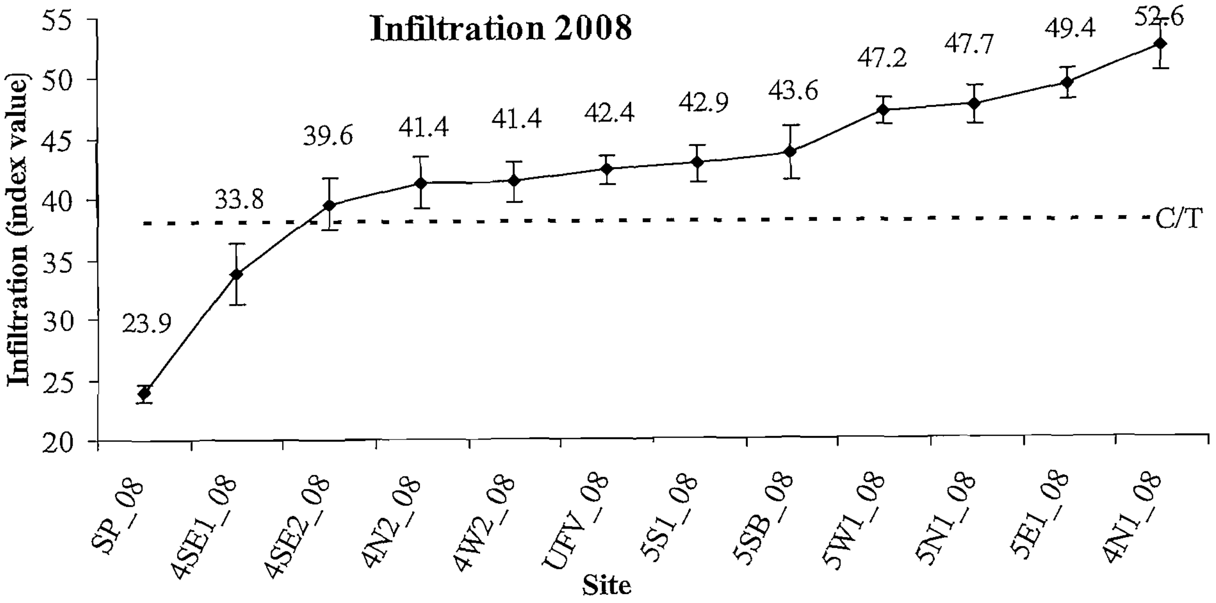

Figure 5.21. Critical threshold values for Infiltration, ranked by their average values from the 2008 data. Values are out of a maximum of 100 index points. The threshold (C/T) was calculated as per Table 5.7. Site names and abbreviations are explained in Appendix A.

Due to using the undisturbed grassland (UFV) values as the upper levels for Infiltration, which had finer soil and higher proportions of surface rock, some TSF sites were able to surpass them in values. As mentioned, the tailings material was far coarser and more homogeneous thus promoting higher Infiltration, although the steep slope angle promoted runoff. It was therefore a good sign that the Infiltration of most TSF sites were above the critical threshold in both years.

5.4.3. Nutrient cycling critical thresholds

The critical threshold value for Nutrient cycling was calculated at 24.87 for 2007 (Table 5.8). Although this value was very low, the undisturbed grassland (UFV) values were also intrinsically low, averaging just 31.8 (Figure 5.22). This was because of a combination of factors occurring in the UFV: (1) surface cryptogams were almost entirely absent; (2) there were higher proportions of surface rock; (3) interpatches had very high resistance to disturbance, and even patches had high resistance; (4) the substrate particle size distribution was far less homogenous than the uniform tailings, leading to slightly higher crust formation for patches/interpatches than in the TSF's.

Table 5.8. Critical threshold (C/T) values for Nutrient cycling in 2007, showing how the C/T values were calculated, based on the reference site (UFV) value for Nutrient cycling and the lowest TSF value for Nutrient cycling (also indicating which TSF site had the lowest value). Site names and abbreviations are explained in Appendix A.

Nutrient Cycling **Reference value 2007**	**Minimum TSF Value 2007**	**C/T**	**Sites falling below C/T**
31.79798712	17.93896315	24.8685	SP_07
UFV	4SE1		4SE1_07
			4N2_07

As Table 5.8 showed, the spillage site (SP) (9.2, Figure 5.22), 4SE1 (17.9, Figure 5.22) and 4N2 (21.0, Figure 5.22) all fell below the critical threshold values, demonstrating that they had not yet reached the purported levels to commence being self-sustaining over time. All of these sites had very low vegetation cover in common and most often fell within the least functional groups as discussed earlier. Levels of litter production, accumulation and incorporation were very low, leading to low levels of organic matter buildup to promote Nutrient cycling. Infiltration was low and crust formation was high in these landscapes and was further aggravated by poor microtopography. These factors then combined to produce poor measured Nutrient cycling potential.

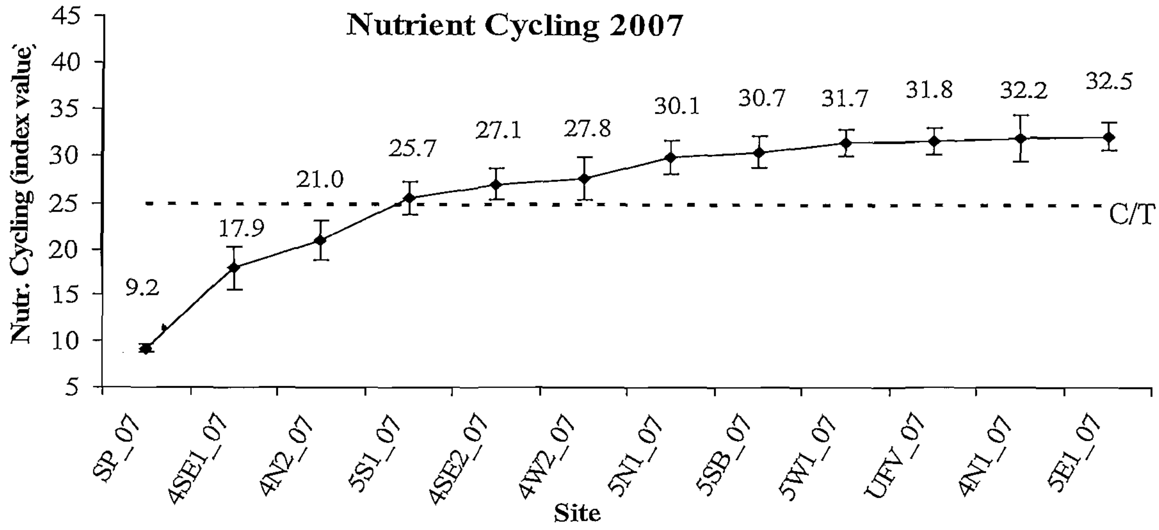

Figure 5.22. Critical threshold values for Infiltration, ranked by their average values from the 2008 data. Values are out of a maximum of 100 index points. The threshold (C/T) was calculated as per Table 5.8. Site names and abbreviations are explained in Appendix A.

Although 5S1 (25.7, Figure 5.22), 4SE2 (27.1, Figure 5.22), and 4W2 (27.8, Figure 5.22) fell above the critical threshold divide (24.87, Table 5.8), they were still within five index points for Nutrient cycling and therefore not yet ecologically significantly self-sufficient. The major discerning factors between these sites and the sites below the threshold were driven by higher vegetation density and biomass, as well as the associated litter produced and captured by the patches. They may have reached the levels where they started to become self-sustaining, but stochastic disturbances affecting vegetation performance would, in all probability, lead to declines in Nutrient cycling potential. This then resulted in the recommendation that they also be monitored closely over time.

For 2008, the critical threshold value was at 19.35, a full 5.5 points lower than in 2007 (Table 5.9). This was ecologically significant and was driven by the decrease in Nutrient cycling for the upper levels (as represented by the UFV site) and combined with higher levels in the poorest TSF site (Figure 5.23). The UFV sites suffered declines in Nutrient cycling for 2008, not because of changes in the functioning of patches and interpatches, but because of changes in the LOI. In most UFV transects, GP and BS declined and were offset by increases in SGP's (see Table 5.2 and Appendix D for patch/interpatch abbreviations). This was a similar phenomenon to that observed on the TSF slopes and may have been as a result of some senescence of the less vigorous perennial plants following the 2006/2007 season's poor rainfall. The senescence was supported by the increase in SGP, which, as mentioned, largely consisted of creeping *C. dactylon*. The slight increase in Nutrient cycling observed in 4SE1 was also driven by litter accumulation, but less so by litter production or incorporation

Table 5.9. Critical threshold (C/T) values for Nutrient cycling in 2008, showing how the C/T values were calculated, based on the reference site (UFV) value for Nutrient cycling and the lowest TSF value for Nutrient cycling (also indicating which TSF site had the lowest value). Site names and abbreviations are explained in Appendix A.

Nutrient Cycling			
Reference value 2008	**Minimum TSF Value 2008**	**C/T**	**Sites falling below C/T**
27.9976215	23.67258489	19.3475	SP_08
UFV	4SE1		4SE1_08

The majority of the sites were above the critical threshold value for 2008 and the value for 2007. This showed that although values may have changed in the upper and lower levels, most sites did not change much and were in the phase of becoming self-sustaining in terms of regulating Nutrient cycling.

The sites falling below the threshold in2008 were similar in 2008, although 4N2 showed increased Nutrient cycling from 21 (Figure 5.22) to 26 (Figure 5.23), taking it above the C/T levels. As elsewhere, this was also largely directed by litter availability.

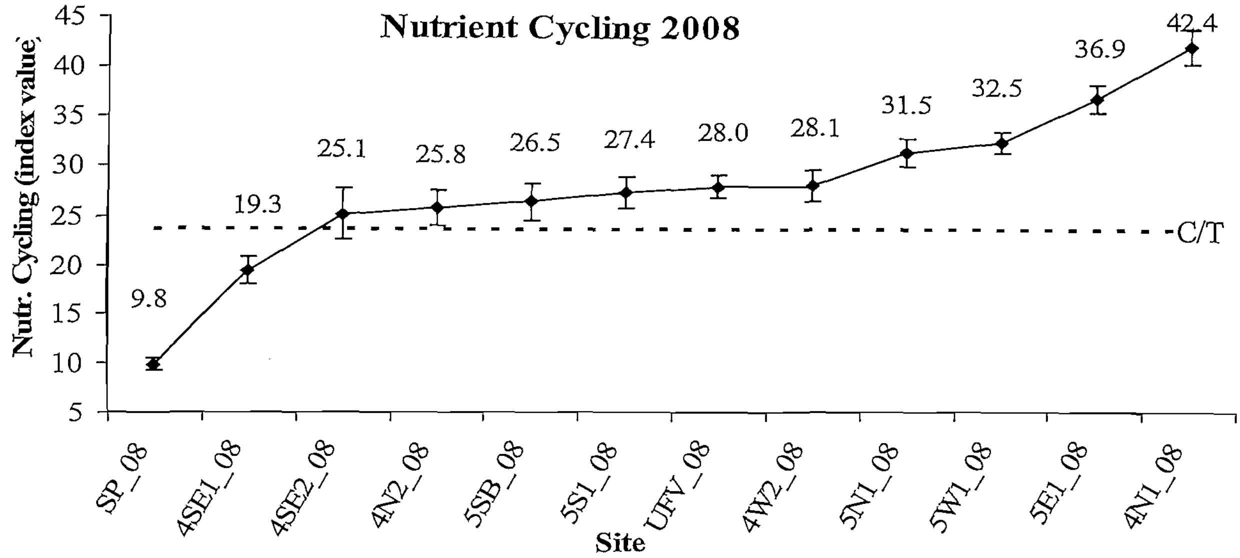

Figure 5.23. Critical threshold values for Nutrient cycling, ranked by their average values from the 2007 data. Values are out of a maximum of 100 index points. The threshold (C/T) was calculated as per Table 5.9. Site names and abbreviations are explained in Appendix A.

5.4.4. Summary of critical thresholds for LFA indices

In summary, there were only two sites that consistently fell below threshold values for all three LFA indices (Stability, Infiltration and Nutrient cycling) and across both years (Table 5.10). These were the spillage site (SP) and 4SE1 (for site localities please see Figure 4.1). These were the two least functional sites and presented some level of concern, as their landscape function was declining over time. However, as the spillage site was situated on flat slope and the majority of surface material consisted of actual soil, it was of less concern for Stability if the current levels of spontaneous vegetation colonisation could be maintained. Strategic positioning of brush packs would certainly be very beneficial to this site by collecting mobile seed and topsoil and creating a safe microclimatic zone for germination., These strategies are further explained in section 6.5.

4SE1, on the other hand, appeared to be deteriorating faster than any of the other sites and required urgent management attention to prevent significant erosion damage due to poor Stability, aggravated by declines in Infiltration (increasing runoff) and Nutrient cycling (decreasing plant cover).

Table 5.10. Summary of sites falling below critical threshold values for the LFA indices, Stability, Infiltration and Nutrient cycling in 2007 and 2008.

Summary **Index**	**Infiltration 2007**	**Infiltration 2008**	**Nutrient Cycling 2007**	**Nutrient Cycling 2008**	**Stability 2007**	**Stability 2008**
Below-threshold sites LFA	4N2_07	-	4N2_07	-	-	4N2_08
	4SE1_07	4SE1_08	4SE1_07	4SE1_08	4SE1_07	4SE1_08
	-	-	-	-	4SE2_07	4SE2_08
	-	-	-	-	-	4W2_08
	-	-	-	-	5N1_07	-
	-	-	-	-	5S1_07	5S1_08
	-	-	-	-	5SB_07	5SB_08
	SP_07	SP_08	SP_07	SP_08	SP_07	SP_08

As has been mentioned, 4N2 was only flagged as a problem site during the first year (2007), but had, in some instances, increased in function (although the increases were in some cases only ostensible due to lower critical threshold values). For these reasons, it is recommended that it be closely monitored to establish whether the increasing trend persists.

Many sites showed problematic Stability, as was to be expected on the excessively steep TSF slopes, but did not fall below C/T levels for Stability or Nutrient cycling (4SE2, 4W2, 5N1, 5S1 and 5SB; Table 5.10). If the current vegetation levels on these transects are not maintained, then there will be permanent concerns as to the sustainability of these TSF systems. If Stability continues to deteriorate on these sites, then Infiltration and Nutrient cycling will inevitably follow as the indicators that make up Stability also influence Infiltration and Nutrient cycling (Figure 4.5). Persisting levels of high biomass vegetation as found on some of these TSF slopes was not the norm in South Africa and all older sites had suffered significant long-term losses of the originally introduced pasture species (Weiersbye *et al.*, 2006). The LFA indices confirmed that the biological community, which supports all levels of function almost on its own, was only a thin 'veneer' that separated the tailings and their associated hazards from the environment and receptors. Ultimately, the only sustainable means of ensuring slope Stability would (in order of preference), involve decreasing the slope angle to no more than 16° (but preferably 12°; Barnhisel and Hower, 1997; van Wyk, 2002) or gradually establishing native vegetation that is able to tolerate the physical and chemical environment over the long term. Ideally, a management solution would combine both, but the cost implications of decreasing slope angle (and preferably slope length as well) and thus increasing the TSF footprint are unlikely to be embraced by the mining company. Therefore, experimentation with suitable plant species should be conducted for this site, and many lessons may be learnt from the investigations of Weiersbye *et al* (2006 and ongoing).

5.5 Soil chemical analyses

As has been mentioned in the materials and methods of this thesis (section 4.5), the soil sampling and analyses did not all go according to plan. The laboratory analyses that were done for all sites across both years were presented in Figures 5.24 and 5.25 and Table 5.11. Due to budget constraints and circumstances beyond reasonable control, composite samples were taken for both years and not all of the analyses were performed across all sites in both years (Table 5.12). Whilst the results presented in Table 5.12 were therefore not directly used in most of the analyses in this section, they were used in a supportive or explanatory capacity. Samples from the undisturbed grassland (UFV) and starter wall (5SB) were most often not chemically analysed in the same detail as the TSF slopes and spillage area (SP), as per the mining company's monitoring plan. Electrical conductivity (EC), Sulphates (SO_4), Nitrates (NO_3) and Ammonia (NH_4) were measured for all sites in 2008 (Table 5.12) (except of course for those sites that had been destroyed due to reprocessing) and are used in the analysis in Figure 5.26. The other results presented in Table 5.12 were also used in the multivariate data analyses in section 5.6.2 and section 5.6.3 and are shown here for reference.

In 2007, one composite sample was taken for the whole of Dam 5, as its chemistry had been thought to be very homogeneous (as per section 4.5). This complicated comparison with the 2008 data, for which composite samples were taken for each site individually. Only chemical symbols are henceforth referred to, as they have been laid out in section 4.5 but for a glossary of abbreviations and symbols please refer to Appendix B.

In addition to the unfortunate sampling constraints, variances within the data were observed that could not be explained by natural phenomena and either resulted from sample concentration or contamination in the field or in the laboratory. These constraints were also beyond reasonable control, emphasising that samples must be self-collected in such studies and that others cannot necessarily be relied upon. P (Bray 1) was perhaps the best example where significant inconsistencies occurred in the data and severely hampered analysis. P is a largely static nutrient that does not move through the soil profile rapidly and is not taken up by plants in large concentrations. It also does not occur naturally in the tailings material and almost negligible amounts of P will have entered the profile through litter decomposition. Lastly, we were assured that no P was added between the two sampling periods. However, when scrutinising the data in Table 5.11, one can see that the variance between samples is almost randomly distributed and some of the increases or decreases were too large to be explained by either mineralisation or plant uptake. P was initially used in the multivariate ordinations but showed inconsistent relationships and was thus omitted and analyses re-performed.

As could be seen in the first column of Table 5.11, the amounts of agricultural dolomitic lime (Ca/MG CO_3) added as initial ameliorants to combat acidity were quite variable. The first slope of Dam 4 (thus 4N1, 4SE1, 4SW1 and 4W1) had a reported pyrite content of 1%, the second slope (thus 4N2, 4SE2, 4SW2 and 4W2) contained 2%, and the first slope of Dam 5 (thus 5N1, 5E1, 5S1 and 5W1) contained <1%. Pyrite content is measured at the time of tailings stacking, after it has come from the mining plant and is therefore very homogeneous, as is reflected by the values given above. The pyrite content would have guided the volumes of lime applied to some extent, but other forms of active and reserve acidity would also have been calculated on the basis of soil testing. Although the pyrite content (which is the largest pool of reserve acidity in the TSF's) was variable between slopes due to the variable parent material of the tailings deposited there, identical amounts of lime were applied to each aspect.

Table 5.11. Results of the soil chemical analyses that were performed across all sites for 2007 and 2008 (excluding the sites that had been destroyed in reprocessing, indicated by X in 2008). These were the parameters included in the comparative analyses. The site names and abbreviations are explained in Appendix A, whilst the chemical symbols are explained in Appendix B.

Site	Lime (T/Ha)	pH KCL		CEC (cmol/kg)		K (mg/kg)		Ca (mg/kg)		Mg (mg/kg)		Na(mg/kg)		P Brayl (mg/kg)	
Year		*07*	*08*	*07*	*08*	*07*	*08*	*07*	*08*	*07*	*08*	*07*	*08*	*07*	*08*
4N1	70	6.4	6.4	1.3	2.3	15	21	3372	2547	105	170	88	158	4	9
4N2	70	6.4	4.7	1.5	1.7	32	19	2958	3326	208	232	127	145	3	0
4SE1	30	6.8	3.6	1.0	2.0	23	9	2234	2011	85	217	127	66	1	0
4SE2	30	5.8	6.5	1.0	2.5	9	23	2627	2430	35	135	26	49	0	0
4SW1	65	7.5	X	1.9	X	53	X	1447	X	38	X	5	X	40	X
4SW2	65	7.5	X	1.7	X	27	X	940	X	61	X	5	X	20	X
4W1	65	6.4	X	1.5	X	10	X	1335	X	51	X	4	X	26	X
4W2	65	6.4	5.6	1.5	2.8	10	28	1335	2475	51	191	4	17	26	1
5N1	30	4.3	6.9	0.4	1.3	21	27	3784	2073	85	67	18	15	3	10
5E1	30	4.3	5.0	0.4	1.5	21	41	3784	4844	85	218	18	119	3	5
5S1	30	4.3	7.2	0.4	1.6	21	33	3784	595	85	83	18	49	3	14
5W1	30	4.3	6.8	0.4	1.7	21	22	3784	3807	85	48	18	6	3	16
5SB	0	4.8	4.5	4.4	5.1	200	129	509	306	160	70	5	4	3	0
UFV	0	4.6	4.7	3.0	5.4	98	92	334	286	39	59	4	6	2	0
SP	0	4.0	3.8	2.1	4.2	28	20	95	103	9	32	0	6	1	0

Looking at the pH of the sites (Table 5.11), the undisturbed grassland (UFV), spillage site (SP) and starter wall (5SB) all showed very similar values for both years, but the pH of the two TSF's was far more variable. There was a pattern that emerged when consulting Table 5.11 in conjunction with Figure 5.7, which will be explored using multivariate data analyses in section 5.6.3. There also appeared to be no influence of aspect on pH with northern and southern slopes varying by different degrees in both years. However, the site with the most neutral pH was 4N1 (pH 6.4 in 2007 and 2008, Table 5.11), which was also the most functional site with the highest vegetation cover, whilst the most acidic site was 4SE1 (pH 3.6 in 2008, Table 5.11), which was also the least functional and had the lowest vegetation cover. One would thus expect the buffering capacity of these two soils to be very different, as was reflected by their CEC (Table 11) and organic C (Table 5.12) content, which are good indicators of how well they are able to resist acidification.

Table 5.12. Results of the soil chemical analyses for 2007 and 2008 that were not performed across all sites due to budget and other constraints (including the sites that had been destroyed in reprocessing, indicated by 'X' in 2008). Sites marked with 'XX' were neither sampled for nor analysed for the specific analysis in either year. Site names and abbreviations are explained in Appendix B.

Site	**EC (mS/m)**		**SO4-S (mg/kg)**		**NO3 (mg/kg)**		**NH4 (mg/kg)**		**Cl (mg/kg)**		**Lime req (T/Ha)**		**Organic C (%)**	
Year	***07***	***08***	***07***	***08***	***07***	***08***	***07***	***08***	***07***	***08***	***07***	***08***	***07***	***08***
4N1	353.0	457.6	284.9	350.4	0.7	0.4	X	350.4	29.4	94.3	30.7	61.9	X	0.3
4N2	427.0	540.8	353.0	537.2	0.2	0.9	X	537.2	54.0	101.5	28.0	56.1	X	0.2
4SE1	362.0	505.6	286.2	770.9	1.3	1.0	X	770.9	44.8	30.9	14.5	71.0	X	0.3
4SE2	270.0	406.4	230.4	296.0	0.3	0.3	X	296.0	7.7	17.3	22.3	44.6	X	0.2
4SW1	147.0	X	105.3	X	0.4	X	X	XX	1.5	XX	0.0	XX	X	XX
4SW2	162.0	X	117.9	X	0.9	X	X	XX	1.3	XX	16.3	XX	X	XX
4W1	211.0	X	170.6	X	0.9	X	X	XX	1.3	XX	26.9	XX	X	XX
4W2	207.0	416.0	174.0	314.6	0.9	0.6	X	314.6	1.3	16.5	24.0	57.7	X	0.4
5N1	341.0	435.2	396.9	233.3	0.9	0.3	X	233.3	10.4	11.3	17.5	32.8	X	0.2
5E1	341.0	809.6	396.9	595.2	0.9	0.8	X	595.2	10.4	98.5	17.5	72.6	X	0.3
5S1	341.0	230.4	396.9	256.0	0.9	0.4	X	256.0	10.4	24.7	17.5	6.3	X	0.3
5W1	341.0	502.4	396.9	211.4	0.9	0.3	X	211.4	10.4	3.6	17.5	50.0	X	0.3
5SB	12.0	26.9	65.0	18.2	1.3	2.4	X	18.2	XX	4.1	XX	4.0	X	0.7
UFV	XX	12.8	XX	5.4	XX	2.6	X	5.4	XX	3.6	XX	4.0	X	0.9
SP	31.0	86.4	4.8	101.0	0.1	1.4	X	101.0	0.4	1.6	XX	5.0	X	0.5

The correlations of all of the variables that were measured across all sites for both years are shown by the Principal Component Analyses (PCA's) in Figure 5.24 and Figure 5.25. In 2007 (Figure 5.24), the ordination showed that, according to the first ordination axis, the strongest predictors for differentiating between sites were their Ca content, their CEC and their K content. This was because those variables correlated more strongly with the first axis, which accounted for 45.8% of variance (Eigenvalue 0.458) within the dataset. However, where Ca occurred in high concentrations (all TSF sites), CEC and K were low and where Ca was low, CEC and K were higher (SP, UFV and 5SB). CEC correlated very strongly with K, thus K was limiting where CEC was low, as for the TSF slopes. The high Ca content of the TSF's was as a result of the ameliorative applications of calcitic agricultural lime to combat acidity. Ca is very important for seedling development and only reduces in availability at lower pH levels (< 5.5), as occurred on Dam 5 (although the pooling of samples from all aspects in 2007 negates meaningful comparison) and the reference sites (UFV, 5SB and SP). Ca is also preferentially adsorbed onto colloidal surfaces above the other base cations and although it can be easily leached, the persistently high levels may have resulted in any present or developing colloids preferentially adsorbing Ca. K, on the other hand, is highly mobile and any fertiliser applications that were not taken up by the plants in the first years would almost certainly have been lost from the tailings, as was reflected by the relatively low exchangeable concentrations in the TSF's (Table 14). Although there were high concentrations of some base cations, the overall cation exchange capacity on the TSF's was exceptionally low, indicating the low nutrient status of the tailings material.

Cumulatively, the first two ordination axes (to which the graphs were limited) explained 78.8% of the variance in the 2007 dataset. Na, pH and Mg all correlated more strongly with the second ordination axis in 2007 and together accounted for 33% of the variance in the dataset (Eigenvalue 0.33) (Figure 5.24). They correlated very well together, all falling within 40° of one another. This meant that where pH levels were higher (4N1, 4N2, 4SE1) (alkaline to slightly acidic), Mg and Na were available in high concentrations. 4W2 fell very near to the centre of the ordination and thus had intermediate values for all variables.

In the following sections, cation ratios and base saturation are often referred to. The ideal cation ratios and calculations for base saturation are explained in Appendix B. In relation to the Ca concentrations, Mg was very low. The ideal Ca:Mg ratio is about 1.5-4, whereas on the TSF's it was between 15 and 32. The UFV and SP also had slightly too little Mg in relation to Ca (8.6 and 10.6 respectively), whereas the ratio in the starter wall (5SB) was within ideal range at 3.2. Excess Ca, which was the case on the TSF's, is known to cause deficiencies in both K and Mg, also observed on the TSF's. The Na concentrations in Dam 4 were too high (Table 5.11), except in 4W2, whereas Dam 5 had adequately low Na concentrations. The high Na could become problematic if the exchangeable fraction is displaced into solution in the tailings and combines with free sulphates or Cl, as occur on Dam 4 (Table 5.12) to precipitate as salts.

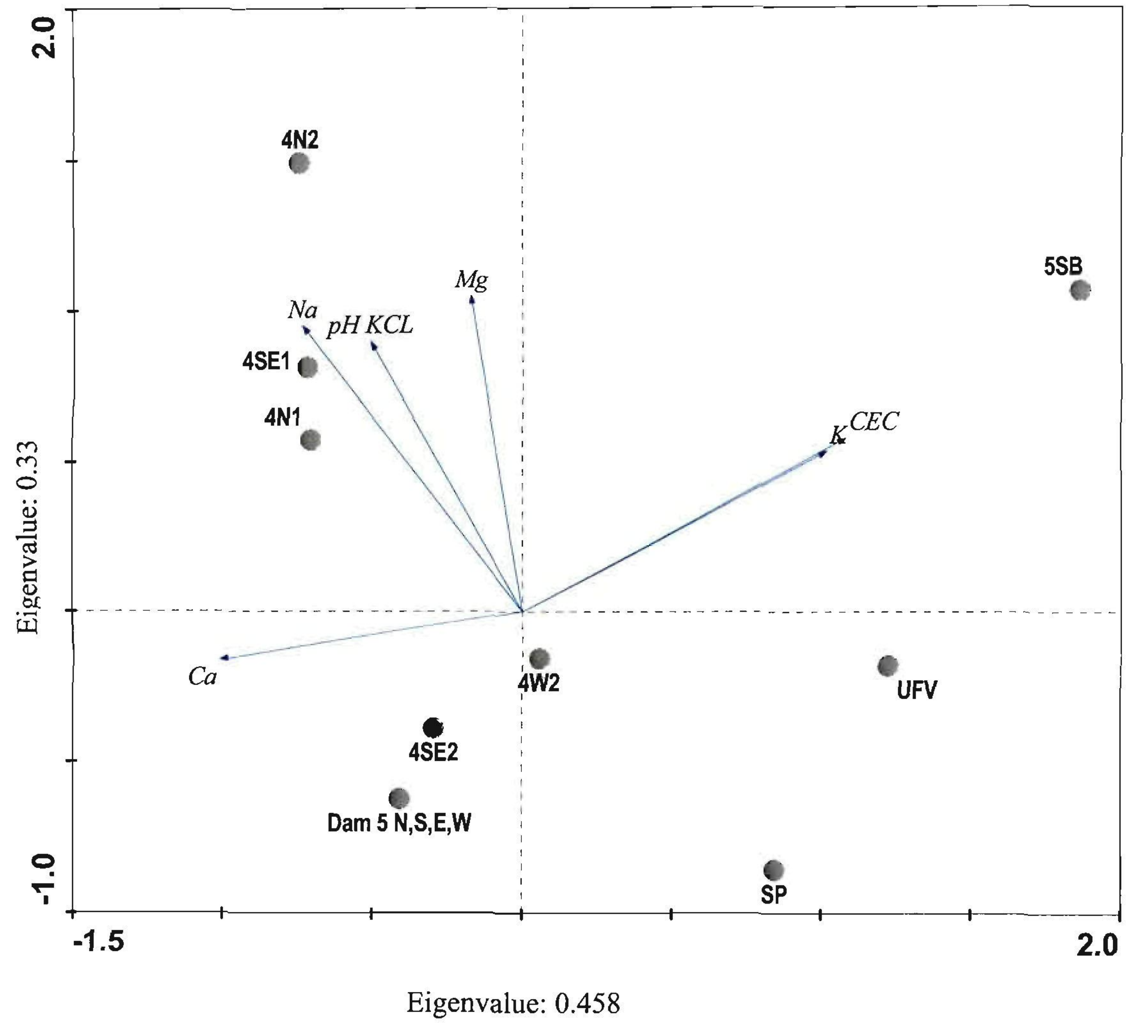

Figure 5.24. Principal Component Analysis (PCA) of the 2007 soil chemical analyses, showing only those variables that were measured across all sites. The site names and abbreviations are explained in Appendix A, whilst the chemical symbols are explained in Appendix B.

In 2008, the PCA showed similar trends as for 2007, but some of the variables became more important predictors of associations (Figure 5.25). In 2008, Na, Mg, CEC, Ca and K all associated with the first ordination axis, together accounting for 49.2 % of the variance in the dataset (Eigenvalue 0.492). The data for Dam 5 were pooled again in the 2008 PCA to facilitate direct comparison with the 2007 data. Unpooled data for Dam 5 in 2008 were presented later in Figure 5.26.

Mg, Na and Ca correlated positively with one another, indicating that they were all reasonably high in most of the TSF's, whereas CEC and K, which correlated together as in 2007, were again low on the TSF's. Again, Ca was present in excess concentrations and although it correlated with Mg, the Ca:Mg ratios were again too high on the TSF's with Dam 4 having a ratio 9-14 and Dam 5 having a ratio of 22-100, both showing that Ca occurred in excess in relation to Mg and also to the other base cations. However, Ca was more in line with 'normal' values for the reference sites (UFV, 5SB and SP) and there was more confidence in the 2008 data, which was self-sampled. UFV had a Ca:Mg ratio of 4.85, 5SB of 4.4 and SP of 3.22, all much closer in line with the 'ideal' range of 3-4. As in 2007, the excess Ca led to Mg and K deficiencies on the TSF's. CEC and K were again closely correlated and were only not deficient in the UFV and 5SB sites. There were observed increases in CEC over all sites in 2008, which were hopefully a true reflection of the actual state and not an artefact of the sampling constraints.

Cumulatively, the first and second axis explained 78.7 % of the variance, down by 0.10% from 2007. The only variable that associated with the second ordination axis in 2008 was pH and thus explained 29.5 % of the variance in the dataset (Eigenvalue 0.295) (Figure 5.25). Although pH did not associate with the first ordination axis, there was a tendency to correlate positively with Ca and K (angles between vector arrows $<90^{\circ}$), all being generally higher where pH was higher and vice versa. There was also a positive correlation with Na, although less so than for Ca and K, as can be seen by the larger angle between pH and Na than between pH and either Ca or K (Figure 5.25). CEC was, however, independent of pH, as the angle between them in the PCA ordination was $>90^{\circ}$ (Figure 5.25). SP and 4SE1 showed very low values for all variables, with the decline of 4SE1 from pH 6.8 to 3.6 over one year being most disconcerting for vegetation persistence (Table 5.11). 4W2 again aligned near the centre of the ordination, showing intermediate values for all variables.

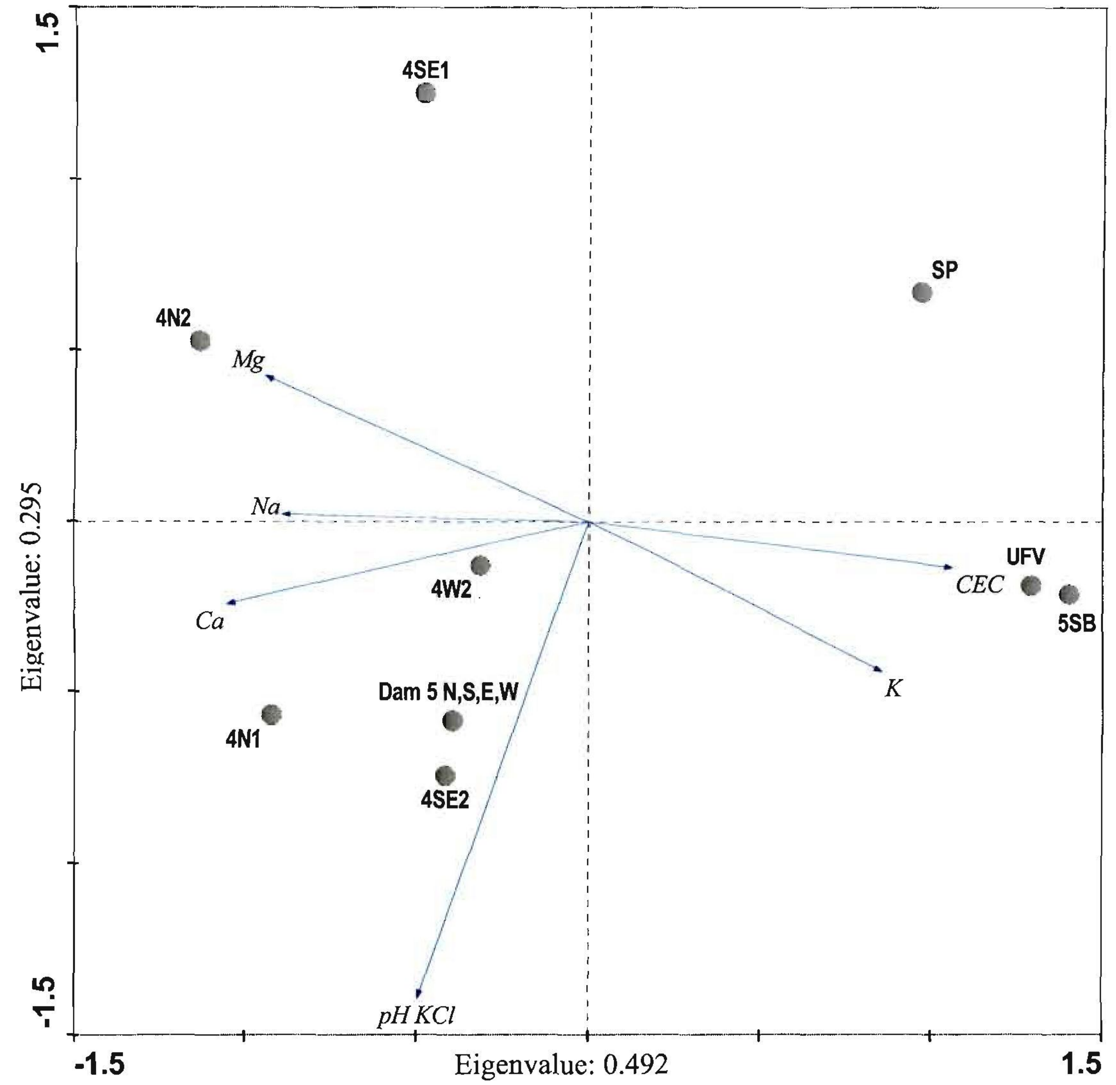

Figure 5.25. Principal Component Analysis (PCA) of the 2008 soil chemical analyses, incorporating just those variables measured in 2007 for direct comparison. Site names and abbreviations are explained in Appendix A, whilst chemical symbols are explained in Appendix B.

Figure 5.26 showed the full suite of variables for all sites for 2008. This PCA ordination had a greater likelihood of reflecting actual site chemical characteristics, as it contained far more variables and had a finer spatial resolution. Ca and EC both associated strongly with the first ordination axis, indicating that they accounted for most of the variance, whereas only pH associated strongly with the second ordination axis. All of the other variables, whilst not associating particularly strongly with either axis did have strong associations with specific sites. Only 4W2, as in the previous ordinations, aligned towards the centre of the graph, showing intermediate values. The first axis accounted for 58.1 % of the variance (Eigenvalue 0.581) and the second axis for 19.1 % of the variance (Eigenvalue 0.191), together accounting for 77.1 %.

Higher pH levels were strongly associated with most Dam 5 sites (5W1, 5N1, 5S1) and slightly lower for 4SE2 (Figure 5.26), and these sites then had lower CEC, organic C, Mg, Na, Cl and SO_4. pH was also marginally related to Ca and EC (<90° between variables, Figure 5.26), indicating that the more alkaline sites also had generally more Ca and higher EC than the more acidic sites.

Ca and EC were highest in 4N1, and slightly less so in 5E1, 4N2 and 4SE1, as Ca and EC were also related to SO_4, Na, Cl and Mg, which were highest in those sites. The close relationship between Na, Cl, Mg and SO_4 was disconcerting, as this indicated the high potential for those variables to combine and precipitate as salts of NaCl, $NaSO_4$, MgCl and $MgSO_4$ with the possibility of Ca also forming salts. This is further exacerbated by the relationship with EC, with values ranging between 450 and 800 mS/m, far above the recommended upper limit of 400 mS/m. This already indicates problems with salinity and the Sodium Adsorption Ratio (SAR) of <15 further increases salinity. The negative impacts that salinity has on the non-tolerant vegetation may have adverse effects on the rehabilitating slopes if not addressed. The impacts of the substrate chemistry on vegetation is full explored and explained in the multivariate data analyses of section 5.6.2.

These sites (4N1, 4N2, 4SE1 and 5E1) did not have strong associations with pH, indicating increased acidity, and also negatively associated with CEC, organic C and K, which are all essential for Nutrient cycling and turnover, and also for plant growth and persistence. The pseudo-analogue sites, 5SB, UFV and SP clustered together, separate from the two groups of TSF sites and were differentiated from the TSF sites by their higher levels of organic C, CEC, K, NO_3 and NH_4.

All transects on Dam 4 and Dam 5 had excessively high Ca and as percentage of the base saturation made up 82-89% and 75-97% respectively, as opposed to recommendations of 65-70 %. Only 5S1 and 4W2 were closer to the recommendations with 80% and 75%

respectively. As discussed, Ca is primarily required for root development and cell structure, but excess Ca leads to deficiencies in Mg and K, as has been observed in this case. The pseudo-analogue sites were well in line with 62% (5SB), 65% (UFV) and 60% (SP). These sites should then have experienced no deficiencies and seedling vigour should have been good.

For Mg, Dam 4 and Dam 5 had deficiencies as related to percentage of base saturation (recommended levels at 15-20%), with 8-11% and 2-6% respectively with only 4W2 (14%) and 5S1 (17%) having Mg in the correct amounts. Therefore although there were high concentrations of Mg, the concentrations were too low in relation to Ca concentrations. Mg is a macronutrient required for photosynthesis, carbohydrate metabolism and the uptake of P. The deficiencies in Mg were not directly observed on the TSF sites although chlorosis was observed in 4N1. 5SB (23%) and UFV (22%) had slight excesses, whereas SP (31%) had moderate excesses. These slight excesses are not harmful to vegetation but could result in increased P requirements.

For K, both TSF's had severe deficiencies, with most values ranging from 0.2-0.5%, but with the highest values in 5S1 at 2%. Recommendations for K are at 3-5% of base saturation and all of the TSF sites are thus low. K is essential for maintaining plant vigour through increasing disease resistance, growth, protein synthesis and CO_2 regulation. The poor biomass production on most sites and perhaps poor photosynthetic rates (if they occur) may have been related to the K-deficiencies on the TSF's. The vegetation on the TSF's would thus greatly have benefited if K concentrations were maintained at the correct levels in relation to other cations. The pseudo-analogue sites had slight to moderate excesses of K with 13% (5SB), 10% (UFV) and 6% (SP).

For Na the recommended portion of the base saturation is set at <1%. Dam 4 had excess levels in relation to other cations with all values above1% (1.5-4.6%) except for 4W2, which had 0.5% Na. Although the PCA ordination did not reflect it well, it is in Table 5.11. On Dam 5, 5N1 and 5W1 had <1% Na, but 5S1 and 5E1 had 5.4% and 1.9% respectively. These excess Na-levels in relation to the other base cations may, as discussed, result in salt build-up and precipitation, reducing stomatal efficiency and causing crust formation and poor root development and penetration, all as a result of increased salinity. Although salinity may be problematic, sodicity was not, largely due to the low pH levels. 5SB had sufficiently low Na percentages (0.7%), UFV was at the upper limit (1.09) and SP was also in excess (3%).

Similarly, these sites with high Na had lower concentrations of the remainder of the base cations, pH, EC and SO_4 and, as explained, have healthier ratios of base cations that do not incur deficiencies in other elements.

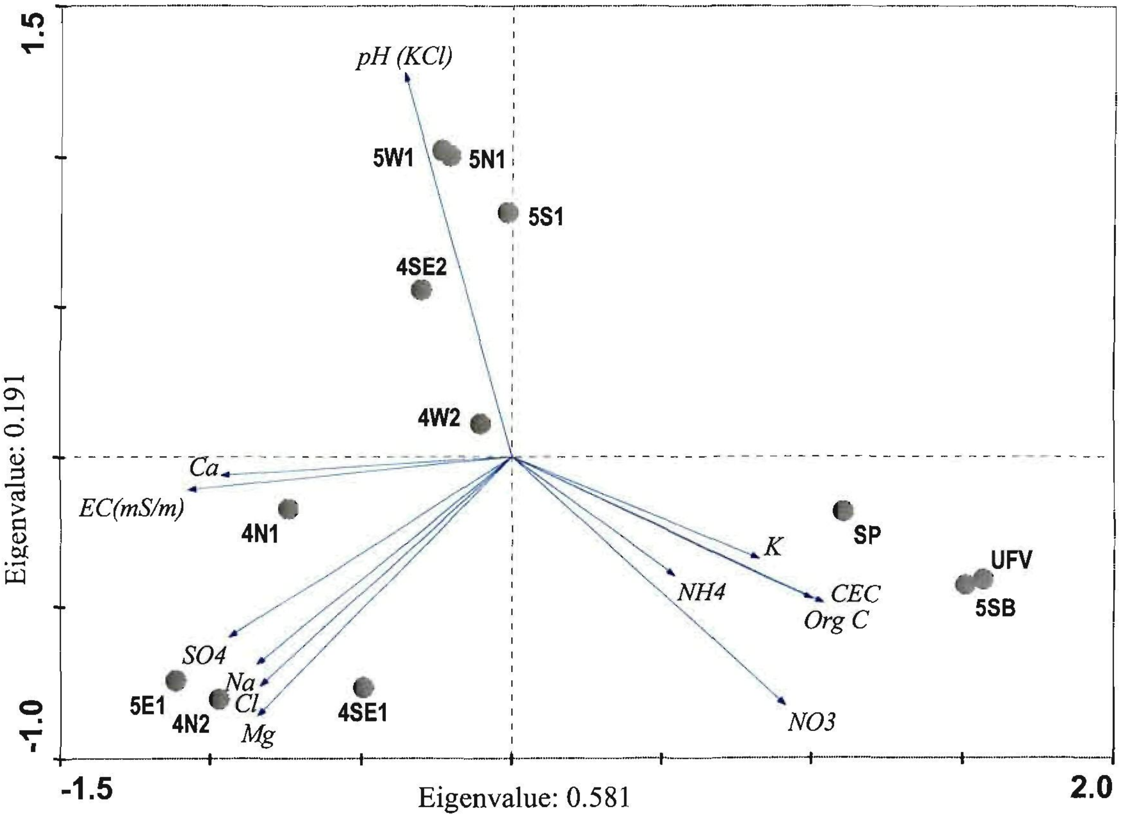

Figure 5.26. Principal Component Analysis (PCA) of the 2008 soil chemical analyses, with all of the measured variables. Site names and abbreviations are explained in Appendix A, whilst chemical symbols are explained in Appendix B.

5.6. The relationships between landscape function, vegetation composition and substrate chemistry

5.6.1. LFA variables, vegetation data and survey transects

The LFA variables were analysed together with the vegetation composition data, relative to their prominence in the different transects of each study site. Essentially, the results of section 5.2 and 5.3 are integrated in this section to explore the relationships between vegetation composition and landscape function. Canonical Correspondence Analyses (CCA's) are a direct gradient analysis that are well-suited to analysing these data by expressing the patterns of variation in the vegetation data and simultaneously demonstrating the principle relationships between the sites and LFA variables. This was performed over both years and site age was included as a variable in order to establish whether any trends were evident over time as well as over space. Figure 5.27 showed the data across all sites for 2007, whereas Figure 5.28 showed the data across all sites for 2008. However, the age distribution for the different sites was skewed towards the younger sites, as ten of twelve sites (the TSF's) were below 15 years old, one site was 67-years old (5SB) and one site was 100+ years old (UFV). Due to the oldest sites having had the highest species richness, most complex composition and high landscape function, the trends automatically showed increases over time, whereas this did not necessarily reflect the actual status of the rehabilitating TSF slopes. Therefore, the analyses were run again for both years, without the two oldest sites, to establish whether the observed trends would be similar. These analyses were presented separately in Figure 5.29 for 2007 and Figure 5.30 for 2008.

5.6.1.1. CCA ordinations and analyses of all sites for 2007 and 2008

As expected, Figure 5.27 showed a very strong relationship with the first ordination axis, with site age explaining most of the variance in data for 2007 (Eigenvalue 0.827). However, this was caused by the aforementioned skewed age distribution. Although the first ordination axis explained most of the variance, the second axis also contributed a large amount to the variance (Eigenvalue 0.496) in 2007. Figure 5.28 showed the same ordination sites and variables as Figure 5.27, but for the 2008 data. The results and trends observed were very similar, with slight changes in species composition due to the increased rainfall and ruderal flush in 2008. The first ordination axis again explained the majority of variance (Eigenvalue 0.827) observed in the data and again correlated strongly with site age in 2008, which was a poor reflection of the data, as mentioned earlier. The second ordination axis also contributed significantly to explaining the variance in 2008 (Eigenvalue 0.597) and associated more strongly with all variables other than site age. Stability fell midway in between the axes in 2007 and 2008 and did not associate strongly with any sites, showing that it had low variation across all sites, as was also shown in the data (Table 5.3). As in 2007, the 2008 ordination showed distinct groupings of transects, with the TSF's, SP, UFV and 5SB all clustering in discernible groups with their associated species'-mix and concordant LFA variables. As most of the variables associated with the second ordination axis or fell between the first and second axes, they are only briefly explained here, with an emphasis on the UFV and 5SB sites, as they were excluded from the CCA in Figure 5.29 and Figure 5.30.

The UFV and 5SB sites were the sites that associated most strongly with site age, indicating that they were the oldest sites, as can also be seen from Table 4.1. UFV was characterised by the presence of *Setaria sphacelata* var. *sphacelata, Felicia muricata* and *Liliaceae* sp. in 2007 and 2008, but *Aristida junciformis* was more prominent in 2007 (Figure 5.27) and *Cyperus rotundus, Berkheya setifera* and *E. gummiflua* were more prominent in 2008 (Figure 5.28). UFV also correlated negatively with patch area and to a lesser extent with number of patches and interpatch length. UFV did not have positive correlations with interpatch length or patch area in either year, meaning that it consisted of fewer, smaller patches, but also had smaller interpatches. This indicates a very retentive spatial organisation due to the existing vegetation and was reflected by its relatively high LOI and LFA index values as explained in section 5.3.4 (Table 5.3). This pattern was observed in UFV in 2007 and 2008, meaning that the spatial patterns had not changed.

5SB transects had positive correlations with one another and separated from all other sites in 2007 and 2008. In both years, the site was characterised by the common species *Eragrostis lehmanniana, Melinis nerviglumis, Urochloa trichopus, Heteropogon contortus, Indigofera comosa* and *Aristida stipitata*, as was seen earlier in the DCA in section 5.2.2.3. However, there were slight differences between species composition in the two survey years with *E. biflora* being more prominent in 2007 and *A. congesta* subsp. *congesta, Loudetia simplex, Clematopsis scabiosifolia* and *Schizachyrium sanguineum* were more prominent in 2008. *S. sphacelata* var. *torta* occurred with almost equal abundances in 5SB and UFV but not at all in the other sites. 5SB correlated negatively with interpatch length and patch area but positively with number of patches/10m (i.e. patch density) for both years (Figure 5.27 and 5.28), meaning that the transects typically consisted of many smaller patches with small bare areas in between. The vegetation creating this spatial pattern was moderately functional, although Stability and LOI were slightly lower than in the UFV (well shown in Table 5.3 but not in Figure 5.27 or 5.28). Although this ordination did not reflect it well, the differences in LFA indices and structural dimensions were not great between 5SB and UFV. The differences were largely driven by species composition and not landscape function, in relation to the other sites.

SP also had a similar grouping in 2007 and 2008, clustering together and away from other sites in the quadrat that corresponded with low spatial organisation and low landscape function. SP was strongly positively correlated mainly with interpatch length and negatively with all of the other variables in both years (as per Figure 5.27 and Figure 5.28). This showed that it had very few patches and very low function, characterised in both years by sparse *Paspalum dilatatum* and *Elephanthoriza elephantina,* but strengthened by the addition of *Panicum maximum*, which had increased in the shade of a shrub on one of the transects in 2008. These poor vegetation patterns resulted in landscapes with very poor resource retention and massive amounts of resource loss.

The TSF's clustered together and were distinctly different from other sites in their species composition but to a lesser extent in terms of their landscape function and spatial patterns. This separation was consistent in 2007 (Figure 5.27) and 2008 (Figure 5.28). They were characterised by a similar mix of species that generally did not occur in other sites, but when they did it was in lower relative abundances than on the TSF's (will be explained thoroughly in section 5.6.1.2). In 2007, the TSF sites were divided by the first ordination axis, those above the axis with vegetation showing lower levels of spatial organisation and landscape function, whilst those below the axis had vegetation showing better spatial organisation, higher landscape function and also lower interpatch lengths and more, larger patches. In 2008, there were many more sites falling below the first ordination axis on the more functional side. The sites that correlated less with the LFA indices (above first axis) in both years also had low LOI, lower patch area (smaller patches) and greater interpatch lengths. This poor spatial pattern was reflected by the lower LFA index values (Table 5.3). The more functional sites that fell below the first ordination axis for both years had negative correlations with interpatch length and tended to correlate more strongly with patch area, number of patches and LOI, all meaning that the spatial pattern consisted of a greater number of larger patches that were closely spaced. This resulted in more retentive landscape pattern, as reflected by the higher LFA index values for these sites in 2007 and 2008 (Table 5.3).

Whilst vegetation certainly plays an important role in dictating landscape function, there are many other environmental variables that must also be assessed. These are addressed in the LFA SSA indicators (see section 4.4.2). However, these CCA ordinations showed that a different suite of species with their own inherent function was likely to develop on a steep slope that was different to flat areas. This suggests that, whilst they are very different at the moment, the spillage site was more likely to resemble UFV over time as successional progression occurred. However, this is likely to take many decades, perhaps longer to occur. The steep areas should have inherently lower landscape function, but the TSF's were supported by introduced vegetation which may or may not persist over time and are threatened by their substrate limitations.

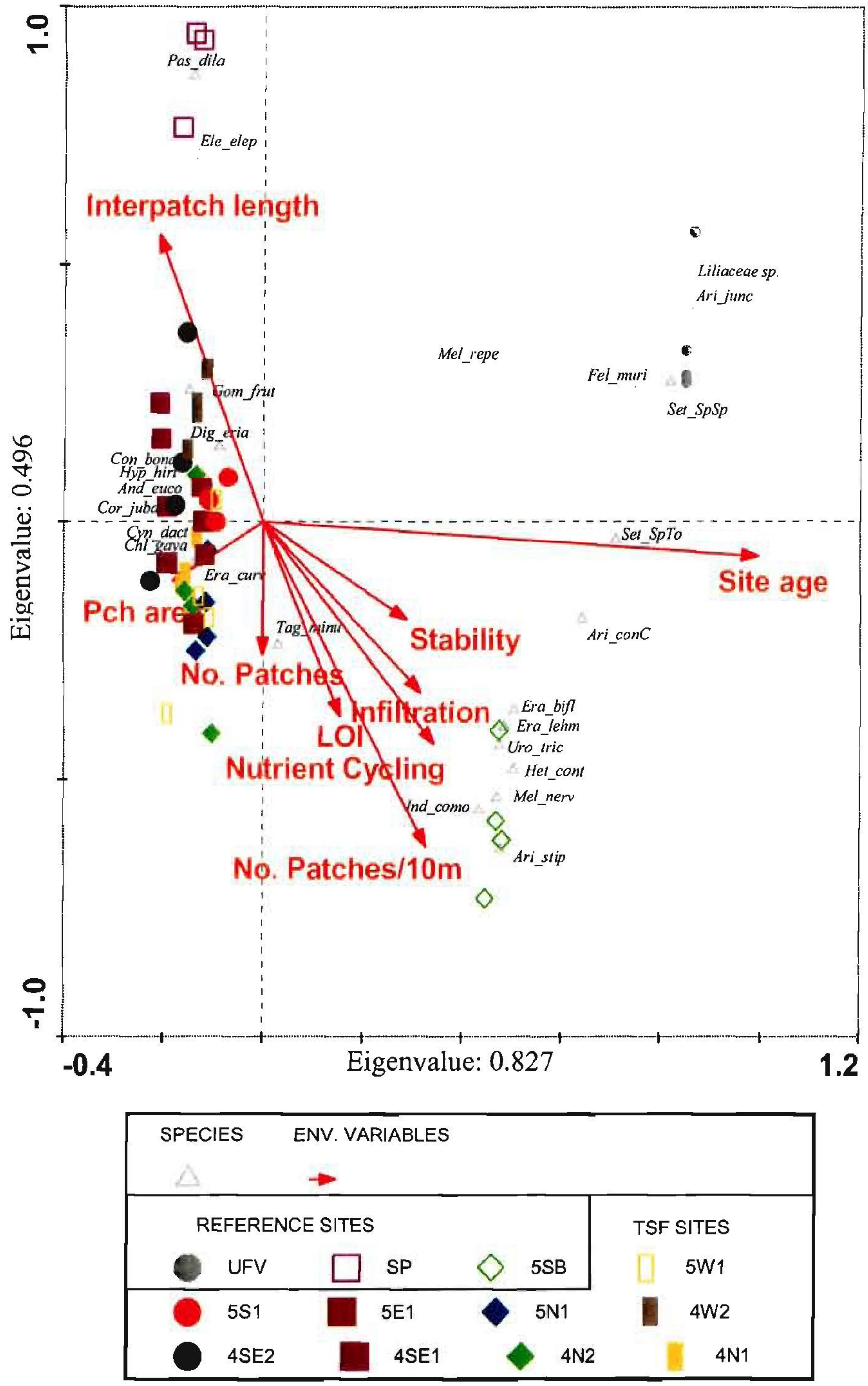

Figure 5.27. Canonical Correspondence Analysis (CCA) of the vegetation composition and LFA variables (represented as environmental variables) on the TSF and reference sites for 2007. The LFA variables are those selected in section 5.3.4. Site names and abbreviations are explained in Appendix A.

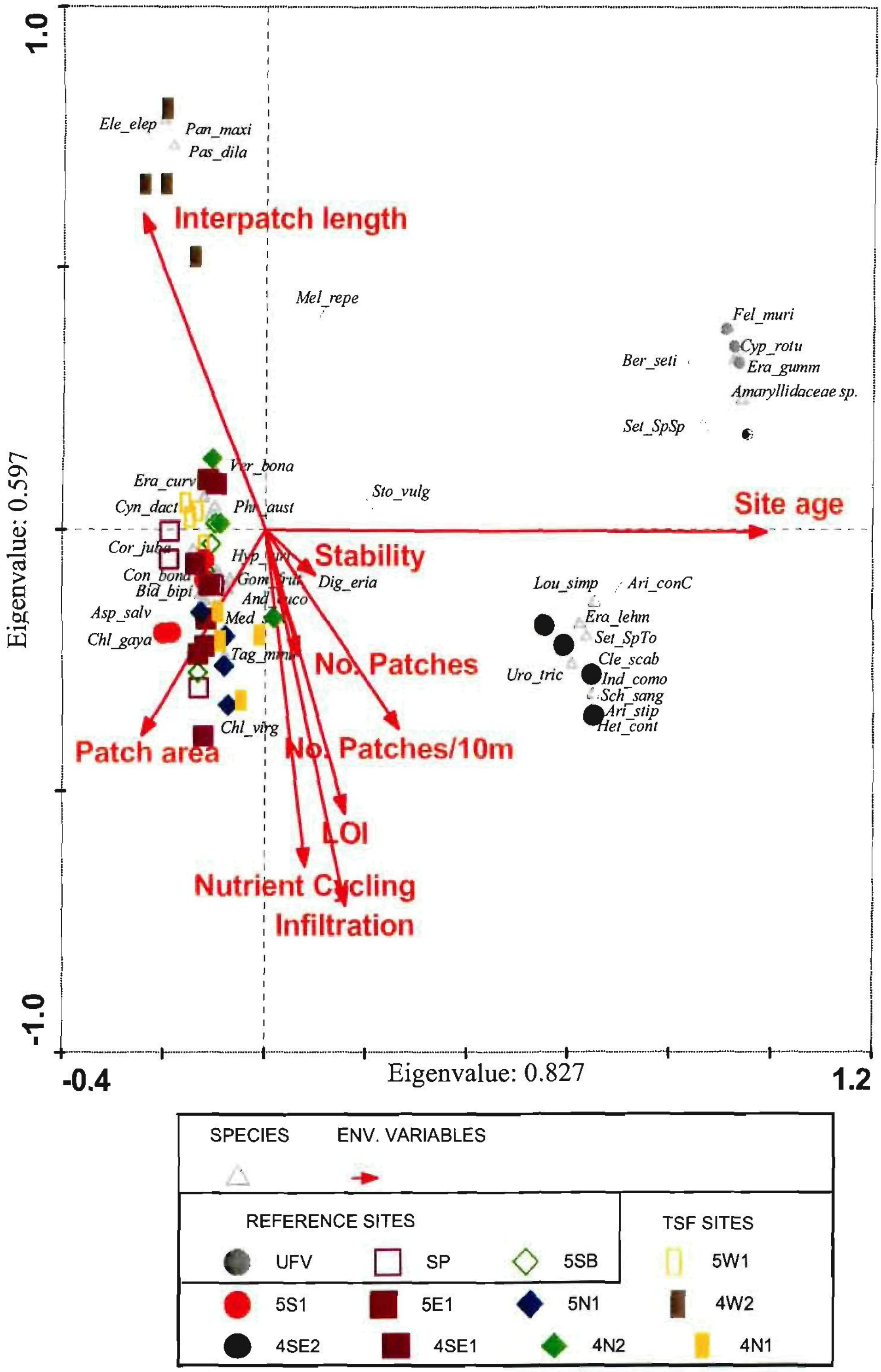

Figure 5.28. Canonical Correspondence Analysis (CCA) of the vegetation composition and LFA variables (represented as environmental variables) on the TSF and reference sites for 2008. The LFA variables are those selected in section 5.3.4. Site names and abbreviations are explained in Appendix A.

5.6.1.2. CCA ordinations and analyses of the younger sites (TSF and SP only) for 2007 and 2008

As mentioned, the uneven age distribution of the stratified sites in the previous section did not lend itself to discerning differences within and between the younger sites (SP and the TSF sites: 2-14 years old) and therefore the ordinations were recalculated, omitting data from the older sites (5SB and UFV: 67-100+ years old). This allowed for a finer-scale investigation of the differences in LFA indices and structural variables and how these changed over space and time.

Figure 5.29 and Figure 5.30 showed CCA's of all of the LFA variables, the TSF and SP sites, their characteristic species and how these related to site age in 2007 and 2008 respectively. Site age is indicated by both an arrow and the contour lines (with contour values corresponding to age since rehabilitation). The age distribution showed that the SP sites were ± 2 years old, with 4SE1 and 4SE2 falling between 4 and 8 years and the remainder of sites were between 8 and 14 years old in 2007. In 2008 the age of each site had increased by exactly one year.

In 2007, site age formed a gradient from the bottom right to top left of the diagram (Figure 5.29) and in 2008 (Figure 5.30), the pattern was repeated, although the gradient ran from top right to bottom left. In both years site age formed positive relationships (as sown by the angle between arrows at <90°) with all of the LFA indices and structural variables whilst having a strongly negative relationship with interpatch length (obtuse angle). Although the LFA variables changed slightly in their relative associations, the same trend was observed in both years. Essentially, this meant that there was a tendency for landscape function and structural complexity to increase as sites got older, accompanied by a decrease in the leakiness of these landscapes. This was a significant result and was consistent in both years, suggesting that ecosystem development, in terms of the functionality of the landscapes, appeared to be taking place over time, albeit in small fractions. The gradient in terms of landscape function showed an increase from right to left on the first ordination axis (Figure 5.29 and Figure 5.30). This again showed aspects of ecosystem development over time on the rehabilitating chronosequence. SP, the youngest site, and to an extent 4SE1 and 4SE2, the next youngest sites (4 years old in 2008) showed strong positive relationships with interpatch length and low function in both years, which corresponds with the other analyses (see section 5.3.4).

Whilst the LFA variables illustrated the trend over time, the vegetation composition did not really follow this trend. Most of the characteristic species clustered towards the centre of the ordination in 2007, indicating that they had more or less even abundances across all TSF sites, regardless of landscape function or site age (Figure 5.29). The vegetation data for 2008 were more variable, leading to a wider spread of site-species associations (Figure 5.30). This was largely as a result of small changes in the composition and structure of transects and the influx of ruderal species following the above-average rainy season (see Figure 3.2 and Figure 3.3). Unfortunately the age-contours in 2008 were slightly inaccurate, due to the intermediately aged sites (4SE1 and 4SE2) responding more like the less functional older sites. However, the general trends still held true and the relationships between variables were not affected. The relationship between the sites and species and how these influenced landscape function were investigated below.

Only SP had a highly distinct species suite, characterised by *P. dilatatum* and *E. elephantine* in both years and additionally by *P. maximum* in 2008, as mentioned in the previous section. The poor species patterns were supported by the ANOVA in both years (section 5.2.2.2), which found no significant differences within the TSF sites ($p>0.05$ for all).

In 2007, 4SE1 and 4SE2, the intermediately-aged sites (3-years old), had longer interpatches, poor spatial organisation and showed low LOI and patch area values which reflected the many, small and widely spaced pattern of patches (Figure 5.29). This was most evidently shown in the low Stability values, as the poor spatial pattern combined with steep slopes encouraged runoff with very few, small and sparse patches to enhance Infiltration. These sites had slightly higher densities of *C. jubata* and the annual *G. fruticosa* than other sites (Figure 5.29). These findings correlate well with previous results in section 5.2.2.2). In 2008, 4SE1 and 4SE2 (4-years old) again had strongly negative correlations with Stability, and slightly less so for LOI (Figure 5.30). These sites had weak positive correlations with interpatch length, indicating a tendency for long interpatches as was supported by the lower LOI. However, it correlated more negatively with Infiltration and Nutrient cycling and more strongly with number of patches and patch area. This meant that the transects still consisted of more patches than interpatches, with the same number of slightly larger patches, without really decreasing the length between patches between years. This suggests that patch size was increasing perpendicular to the slope and not down-slope, by the increase of *C. dactylon* stoloniferous spreading along the terracette contours. The increase of *C. dactylon* was accompanied by increasing *C. jubata* seedlings and decreases in abundance of other species (such as *Digitaria eriantha, Andropogon eucomus* and *Conyza bonariensis*), resulting in declines in landscape function. The changes were thus composite, but ultimately led to a decline in function, caused by the increase of poorer quality patches (largely SGP's) at the expenses of perennial patches. These declines in perennial patches will be investigated later.

In 2007, the 5S1 sites (12.5-years old), some 4W2 (11-years old), one 5N1 (13-years old) and the two burnt 5W1 (12.5-years old) sites, corresponding to groups 2 and 3 in Figures 5.14 and 5.15 (section 5.3.4.2 and section 5.3.4.3), also showed greater affinity to interpatch length than to the other LFA variables, indicating their poorer landscape function. These sites were offset by 5E1 (13-years old), the unburnt 5W1 (12.5-years old), the other 5N1 (13-years old) and one 4N2 (11-years old) sites that showed negative relationships to interpatch length, strong positive relationships with Infiltration, Nutrient cycling and number of patches, and moderately strong relationships with patch area, LOI, Stability and site age. This indicated that these intermediately-functional sites were -aged, comprised more of patches than interpatches, although patches were fairly dense, many and not very large, leading to retentive landscape patterns with higher Infiltration and Nutrient cycling values (Figure 5.29). In 2007, the transects from 4N1 (11-years old) and 4N2 (11-years old)clustered somewhat separately from the other TSF sites and correlated more strongly with site age, LOI, patch area and Stability, although they also had positive associations with the other LFA variables and a negative association with interpatch length. These transects also appeared to have slightly higher densities of *C. gayana* than other sites and the larger patch area and higher LOI lent the transects greater Stability than that of the other sites (Figure 5.29).

In 2008, there was a distinct split on the TSF's with the transects of Dam 4 splitting from those on Dam 5 (Figure 5.30). The more functional sites of Dam 4 (4N1, 4N2, 4W2) grouped together, more closely related to the 4SE1 and 4SE2 sites than to the Dam 5 sites. This was as a result of a combination of species composition and landscape function variables. In 2008, these Dam 4 sites had higher relative proportions of the annual species *Bidens bipinnata*, with 4W2 showing a large increase in *Medicago sativa* and a decline in *C. gayana* in 4N1. These differences made these sites more alike and less like the Dam 5 sites that showed increases in a different annual herb, *Tagetes minuta.* Although these Dam 4 sites correlated more strongly with patch area and number of patches, the changes in Stability was less important than the changes in Nutrient cycling and Infiltration, both which increased slightly as Stability declined or remained unchanged (Figure 5.30). This showed that although LOI and Stability decreased slightly, relative patch sizes did not shrink because the number of patches had also increased.

The Dam 5 sites grouped together in 2008, further from the centre of the ordination and distinct from most Dam 4 sites. As mentioned, this was as a result of a combination of species composition and landscape function, with the relative abundance of *T. minuta* increasing accompanied by a decrease in the relative abundance of *E. curvula* on Dam 4. There were slight concerns as to whether this perceived difference was not an artefact of less perennial plants being recorded in 2008, as the nearest plant in each quarter was more likely to be an opportunistic annual following the above-average rains. Nonetheless, LFA ignores species composition so should still be able to show the magnitude of any changes that may have taken place. Figure 5.30 showed that the importance of LOI and interpatch length did not change much, the number of patches decreased in importance and patch area remained largely the same. Infiltration and Nutrient cycling remained static or increased slightly, although Stability may have decreased in some sites. This therefore showed that the perceived differences caused by the apparent change in species composition did not change the LFA structural variables much, with the only difference being a slight decrease in the number of patches. The functionality of these sites also remained largely unchanged by the perceived change in apparent species composition, with only Stability perhaps decreasing slightly in some sites.

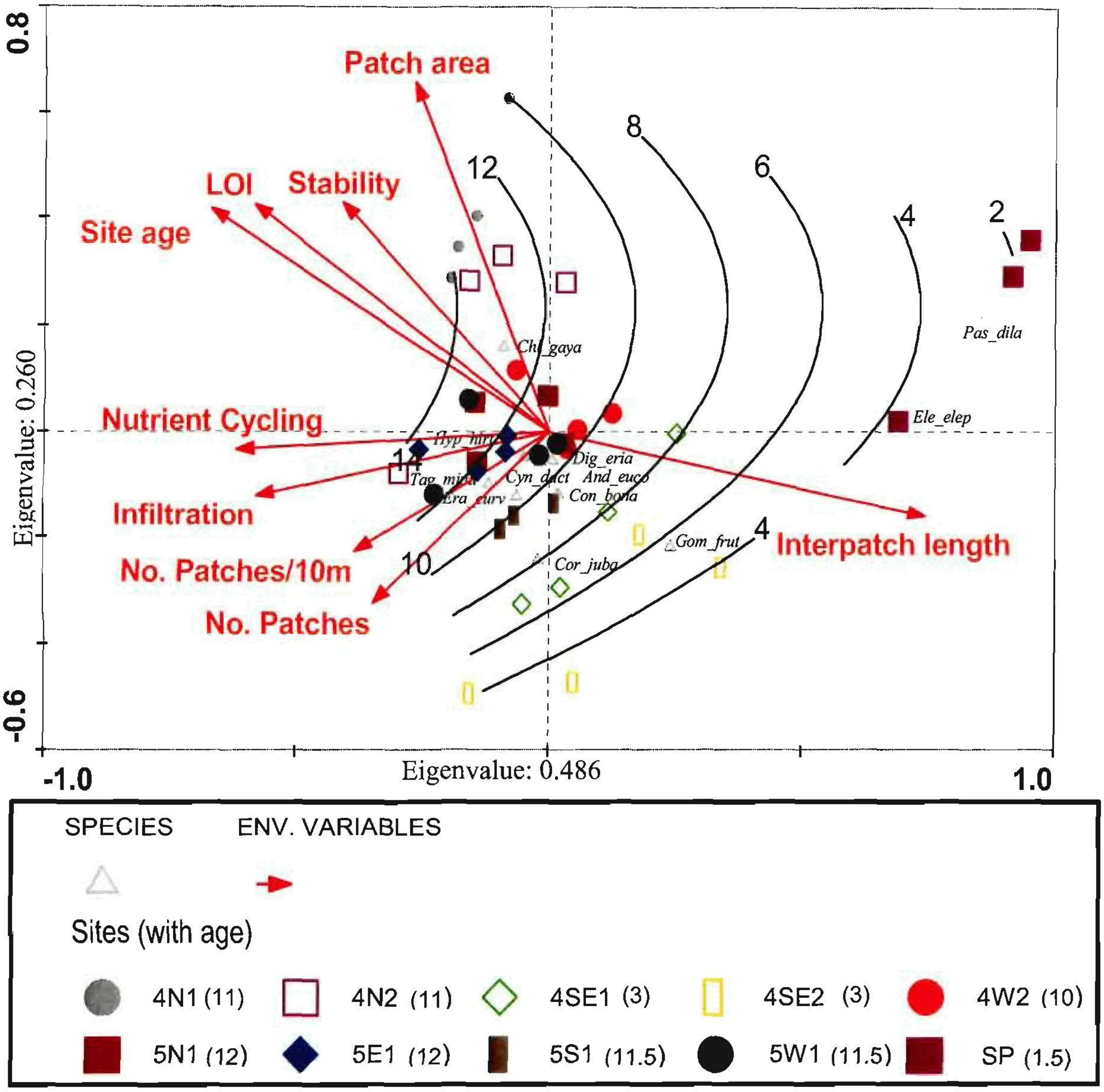

Figure 5.29. Canonical Correspondence Analysis (CCA) of the 2007 vegetation composition and LFA data, without the UFV and 5SB sites. UFV and 5SB were omitted due to uneven age distribution of these sites. The ages of sites are indicated in brackets in the legend and the ordination diagram shows site ages by means of contours. LFA variables are those selected in section 5.3.4. Site names and abbreviations are explained in Appendix A. Species codes and names are explained in Appendix C.

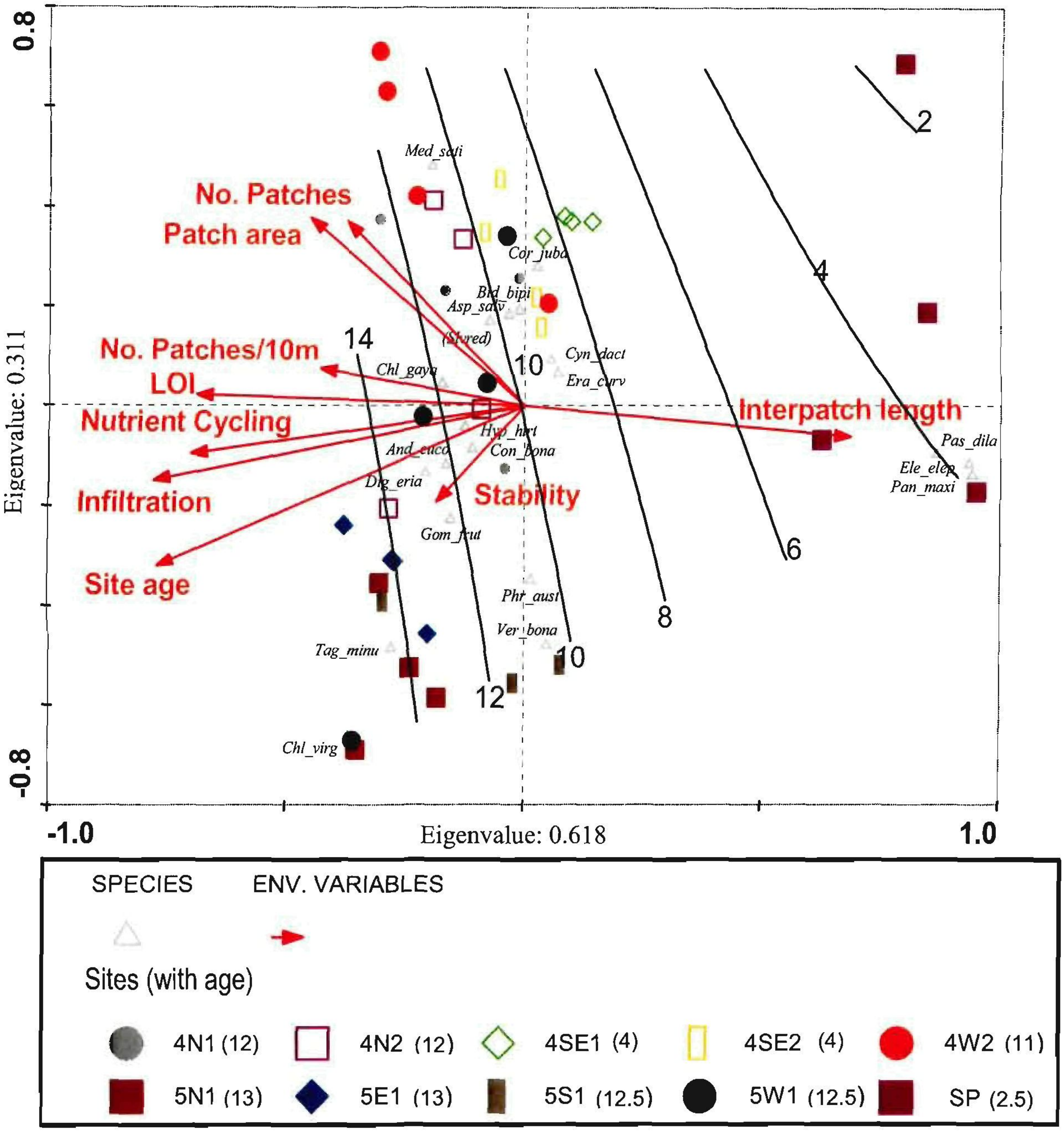

Figure 5.30. Canonical Correspondence Analysis (CCA) of the 2008 vegetation composition and LFA data, without the UFV and 5SB sites. UFV and 5SB were omitted due to uneven age distribution of these sites. The ages of sites are indicated in brackets in the legend and the ordination diagram shows site ages by means of contours. LFA variables are those selected in section 5.3.4. Site names and abbreviations are explained in Appendix A. Species codes and names are explained in Appendix C.

Ultimately, the ordinations for both years showed that older sites generally had higher landscape function as a result of better spatial organisation and higher values for soil surface indicators (which make up the LFA indices) than younger sites. These ordinations also suggest that a spatial pattern with a greater inclination towards resource regulation would develop over time. However, these generalisations would only hold true if there were no large-scale chemical imbalances that would negatively influence the vegetation, which, as mentioned, was a thin biological 'veneer' that provided most of the function and provided the only barrier between the tailings and the environment. This prompted the investigation of the relationships between soil chemistry, landscape function and vegetation composition.

5.6.2. Soil chemistry, vegetation and survey transects

Canonical Correspondence Analyses were conducted to investigate the relationship between the vegetation at the different sites and the substrate chemistry. For the 2007 dataset, only those variables that were measured for all sites were included in the analysis and were presented in Figure 5.31.

In 2007 (Figure 5.31), the vegetation split into distinct groupings, as in the other analyses (see section 5.5.2 and section 5.6.1). The first ordination axis aligned with most variables and explained most of the data variance (Eigenvalue 0.843). The second ordination axis also explained a significant amount of variance (Eigenvalue 0.631) and aligned most strongly with Mg. The TSF sites clustered in the centre of the ordination, showing that their species composition comprised none (or very little) of the vegetation on other. The TSF's had the strongest positive correlations with Ca, then with pH and then with Na and P. This meant that the TSF sites were all slightly acidic to neutral, had very high exchangeable Ca concentrations and higher P and Na than occurred in the surrounding environment. These higher values were most likely from remnants of the ameliorants and chemical fertilisers added during rehabilitation. The TSF's had negative correlations with both CEC and K, which thus occurred at much lower levels than in the surrounding environment. As CEC is a good measure of soil chemical fertility, it showed the low fertility of the tailings material, even though some nutrients were present in excesses (as per section 5.5). As discussed earlier, one of the symptoms of Ca excess is that it suppresses Mg and K, both of which were in short supply on the TSF's (relative to other base cations).

In 2007, SP was very nutrient poor in relation to the other sites and correlated negatively with all of the soil chemical variables (Figure 5.31). This meant that it had very low concentrations of the base cations, was fairly acidic and had a low CEC, all reflecting the nutrient-poor substrate. The characteristic plant species that were able to tolerate these acidic, nutrient-starved conditions were *P. dilatatum* and *E, elephantina.*

5SB and UFV were different from other sites in 2007 with distinct species associations (as has been discussed relating to previous CCA's) and correlated to some extent with CEC and K, showing their relatively higher levels in comparison to other sites (Figure 5.31). Both sites have substrates consisting of soil as opposed to tailings. The vegetation of the two sites most likely reflected other edaphic variables than chemistry, primarily slope angle.

UFV had lower relative concentrations of the other base cations (Ca, Mg, Na and P) than the TSF's and had slightly lower pH (as per Table 5.11 and section 5.5). The major differences between the chemistry of UFV and other sites was that UFV had lower CEC, Mg and K than 5SB and lower concentrations of all other elements than the TSF's (Figure 5.31). The characteristic species of UFV (as in section 5.2.2.4 and 5.6.1) were *S. sphacelata* var. *sphacelata, Felicia muricata, Aristida junciformis, Melinis repens* and *Liliaceae* sp. These species then apparently did not require high concentrations of the measured chemical elements or neutral acidity and that there were most likely other edaphic or ecological variables that constrained their colonisation of the TSF's.

5SB also had lower relative concentrations of base cations than the TSF's in 2007 but had higher K, Mg and CEC than UFV and the TSF's (Figure 5.31). However, one site, 4N2, had higher Mg concentrations in 2007 (Table 5.11) but interestingly Mg had decreased considerably on 5SB in 2008. 5SB was also generally more acidic than the TSF's in 2007 and showed negative correlations with pH. These associations link well with the findings in section 5.5. In 2007, the characteristic species on 5SB were *E. lehmanniana, E. biflora, H. contortus, M. nerviglumis, I. comosa, A. stipitata* and *U. trichopus*, as seen in section 5.2.2.3

and section 5.6.1. The species associations suggested that those characteristic species in 5SB required higher CEC and K to grow and thus would not survive in the lower nutrient soils of the other sites.

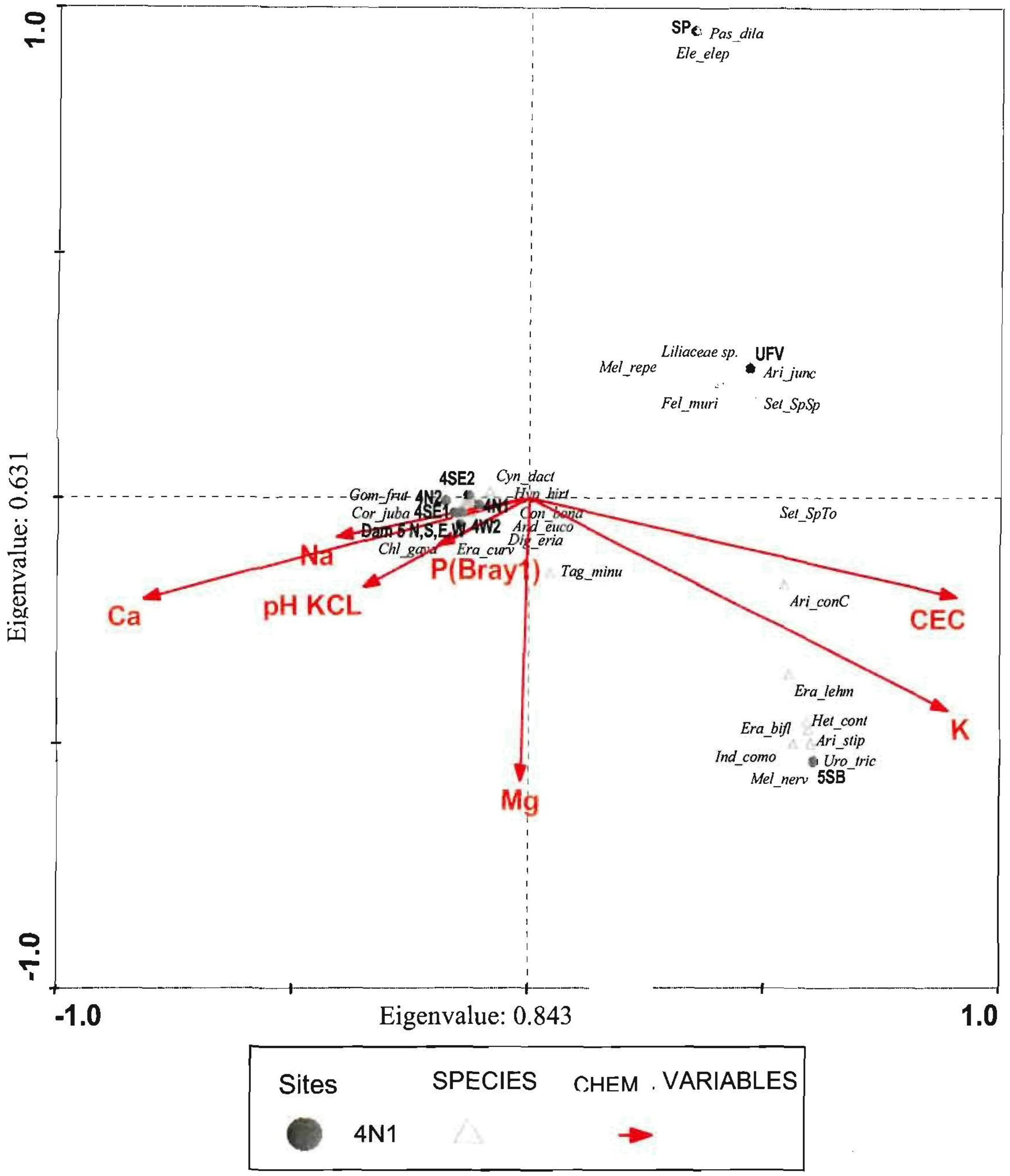

Figure 5.31. Canonical Correspondence Analysis (CCA) of the 2007 vegetation composition and soil chemistry data of all sites. Site names and abbreviations are explained in Appendix A and chemical symbols are explained in Appendix B.

The 2008 data were presented in Figure 5.32. In the 2008 ordination, all of the variables that were measured for all sites were included, except for NO_3, which correlated exactly with NH_4. The larger set of variables was thought to have given a clearer indication of the relationships between site-species associations and the chemical variables that caused them. The first ordination axis again accounted for a large portion of the variance in the 2008 data (Eigenvalue 0.843) although the second ordination axis also explained a significant amount of variance (Eigenvalue 0.637). Organic C, CEC and K had strong positive correlations with the first ordination axis, NH_4 (and thus NO_3) had a strong positive correlation with the second axis, whilst the remaining variables were strongly associated with the TSF sites (Figure 5.32).

As in 2007, the 2008 vegetation and chemistry split the sites into distinct units. The TSF's clustering in the centre of the graph and showed positive relationships with the first ordination axis. SP had a strong positive relationship with the second ordination axis. UFV and 5SB, however, were not strongly correlated with either axis and showed greater affiliation with specific species and chemical variables that will be discussed below.

One of the TSF sites, 4SE1, fell midway between the other TSF sites and SP, indicating that it shared species and chemical characteristics of both sites. The TSF sites generally correlated strongly with the first ordination axis and with the variables Ca and Lime requirement. Ca was again present in excesses and had thus not leached through the profile but was probably occupying what little colloidal surfaces exist in the tailings material through pedogenesis. Lime requirement is a capacity measure of the extent required to combat both the active and reserve acidity of a substrate. All of the TSF sites correlated strongly with Lime requirement and were therefore still at threat of continuous and chronic acidification, which would most likely have a negative impact on the vegetation if the buffering capacity (as indicated by CEC) was not sufficient to combat these increases in acidity. Then there were a group of variables, Na, P, pH and Mg that all had more or less even contributions to expressing the variability between the TSF sites. This meant that all values were also rather high in relation to values from the natural environment. Although these values were high, previous discussions have shown that the ratios in which these elements occur on the TSF's was too low in relation to Ca, which reduced uptake or availability of the elements. pH had positive correlations with most TSF sites, indicating that at least their current acidity levels would not immediately cause vegetation senescence. Only 4SE1positioned itself sufficiently far away from the pH gradient to be of concern, and this was reflected by the values of 3.6 in Table 5.11. The CCA ordination showed that *C. dactylon, Digitaria eriantha* and *E. curvula* occurred in higher densities on transects with lower pH, indicating a tendency for tolerance of moderate levels of acidity. The TSF's associated negatively with K, CEC and organic C, whilst NH_4 (and therefore NO_3) was evenly low in all TSF sites. The negative association with K was most prominent in 4SE1, 4N2 and 5W1, the three sites that had the lowest vegetation cover (as shown by their low LOI and patch dimensions in section 5.3.2 and Table 5.3). This supports the notion that K is primarily cycled through leaf litter and only available in a bio-organic fraction. This was supported by the low levels of organic C occurring on these sites. The low levels of organic C and low CEC were good indicators of just how poor the buffering capacity and nutrient status of the tailings was in relation to the surrounding environment.

SP showed very similar trends in vegetation and soil chemistry to 2007. The site again had a positive correlation with the second ordination axis, but in 2008 it became evident that this was driven by high levels of NH_4 (and therefore NO_3), combined with low levels of everything else, whereas in 2007 (when NH_4 and NO_3 were not measured) it was shown to be just because of low levels across the board. Although the origins of the high N levels could not be directly established, the presence of both forms may have indicated the workings of *Nitrosomonas* and *Nitrobacter* bacteria that were able to oxidise NH_4 to NO_3, although this would need to be confirmed by measuring the changes in their relationship as well as NO_2 in future as well. Fortunately, SP correlated negatively with both pH and lime requirements, showing that although the site was moderately acidic, it did not require large volumes of ameliorants to rectify. The species associations remained largely unchanged, with just the abundances of *P. maximum* increasing significantly in 2008.

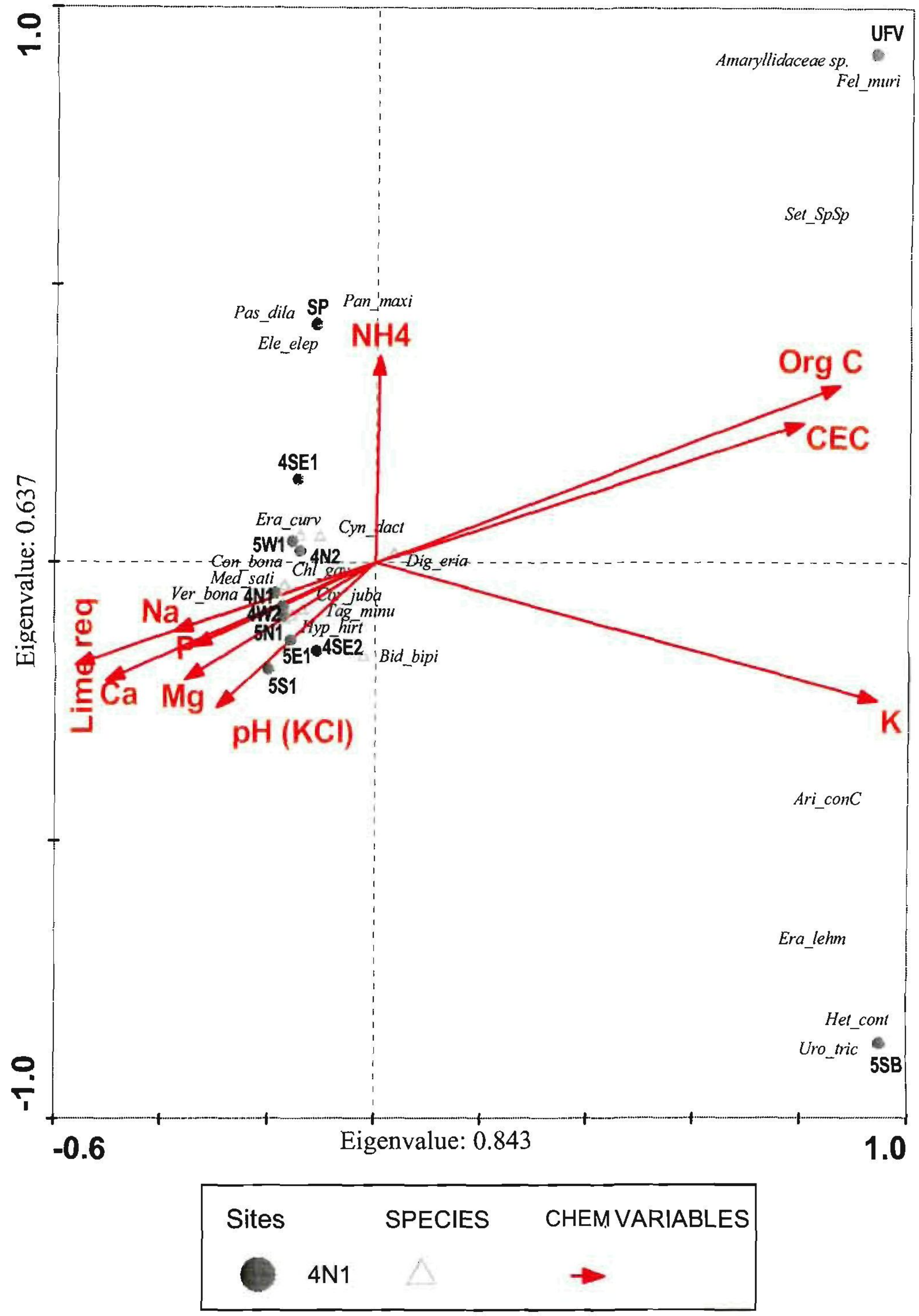

Figure 5.32. Canonical Correspondence Analysis (CCA) of the 2008 vegetation composition and substrate chemistry data of all sites. The site names and abbreviations are explained in Appendix A and the chemical symbols are explained in Appendix B.

The UFV and 5SB sites again clustered out separate from the other sites and highly distinct from one another, caused by their discrete species and substrate chemistry associations. Both UFV and 5SB were almost equidistant from either axis, showing that neither a single element nor a group of variables were able to explain the relationships between substrate chemistry and vegetation. However, CEC, organic C and K were more strongly associated with these sites (according to the first ordination axis), as were lower levels of pH, the other base cations and lime requirement. Organic C and CEC, which had a very good relationship, were slightly higher in UFV, whilst K was slightly higher in 5SB. NH_4 was no more than auxiliary in explaining the variance between sites. Although these sites had low pH, they also had low lime requirements, coupled with high buffering capacity thanks to their higher CEC and organic C. This resulted in well-balanced, reasonably fertile soils that were able to withstand harmful chemical changes. The vegetation associations were different, with 5SB being characterised by *U. trichopus, H. contortus* and *E. lehmanniana,* whilst UFV was characterised by *Liliaceae* and *Amaryllidaceae* sp. and *Felicia muricata. A. congesta.* subsp. *congesta* occurred in slightly higher densities in 5SB than in UFV and *S. sphacelata.* var. *sphacelata* occurred in higher densities in UFV.

5.6.3. Substrate chemistry, landscape function and survey sites

The patterns that emerged from the LFA and vegetation ordinations gave insight into the role that vegetation played in relation to dictating landscape function, especially on the TSF slopes. Then the ordinations of vegetation and soil chemistry further explored the links between the chemical variables that affected the distributions of plants. Soil chemistry was examined together with LFA variables, to establish whether there were any relationships between the two that would cause a certain set of chemical characteristics to bring about changes in landscape function. The links between vegetation and how it was affected by soil chemistry would certainly bring about changes in landscape function, but displaying them simultaneously in multivariate space is incredibly complex. Therefore certain inferences must be made on the basis of each ordination result.

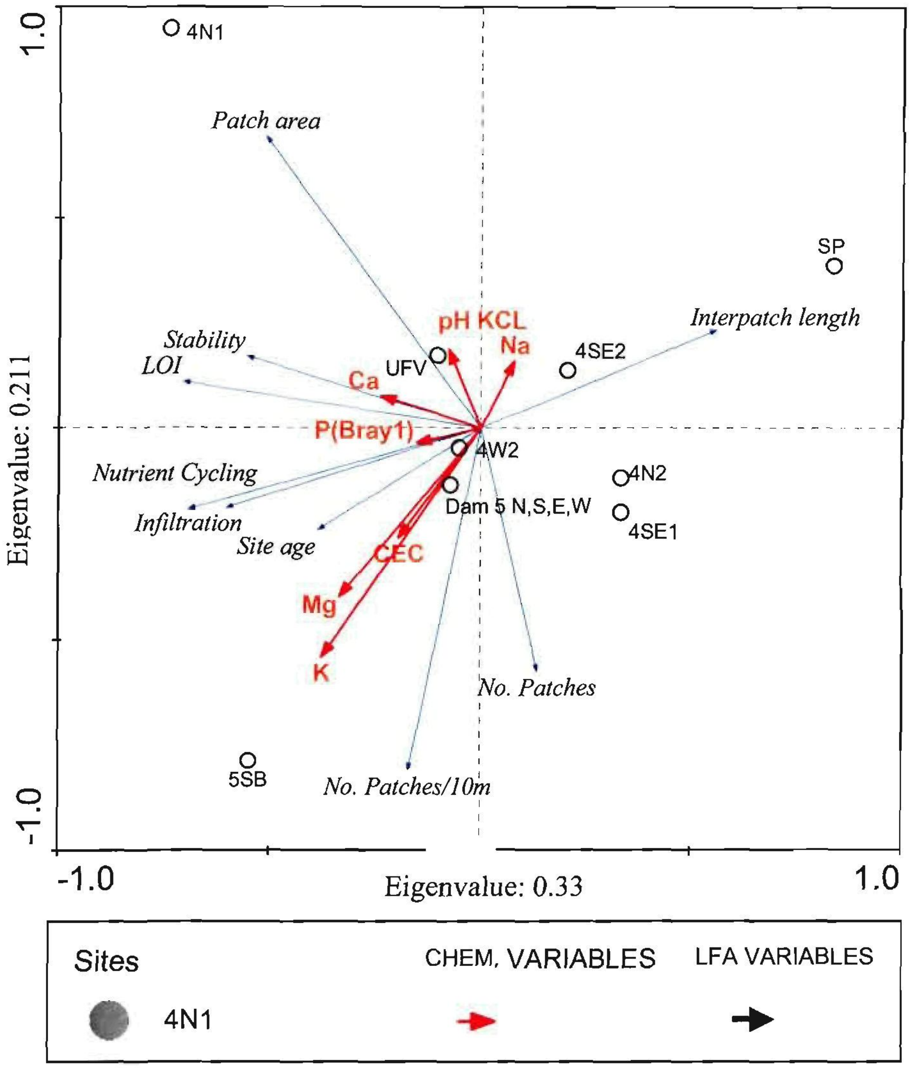

Figure 5.33. Redundancy Analysis (RDA) of the 2007 LFA and substrate chemistry data. The site names and abbreviations are explained in Appendix A and the chemical symbols are explained in Appendix B.

For 2007, the relationships between LFA variables, substrate chemistry and survey sites was explored making use of Redundancy Analysis (RDA) and the ordination diagram depicted in Figure 5.33. The first axis explained some of the variation in the 2007 data (Eigenvalue 0.33) but the second axis also explained a lot of variation (Eigenvalue 0.211), cumulatively explaining 76% of the species (LFA variables) to environment (soil chemistry) variance, but only 54% of the survey site-LFA variance. Therefore, all variables, regardless of the axis-associations, were used to explain the relationships.

The sites had high variance when compared to the other ordinations. The TSF's were clustered around the centre of the ordination (except for 4N1) but the TSF's and particularly SP and UFV did not have as strong negative correlations as in other ordinations. 5SB separated out distinctly from the other sites, as did 4N1.

The less functional sites, SP, 4SE1, 4SE2 and 4N2 (as per Figure 5.7), all fell on the right of the second ordination axis and had positive correlations with interpatch length and negative correlations with the LFA indices (Stability, Infiltration and Nutrient cycling), LOI and site age (except for 4N2, which responded to variation like the younger sites). These sites also had positive correlations with Na and negative correlations with CEC, Mg, K, and, to a lesser extent, P. This meant that the younger, less functional sites were 'leakier' and tended to have lower CEC and K, with lower than required ratios of Mg and higher Na.

There was then a group of TSF sites that had slightly higher function (4W2 and Dam 5), clustering towards the centre of the ordination, although it would appear that they had lower relative Na and shorter interpatches. This meant that moderately functional sites tended to have shorter interpatches, better cation ratios and a larger number of smaller patches.

4N1, although not a lot more functional than some of the other sites, aligned well away from other sites because of its primary relationship with patch area and strong positive correlation with number of patches. Its position in the ordination was not necessarily reflective of its chemical segregation, although it did have higher pH, Ca and N concentrations than other sites. It would be too much of a generalisation to draw conclusions from this extreme site and say that sites with large patch areas would have lower Nutrient cycling and Infiltration but better Stability because of higher pH, Ca and Na levels.

The differences between UFV and 5SB were not well explained by this ordination, as one of the major chemical variables that separated them from other sites, organic C, was not measured in 2007. CEC and K had very high inflation factors in the analysis and therefore no accurate conclusions could be drawn. However, the 2008 data were more comprehensive and reduced the inflation factors for these variables from 8671 to 237 and from 5719 to 121 respectively. Whilst these were still higher than generally accepted values, they were better able to give an indication of relationships between substrate chemistry and landscape function.

The 2008 LFA and substrate chemistry relationships were presented in the RDA in Figure 5.34. As mentioned in section 4.5, surveying was more comprehensive in terms of the higher number of chemical variables analysed and the increased resolution of sampling on Dam 5. The relationship between the axes was similar for both years with the 2008 ordination's first axis (Eigenvalue 0.338) explaining slightly more variance than the second axis (Eigenvalue 0.255). Although these were only sufficient to explain 59.3 % of the variance in LFA variables, they were able to explain 75.1% of the variance between LFA variables and substrate chemistry.

The spread of sites was more intuitive in 2008 than in 2007, due to the stratified units separating out from one another. This was as a result of inflation factors being much lower for all variables. The landscape function rehabilitation gradient observed in previous analyses (section 5.3.4 and section 5.6.1) was also present in this CCA ordination (Figure 5.34), running from the bottom left of the ordination to the top right. The gradient was again related to positive correlations between the LFA indices (Stability, Infiltration and Nutrient cycling) and LOI, which together had strong negative correlations with Interpatch length. This gradient did not correlate particularly strongly with sites age, but, as mentioned in 5.6.1, this was due to the uneven age distribution of sites. The least functional sites (SP) (as per Figure 5.7) correlated positively with Interpatch length and the gradient ran along sites with increasing function until reaching the most functional site (4N1). Both SP and 4N1 tended to correlate more positively with the second ordination axis than the first. The remaining TSF sites were then clustered along the gradient according to their relationships with function and substrate chemical variables, which are discussed below.

SP was the site most characterised by long interpatches, fewer and smaller patches, low LOI and low LFA index values. In 2008 there were no specific chemical substrate characteristics that had strong positive correlations with SP, other than its nutrient concentrations were always lower than all the other sites and it tended to have the lowest pH values.

The next, least functional group of TSF sites, 4SE1, 4SE2, 4N2 and 5S1 (as per section 5.3.2 and Figure 5.3) had weak positive correlations with number of patches, patch area and interpatch length. This indicated that they had a higher number of larger patches than SP, but these patches were not as numerous nor as large as the more functional TSF sites. These sites also had shorter interpatches than SP, but had higher LOI and LFA index values. Important here were the relatively low values for pH, lime requirement and base cations (excluding K) and the very low values (as indicated by the negative correlations) for K, CEC and organic C. These chemical characteristics were thus features of these intermediately functional sites.

The more functional TSF sites, 5N1, 4W2 and 5W1 (as per section 5.3.2 and Figure 5.7) had negative correlations (and thus low levels of) with K, CEC and organic C, although higher pH levels and better ratios and concentrations of the other base cations. The differences between the more and less functional TSF sits were structural, rather than functional, with better functioning sites having positive correlations with patch area and number of patches, thus more, bigger patches and higher LOI (and thus lower interpatch lengths). This suggests that those sites that were developing in landscape function and spatial pattern were constrained by the absence of decomposing organic matter, as it would provide K, CEC and organic C required to positively influence vegetation performance and thus landscape function.

The 5W1, 5E1 and 4N1 sites were the most functional TSF sites with the strongest positive correlations with Patch area, LOI, the LFA indices, pH, Ca, Mg, Na and P (Bray 1). This meant that not only did these sites have the highest index values for landscape function, but they also had the best organised and biggest patches, coupled with the highest nutrient concentrations. However, they were negatively correlated with CEC, K and organic C, meaning that their apparent "fertility" was more as a result of over-fertilisation than actual and sustainable substrate processes.

The UFV and 5SB sites were similar in function and chemical composition in 2008. They were older sites, had strong positive correlations with K, CEC and organic C, lower pH and lime requirements, and generally had marginally fewer, smaller patches than the TSF's. What most distinguished them from other sites were their lower base cation values (except for K, which they have more of than TSF sites) due to their never having been fertilised. The specific chemical differences between these sites is the same as in section 5.5 and section 5.6.2 and the greater discerning factors between these sites is therefore their landscape function and not their chemical composition.

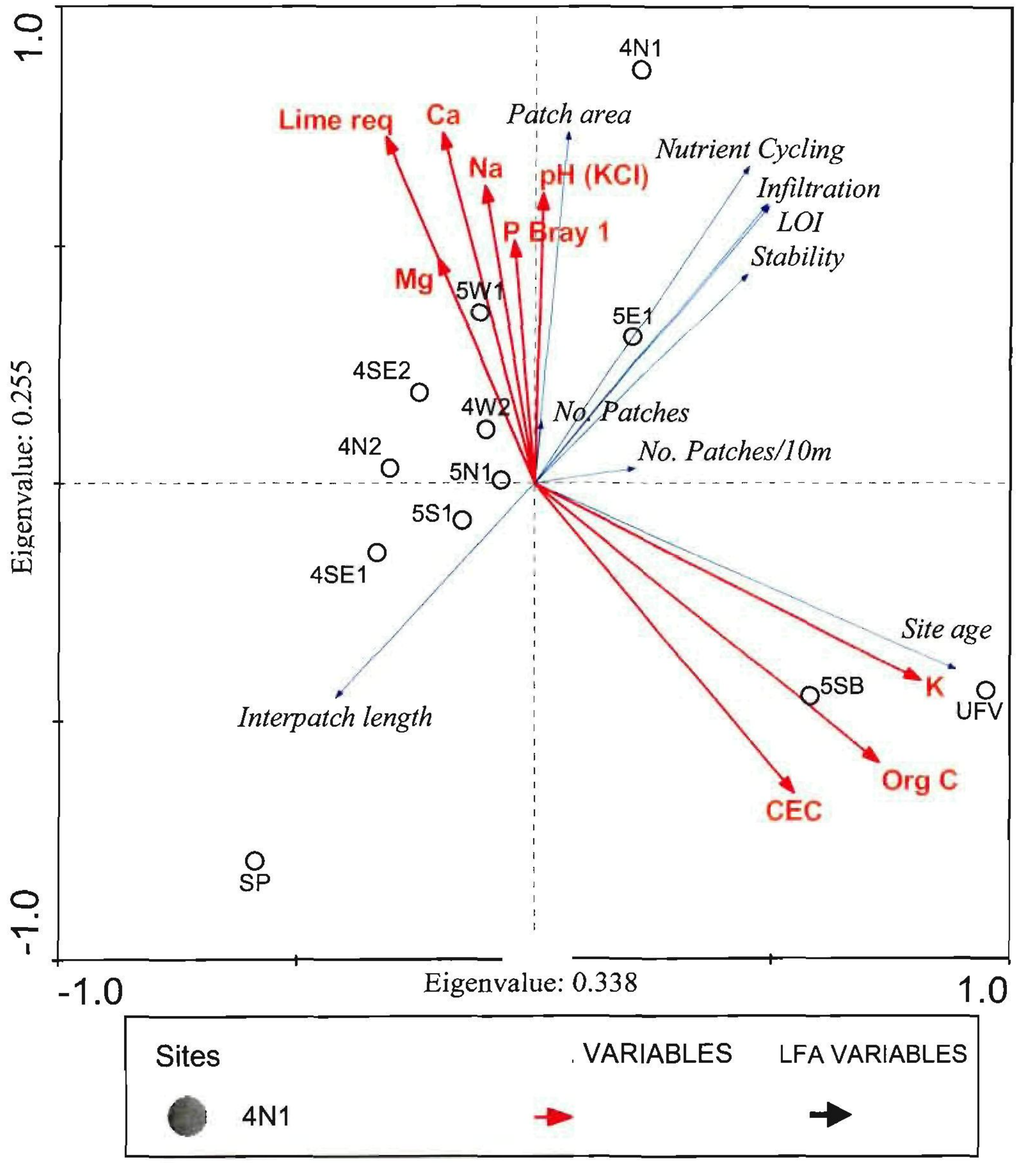

Figure 5.34. Redundancy Analysis (RDA) of the 2008 LFA and substrate chemistry data. The site names and abbreviations are explained in Appendix A and the chemical symbols are explained in Appendix B.

This RDA ordination thus showed that organic C, CEC and K increased sharply as site age increased, with patch density increasing less so, but coupled with a decrease in interpatch length. Therefore, the higher the LOI, or proportion of 'fertile' patches, the shorter and smaller interpatches became, the more landscape function increased, accompanied by increasing K, CEC and organic C levels. The ordination also showed that whilst landscape function did not necessarily depend on high concentrations of base cations, they could be beneficial in the correct ratios to aid in biomass production (as reflected by patch area and LOI) and thus enhanced spatial organisation. Similarly, high landscape function, as occurred on some TSF sites, did not depend on organic C, K or CEC, although the constant threat of increasing acidity (as reflected by the high lime requirements of TSF sites) required these to be present to aid in buffering the substrate against acidification.

5.7. Evaluating monitoring outputs

Whilst the rest of the results and discussion so far have focussed on directly examining relationships between the LFA indices and either substrate chemistry or vegetation composition, the precision of either type of monitoring data has not yet been explored. Figure 5.35 showed the relationship between the measure-outputs of the two main monitoring techniques: species richness and combined landscape function. Because of the different scales of data measurement, the natural logs of all values were used as the basis for comparison. Species richness was equated with β-species diversity as it is a measure of total number of species within a site.

The spillage site (SP) had the third lowest β-species diversity (section 5.2.1 and Figure 5.35), with only the two North-facing slopes of Dam 4 having less plant species. 4N1 was one of the most functional landscapes but had the lowest species richness (almost a monoculture of *C. gayana*) and 4N2 was one of the least functional landscapes and also had very low species richness, indicating that the relationship between species richness and landscape function was certainly not linear (as per section 5.6.1). Predictably, the UFV sampling unit showed the greatest species richness and, narrowly followed by 5W1, a sampling unit that fell midway on the functionality continuum (Figure 5.7). 4SE2 also had surprisingly high species richness in light of its poor functionality and the species that made up its richness were mostly perennial plants. Ultimately, Figure 5.35 indicated that sites with relatively healthy species richness were likely to have some degree of landscape function, but that the reverse was not always true. Some sites had high richness and relatively low function, such as 4SE2, whereas other sites had low richness and high landscape function, such as 4N1. Poor β-species diversity is most often an attribute of fallible systems as the ability to withstand biological invasions and to regenerate following disturbance is very low. Therefore whilst some TSF sites were highly functional, their persistence and resilience were questionable.

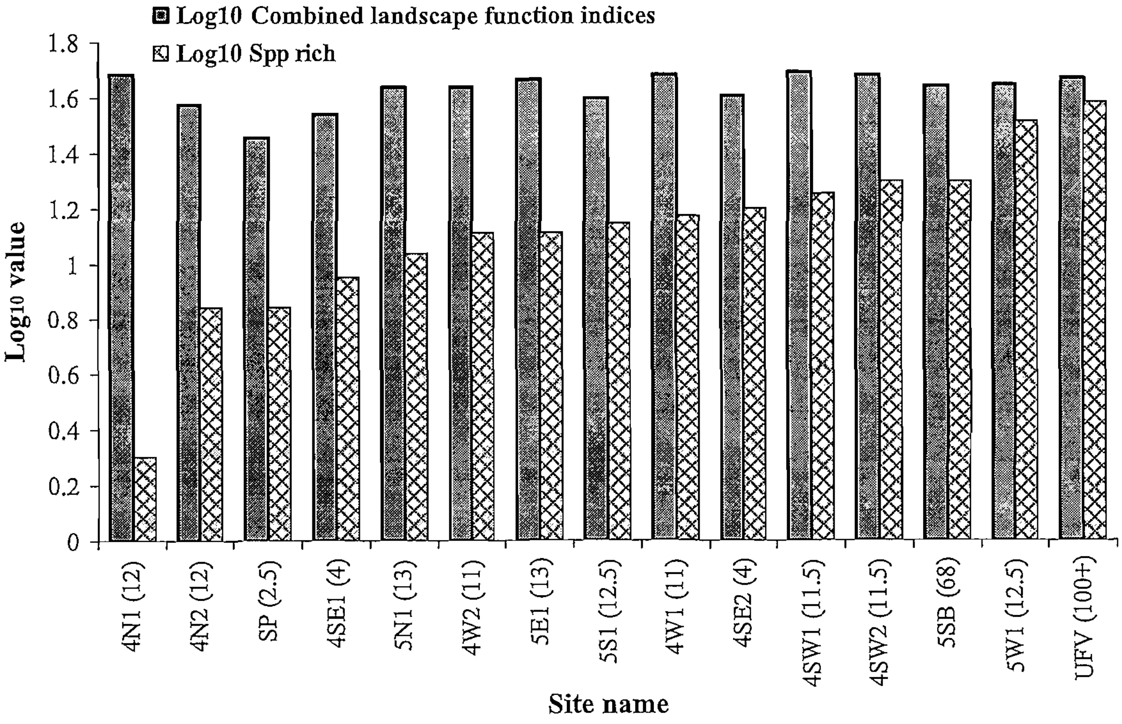

Figure 5.35. Log_{10} values of the species richness (β-diversity) of each site, plotted against the Log_{10} values of the combined LFA indices (Stability, Infiltration and Nutrient cycling). The values in parentheses indicate site age and the site names and abbreviations are explained in Appendix A.

It is highly unlikely that any 35° TSF slope would have better Stability than an undisturbed, flat, natural grassland over the long-term. These high stability values on some TSF sites are highly dependent on the persistence of the vegetation cover. It is therefore vital that cover be maintained and stochastic disturbances be kept minimal until further research on the site has concluded that the more functional TSF slopes have a suite of vegetation that is able to recover from e.g. fire without leading to erosion. It is also important to remember that LFA assesses Stability only in the top few centimetres of tailings, and that sub-surface processes, such as capillary rise of an acid or sodic head or sub-surface erosion (commonly called 'rat-holes') must also be monitored for to prevent vegetation die-off. This may call the long-term sustainability of the site into question, but if latent threats such as increased surface acidity through pyrite oxidation can be addressed, then it is believed that Stability may not be a future issue. However, it must be added that there is a proviso that a stable and self-perpetuating vegetation community that is tolerant to the on-site conditions (and fluxes therein) must be established (as per Weiersbye *et al.*, 2006).

The broad aims of this study were to assess how the substrate chemical development was taking place on the different TSF sites and how this would in turn influence their capacity to sustain a functional vegetation cover. Ultimately, the monitoring outputs were well suited to examine the required relationships and enumerated the differences between sites, highlighting which required management intervention for their persistence. It was found that chemical instability (especially acidity and salinity) in some sites (4SE1, 4SE2, 4N2) was causing vegetation senescence, which decreased the function of the landscapes and thus nett outflow of resources. These sites were certainly not sustainable and especially vulnerable to stochastic disturbances. Other TSF sites were of less immediate concern in terms of vegetation senescence due to acidity and salinity (5N1, 5E1, 5S1, 5W1, 4N1 and 4W2) but close monitoring is required to establish whether and when intervention will be required. In the long term, closure is the ultimate goal of this site. The MPRDA requires that the end land-use designation of a site must conform to sustainable development principles. Based on the outcomes of this study, monitoring these sites for a much longer period (preferably ten years or more) will be required in order to demonstrate that the designated end-use will be sustainable.

Chapter 6. Conclusion and recommendations

6.1. Introduction

The self-sustainability of mine waste stockpiles such as TSF's and Waste Rock Dumps is a long-term and recurring problem in the South African mining industry that is seldom proactively addressed at large scales. Whilst there are programmes aimed at initiating sustainable solutions to ensure the perpetual stability of residue deposits, there is a lack of industry commitment in some sectors regarding closure planning which is hindering these attempts. There may be many reasons for this: lack of legislative enforcement; ignorance; poor regulation; inadequate funding; lack of protocol and precedent; or a combination of these and other factors. Ultimately, the prevailing TSF construction, amelioration and environmental management systems have not yet been able to demonstrate the sufficiency to support the desired ecosystems that conform to the stipulated sustainable end land-use and that are able to suitably address latent and residual environmental impacts (as per the MPRDA). The Chemwes Preliminary Closure Plan (van Deventer, 2003) is used as the primary reference for assessments and recommendations in this chapter.

There has been a large body of research put forward in the last decade regarding phytoremediation possibilities and the rehabilitation of minesites to the extent that closure can be granted. This research has been local and international, academic and institutional. Some of the research has been driven by mining companies themselves in pursuit of cleaner technologies and the realistic attainment of closure. The proverbial rehabilitation toolbox has expanded and decision-makers have acknowledged the limitations that former actions have had on achieving sustainability. Large mining houses are coming to realise the cost-saving and sustainability of integrated ecological solutions over rigid engineering designs. Data and information sharing have improved and international seminars are held where rehabilitation practitioners, engineers, ecologists, sociologists, regulators and others come together to learn from successful projects and discuss and debate salient topics.

With all of this positive outflow, the near future of minesite rehabilitation is an exciting prospect where the opportunity for mining companies to embrace the latest research could result in closure solutions at the end of mine life. Both locally and globally, the industry is at the brink of implementing new procedures and technologies that could make mine closure a reality, as opposed to the vague obligation it has been in the past. However, it will in all likelihood require innovative companies and protocol to lead the way and set the precedent before the remainder of industry will follow.

The Chemwes TSF complex is undergoing reprocessing of the majority of its tailings dams and the opportunity exists for the tailings material to be treated, stacked and ameliorated in a fashion that will promote sustainability of the structures to the extent that they no longer pose human or environmental hazards. The principles of landscape ecology that were successfully applied at these sites highlight the need for change and the fragility of these TSF systems under current 'command and control' regimes.

In the following sections, the outcomes of the monitoring methods will be briefly summarised to highlight the required management intervention, both for short and long-term rehabilitation success. Then a site-specific, streamlined monitoring plan will be proposed to enhance the efficacy of data into relevant management information and understanding the role that vegetation plays in creating and maintaining landscape function.

6.2 Vegetation surveys

The vegetation on the TSF's is part of a thin biological cover that represents the only barrier between the hazardous tailings material and the surrounding environment. However, this biological cover does have the potential to suppress many environmental impacts such as tailings dust generation and surface and groundwater pollution. It is also able to decrease the visual impact of these TSF's that are an alien feature of the highveld grasslands. Persistent and functional vegetation cover is therefore crucial in maintaining ecological processes that provide stability to the TSF structures and the spillage area.

The Chemwes Preliminary Closure Plan (van Deventer, 2003), stipulates that the objectives of rehabilitation on the TSF's and spillage site are to establish a self-sustaining vegetation community that is able to minimise environmental impacts. The monitoring conducted throughout thus study was aimed at assessing the capability of the introduced vegetation to provide ecosystem functions through sustaining itself and facilitating natural colonisation of other tolerant species.

The vegetation surveys provided valuable information on the performance of introduced (initially planted or introduced in the form of seed) vegetation and also showed the potential for tolerant species to naturally (without human intervention) disperse to and colonise the TSF's. A total of 39 species had naturally colonised the two TSF's, of which most were observed producing propagules, indicating their tolerance of often acidic and saline conditions and their propensity to establish local populations. These species should be encouraged wherever possible, as the distributions showed that colonisation was very localised (overlap of only 19 species between the two TSF's). Some of the species, such as *T. chinensis* and *C. jubata,* were introduced before the amendments to CARA (Act 43 of 1983) classified them as invaders that were legally required to be controlled. Whilst *T. chinensis* was recorded on the TSF's it was highly likely that *T. usneoides*, an indigenous form, also occurred and was overlooked due to confusion with *T. chinensis*. The opportunity now exists for local, resilient, hardy phenotypes that naturally occurred on the TSF's (as per Appendix C) to be selectively reproduced and introduced onto the tailings. This could result in a vegetation cover that is able to form stable islands of fertile patches that have the potential to persist and procreate into virtual perpetuity. The importance of specific patch types, as identified by the LFA landscape organisation showed that woody species, especially the indigenous *Stoebe vulgaris* (name has recently changed to *Seripheum plumosum*), *R. pyroides* and *R. lancea* can contribute enormously to landscape function and create microhabitats for other species to colonise. Therefore these woody species could also be intentionally introduced during early rehabilitation by planting in plausible patterns and densities.

Whilst proactive introduction of tolerant species' populations should form an integral part of managing these TSF's in an attempt to one day prove sustainability and achieve closure, the factors that hindered sustainable vegetation establishment of the introduced species could also be elucidated from the analyses. Firstly, the patterns of species development in terms of number and complexity were not consistent either over space or over time. The 13-year old sites had lower species richness than 4-year old sites, which were both lower than the 11-year old sites. This showed that the complexity of species composition and richness was a symptom of management, ecological and substrate chemical processes. Secondly, there was no real consistency with aspect, as even similarly-aged sites on the same TSF showed vastly different levels of species composition and cover/density. This also indicated that whilst aspect may have been important, it was overshadowed by topographic and substrate variables with more influence.

Results of the multivariate data analyses showed that vegetation was limited by increasing levels of acidity and salinity and shortages of K, problems that were likely to escalate on both TSF's. The excess levels of most base cations introduced through initial fertilising had not yet become incorporated into cycling processes and this slower turnover suggested impoverished soil microbial communities. It was also reflected by the poor CEC and organic C levels of all tailings, regardless of age post-revegetation. These were indicators that the substrates had insufficient buffer capacity to cope with the increasing acidity that would cause senescence of introduced vegetation species such as *C. gayana, M. sativa* and *H. hirta*. The increasing salinity was also identified as a potential problem for vegetation persistence and the intentional introduction of halophytic species may be required as a medium-term intervention to remove excess salts and continue the dust suppression and erosion control function of the vegetation.

Results of the multivariate data analyses also showed that vegetation responses to chemical conditions were essential in maintaining landscape function, especially Stability and Infiltration. Whilst individual species were not important, growth form was as woody patch-types (WLP, SP and TP) were more functional than the herbaceous patch types (GP, GLP, SGP, HP and PP). There were no particular species that were always associated with high landscape function, including the woody species, as they never occurred in great enough densities to be significant.

Therefore vegetation sampling, whilst giving a good indication of the how short-term fluctuations in environmental conditions changed, was not able to elucidate process changes on its own and required investigations of substrate chemistry and landscape function. Whilst the vegetation surveys showed some sites to be relatively "healthy", substrate chemical monitoring and LFA analyses showed that this was not always the case. The analyses highlighted the importance of tolerant indigenous plants and the spatial patterns of these plants. In order to assist vegetation persistence and to maintain the high levels of function that it can contribute, management interventions will be required and are suggested in sections 6.5 and section 6.6.

6.3 Landscape Function Analyses

The LFA analyses presented a clearer picture of the processes that shape and maintain the TSF's. The composition of patches and interpatches and the relative contributions of these to overall landscape function were well discerned from the data. It was established that vegetation played the greatest role in maintaining landscape function on the generically 'leaky' TSF slopes. The patterns that were found on the flat areas were consistent with the slopes, as Stability, Nutrient cycling, Infiltration, LOI, patch area, interpatch length, number of patches and patch density were important in all habitats.

The indices that separated the more functional from the less functional sites were Infiltration and Nutrient cycling. Stability was less variable than the other indices, most often being equally poor across sites. The indicators that contributed most to Infiltration and Nutrient cycling (and that were variable between sites) were litter cover and degree of litter decomposition, perennial plant cover, cryptogam cover and microtopography. This emphasises that monitoring landscape function is essential and that vegetation monitoring alone is insufficient to develop a predictive understanding of ecological responses. These indicators, but predominantly litter and perennial vegetation cover, had the greatest variance between the most and least functional sites. This indicated their importance in contributing to the ability of a site to sustain the ecological processes necessary for ecosystem persistence. Therefore, this also indicated that (1) increasing perennial vegetation cover and (2) increasing litter deposition and breakdown, perhaps through mowing moribund swards, were key rehabilitation objectives that needed to be addressed through management actions. An alternative to mowing to achieve (2) may involve active rehabilitation in planting tolerant herbaceous and woody species to accomplish a more rapidly developing plant community and thus attaining higher quality litter. The higher quality of woody (including dwarf shrubs and non-graminoid herbs) litter in terms of its contribution to landscape function was shown by the high indicator values for Stability, Infiltration and Nutrient cycling.

The importance of litter was highlighted by highly functional, natural brush-packs that accumulated even more transported litter and seed and created positive microclimatic conditions for colonising species. These were the most functional patch types on the TSF's and had one of the highest degrees of litter incorporation into the soil, which boded well for pedogenesis, a process that is very slow on tailings material.

The influence of stress and disturbance was also learnt from studying landscape function on the TSF's. There were multiple stressors for the vegetation that supported landscape function, such as increasing acidity/salinity (see section 5.5) and indiscriminate herbicidal applications (see section 5.2.2.1, section 5.3.1 and section 6.3). These stressors had negative impacts on vegetation cover and functional responses, although the stressors fortunately never occurred at the same sites. Those sites that were sprayed for alien plants were incidentally the sites with the highest alkalinity, so the effects of multiple stressors were not compounded during the study period and could not be observed in the short, two-year timeframe of this study. However, disturbance factors such as fires were also observed during the study period and their interactions with stressors yielded different vegetation, and thus different functional, responses. The sites that had been subject to both injudicious herbicidal applications and fire were very slow in recovering and in some cases were either just maintaining function or slightly declining. The major driver here was poor perennial vegetation cover that yielded low stability and increased the susceptibility to erosion. Those sites that had only been subject to herbicidal applications had lost live biomass but the litter had not been lost and was therefore enhancing Nutrient Cycling and Infiltration. Similarly, those sites that had only been burnt were showing some signs of recovery but the low litter production (due to low live phytomass) and retention (due to poor patch size and pattern) were already showing signs of decreasing LFA index values. It is important to note that the sites that were only burnt or only treated with herbicide only fell below the critical threshold levels for stability, whereas the sites that were subject to stressors and disturbances had problems with all functionality indices.

Those sites that fell below the critical threshold values require, as mentioned, some management intervention to reach the point where they start to become self-sufficient. It is important to design this maintenance in such a way that it does not become a recurrent requirement to maintain function, but is rather a 'kick-start' to facilitating process development. This will allow ecosystem goods and services to develop to the point where the

TSF's are self-sufficient and to contribute to the retention and recycling of vital resource economics.

It appeared that throughout, landscape function variables were increasing on the TSF's over time, and that the limiting factor of interpatch length was decreasing. However, some of the oldest sites (4N2 and 5S1) did not fit this pattern entirely and were classified in amongst the younger, more dysfunctional sites. It is hypothesised that either amelioration at these younger sites was less effective or that the combined influences of early stressors and unrecorded disturbances has resulted in low landscape function. There is danger that the other older sites that are currently showing high functionality may well follow the trends of these less functional older sites into regression over time. The results of the multivariate data analyses between LFA and substrate chemistry reflected this, as lowering pH and increasing Na, accompanied with lower base cation concentrations or imbalances, CEC and organic C, were detrimental to landscape function and therefore landscape sustainability. The TSF's did not support the vegetation communities that made the UFV and 5SB sites more functional and sustainable, although this may have been a result of topographical and substrate limitations to the colonisation of the ecological climax species characterising those sites (e.g. *Setaria sphacelata* var. *torta* and *S. sphacelata* var. *sphacelata*).

Therefore, the observed increases in landscape function over time were unlikely to be sustained in the longer term. To sustain the improved landscape function, the required chemical and physical ameliorations to the substrates would be extensive and expensive. It is thus advisable that the tailings material that has been and is currently being reprocessed either be treated or capped. This will prevent the limitations to vegetation establishment and increasing functionality, such as increasing acidity and salinity, from escalating.

6.4. Substrate chemistry

The chemical properties of the tailings were vastly different to the other sites. The physical properties, such as slaking and texture, were also different from the natural soils, although they had very little internal variability. The nutrient status of the tailings was a direct function of the chemical ameliorants added in the form of fertiliser and agricultural lime. This resulted in large cationic imbalances, with K being highly deficient on all TSF sites. However, the remaining base cations did not appear to be leaching from the system or were perhaps being supplemented by limited nutrient cycling. The tailings material also held large acid generating potential with pyrite contents ranging from <1% (Dam 5) to 1-2% (Dam 4), which was further demonstrated by high lime requirements. However, a recent modelling study (Bezuidenhout and Rousseau, 2008) suggests that the outlook for tailings acidity is not as bleak as others may suggest. They propose that whilst the long-term acid generating capacity of most TSF's far exceeds the neutralisation potential, it initiates at the time of stacking and is only rapid for the first ten years, whereafter it slows down. They also propose that the neutralisation potential will only be consumed within hundreds to thousands of years.

The TSF's, although possessing large concentrations of some base cations, showed very low CEC, reflecting that the total colloidal surface area was very low and that most of the cations were thus in solution and not adsorbed. This made them prone to leaching, which, whilst not yet problematic, could become problematic in future. The poor CEC combined with poor levels of organic C showed the tailings' poor buffer capacity to combat changes in pH. Although the soil surface processes were very active and often developing positively on the tailings, the volatile sub-surface chemistry and lack of biological activity resulted in a thin biological 'veneer' suppressing the subterranean threats and supporting most of the landscape function (in the form of vegetation). The substrate chemistry on the TSF's thus showed that tailings is not a good medium to plant directly into, regardless of the amount or extent of soil amelioration. This then supported the call for capping of the structures and introducing a more suitable growth medium, as pedogenesis on TSF's is far too slow to support ecosystem development ahead of the capillary rise of salts or acidity.

The multivariate data analyses result showing both vegetation species composition and landscape function characteristics confirmed that the tailings was an extreme medium for sustained plant growth and therefore landscape function. The substrate chemistry in the surrounding grassland areas (UFV) did not show unusually high levels of any base cations and even had fairly low pH and CEC values. Therefore the natural vegetation occurring in the area (as represented by the UFV site) did not require highly nutrient-rich soils with large amounts of organic matter to sustain the vegetation structure, composition or function. This should be remembered in future chemical fertilisation schemes on the TSF's, once latent acidity and salinity problems have been addressed, as imbalances or excesses can lead to domination of monocultures or undesirable species (van Wyk, 2002).

One aspect of substrate fertility, an important one that requires in-depth further investigation, is soil microbiology. Whilst nematode studies have been undertaken at Chemwes, the results of mycorrhizal-inoculated trial plots have not yet been analysed. Straker *et al.* (2007) found very poor microbial and especially arbuscular mycorrhizal fungi (AMF) associations in gold tailings. It was found that once ameliorative actions ceased, there were sharp declines in infection levels, and once the pasture grass cover failed, all mycorrhizal infections ceased. Another finding was that the lowest infection levels occurred on TSF slopes (as opposed to the tops), largely due to poor vegetation cover and poor organic matter retention due to erosion. However, the three most mycotrophic species that were found growing on TSF's were *Asparagus laricinus, Asclepias fruticosa* and *Cynodon dactylon*. These three species all occurred on the Chemwes TSF's, although *A. laricinus* only at a few of the oldest sites. In essence, the fertility of the tailings depends to a large extent on the microbiological community that can persist in these adverse conditions. Whilst the actual status of microbial populations at Chemwes is largely unknown, the infection levels are expected to be poor. Once biogeochemical issues have been addressed, it may be worthwhile to further investigate the inoculation and ecology of soil microfauna and flora.

6.5. Overall assessments and recommendations

Most of the Chemwes TSF's are currently supporting moderate (5S1, 5N1 and 4W2) to high (5W1, 5E1 and 4N1) levels of landscape function and varying vegetation cover. However, some specific sites (4SE1, 4SE2 and 4N1) are under threat of having the life-support biological 'veneer' cut off by critically unfavourable chemical changes in the top 30cm of substrate causing vegetation senescence. The spillage site (SP) appears to be recovering following removal of most of the spilled tailings and appreciable increases in species richness. However, vegetation cover and density, and landscape function did not increase significantly between years. Cover and function are likely to increase over time, especially if management actions to improve resource regulation are implemented.

The signs point towards the Chemwes TSF's not being able to attain self sustainability, due to biogeochemical limitations that cannot be undone by sporadic management intervention. Tongway and Ludwig (2007) proposed the seral development of recovering or rehabilitating ecosystems as a series of stages in a stepped pyramid (Figure 6.1). In the diagram, the foundation phase is most critical and must be suitably addressed before the stability stage can be entered into. The foundation stage consists of geotechnical issues, such as the shaping and orientation of the landforms, full chemical amelioration and also the preparation of substrates that will be able to sustain the desired vegetation community in line with the end land-use objectives. Likewise, the landscape must first become well-established during the stability stage with increasing species richness and proof that erosion losses are minimal, that infiltration is increasing and that the runon-runoff balance is in favour of infiltration and thus reflects the stability of the landforms. If the geotechnical issues are not adequately addressed during the foundation stage, then the stability stage will not last and the next, sustainability stage, will not be maintained if it does develop.

The Chemwes TSF's are currently between the landscape establishment and maturing landscape stages, indicating that they are somewhere between stable and sustainable. However, the geotechnical stage was not sufficient to be able to support the ecosystem development required to reach the fully functional stage. The substrate chemistry and vegetation responses (and therefore inferred landscape function) in some of the older sites have deteriorated. The initial ameliorants have started being overcome by the latent and residual threats such as increasing acidity and salinity. The existing introduced pasture species are unable to cope with these extreme conditions and will require large-scale intervention to go through the development stages without regression.

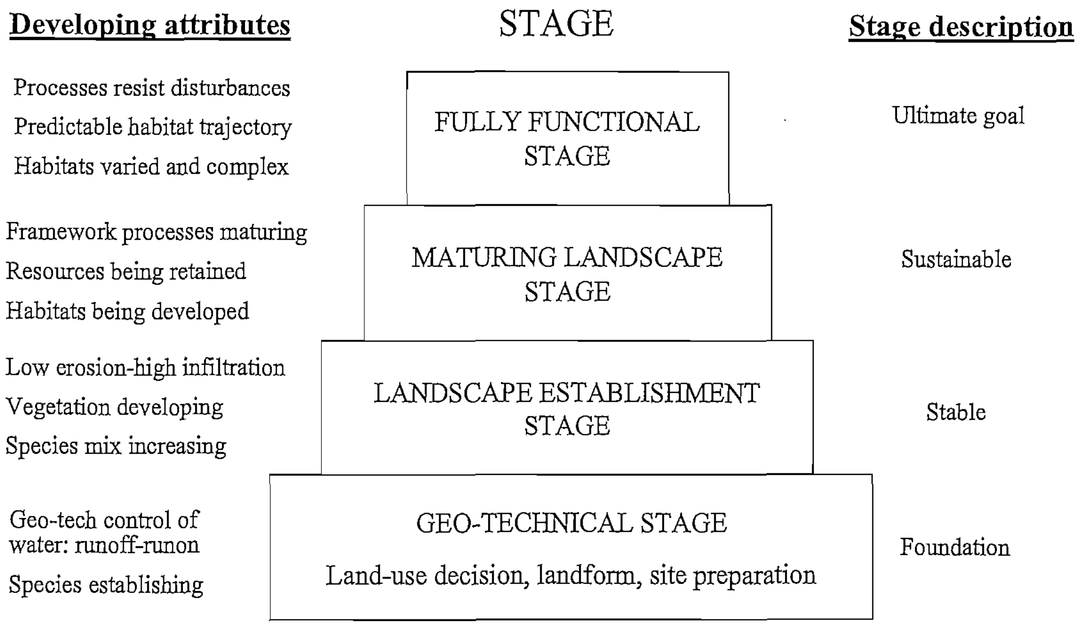

Figure 6.1. Stages required in the rehabilitation of mined sites, giving a description of the sites and the attributes that must be developed inn each stage before sustainable progression can be made to the next (From Tongway and Ludwig, 2006).

The biogeochemical limitations on the Chemwes TSF slopes that were identified during the study and that should be addressed are:

1. Slope angle.
2. Homogeneous substrate texture.
3. Salinity and acidity.
4. Nutrient excesses and deficiencies.
5. Deficient soil organic matter and poor inferred microbiology.
6. Initial species selection and introduction.

The current method of using ameliorated, chemically fertilised tailings as a growth medium to sustain vegetation cover on excessively steep slopes has resulted in the above limitations on the TSF slopes (points 1-6). The fragility of the system resulting from current rehabilitation methods was well-proven when, at the onset of 2008 sampling, scars were still evident where one researcher had walked up and down the slopes a year earlier. The spillage site (SP) will require far less active management as points 1 and 2 above do not apply. There are still acidity problems on the SP site and deficiencies of some nutrients, but the CEC and organic C are higher than on the TSF's. The legislation (MPRDA) requires that the state of the rehabilitation conforms to an end-use based on principles of sustainable development before closure certificates can be issued. Closure is the ultimate goal of all minesites and waste complexes as it releases the company from legal and financial liability. The SP site has the potential, once vegetation establishes and monitoring proves function, for a wide variety of end land-use options, providing all latent and residual pollutant threats are addressed. As they currently are, the TSF's cannot be used for grazing, crop production, conservation, residential development, recreation or industrial use because of unknown heavy metal and acidity threats, as well as the instability and erodibility of the structures. Aside from this, the literature suggests that the vegetation on the TSF's will degenerate, once more increasing wind-borne and water pollution problems. Therefore, in order to achieve sustainability, and thus closure, a holistic and integrated approach must be funded and maintained until monitoring has shown that the system is self-sustaining

To address the limitations above, there are various options that can be considered. These options will vary greatly in cost, dictated largely by the desired longevity of the TSF structures and their efficacy for attaining closure. The less thorough options (that do not necessarily address all of the limitations in points 1-5 above) are likely to have the lowest initial costs but are likely to have the shortest life-span. This makes them 'stop-gap' options that will most likely require higher maintenance and costly repeat implementations further down the line and thus not be sufficient for closure purposes as they will not be sustainable. The more thorough options (addressing most or all of the limitations in points 1-5 above) are likely to initially be far more cost-intensive as they require intensive and consultative design, more expensive materials and the use of earth-moving equipment. However, if designed and constructed correctly, these options will require lower maintenance and should be sufficient to attain closure, thus saving money in the long-term. The maintenance phase should cost less and be less intense than the current method where continuous (rather than sporadic) amelioration, replanting and reseeding will be required.

Three basic options are presented here, numbered A, B and C. The focus in each case is on the TSF's themselves, but in each option the SP site must also be addressed. The route taken for the SP site will be the same in all three options and is addressed after the presentation of TSF options. Option A is the most desirable and has the best chance of standing up to regulators' scrutiny during closure application as it would likely yield the most sustainable vegetation cover and the widest end land-use capabilities as required by the MPRDA. Option B is slightly less desirable but has the potential to result in a self-sustaining vegetation cover that may be able to attain closure, but it restricts the end land-use options. Option C largely involves continuing maintenance with slight improvements on the current rehabilitation methods. It is doubtful whether option C will result in an end-state that could be considered for closure. The possibility also exists for combinations of these three options to be explored. The options (A, B and C) are:

Option A. This option addresses all of the limitations discussed above. Slopes should be flattened to no more than 14° (van Wyk, 2002). This should be attained by increasing the footprint and decreasing total height. During reconstruction, care should be taken to avoid geometric designs and to encourage heterogeneity, which will in turn engender functional micro-habitat diversity. The limitation of this option is that costs will initially be very high, but maintenance costs will be lower and the costs of sporadic reworking will be ruled out.

i. Tailings should not be used as growth medium. The ideal would be to have removed and stockpiled a mixture of topsoil and regolith material from the extended footprint area or borrow pits. This soil mixture should then be used as the upper layer of a store-and-release cover. The cover should consist of a capillary break layer of gravel and fine particles, overlain with the topsoil/regolith mixture. The specific thickness and required compaction of both layers must be determined specifically for the intended materials, following the guidelines of the ITRC (2003). This should preferably consist of lysimeter testing to evaluate the efficiency of the cover to prevent water penetration into the tailings. A well-designed store-and-release phyto-cover will be able to negate polluted runoff and groundwater contamination and thus AMD. Due to the semi-arid climate, clay covers should not be considered and geotextiles should also be forgotten due to excessive costs and poor lifespan. Slaking tests must first be conducted on the regolith material to assess its cohesiveness/dispersion tendency and thus it's suitability as part of the cover. LFA provides a rapid assessment in the Slake Test, scoring the medium's response to rapid wetting rather accurately, indicating whether a soil is dispersive and therefore unsuitable for use as a cover medium.

ii. Salinity and acidity will cease to be problematic if the growth medium is separated from the tailings by an effective capillary break layer. The layer will decrease gas movement and exchange and also prevent moisture fluctuations. This means that anoxic conditions will prevail and that pyrite cannot oxidise to increase acidity. Likewise, the capillary rise of salts would be blocked by the break layer.

iii. Having a more natural substrate in the store-and-release cover and lower potential leaching losses would then necessitate more conservative fertiliser regimes. More important than achieving agricultural fertility levels will be kick-starting the soil microbial activity through introducing and incorporating inoculated organic matter. Host-specific microbes can be introduced when mycotrophic plants are introduced. The soil microbial ecology will ensure more even distribution, better utilisation and enhanced cycling of nutrients, thus more sustainably facilitating soil fertility.

iv. As mentioned in 4 above, soil organic matter is a crucial and often limiting factor in process and biological development. Initially, organic matter should be disked into the upper soil horizon and strewn litter or sludge/mulch mixtures should be protected from aeolian and water removal by installing wind-breaks or holding-pegs. These wind-breaks could either be artificial netting or, more preferably, natural brush-packs secured onto the slopes. If enough woody material can be sourced, the brush packs would immediately enhance landscape function, as explained earlier.

v. The initial species selection for vegetating the TSF slopes should focus on indigenous species that are common on local sites with similar topography. Initially, non-propagating nurse crops can be utilised whilst the facultative second crop is being introduced. The starter wall presents a good array of guide species that were able to persist and reproduce on 35° slopes, such as *Themeda triandra, Melinis nerviglumis,* *Cymbopogon plurinodis, Cynodon dactylon, Heteropogon contortus* and various *Eragrostis* and *Aristida* species. Clones of these species should form the crux of the species selection, but hardy clones are preferred over commercial seed. Woody species such as *Rhus lancea, R. pyroides, Asparagus laricinus, Acacia karroo* and *Stoebe vulgaris* should be vigorously introduced from the beginning as well. This intensive rehabilitation approach will require construction of a greenhouse or plant shelter on site.

Option B. A slightly more intensive but ecological approach would entail selective reproduction and introduction of plant species that are able to tolerate the chemically harsh tailings environment. This approach involves either planting large numbers of commonly available commercial indigenous species directly into tailings (i) or directly making clones of species with proven tolerance and planting them directly into tailings (ii).

(i) Planting large volumes of different readily-available indigenous seeds (such as *Cynodon dactylon, Eragrostis curvula, Chloris gayana, Digitaria eriantha*) directly into tailings in germination, survival and persistence trials. A small percentage of individuals are expected to show higher tolerance to tailings conditions than the rest of the population, representing those that are able to persist in the upper or lower tolerance limits. The surviving cohort can then be systematically 'hardened' through increasing the growth mediums' acidity and salinity. Once the plants have matured, cuttings can be taken or tufts can be divided to create clones. These clones should then be propagated, seeds collected and both planted into the tailings on the TSF's along with a non-propagating nurse crop. This approach would require high initial costs and will initially be time-consuming. If the tolerant plants establish and reproduce, then LFA monitoring can dictate whether supplemental planting will be required. If supplemental planting is not required, then costs and maintenance will sharply decline. It would be highly beneficial to include woody species but this would be even more time consuming, as the plant maturity and life cycles are slow. However, this can be avoided by using cuttings and growth hormones to propagate woody plants. This approach largely negates the impacts of salinity, acidity, nutrient imbalances and the problem of species selection, as raised above. However, it cannot address the limitations imposed by slope angle, homogeneous substrate texture and deficient soil organic matter and microbial activity. These limitations may continue to curtail the establishment of a self-sustaining vegetation cover, and thus closure attempts.

(ii) The other option is to collect cuttings or to divide tufts of indigenous, self-colonised species from the TSF's (or other gold TSF's in the near region) that have been proven (through monitoring) to be able to survive the harsh conditions. These clones can then be propagated and re-cloned until sufficient numbers exist to vegetate the TSF slopes. These clones can be replanted directly into the tailings on the TSF slopes. Species selection will be important and should include a mixture of graminoid herbaceous, non-graminoid herbaceous and woody species. Naturally colonising species that were present in significant numbers across both survey years and that are suitable for such trials are: *Andropogon eucomus, Melinis repens, Cynodon dactylon, Stoebe vulgaris* (now known as *Seriphium plumosum*), *Asparagus suaveolens, Berkheya setifera, Cirsium vulgare, Rhynchosia minima, Rhus pyroides, R. lancea* and *Tamarix usneoides.*

Neither of these approaches requires destruction of the existing vegetation cover. Although this is a more sylvicultural approach, the emphasis is rather on improving plant tolerance to adverse conditions and thus amelioration, irrigation and fertilisation should be kept to the minimum, if required at all. However, introduction of sufficient organic matter and inoculation of VAM fungi and other microbes must be achieved for sustained persistence. These approach still have unknown outcomes, as the extent to which acidity and salinity will increase is unknown, and the vegetation response is also unknown. Furthermore, these approaches will in all likelihood require maintenance and sporadic replanting, especially in initial stages before suitable cover has been established to control erosion.

Option C. This approach is similar to the current rehabilitation and maintenance plans at Chemwes but will require higher levels of introduced and affixed organic matter, less chemical fertilisation and inoculation with beneficial microbial spores.

i. This would involve systematically reworking sites that fell below critical threshold levels for landscape function (4SE1, 4SE2, 5S1 and 4W2) by adding and incorporating seed-rich mulch, brush-packs or sludge over acid-ameliorated and chemically fertilised tailings.

ii. The tailings should be re-ameliorated by incorporation preferably a non-Ca alkalising source such as increasing the organic fraction. This could be achieved by incorporating water treatment sludge, vermicompost, organic compost, treated sewage sludge or various mulches. Increasing the organic fraction of the tailings material will increase the CEC and buffer capacity of the soils and therefore enhance the substrates' ability to withstand acidification. The organic fraction also brings in the much-needed colloidal fraction, absent from pure tailings due to absence of clay-sized particles. Increased colloidal fraction increases the number and area of exchange surfaces and thus better nutrient retention and nutrient cycling. The organic matter must be incorporated into the tailings to prevent its alluvial transport down the steep slopes and thus being lost from the system. The organic matter can be manually disked into the upper portion of tailings and brushpacks can be affixed to the surface with wooden pegs.

iii. Further organic material such as garden refuse, roadside grass cuttings and teff-bales can also be used in brushpacks on the tailings surface and should form nuclei for seed germination by creating microclimatic 'safe zones'. The species selections would ideally contain a larger variety of indigenous grasses but also locally harvested woody and non-graminoid herbaceous plants as mentioned in option B above.

iv. Chemical fertiliser additions should be limited to the addition of Potassium Nitrate (KNO_3). The nutrient cycling capacity of the substrate will have been greatly enhanced by the improved organic fraction and mineralisation of K is likely to occur, thus preventing its loss through rapid leaching of this very mobile nutrient. Nitrate values were very low on the TSF's, compared with the UFV and 5SB sites, and will also be supplemented by the addition of KNO_3.

v. Whilst substrate amelioration will be beneficial in kick-starting vegetation establishment, microbial inoculation of root zones will be essential for persistence of substrate processes, especially pedogenesis and nutrient cycling. The results of the microbial trials currently underway at Chemwes by FAT will prove useful in building upon this recommendation.

This approach may only serve as a short-term solution and it is only advocated on the TSF's if reprocessing is planned for the near future. The vegetation will again serve to reduce dust and decrease erosion and runoff, as in options A and B. This option is likely to be most cost-effective in the short-term, but longer-term maintenance will increase eventual total cost. If the sites that are currently showing healthy landscape function were also to lapse into regression, then they would also require reworking, as discussed here. It must be reiterated that although this approach may establish a vegetation cover that suppresses dust, it will not be able to prevent percolation of all precipitation into the lower tailings material where it will add to the oxidation and increasing acidity. Furthermore, precipitation is likely to be lost through infiltration, which may end up in groundwater sources, or in adjacent areas and drainage lines due to runoff (in contravention with the NWA). Therefore, drainage and cycling of runoff water to a return-water dam will be an ongoing maintenance task. The TSF slopes will also remain fragile to disturbance and there is no guarantee that periodic fires will not negate the rehabilitation efforts through removal of live phytomass and organic material. This then further decreases the land-capability options for end land-use, perhaps restricting it to 'wilderness area', unless innovative means of sustainable options are explored, such as the erection of wind-farms or solar-farms for electricity generation.

Ideally, the SP sites should be cleaned up to further remove the pockets of remaining tailings, as infiltration is low and runoff thus high in this site. This leads to contamination of rainwater (with, amongst others, radionuclide and heavy metal compounds) that either drains into the groundwater or flows towards the Koekemoerspruit, a tributary of the Vaal River. This is in direct contravention of the National Water Act (NWA, Act no. 36 of 1998) which stipulates that any clean water entering a site must leave the site in an unpolluted state. There is also dust generation on the SP site, mobilising some of the remaining tailings material and potentially depositing it over the Stilfontein municipality or even further afield. This is in direct contravention of the National Environmental Management Air Quality Act (NEMAQA, Act no. 39 of 2004). Establishing a functional vegetation cover that is able to retain mobile resources (water, seeds, topsoil, litter), promote infiltration and provide microclimatic 'safe zones' for further seed germination, will be crucial in increasing land capability and thus qualifying the SP site for closure. Encouraging rapid and persistent vegetation establishment will also be the best route to legal compliance. To best achieve this, strategic positioning of 'patches' will be required. These patches could consist of affixed brush packs (analogous to WLP's), affixed seed and topsoil filled seed-bags, half-buried cardboard boxes or even old tyres, all of which would create islands in the site where germination and establishment is promoted. These islands will then serve as source points for dispersal and further resource accumulation. Seeding these patches will be beneficial to early establishment and the inoculation of VAM fungi and actinomycetes in the patches will aid persistence. Further chemical monitoring in the SP site will be important, especially under the introduced patches to establish whether the phytoremediation efforts are successful.

6.6. Future monitoring at Chemwes

The results of this study have shown the importance of using process-based monitoring indicators, such as LFA, and that the structure, function and composition of rehabilitating systems should be looked at both in isolation and simultaneously. It was also shown that the principles of landscape ecology could be used on rehabilitating minesites in South Africa to identify problems and guide rectification. However, it must be reiterated that the different monitoring techniques are complementary and that none can be omitted if the ultimate goal is an incontrovertible case for closure. Therefore, combinations of vegetation sampling, LFA and chemical analyses must be conducted on all sites.

On the basis of the monitoring data from 2007 and 2008, a streamlined monitoring regime for future assessments at Chemwes is proposed (Table 6.1). If no management action is taken to reduce slope angle, cap the structures or introduce tolerant native species (i.e. approach C), then the proposed monitoring regime should serve to give accurate assessments of the state of the rehabilitation and to guide appropriate ameliorative actions (even if closure is an unlikely end-point). If the 'sylvicultural' approach (B) were followed, then the proposed monitoring regime would also give accurate reflections on the state of rehabilitation and it would guide the ameliorative actions required to maintain or regain function where it is lost. However, if approach (A), the capping approach is taken, then the proposed monitoring regime would also be relevant, as it will be able to track ecosystem development and identify potential future problems as well as best methods of addressing them.

It is proposed that the number of replicates can be reduced from five to three in all sites, as internal variance was rather low. Three permanent transects per site should thus be randomly selected and marked. It is further proposed that, due to low variance in patch/interpatch indicator scores, the Soil Surface Assessments (SSA) needn't be performed every year, but that the landscape organisation stage of LFA must. The number of indicators in the SSA will not be reduced, as this would require further technical adjustments to the existing LFA software, and may make the data analysis package less user-friendly. However, texture and slaking need only be measured every five years, as they are very unlikely to change in the short-term. Therefore they can be put into the data entry spreadsheet as constants and thus need not be sampled in field. The proposed monitoring regime should be seen as fixed, but can be adapted to suit the rate of ecosystem development. If approach (A) is selected (decrease slope angle and cap), then monitoring will only be intense initially, whereafter five-yearly assessments should be adequate to eventually prove to regulators that ecosystem development is taking place as required. This may even lead to partial bond return with respect to rehabilitation funds that were required to be set aside prior to licensing and according to the regulations of the MPRDA. If approaches (B) (continue current passive rehabilitation approach after fixing problem areas) or (C) (introduce tolerant species) are selected, then the intense monitoring may need to be extended, depending on the monitoring outputs. The key is that adaptive management and interpretation is required for the best synergy between cost and data quality.

The Chemwes Preliminary Closure Plan (van Deventer, 2003) stipulates annual monitoring of vegetation, erosion and substrate chemistry for TSF Dam 4 and TSF Dam 5 and the SP sites. The proposed monitoring framework (Table 6.1.) has very similar frequency and intensity as that proposed by van Deventer (2003) and seeks to integrate the monitoring components into a cost-effective and efficient way of monitoring performance on the TSF's and SP site. EFA (Ecosystem Function Analysis), comprising LFA and the vegetation sampling, will replace the erosion monitoring and existing vegetation sampling. The results of this study have shown both techniques to be highly applicable and efficient monitoring tools for minesite rehabilitation. The substrate chemical analyses will remain largely as recommended by van Deventer (2003), but the frequency of different variables is to change, as discussed below. The proposed monitoring framework is to apply to both the TSF's and the SP site.

In Table 6.1, EFA refers to just the vegetation monitoring. The full PCQ (point-centred quarter) is to be conducted biennially (every alternate year) for the first eight years, then four-yearly and five-yearly after that and involves the complete method as outlined in chapter 4. The half PCQ is to be done biennially for the first twelve years before being replaced by infrequent, full PCQ's. The half PCQ will only measure species composition and density by recording the nearest plant in each quarter, plus the distance from the central point. Density is being proposed here as a better substitute for cover, as cover is subjectively measured (qualitative) whereas density is quantitative.

The LFA landscape organisation should be conducted annually for the first eight years (Table 6.1), after which it should be carried out biennially for the next four and then every five years thereafter. Landscape organisation is measured annually because it is more likely to change on a year-to-year basis than SSA scores. This is because many patches are transient (e.g. made up of litter) and will only last a few years. Similarly, patches and interpatches increase and decrease in size over time. The SSA, on the other hand, indicates patch or interpatch quality and is far less likely to change in the span of a year or two for a given patch type. Therefore SSA should be conducted biennially for the first eight years, then every three years thereafter, before extending to five-year intervals.

The substrate chemical analyses should be carried out alternately between full and half analyses (Table 6.1). Full analysis refers to texture, base cations, P, CEC, EC, SO_4, total S, NH_4, NO_3, Cl, organic C and pH. This is very similar to the analysis requirement of van Deventer (2003), but includes measurement of total S, NH_4 and NO_3, whilst omitting Al. The full analyses are important to assess substrate development as a growth medium, regardless of approach followed (A, B or C). The half analyses need only measure pH, CEC, EC and base cations, just to establish that no major chemical changes take place between full survey years. After alternating between full and half for the first nine years, sampling periods can extend to every three years for two alternations, before fixing on only full analyses every five years. The proposed substrate chemistry monitoring is thus less intensive overall than that of van Deventer (2003).

The soil microbial ecology, whether inoculations are effected or not, should be measured biennially for the first five years, then every three years, then every four years and then every five years. These are the maximum suggested sampling intervals and if inoculations are done, then sampling frequency may have to increase. This can be linked in with the current investigations into the use of Mycorrhyzae on the Chemwes TSF's.

Lastly, the fixed-point photography should be conducted every year for the first twelve years and then every five years thereafter. If possible though, photographs should be taken every year, especially after the twelve year mark when other monitoring efforts have slowed considerably, for record purposes and to help illustrate development or inconsistencies.

Apart from the monitoring that is required, good record keeping of all management action is required, with dates and costing. The exact seed mixtures or species selections and densities, lime applications, the amounts of organic material and fertiliser, irrigation, herbicidal applications, accidental or management burns, re-working, re-seeding and all others must be accurately and precisely kept on record. It is strongly recommended that a permanent weather station be erected on site with electronic tipping rain gauges that are able to measure both rainfall intensity and volume. If there daily readings can not be maintained, then digital data transfer systems can be installed for automatic upload to remote computers.

It must also be reiterated that the proposed regime for Chemwes presented here is site specific. Because conditions are most often very local, different variables may have different levels of influence at different sites. Therefore, before a streamlined monitoring programme can be proposed for another rehabilitating gold TSF, it is recommended that the same initial baseline work be done to understand the functional dynamics of the system.

Table 6.1. Proposed future monitoring regime for all sites on the Chemwes TSF complex. The first row of headings in the table is the broader monitoring classification, which consist of specific monitoring techniques as laid out in the second row.

Each X indicates which monitoring technique is to be done in which year. Please note that gaps are not necessarily even between years and often extend as time passes. For a full list of abbreviations refer to Appendix D.

	EFA		**LFA**		**Substrate chemistry**		**Microbial**	**Auxiliary**
Year	***Full PCQ****	***Half PCQ*****	***L/O*+**	***SSA*++**	***Full chem.* †**	***Half chem.* ††**	***Full work-up* °**	***Fixed-photos*¤**
2009		X	X			X	X	X
2010	X		X	X	X			X
2011		X	X			X	X	X
2012	X		X	X	X			X
2013		X	X			X	X	X
2014	X		X	X	X			X
2015		X	X			X		X
2016	X		X	X	X		X	X
2017		X				X		X
2018			X					X
2019		X		X	X			X
2020	X		X			X	X	X
Beyond	5-yearly	-	5-yearly	5-yearly	5-yearly	-	5-yearly	5-yearly

*Full PCQ entails sampling for vegetation density, composition and biomass.

**Half PCQ entails vegetation sampling for composition and density.

+L/O is Landscape Organisation refers to delineating and measuring patches/interpatches on fixed transects.

++SSA refers to Soil Surface Assessment where the 12 LFA indicators are measured.

†Full chem. Refers to substrate chemical analyses of P, CEC, EC, SO_4, NH_4, NO_3, total S, Cl, organic C, base cations and pH.

††Half chem. Refers to substrate chemical analyses of pH, CEC, EC and base cations.

°Full microbial work-up entails population-demographic investigations.

¤Fixed-photos refer to repeated fixed-point photography.

6.7. Recommendations for future studies

- Future studies on rehabilitating TSF's should include examinations of the influence of stress and disturbance on re-established vegetation communities. Stress and disturbance studies should extend to trials that track the recovery of TSF vegetation communities after fires of different intensities and at different slope angles. This will most likely add to the already significant body of literature that has shown that TSF slopes should not exceed 14°. Different plant species could also be tested for their capacity to persist under stress-conditions, such as exist when acidity or salinity increase, both separately and in combination. Such trials could be performed under field conditions or in laboratories and greenhouses to get a better understanding of the adaptations and adaptability of these species under controlled conditions.
- As mentioned, the microbial biota has been largely neglected in rehabilitation efforts around the world but has relatively recently attracted more research. The survival and reproductive patterns of microorganisms could be studied in a typical root environment in tailings. Correlations of microbial diversity with landscape function may help to produce a functionality index for predicting microbial population health.
- This study could readily be repeated at other sites and the LFA data could be compared to gain a better understanding of vegetation-substrate relationships on gold and other TSF's. The route taken during this study, to ensure the precision and reliability of LFA data, was properly describing and recording a graphic database of different patch/interpatch types to exclude observer bias. Observer bias could affect patch/interpatch delineation, and therefore affect overall results. If multiple observers are to be used then patch/interpatch identification and delineation must be standardised, as in this study, to eliminate observer bias.
- One limitation to the current study was the availability of appropriate reference sites. All rehabilitation projects should have reference ecosystems as targets, depending on the prerequisite end land-use design. There are very few appropriate local reference sites for most gold TSF's, as their contrived topography is entirely alien to the flat highveld grasslands. The tailings substrate is also alien and no reference soils exist for direct comparisons. This study followed a very cautious approach and used the high benchmark of undisturbed grasslands to assess self-sustainability of different

landscapes. It is recommended that this same, cautious approach be used in other studies of this nature, as the danger of air, water and groundwater pollution exists if sites are improperly classified.

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Appendix A

Site and transect codes with aspect, slope and transect number

Site *TSF's*	Aspect	Slope number	Transect number	Code
Dam 4	Northern aspect	Lower slope	1st transect	4N101
Dam 4	Northern aspect	Lower slope	2nd transect	4N102
Dam 4	Northern aspect	Lower slope	3rd transect	4N103
Dam 4	Northern aspect	Lower slope	4th transect	4N104
Dam 4	Northern aspect	Lower slope	5th transect	4N105
Dam 4	Northern aspect	Upper slope	1st transect	4N201
Dam 4	Northern aspect	Upper slope	2nd transect	4N202
Dam 4	Northern aspect	Upper slope	3rd transect	4N203
Dam 4	Northern aspect	Upper slope	4th transect	4N204
Dam 4	Northern aspect	Upper slope	5th transect	4N205
Dam 4	Southern aspect, eastern half	Lower slope	1st transect	4SE101
Dam 4	Southern aspect, eastern half	Lower slope	2nd transect	4SE102
Dam 4	Southern aspect, eastern half	Lower slope	3rd transect	4SE103
Dam 4	Southern aspect, eastern half	Lower slope	4th transect	4SE104
Dam 4	Southern aspect, eastern half	Lower slope	5th transect	4SE105
Dam 4	Southern aspect, eastern half	Upper slope	1st transect	4SE201
Dam 4	Southern aspect, eastern half	Upper slope	2nd transect	4SE202
Dam 4	Southern aspect, eastern half	Upper slope	3rd transect	4SE203
Dam 4	Southern aspect, eastern half	Upper slope	4th transect	4SE204
Dam 4	Southern aspect, eastern half	Upper slope	5th transect	4SE205
Dam 4	Southern aspect, western half	Lower slope	1st transect	4SW101
Dam 4	Southern aspect, western half	Lower slope	2nd transect	4SW102
Dam 4	Southern aspect, western half	Lower slope	3rd transect	4SW103
Dam 4	Southern aspect, western half	Lower slope	4th transect	4SW104
Dam 4	Southern aspect, western half	Lower slope	5th transect	4SW105
Dam 4	Southern aspect, western half	Upper slope	1st transect	4SW201
Dam 4	Southern aspect, western half	Upper slope	2nd transect	4SW202
Dam 4	Southern aspect, western half	Upper slope	3rd transect	4SW203
Dam 4	Southern aspect, western half	Upper slope	4th transect	4SW204
Dam 4	Southern aspect, western half	Upper slope	5th transect	4SW205
Dam 4	Western aspect	Lower slope	1st transect	4W101
Dam 4	Western aspect	Lower slope	2nd transect	4W102
Dam 4	Western aspect	Lower slope	3rd transect	4W103
Dam 4	Western aspect	Lower slope	4th transect	4W104
Dam 4	Western aspect	Lower slope	5th transect	4W105
Dam 4	Western aspect	Upper slope	1st transect	4W201
Dam 4	Western aspect	Upper slope	2nd transect	4W202
Dam 4	Western aspect	Upper slope	3rd transect	4W203
Dam 4	Western aspect	Upper slope	4th transect	4W204
Dam 4	Western aspect	Upper slope	5th transect	4W205

Appendix A (continued)

Site *TSF's (continued)*	Aspect	Slope number	Transect number	Code
Dam 5	Northern aspect	Lower slope	1st transect	5N101
Dam 5	Northern aspect	Lower slope	2nd transect	5N102
Dam 5	Northern aspect	Lower slope	3rd transect	5N103
Dam 5	Northern aspect	Lower slope	4th transect	5N104
Dam 5	Northern aspect	Lower slope	5th transect	5N105
Dam 5	Eastern aspect	Lower slope	1st transect	5E101
Dam 5	Eastern aspect	Lower slope	2nd transect	5E102
Dam 5	Eastern aspect	Lower slope	3rd transect	5E103
Dam 5	Eastern aspect	Lower slope	4th transect	5E104
Dam 5	Eastern aspect	Lower slope	5th transect	5E105
Dam 5	Southern aspect	Lower slope	1st transect	5S101
Dam 5	Southern aspect	Lower slope	2nd transect	5S102
Dam 5	Southern aspect	Lower slope	3rd transect	5S103
Dam 5	Southern aspect	Lower slope	4th transect	5S104
Dam 5	Southern aspect	Lower slope	5th transect	5S105
Dam 5	Western aspect	Lower slope	1st transect	5W101
Dam 5	Western aspect	Lower slope	2nd transect	5W102
Dam 5	Western aspect	Lower slope	3rd transect	5W103
Dam 5	Western aspect	Lower slope	4th transect	5W104
Dam 5	Western aspect	Lower slope	5th transect	5W105
Pseudo-analogue/reference sites				
Starter wall Dam 5	Eastern aspect	Only slope	1st transect	5SB01
Starter wall Dam 5	Eastern aspect	Only slope	2nd transect	5SB02
Starter wall Dam 5	Eastern aspect	Only slope	3rd transect	5SB03
Starter wall Dam 5	Eastern aspect	Only slope	4th transect	5SB04
Starter wall Dam 5	Eastern aspect	Only slope	5th transect	5SB05
Undisturbed, flat veld	Flat	Only slope	1st transect	UFV01
Undisturbed, flat veld	Flat	Only slope	2nd transect	UFV02
Undisturbed, flat veld	Flat	Only slope	3rd transect	UFV03
Undisturbed, flat veld	Flat	Only slope	4th transect	UFV04
Undisturbed, flat veld	Flat	Only slope	5th transect	UFV05
Spillage site	Flat	Only slope	1st transect	SP01
Spillage site	Flat	Only slope	2nd transect	SP02
Spillage site	Flat	Only slope	3rd transect	SP03
Spillage site	Flat	Only slope	4th transect	SP04
Spillage site	Flat	Only slope	5th transect	SP05

Appendix B

Chemical symbols with ionic name and form, ideal values and the percentage of the base saturation (where relevant)

Element	Symbol	Ionic form	Ion name	Ideal value	% of base saturation
Base cations					
Potassium	K	K^+	Potassium	20-40 mg.kg-1	3-5%
Calcium	Ca	Ca^{2+}	Calcium	>100 mg.kg-1	65-70%
Magnesium	Mg	Mg^{2+}	Magnesium	15-35 mg.kg-1	15-20%
Sodium	Na	Na^+	Sodium		>1%
Phosphorus	P	HPO_4^{2-}	Hydrogen Phosphate	1.5-2.5 mg.kg-1	
	P	$H_2PO_4^-$	Dihydrogen Phosphate		
Other cations and anions					
Nitrogen	N	NO_3^-	Nitrate	80-165 mg.kg-1	-
	N	NH_4^+	Ammonium	80-165 mg.kg-1	-
Sulfur	S	SO_4^{2-}	Sulfate	36-100 mg.kg-1	-
Carbon	C	CO_3^{2-}	Carbonate	n/a	-
Cation ratios					
Calcium:Magnesium	Ca:Mg	-	-	1.5-4 cmol.kg-1	-
Magnesium:Potassium	Mg:K	-	-	3-4 cmol.kg-1	-
Calcium+ Magnesium:Potassium	(Ca+Mg)/K	-	-	10-20 cmol.kg-1	-

Other chemical variables measured, with ideal values

Variable	Explanation	Ideal value
organic C	Organic Carbon	n/a
CEC	Cation exchange capacity	5-20 cmol.kg-1
EC	Electrical conductivity	60-100 mS.m-1
pH (KCl)	Acidity/alkalinity using ammonium-chloride extraction	5.5-7
pH (H_2O)	Acidity/alkalinity using 1:2 water extraction	5.5-7.2
ESP	Exchangeable Sodium percentage	<10%
SAR	Sodium adsorption ratio	<4

Lyotrophic series

$H^+ = Al^{3+} > Ca^{2+} > Mg^{2+} > K^+ = NH_4^+ > Na^+$

Appendix C

Species recorded at the Chemwes TSF complex, with family, ordination code, indigenous/exotic status and growth form, and mode of colonisation (planted/natural)

Species	Family	Code in ordination	Status	Mode of colonisation
Cf. *Harpochloa falx*	*Poaceae*	(Har_fa)	Indigenous herb	Natural
(Lily)	*Liliaceae*	Liliaceae sp.	Indigenous herb	Natural
(*Oxalis* sp.)	*Oxalidaceae*	(Oxa_sp)	Indigenous herb	Natural
(Tulip)	*Amaryllidaceae*	naryllidaceae	Indigenous herb	Natural
Acacia caffra	*Fabaceae*	Aca_caff	Indigenous herb	Natural
Acalypha angustata	*Euphorbiaceae*	Aca_angu	Indigenous herb	Natural
Andropogon chinensis	*Poaceae*	And_chin	Indigenous herb	Natural
Andropogon eucomus	*Poaceae*	And_euco	Indigenous herb	Natural
Aristida canescens	*Poaceae*	Ari_cane	Indigenous herb	Natural
Aristida congesta subsp. barbicollis	*Poaceae*	Ari_conB	Indigenous herb	Natural
Aristida congesta subsp. congesta	*Poaceae*	Ari_conC	Indigenous herb	Natural
Aristida junciformis	*Poaceae*	Ari_junc	Indigenous herb	Natural
Aristida stipitata	*Poaceae*	Ari_stip	Indigenous herb	Natural
Asparagus suaveolens	*Asparagaceae*	Asp_salv	Indigenous shrub	Natural
Berkheya setifera	*Asteraceae*	Ber_seti	Indigenous herb	Natural
Bidens bipinnata	*Asteraceae*	Bid_bipi	Exotic herb	Natural
Boophane distichia	*Amaryllidaceae*	Boo_dist	Indigenous herb	Natural
Brachiaria serrata	*Poaceae*	Bra_serra	Indigenous herb	Natural
Buddleja salvifolia	*Loganiaceae*	Bud_salv	Indigenous shrub	Natural
Celtis africana	*Ulmaceae*	Cel_afri	Indigenous tree	Natural
Chaetacanthus costatus	*Acanthaceae*	Cha_cost	Indigenous herb	Natural
Chamaecrista comosa	*Fabaceae*	Cha_como	Indigenous herb	Natural
Chamaecrista mimosoides	*Fabaceae*	Cha_mimo	Indigenous herb	Natural
Chloris gayana	*Poaceae*	Chl_gaya	Indigenous herb	Planted
Chloris virgata	*Poaceae*	Chl_virg	Indigenous herb	Natural
Cirsium vulgare	*Asteraceae*	Cir_vulg	Exotic herb	Natural
Clematopsis scabiosifolia	*Ranunculaceae*	Cle_scab	Indigenous herb	Natural
Convolvulus saggitatus	*Convolvulaceae*	Con_sagg	Indigenous herb	Natural
Conyza bonariensis	*Asteraceae*	Con_bona	Exotic herb	Natural
Cortaderia jubata	*Poaceae*	Cor_juba	Exotic herb	Planted
Crepis hypochoeridia	*Asteraceae*	Cre_hypo	Indigenous herb	Natural
Cymbopogon excavatus	*Poaceae*	Cym_exca	Indigenous herb	Natural
Cymbopogon plurinodis	*Poaceae*	Cym_plur	Indigenous herb	Natural
Cynodon dactylon	*Poaceae*	Cyn_dact	Indigenous herb	Planted
Cyperus rotundus	*Cyperaceae*	Cyp_rotu	Indigenous herb	Natural
Dactyloctenium mossambicensis	*Poaceae*	Dac_moss	Indigenous herb	Natural

Appendix C (continued).

Species	**Family**	**Code in ordination**	**Status**	**Mode of colonisation**
Dicoma macrocephala	*Asteraceae*	Dic_macr	Indigenous herb	Natural
Digitaria eriantha	*Poaceae*	Dig_eria	Indigenous herb	Planted
Diheteropogon amplectens	*Poaceae*	Dih_ampl	Indigenous herb	Natural
Elephanthorriza elephantina	*Fabaceae*	Ele_elep	Indigenous herb	Natural
Elionurus muticus	*Poaceae*	Eli_muti	Indigenous herb	Natural
Eragrostis biflora	*Poaceae*	Era_bifl	Indigenous herb	Natural
Eragrostis chloromelas	*Poaceae*	Era_chlo	Indigenous herb	Natural
Eragrostis curvula	*Poaceae*	Era_curv	Indigenous herb	Planted
Eragrostis gummiflua	*Poaceae*	Era_gumm	Indigenous herb	Natural
Eragrostis lehmanniana	*Poaceae*	Era_lehm	Indigenous herb	Natural
Eustachys paspaloides	*Poaceae*	Eus_pasp	Indigenous herb	Natural
Felicia muricata	*Asteraceae*	Fel_muri	Indigenous herb	Natural
Flaveria bidentitis	*Asteraceae*	Fla_bide	Exotic herb	Natural
Gomphocarpus fruticosus	*Asclepiadaceae*	Gom_frut	Indigenous herb	Natural
Gomphocarpus physocarpa	*Asclepiadaceae*	Gom_phys	Indigenous herb	Natural
Grewia flava	*Tiliaceae*	Gre_flav	Indigenous tree	Natural
Helichrysum krausii	*Asteraceae*	Hel_krau	Indigenous herb	Natural
Heteropogon contortus	*Poaceae*	Het_cont	Indigenous herb	Natural
Hyparrhenia hirta	*Poaceae*	Hyp_hirt	Indigenous herb	Planted
Indigofera comosa	*Fabaceae*	Ind_como	Indigenous herb	Natural
Indigofera daleoides	*Fabaceae*	Ind_dale	Indigenous herb	Natural
Ipomoea bathycolpos	*Convolvulaceae*	Ipo_bath	Indigenous herb	Natural
Kohautia cynanchica	*Rubiaceae*	Koh_cyna	Indigenous herb	Natural
Lantana rugosa	*Verbenaceae*	Lan_rugo	Indigenous shrub	Natural
Ledebouria marginata	*Hyacinthaceae*	Led_marg	Indigenous herb	Natural
Loudetia simplex	*Poaceae*	Lou_simp	Indigenous herb	Natural
Medicago sativa	*Fabaceae*	Med_sati	Exotic herb	Planted
Melinis nerviglumis	*Poaceae*	Mel_nerv	Indigenous herb	Natural
Melinis repens	*Poaceae*	Mel_repe	Indigenous herb	Natural
Oxygonum sinuatum	*Polygonaceae*	Oxy_sinu	Indigenous herb	Natural
Panicum maximum	*Poaceae*	Pan_maxi	Indigenous herb	Natural
Paspalum dilatatum	*Poaceae*	Pas_dila	Exotic herb	Natural
Phragmites australis	*Poaceae*	Phr_aust	Indigenous herb	Natural
Pogonarthria squarrosa	*Poaceae*	Pog_squa	Indigenous herb	Natural
Polygala hottentotta	*Polygalaceae*	Pol_hott	Indigenous herb	Natural
Portulaca oleracea	*Portulacaceae*	Por_oler	Exotic herb	Natural

Appendix C (continued).

Species	**Family**	**Code in ordination**	**Status**	**Mode of colonisation**
Pseudognaphalium lateo-album	*Asteraceae*	Pse_late	Indigenous herb	Natural
Rhus lancea	*Anacardiaceae*	Rhu_lanc	Indigenous tree	Natural
Rhus pyroides	*Anacardiaceae*	Rhu_pyro	Indigenous tree	Natural
Rhynchosia minima	*Fabaceae*	Rhy_mini	Indigenous herb	Natural
Schizachyrium sanguineum	*Poaceae*	Sch_sang	Indigenous herb	Natural
Schkuhuria pinnata	*Asteraceae*	Sck_pinn	Exotic herb	Natural
Setaria sphacelata var. sphacelata	*Poaceae*	Set_SpSp	Indigenous herb	Natural
Setaria sphacelata var. torta	*Poaceae*	Set_SpTo	Indigenous herb	Natural
Solanum panduriforme	*Solanaceae*	Sol_pand	Indigenous herb	Natural
Stoebe vulgaris	*Asteraceae*	Sto_vulg	Indigenous shrub	Natural
Tagetes minuta	*Asteraceae*	Tag_minu	Exotic herb	Natural
Tamarix chinensis	*Tamaricaceae*	Tam_chin	Exotic tree	Planted
Themeda triandra	*Poaceae*	The_tria	Indigenous herb	Natural
Trachypogon spicatus	*Poaceae*	Tra_spic	Indigenous herb	Natural
Triraphis andropogonoides	*Poaceae*	Tri_andr	Indigenous herb	Natural
Triumfetta sonderi	*Tiliaceae*	Tri_sond	Indigenous herb	Natural
Urochloa mossambicensis	*Poaceae*	Uro_moss	Indigenous herb	Natural
Urochloa trichopus	*Poaceae*	Uro_tric	Indigenous herb	Natural
Verbena bonariensis	*Verbenaceae*	Ver_bona	Exotic herb	Natural

Appendix D. Glossary of abbreviations

Abbreviation	Meaning
General	
GGP	Gross Geographic Product
GDP	Gross Domestic Product
AMD	Acid Mine Drainage
EFA	Ecosystem Function Analysis
LFA	Landscape Function Analysis
LOI	Landscape Organisation Index
SSA	Soil-Surface Assessment
PCQ	Point-Centred Quarter
TSF	Tailings Storage Facility
C/T	Critical Threshold
ANZMEC	Australia-New Zealand Mining And Energy Council
SER	Society for Ecological Restoration International
EMP	Environmental Management Plan
FAT	Fraser Alexander Tailings
ISO	International Standards Organisation
GPS	Global Positioning System
GIS	Geographic Information System
Statistics and Analyses	
ANOVA	Analysis of Variance
BCS	Bray-Curtis Similarity
HCA	Hierarchical Cluster Analysis
MDS	Non-Metric Multidimensional Scaling
PCA	Principle Component Analysis
DCA	Detrended Corresponded Analysis
RDA	Redundancy Analysis
CCA	Canonical Correspondence Analysis
SD	Standard Deviation
SEM	Standard Error Margin
Legal	
MPRDA	Minerals And Petroleum Resources Development Act
CARA	Conservation of Agricultural Resources Act
NEMA	National Environmental Management Act
NGO	Non-Governmental Organisation
NWA	National Water Act
NEMAQA	National Environmental Management Air QualityAct

Appendix D. Glossary of abbreviations (continued)

Patches	
CP	Cryptogam Patch
DFP	Dead Forb Patch
GLP	Grassy Litter Patch
GP	Grass Patch
HP	Herb Patch
LP	Litter Patch
PP	Pampas Patch
RP	Rock Patch
RTP	Root Patch
SGP	Sparse Grass Patch
SP	Shrub Patch
TP	Tree Patch
WLP	Woody Litter Patch
Interpatches	
BS	Bare Soil
BT	Bare Tailings
GRI	Gravel Interpatch
Soil Chemistry	
CEC	Cation Exchange Capacity
EC	Electrical Conductivity
ESP	Exchangeable Sodium Percentage
SAR	Sodium Adsorption Ratio