

**Vegetation community development on a chronosequence of  
abandoned gold and rehabilitated nickel tailings around the  
Great Dyke region in Zimbabwe**

**Tatenda Nyenda**

***Dissertation presented  
for the degree of Doctor of Philosophy (PhD) at the Department of  
Conservation Ecology and Entomology, Faculty of AgriSciences,  
Stellenbosch University***



**Supervisor  
Prof. Shayne. M. Jacobs**

**Co-supervisor  
Prof. Willis Gwenzi**

**March 2020**

## **Declaration**

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own original work, that I am the sole owner (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any other qualification.

This dissertation includes two (2) original papers published in peer-reviewed journals or books and four (4) unpublished publications. The development and writing of the papers (published and unpublished) were the principal responsibility of myself and, for each of the cases where this is not the case, a declaration is included in the dissertation indicating the nature and extent of the contributions of co-authors.

## **Acknowledgement**

My profound gratitude goes to my Supervisors Prof. Shayne Jacobs and Prof. Willis Gwenzi for their unwavering support, guidance and above all, patience throughout the study.

My sincere gratitude to the Management of Freda Rebecca, Trojan and the other mines for permission to access their sites for academic studies. You were the foundation of my hope.

I am also greatly indebted to my research assistants Tafadzwa Terrence Piyo, Buckley Dzamara, Tenderano Musungwa, and Ephirionce Chimukoko for their endurance. Tafadzwa your endurance was phenomenal! May God Bless you Team!

My profound gratitude also goes to the staff at the Soil Research and Chemistry Laboratory, in particular Mr. Chifamba and Ms. Badza for their awesome work and assistance with laboratory analyses. The same goes to Mr. Richakara of Bindura University for assistance with laboratory analyses. I am also grateful to Prof. Kidd of Stellenbosch University who assisted with statistical analysis advice at the onset of the project.

Many thanks to the International Foundation of Science (IFS) for partly funding the project in a period when it was greatly needed.

Lastly, I would like to thank my friend and Business Partner Brian “Bruno” Machingura for enduring my absence at work throughout the entire period.

## Abstract

Ecosystem development on unique anthropogenic sites such as mine tailings is poorly understood and there is much controversy on whether the trajectory of vegetation development is towards restoration of pristine conditions or towards formation of novel plant ecosystems. While traditional theories assert that vegetation development is towards restoration of natural conditions which may be accelerated by active rehabilitation or reclamation, emerging theories propose a divergent trajectory. However, studies focusing on the trajectory of natural and assisted revegetation and their abiotic determinants on rehabilitated and unrehabilitated mine tailings are limited. The traditional and emerging theories therefore remain untested on such unique anthropogenic sites. This has led to adoption of expensive mine restoration programs that are not informed by scientific empirical evidence, often without success. In order to contribute to closure of this gap, the study was carried out primarily at Freda Rebecca gold mine and at Trojan nickel mine in Bindura district in the northern part of savanna Zimbabwe, and secondarily at several other ancillary mines situated around the great Dyke of Zimbabwe. The sites have mine tailings of different ages subjected to spontaneous revegetation, in the case of gold mine tailings while nickel tailings were rehabilitated by planting leguminous woody species and left for subsequent self-sustained revegetation.

The main aim of the study was to establish the trajectory of vegetation structural and compositional attributes on a chronosequence of abandoned gold and nickel tailings with reference to adjacent natural vegetation matrices and to identify physicochemical substrate correlates. A secondary aim was to test the contribution of local site factors such as topography and climatic gradients and their interaction with substrate age on revegetation of the mine tailings. The study aimed to answer the following questions: (1) Do trajectories of vegetation succession on unrehabilitated gold and rehabilitated nickel tailings resemble convergence to pristine conditions or divergence towards formation of novel ecosystems?, (2) How do physicochemical properties of gold and nickel tailings vary over time and how do they relate to vegetation patterns?, (3) Are the occurrence patterns of vegetation affected by tailings age, type, local topographic factors and or climatic gradients?, and (4) What are the occurrence patterns of biological crusts (BCs) on gold tailings and what are their relationship with substrate and vegetation attributes?

Unexpectedly, vegetation composition for unrehabilitated gold tailings appeared to gradually follow a convergence trajectory towards natural reference conditions while vegetation composition on rehabilitated nickel mine tailings moved away from reference conditions, likely forming novel ecosystems. However, vegetation structural attributes largely converged towards references for both rehabilitated and unrehabilitated mine tailings.

Substrate physicochemical properties showed differential trajectories with some (total N and available P) increasing towards reference properties, some fluctuating (exchangeable bases, texture and EC), and some declining (e.g. pH, mineral N and bulk density) thereby yielding multiple contrasting end-points

relative to reference sites. Overall, there was a significant effect of age and local site position or topography on total N, available P, OC, and EC and interactive effect of tailings age and position on EC. Areas covered by BCs had enhanced total N, OC, exchangeable bases and higher pH than areas without. Based on substrate physicochemical properties, the gold tailings were distinct from reference conditions suggesting more than 110 years may be needed to restore soil properties or restoration is not possible. On both rehabilitated and unrehabilitated mine tailings, vegetation attributes were mainly correlated to dynamics in total N, OC, available P, pH, EC and bulk density.

Total BC cover significantly increased with tailings age, particularly lichens and mosses showing significant increases while cyanobacteria and algae significantly decreased. Ordination analysis showed a substrate age dependent correlation between BC cover and vegetation cover, species richness and densities, particularly, a positive relationship on 10-82 year-old-dumps and negative correlation thereafter. Moreover, vegetation composition and structure varied with BC cover gradients. Vegetation structure was significantly affected by local site topography while composition was not significantly affected.

A gradient analysis of plant structural and compositional attributes on gold tailings along climatic gradients showed significant increase in vegetation structural attributes (cover, density, richness) with increase in rainfall, particularly for forbs and grass species except for woody species. Life cycle appeared to affect plant response to climatic gradients with annuals significantly decreasing with increase in rainfall, while perennial plants increased. However, plant species composition was generally similar on gold tailings across varying climatic gradients except for those with above 300 mm difference. Rehabilitation, appeared to break the influence of climate on vegetation composition as some unrehabilitated sites in contrasting climatic regions separated while those rehabilitated grouped showing high compositional similarity for rehabilitated tailings.

When contextualized against existing revegetation theories, the results provide evidence that no single trajectory of vegetation composition development can be generalized for mine tailings. However, results confirm general convergence of structural attributes regardless of substrate type and management. Temporal changes in vegetation attributes are correlated to increases in fertility, pH dynamics and a decrease in substrate compaction and salinity. Results also suggest that mine tailings support specific plant species assemblages owing to their uniqueness and that may largely override the effect of climatic gradients. Evidence also suggest BCs and the planted woody species create microsites (nutrient hot spots) most likely due to their soil ecological engineering capabilities, significantly influencing vegetation patterns on mine tailings. Overall, when determining revegetation trajectories on anthropogenic sites, the following factors are important: (1) substrate age, (2) the starting point, reclamation versus no reclamation, (3) substrate type, (4) specific vegetation variables and growth forms, (5) topography, (5) the role of BCs, (7) and (8) to a lower extent climatic variables.

## Opsomming

Ekosisteesontwikkeling op unieke antropogeniese substrate, soos mynuitskot, word nie goed verstaan nie en daar is baie kontroversie oor of die trajek van plantegroei is na die herstel van ongerepte toestande of die vorming van nuwe ('novel') plantekosisteme. Terwyl tradisionele teorieë stel voor dat plantegroei ontwikkel na die natuurlike toestande is en deur aktiewe rehabilitasie of reklamasie versnel kan word, stel nuwe teorieë 'n alternatiewe trajek voor. Ondersoeke wat fokus op die trajek van natuurlike en ge-assisteerde hergroei en hul abiotiese determinante op gerehabiliteerde en ongerehabiliteerde mynuitskot is egter beperk. Die tradisionele en ontluikende teorieë bly dus ongetoets op sulke unieke antropogeniese substrate. Dit het gelei tot die aanvaarding van duur mynherstelprogramme wat nie deur wetenskaplike empiriese bewyse ingelig word nie, dikwels sonder sukses. Om hierdie leemte te vul, is die studie hoofsaaklik by die Freda Rebecca-goudmyn en by die Trojan-nikkelmyn in die Bindura-distrik in die noordelike deel van savanna Zimbabwe uitgevoer, en tweedens by verskeie ander myne wat rondom die groot Dyke van Zimbabwe geleë is. Die studieterreine het uitskotte van verskillende ouderdomme wat aan spontane plantegroei herstelling onderworpe is, in die geval van goudmynuitskot, terwyl nikkeluitskot gerehabiliteer is deur houtagtige peulplant-spesies te plant wat gelos is vir selfonderhoudende herbepanning plantegroei herstel.

Die hoofdoel van die studie was om die trajek van strukturele en komposisionele eienskappe van plantegroei vas te stel op 'n chronosekwensie van verlate goud- en nikkeluitskot-areas met as verwysing die aangrensende natuurlike plantegroei-matrikse, en om substraat fisiko-chemiese korrelate te identifiseer. 'n Sekondêre doel was om die bydrae van plaaslike terreinfaktore soos topografie en klimaatgradiënte en die interaksie daarvan met die substraatouderdom op plantegroei-ontwikkeling van die mynuitskot te toets. Die studie was daarop gerig om die volgende vrae te beantwoord: (1) Is die trajek van plantsuksesie op ongerehabiliteerde goud en gerehabiliteerde nikkeluitskot die van konvergensie na ongerepte toestande of divergensie na die vorming van nuwe ('novel') ekosisteme? (2) Hoe wissel fisiko-chemiese eienskappe met verloop van tyd en hoe hou hulle verband met plantegroeioptrone? (3) Word die voorkomspatrone van plantegroei beïnvloed deur die uitskot-ouderdom, tipe, plaaslike topografiese faktore en / of klimaatgradiënte? en (4) Wat is die voorkomspatrone van biologiese korse? (BK's) op gouduitskot, en wat is die verband met die substraat- en planteienskappe?

Onverwags blyk dit dat die plantesamestelling van ongerehabiliteerde gouduitskot geleidelik 'n trajek van konvergensie na natuurlike verwysingstoestande volg, terwyl plantesamestelling op gerehabiliteerde nikkeluitskot wegbeweeg van verwysingsomstandighede, en waarskynlik nuwe ('novel') ekosisteme vorm.

Strukturele eienskappe van plantegroei konverteer grootliks egter na die verwysingsareas vir sowel gerehabiliteerde as ongerehabiliteerde mynuitskot.

Substraat fisiko-chemiese eienskappe het differensiële trajekte getoon, met sommige (totale N en beskikbare P) wat toeneem na die verwysingsareas, sommige was wisselend (uitruilbare basisse, tekstuur en EC), en sommige wat daal (bv. pH, minerale N en bulkdigtheid), wat meervoudige kontrasterende eindpunte relatief tot die verwysingsareas opgelewer het. In die algemeen was daar 'n beduidende effek van ouderdom en plaaslike posisie of topografie op die totale N, beskikbare P, organiese koolstof en elektriese konduktiwiteit en die interaktiewe effek van die ouderdom en posisie op elektriese konduktiwiteit. Areas gedek deur BK's het 'n verbeterde totale N, organiese koolstof, uitruilbare basisse en hoër pH gehad as gebiede sonder. Gegrand op die fisiko-chemiese eienskappe van die substraat, is die gouduitskot onderskei van die verwysingsareas, wat daarop dui dat meer as 110 jaar nodig mag wees om grondeienskappe te herstel, of dat herstel nie moontlik is nie. Op beide gerehabiliteerde en ongerehabiliteerde mynuitskot, is plantegroei-eienskappe hoofsaaklik gekorreleer met dinamika in totale N, organiese koolstof, beskikbare P, pH, EC en bulkdigtheid.

Totale BK-dekking het aansienlik toegeneem met die ouderdom van die uitskot, veral ligene en mosse wat aansienlike toenames toon, terwyl cyanobakterieë en alge wat aansienlik afgeneem het. Ordeningsanalise het getoon dat 'n substraat-ouderdomsafhanklike korrelasie tussen BC-dekking en plantegroiebedekking, spesierikheid en -digtheid bestaan, met veral 'n positiewe verwantskap op 10-82 jaar oue uitskotareas en negatiewe korrelasie daarna. Verder het die samestelling en struktuur van plantegroei gewissel met BK-dekgradiënte. Die struktuur van die plantegroei is beduidend beïnvloed deur die plaaslike topografiese posisie, terwyl die samestelling nie beduidend beïnvloed is nie.

'n Gradiënt-analise van plantstruktuur- en samestellings-eienskappe op gouduitskot oor klimaatgradiënte het 'n beduidende toename in strukturele eienskappe van die plantegroei (bedekking, digtheid, rykheid) getoon met toename in reënval, veral vir 'forb' - en grasspesies, behalwe vir houtagtige spesies. Dit wil voorkom asof lewenssiklus die reaksie van plante op klimaatgradiënte beïnvloed, met eenjarige wat aansienlik daal met 'n afname in reënval, terwyl meerjarige plante toegeneem het. Plantspesiesamestelling was egter oor die algemeen soortgelyk op gouduitskot oor verskillende klimaatgradiënte, behalwe vir dié met 'n verskil van meer as 300 mm. Rehabilitasie het blykbaar die invloed van die klimaat op plantegroeisamestelling afgebreek, aangesien sommige ongerehabiliteerde

terreine in kontrasterende klimaatstreke uitgeskei het, terwyl die gerehabiliteerde groepe 'n hoë komposisie-ooreenkoms vir gerehabiliteerde uitskot toon.

As dit gekontekstualiseer word teen bestaande plantegroei-onwikkelingsteorieë, lewer hierdie resultate 'n bewys dat daar nie 'n enkele trajek van die ontwikkeling van plantegroeisamestelling veralgemeen kan word vir mynuitskot-areas nie. Resultate bevestig egter algemene konvergensie van strukturele eienskappe, ongeag die substraat-tipe en bestuur. Tydelike veranderinge in plantegroei-eienskappe is gekorreleer met toename in vrugbaarheid, pH-dinamika en 'n afname in substraatverdigting en soutgehalte. Resultate dui ook daarop dat mynuitskot-areas spesifieke plantspesiesamestellings het as gevolg van hul uniekheid en dat dit die effek van klimaatsgradiënte grootliks kan oorheers. Bewyse dui ook daarop dat BC's en die aangeplante houtagtige spesies mikroareas (voedingstof-'hotspots') skep, waarskynlik as gevolg van hul ekologiese ingenieursvermoë in die grond, wat die plantegroei-areas op mynuitskotareas aansienlik beïnvloed. In die algemeen is die volgende faktore belangrik by die bepaling van plantegroei-onwikkelings trajekte op antropogeniese terreine: (1) substraatouderdom, (2) die beginpunt, herwinning teenoor geen herwinning, (3) substraattipe, (4) spesifieke plantegroei-veranderlikes en groeivorme, (5) topografie, (6) die rol van BK's, (7) en (8) in 'n kleiner mate klimaatveranderlikes.



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### List of abbreviations

AAS	Atomic Absorption Spectrophotometer
ANOVA	Analysis of Variance
AS	Arsenic
BC	Biological Crusts
CCA	Canonical Correspondence Analysis
Cd	Cadmium
Cu	Copper
DB	Bulk density
DCA	Detrended Correspondence Analysis
EC	Electrical Conductivity
Fe	Iron
FRGM	Freda Rebecca Gold Mine
GLM	General Linear Model
KCl	Potassium Chloride
LSD	Least Significant Difference
Mineral N	Mineral Nitrogen
Mn	Manganese
N	Nitrogen
Ni	Nickel
nMDS	Non-metric Dimensional Scaling
OC	Organic carbon
OM	Organic matter
P	Phosphorus
PCA	Principal Component Analysis
RDA	Redundancy Analysis
SIV	Species Importance Value
SPSS	Statistical Package for Social Sciences

Total N  
Zn

Total Nitrogen  
Zinc

## CHAPTER 1

### INTRODUCTION

#### 1.1 Background to the study

Extensive mining activities started in the 19<sup>th</sup> century (Tordoff *et al.*, 2000). With technological development, the twentieth century saw an upsurge in mining (Nsimba, 2009). Globally mining activities particularly increased in western USA, northern regions of Mexico, South Spain, Western China, Australia and western India (Mushover, 1994; Tordoff *et al.*, 2000). In Africa, mining activities increased immensely, particularly in the South African Witwatersrand region, the copper-belt of Zambia and the Great Dyke stretch in Zimbabwe.

While mining brings about socio-economic benefits, adverse impacts are also part and parcel of it (Tordoff *et al.*, 2000, Pang *et al.*, 2003, Martinez-Ruiz *et al.*, 2007). Mining produces large volumes of tailings, globally estimated to be about 7 billion tons per annum (Edraki, 2014). Mine tailings often containing, metal-bearing minerals, process chemical, fine texture and sulphides are usually heaped on land above ground (Piha *et al.*, 1995, Nsimba, 2009, Zaranyika and Chirinda, 2011). A number of environmental impacts include loss of vegetation due to land clearance for tailings dump construction and acid mine drainage resulting in pollution of sensitive areas, surface and ground water systems (Tordoff *et al.* 2000). This affects water quality and negatively impacts riparian vegetation and ecological diversity in general. The loss of vegetation and biodiversity creates ecological islands in the middle of natural vegetation matrices. Air pollution also result from release of fine dust from bare and dry tailings. Unrehabilitated tailings are also susceptible to erosion (Morris *et al.*, 2003; Gonzalez and Gonzalez-Chavez 2006), degrading the aesthetic value of the sites (Piha *et al.*, 1995). Mine tailings are a common feature for active or abandoned mines throughout the world with heavily affected areas being regions enlisted above (Tordoff *et al.* 2000).

Disposal of mine tailings has several adverse impacts, as unrehabilitated sites usually remain without vegetation for decades or centuries (Mendez and Maier, 2008). This has been because tailings have poor aggregate structure, low organic matter, and are deficient in macronutrients such as N and P, but rich in toxic metals (Li-Nan Huang *et al.*, 2011; Zaranyika and Chirinda, 2011). Toxic metals have been shown to inhibit germination of plant seed and retard plant growth (Piha *et al.*, 1995; Pelralta *et al.*, 2000). In abiotically stressed regions, establishment of vegetation on mine tailings is further impeded by a number of physical factors such as compaction, poor structure, high infiltration, low precipitation, extreme temperatures and chemical factors including high salinity, extreme pH, low fertility and metal toxicity (Mendez and Maier, 2008). These factors are closely related to the parent material and process chemicals and have a net negative effect on vegetation establishment (Munshower, 1994).

In light of this increasing mining-related land degradation, both ecological and economic imperatives demand that restoration or rehabilitation of land be prioritized (Bradshaw and Chadwick, 1980; Walker and del Moral, 2009; Milner *et al.*, 2016). Although tailings can be stabilized by physical and chemical means, these techniques are expensive and often short-lived (Piha *et al.*, 1995a). The cheaper alternative is to artificially vegetate the dumps (Piha *et al.*, 1995a, Mendez and Maier, 2008) and facilitate subsequent natural vegetation recovery (Mendez and Maier, 2008, Festin *et al.*, 2018). This option, however, requires careful selection of species that can withstand the hostile substrates while promoting the colonization of native species to achieve the required restoration and or rehabilitation. Many revegetation efforts of mine wastes in the world were based on either spontaneous vegetation (e.g. Martinez- Ruiz *et al.*, 2007; Young *et al.*, 2012) or artificial revegetation with woody and herbaceous vegetation (Piha *et al.*, 1995a; Martinez-Ruiz and Santos, 2005; Moreno *et al.*, 2008; Mendez and Maier, 2008; Ahirwaal, 2017; Festin *et al.*, 2018). In the latter case, the major goal of the rehabilitation effort is often to ignite the development of a self-sustaining plant community that resembles the surrounding reference in composition, diversity and structure, while in the former it is hoped spontaneous succession would achieve that. However, there is limited knowledge on the success of the two options in achieving the restoration goals, the trajectory of vegetation development or the principal substrate and non-substrate factors driving the process, despite the existence of several appropriate theories that may help explain the revegetation patterns.

Two main contrasting theories of trajectories of vegetation development on disturbed sites exist: (1) the traditional convergence theory that assert that over time disturbed sites recover towards plant communities similar to adjacent natural reference sites (Young *et al.*, 2012; Simberloff *et al.*, 2015) and (2) the novel ecosystem concept which proposes a trajectory towards formation of alternative states different from the natural or pristine site making it difficult to achieve restoration goals outlined by the mines (Hobbs and Harris, 2011, Hobbs, 2013a,b). The former is largely consistent with the conventional classical succession theory (Clements, 1916), that suggest establishment of vegetation is towards a stable mono-climax end-point, which regardless of other factors is mainly influenced by climatic variation. The later is consistent with the argument conveyed by critiques of the mono-climax theory (Gleason, 1976) that assert that successional pathways are variable and do not follow a specific order. In this context, (Gleason, 1976) suggests partial floristic convergence during succession, highlighting the presence of multiple stable end-points that are controlled by local factors such as topography or soil type (topographic climax and edaphic climax respectively). Some scholars, however, further classified the vegetation trajectories relative to reference sites into four categories namely: asymptotic, linear, unimodal and stochastic (Hobbs and Harris, 2004). In the linear trajectory, species composition and diversity recover over time until they reach reference level or even surpass them. In the asymptotic trajectory recovery is gradual or fast but will never match the pristine features, getting to a climax below the

reference. In the unimodal trajectory, recovery is gradual towards the reference, reaching a peak over time, but feedbacks inherent in the system leads to a decline in diversity to almost the features of a newly degraded site. In the stochastic trajectory the ecosystem features oscillate up and down far below the reference, and recovery is severely limited (Bullock *et al.*, 2011).

Despite the existence of wide literature on succession and restoration trajectories resulting in contrasting debates on convergence and divergence, such studies have been widely tested in secondary succession especially old fields and very few were tested on anthropogenic soils (Chang and Turner, 2019). A number of the studies also focused on changes in floristic composition on single substrates without paying attention to both composition, abundances, structure and function of the vegetation. These studies were also done on short chronosequences, did not compare if end-points would be the same under different management regimes, in particular on anthropogenic sites like mine tailings, rendering the generalization of these theories questionable. Although the studies acknowledge the individual influence of factors such as climate, nutrients, toxicity, dispersal capability (Walker and del Moral, 2009; Higgs *et al.*, 2016; Chang and Turner, 2019), there are little empirical studies investigating multiple factors on unique anthropogenic sites such as mine tailings. Studies that test succession and restoration frameworks on unique anthropogenic substrates jointly investigating individual and interactive effects of substrate, topographic, climatic, biotic factors and management history in a succession remain limited. Further, studies that jointly investigate the trajectory of multiple ecosystems components such as soils, vascular plants and biota such as biological crusts (BCs) in a succession are limited. This hinders the generalization and adoption of lessons learnt into the restoration of unique anthropogenic sites. In the absence of this, generic conceptual frameworks will never be adjusted based on ground experiences from practical evaluation studies (Hobbs and Yates, 1997).

Tailings disposal are a typical exogenous ecosystem disturbance that creates a substrate that is key for primary succession studies (Bradshaw, 2000). Freda Rebecca and Trojan mines in Savanna Zimbabwe have chronosequences of tailings dumps that were subjected to contrasting management histories and therefore presented an ideal opportunity for the study of ecosystem development where no previously developed soil exist. Currently, the field is heavy with debate on trajectories of ecosystem development and this requires continuous testing in order to arrive at substantive generalizations. The primary aim of the present study was to establish the trajectory of development of vegetation structural and compositional attributes on a chronosequence of abandoned gold and nickel tailings with reference to adjacent natural vegetation matrices and to identify physical, chemical and biological substrate correlates in order to understand restoration of unique anthropogenic sites. The secondary aim was to test the contribution of local site factors such as topography and climatic gradients and their interaction with substrate age on revegetation of the mine tailings. Insights from this study will contribute to the understanding of the primary succession patterns and underlying mechanisms of ecosystem development

on tailings. Lessons learnt from the succession trajectories will be crucial in updating ecological restoration theoretical and conceptual frameworks and their interrelationships at least in the context of unique anthropogenic sites. “Studies that take a comparative approach provide an opportunity to understand succession trajectories including whether communities recover to a previous state or diverge to a new state”, (Prach *et al.*, 2016). This is key in “understanding and informing restoration management”, (Suding and Hobbs, 2009, Walker and del Moral, 2009).

## **1.2 Key concepts on ecological succession and restoration**

### **1.2.1 Ecological succession**

Ecological succession is the study of how biological communities re-assemble and change over time following anthropogenic and or natural disturbances (Chang and Turner, 2019). Such studies have been done since the birth of ecology as a discipline, generating a number of theoretical frameworks that now anchor many aspects of the discipline (Prach and Walker, 2011; Walker and Wardle, 2014; Egerton, 2015). These were based on mainly the classical succession theory (Clements, 1916). Recently, novel approaches on ecological succession have been brought forth and with much controversy (Hobbs and Harris, 2006).

Successional theories have an important role in studies of ecosystem genesis and restoration ecology (Walker and Hobbs, 2007; Walker and Wardle, 2014). These provide insights into mechanisms of plant community assemblages such as dispersal limitations (Makoto and Wilson, 2016), abiotic factors (Lobbeck *et al.*, 2014), stochastic processes (Norden *et al.*, 2015), and “biotic interactions such as competition and facilitation”, (Connell and Slatyer, 1977, Tilman, 1993). As such recent studies continue to show the importance of succession in modern ecological theory and application (Chang and Lambers, 2016). As novel perspectives are brought forth, updated succession frameworks may help create new dimension in ecological succession (Purschke *et al.*, 2013). Proponents of the novel ecosystem concept postulate that ecosystems develop beyond climax communities following progressive or retrogressive trajectories (Hobbs *et al.*, 2013a, b; Milner *et al.*, 2016). These novel approaches have revealed some of the determinants of succession such as disturbance, climate, topographic and substrate factors (Norden *et al.*, 2015; Li *et al.*, 2016) as well as influence of biotic factors (Fridley and Wright, 2012).

### **1.2.2 Generalizations about succession**

Recent reviews on trajectories of primary and secondary succession have yielded a number of generalizations on ecological succession (Chang and Turner, 2019). For instance, based on several succession studies across various ecosystems (Prach and Walker, 2019) observed increase in species richness and more divergent trajectories during primary succession than in secondary succession. The review also observed that recovery rates differ among different biomes and along climatic gradients. In a



study at the Mount St Helens in USA following a volcanic eruption in the 1980, Change *et al* (2019), using a 36 year- data set found out that disturbance severity overrides site history and local factors in shaping trajectories of a succession. Fisher *et al*, (2019) examined the influence of disturbance severity following the eruption of Mount St Helens and reported that recovery was site specific, owing to interaction of the disturbance and initial site conditions. Clark *et al.*, (2019) reported a divergent successional trajectory in the herbaceous community in old-fields, most attributable to site conditions and competition including the “the compensatory trade –offs between colonization and mortality rates”.

Another, generalization was that a number of factors such as proximity to seed source, dispersal capability, site conditions, species interactions, space availability, influence which species colonize and persist in a succession and hence determine the succession trajectories (Jones and del Moral. 2009; Makoto and Wilson, 2016). Further, Makoto and Wilson (2019) and van Breugel *et al.*, (2019) observed that dispersal limitations influence all succession stages and were linked to key processes of ecosystem development such as soil carbon accumulation and vegetation cover. Similarly, soil nutrient status was also added as a key determinant of species composition although its importance decreases in late succession van Breugel *et al.*, (2019). In studies conducted in China, Liu *et al.*, (2019) noted the effect of island size on the composition, diversity and direction of succession, with rates being positively correlated to Island size.

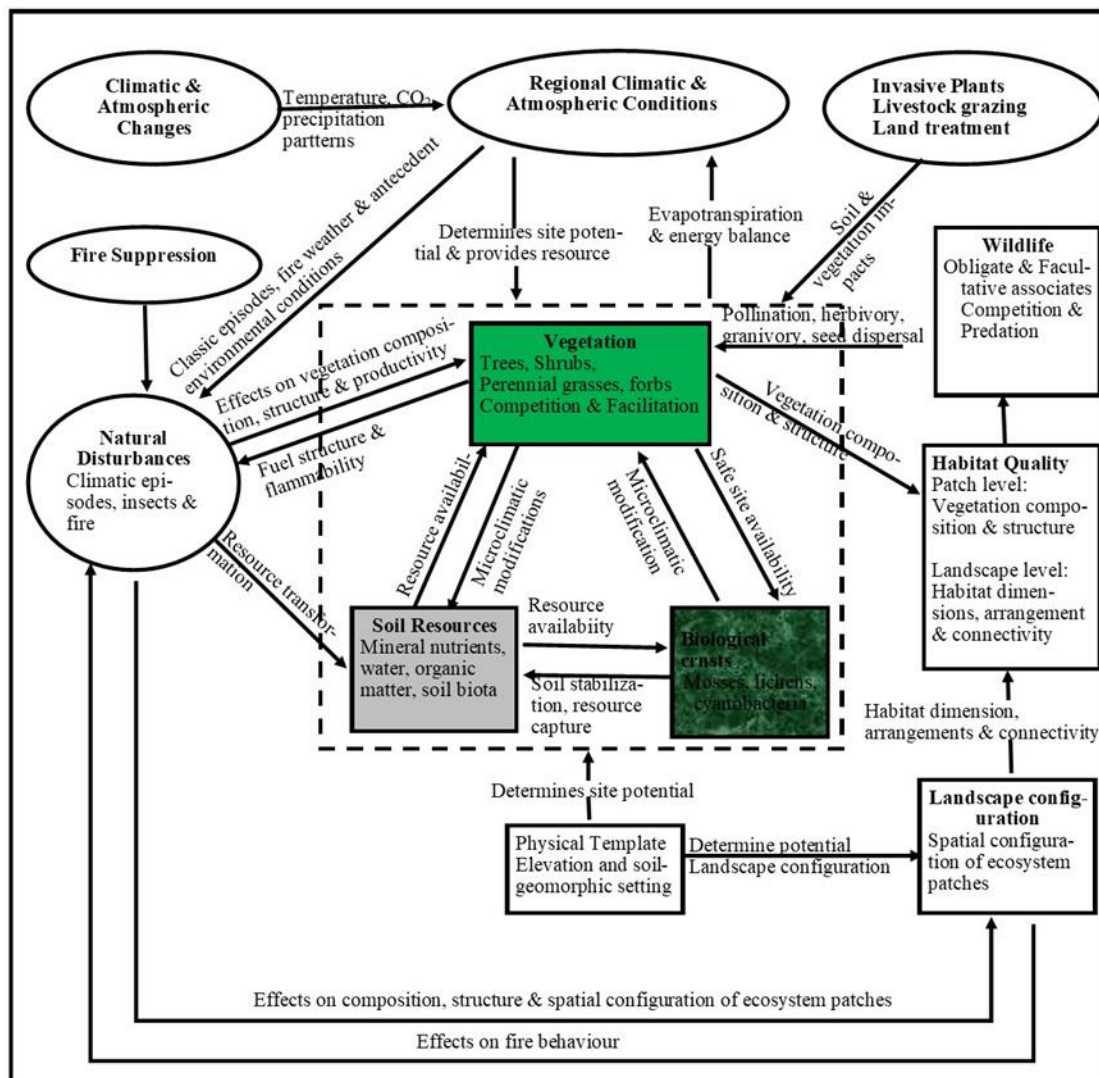
A number of studies across different climatic gradients and timescales have also noted the importance of soil microbes in driving succession (e.g. Whitman and Williams, 2008; Jangid *et al.*, 2013; Uroz *et al.*, 2014; Turner *et al.*, 2019; Koizol and Bever, 2019). Other factors determining succession are natural and human induced disturbance, the interaction between biological crusts and vascular plants and other factors that impact soil resource dynamics (Figure 1.1). Another important generalization is that bare substrates in a primary succession and or open spaces in a secondary succession are eventually occupied by biological crusts (BCs) usually comprising mosses, lichens and some bryophytes, a sere known to engineer the substrate with subsequent replacement by vascular plants or persistence depending on changes in substrate properties (Section 1.2.3).

The accumulation of nutrients and their dynamics in particular nitrogen is reported to be a key determinant of primary succession (Walker and del Moral., 2009). Nitrogen fixers such as BCs and vascular plants in symbiotic relationship with microbes are known to colonize infertile substrates. The plant species colonizing depends on the characteristics of the nitrogen fixers, seed dispersal capability of the species and their effect on the microclimate, (Walker and del Moral, 2003). The dynamics in these substrate and other environmental factors therefore lead to different succession trajectories: progressive, retrogressive and/ or cyclic, which can differ in time scales (Walker and Del Moral., 2009). Usually, nitrogen levels are known to accumulate in a primary succession while phosphorus levels decline as due

to leaching or immobilization of its labile forms (Chang and Turner, 2019). Further, the balance between nitrogen and phosphorus levels in the soils and the plants both is affected and affects successional processes (Sterner and Elser, 2002). On the other hand, alteration of such nutrient ratios either due to active reclamation or natural disturbances leads to differential succession trajectories. Addition of vegetation can also lead to a shift in successional trajectories (Walker and del Moral, 2009).

Another factor that drives primary succession is species interactions owing to species traits. Main mechanisms involved are facilitation and inhibition (Chapin *et al.*, 1994). In addition to dispersal ability, traits such as functional types, germination requirements, growth rates and life spans determine competitiveness of species and in turn succession (Walker and del Moral, 2009). Dispersal and physical stresses limit plant establishment and growth in early primary succession, a situation which is overcome by direct introduction of propagules on the substrate. Models of succession show that seed dispersal usually dictates trajectories in early succession and can be more important than nutrient and water resource availability (Leps *et al.*, 2000; Martineau and Saugier, 2007). The importance of soil properties on vegetation usually occurs after several years (Leps *et al.*, 2000). In this respect, Leps *et al.*, (2007) observed that dispersal limitations create unpredictable successional trajectories.

Germination requirements and time for dormancy breaking can influence vegetation succession (Hooper *et al.*, 2004). Seed predation as well as other natural disturbances can also alter succession trajectories. For instance, invertebrate herbivory has been cited to influence the trajectory of succession by impeding or facilitating plant establishment (Graaf *et al.*, 2007). "As the physical stability and fertility of a primary sere increase, the impact of biotic interactions on succession increases and such interactions can be categorized into facilitative, inhibitive and neutral", (Connell and Slatyer, 1977), with all impacting all succession stages (Chang and Turner, 2019). Important generalizations postulated were: (1) environmental gradients influence the balance between inhibitory and facilitative interactions, and, (2) facilitation dominates where there is more environmental stress (Brooker and Callaghan, 1998), resulting in succession while inhibition tends to arrest succession (Walker *et al.*, 2003; del Moral and Rozzel, 2005). Some studies reported neutral to negative effect of nitrogen fixers on subsequent colonizers (Walker and Vitousek, 1991, Walker and del Moral, 2003).

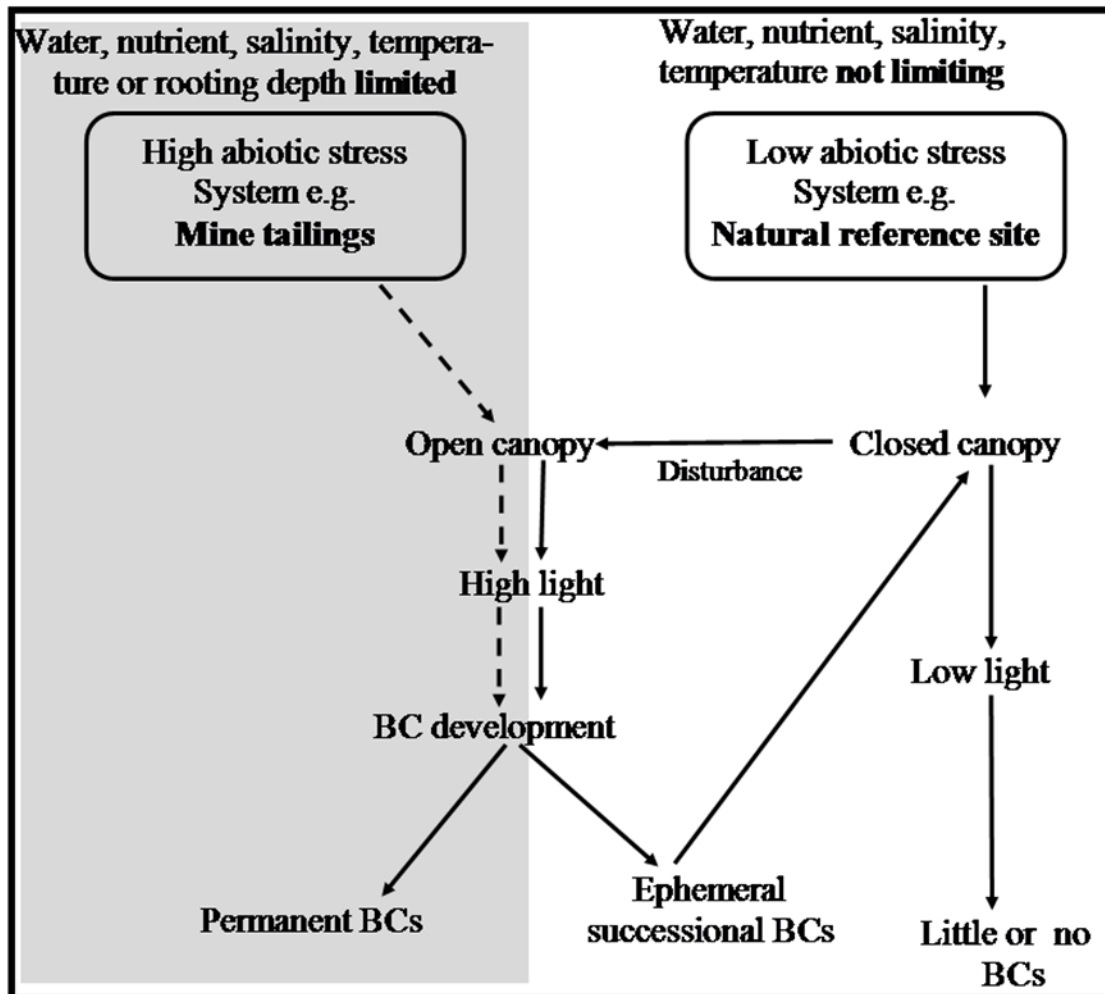


**Figure 1.1:** Schematic diagram showing succession and its general determinants in an ecosystem (Adapted from Higgs *et al.*, 2016).

### 1.2.3 Development of BCs and relationship with vegetation in succession

Biological crusts (BCs) are known early succession seres with ecological engineering capabilities (Clements, 1916; Belnap *et al.*, 2001a; Bowker *et al.*, 2007). These alter substrate hydrological properties and nutrient cycles at least in the top layers (Chamizo *et al.*, 2012). BCs tend to increase with time but are replaced by vegetation in a succession owing to shading effects and competition for space (Bowker, 2007; Langhans, 2008). In highly abiotically stressed environments such as deserts BCs tend to be a permanent feature of the system (Chamizo *et al.*, 2012). However, in low abiotic stress environments or where there is temporal improvement in biotic factors, ephemeral BCs exist and they are subsequently replaced by vegetation (Figure 1.2). Marked disturbance in a dense forest can also result in development

of BCs in a succession (Figure 1.2). BCs have adaptive traits e.g. a photo-protective pigment and N and C fixation that help them withstand hostile environments (Bowker *et al.*, 2002; Bowker, 2007). BCs and plants interact through different pathways with a net facilitative or inhibitory effect in a succession (Figure 1.1). Walker and del Moral (2003) reported that sometimes BCs inhibit the establishment of later seres. This aspect was never investigated on mine tailings but in this thesis it was investigated in Chapter 5.



**Figure 1.2:** Schematic diagram illustrating succession of BCs in high and low abiotic stress systems (adapted and modified from Bowker, 2007).

#### 1.2.4 Primary succession on anthropogenic soils

Many studies of succession on anthropogenic substrates have shown differential results on vegetation dynamics (Gibson *et al.*, 1985; Rebele, 1992; Mars and Bradshaw, 1993; Martinez Ruiz *et al.*, 2001). Some studies reported species turnover in a succession whose rate was dependent on the original parent material (Tilman, 1988; Martinez Ruiz *et al.*, 2001), nutrient availability (Piha *et al.*, 1995), amelioration

(Luken, 1990, Piha *et al.*, 1995), seed immigration (Parrota and Knowles, 2001), climate (Major, 1974) and topography in particular exposure (Martinez Ruiz *et al.*, 2001). Some studies observed more annual plant species in number and cover than perennial plant species for all stages of succession and that climate affected annuals more than perennials (Martinez Ruiz *et al.*, 2001).

Several studies observed a decrease in plant species turnover during primary succession (Titlyanova and Mironycheva-Tokareva, 1990, Prach *et al.*, 1993; Martinez Ruiz *et al.*, 2001). In some cases succession converged compositionally to reference site conditions at rates that depended on factors such as substrate, texture and exposure (Martinez Ruiz *et al.*, 2001).

In temperate areas, the main factors controlling ecological succession are climatic gradients, landscape factors, nearby vegetation, substrate properties (Prach *et al.*, 2007). Key constraints are soil deficiencies and toxicity (Bradshaw, 1997). Similarly, soil acidity, metal and salt toxicity are among factors impeding vegetation establishment on mining sites (Bradshaw, 1997; Prach and Pysek, 2001). In Spain the divergent succession trajectory was the main one observed, determined mainly by the initial conditions of the coal mine substrate and the conserved adjacent vegetation patch (Moreno *et al.*, 2008). Similarly, in central Europe, initial conditions such as substrate pH and meso-climatic gradients have been shown to be key drivers of succession trajectories (Prach *et al.*, 2007).

Studies done outside southern Africa focused on tailings other than gold/nickel in temperate or arid biomes, with savanna underrepresented (Skousen *et al.*, 1994; Boerner *et al.*, 1998; Holl, 2002; Reid and Naeth, 2005; Sourkova *et al.*, 2005; Martinez-Ruiz and Fernandez-Santos, 2005; Singh, 2006; Martinez-Ruiz *et al.*, 2007; Mukhopaday and Maiti, 2011; Rahmonov and Parussel, 2011; Alday *et al.*, 2011; Kullu and Behera, 2011). Many of these studies identified key species occurring on the substrates and their changes along environmental gradients. Most of the studies that were done to investigate trajectories of vegetation development on anthropogenic substrates (Gibson *et al.*, 1985; Rebele, 1992; Mars and Bradshaw, 1993; Martinez-Ruiz *et al.*, 2001) were done on non-tailings material and also yielded differential results. In some cases succession converged towards the floristic composition of reference sites even though at different rates depending on site conditions such as substrate, exposure and texture (Martinez Ruiz *et al.*, 2001). However, such studies were only exploring species composition and seldom factored in abundances and structure in assessing restoration trajectories.

Most importantly, all these studies did not evaluate the changes of BCs along with vascular plants and their interrelationship with substrate and other local factors despite this being critical (Bowker, 2007). Further, combined investigation of different tailing substrates, with different rehabilitation history spontaneous vegetation and assisted revegetation following reclamation but sharing similar climatic conditions as is in the current study has never been explored from a successional trajectory context. In all

studies mentioned above, mainly substrate factors explored in a succession were carbon accumulation and fertility changes without combining dynamics in other physicochemical properties such as metals, exchangeable bases, salinity and compaction. While most studies reported nutrient accumulation in a succession, this was mainly attributed to mycorrhizal association between nitrogen fixing vascular plants, fungi and bacteria but biological crusts were not explored from a succession context.

In Southern Africa, a few studies focused on identifying species occurring on mine wastes (e.g. Hill and Nothard, 1973; Leteinturier *et al.*, 1999, Weirsbye *et al.*, 2006), several on early assisted recovery (e.g. Hill, 1977; Piha *et al.*, 1995, Weiersbye and Witkowski 2002; Mulizane *et al.*, 2005; Rossouw, 2009; Nyakudya *et al.*, 2011., Lange *et al.*, 2011, Lange *et al.*, 2012, Festin *et al.*, 2018), some on soil microbial development ( Weiersbye *et al.*, 1999, Straker *et al.* 2007, Straker *et al.*, 2008, Liebenberg *et al.*, 2013), while a few used remote sensing technologies to assess vegetation recovery (e.g. Gowo and Kativu 2013). Key findings from such studies were identification of tolerant species to mine tailings in particular gramminoids and optimum macronutrient ameliorants for best growth performance. No attempt was done to explore the temporal substrate and vegetation changes to test existing classical ecological restoration or succession theoretical frameworks nor the emerging novel ecosystem concept. Studies linking specific vegetation succession trajectories and their determinants (e.g. Anawar and Freitas, 2012) are limited. While many scholars above reported vegetation attributes on mine tailings were directly linked to nutrient status, metals, microbes, pH, age, substrate, sodium, texture, it is not clear whether this applies for gold and nickel tailings and whether these parameters remain limiting factors over time or are overwhelmed by climatic gradients or local microsite factors.

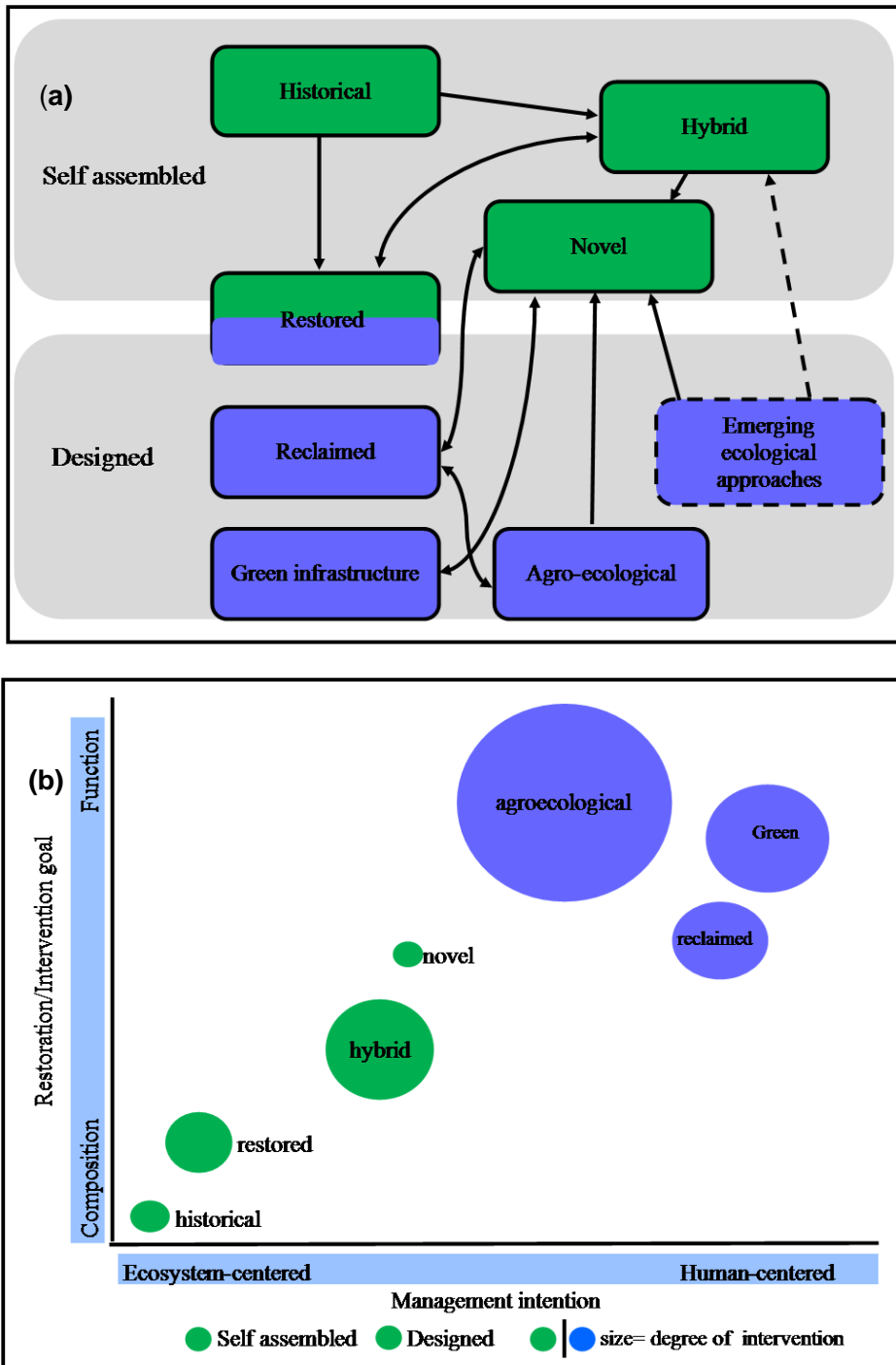
#### **1.2.5 The emerging novel ecosystem concept and the restoration conceptual framework**

The concept of novel ecosystems has recently gained popularity (Chapin and Starfield, 1997; Hobbs *et al.*, 2006, 2009), although it has caused controversy (Hobbs *et al.*, 2014; Murcia *et al.*, 2014; Simberloff *et al.*, 2015, Milner *et al.*, 2016). At its inception novel ecosystems were distinguished by two characteristics: (1) unique species combinations and (2) a genesis in human action (Hobbs *et al.*, 2006). The controversy resulted in proposals for change of terms to “transformed” ecosystems (Aronson *et al.*, 2014) or, “emerging ecosystems”, (Clewell and Aronson, 2013). With more acceptance of the term novel ecosystems, the definition has changed slightly to “a system of abiotic, biotic and social components including their interactions that by virtue of human influence, differs from those that prevailed historically, having a tendency to self-organize and manifest novel qualities without intensive human management” (Hobbs *et al.*, 2013b). The most distinguishing characteristics of such novel ecosystems is their incapacity to be restored to historical states (Hobbs *et al.*, 2013b).

Novel ecosystems are a possible trajectory for both naturally assembling systems and or those human engineered or designed. Similarly restoration in composition, structure and function is a possible trajectory of both naturally assembling and human designed systems (Higgs *et al.*, 2016). Figure 1.3 illustrates the novel and restoration trajectories as a result of both natural processes and human intervention. Designed systems can over time become restored or become novel ecosystems (Higgs *et al.*, 2016). However, contrasting views on novel ecosystem is based on irreversibility and the native species concept (Milner *et al.*, 2016).

Based on the above literature the current study viewed ecosystem development on unique anthropogenic sites such as mine tailings to follow a trajectory towards formation of novel ecosystems particularly where there was no reclamation. Alternatively, reclamation by applying nutrients and planting a few leguminous native species among other factors would drive the ecosystem towards restoration of pristine conditions in terms of vegetation composition and structure (Figure 1.4). In this study novelty was determined by the extent of divergence from adjacent reference site conditions in terms of species composition, combinations and structure over time (Hobbs *et al.*, 2006), without showing a reversal (Hobbs *et al.*, 2013a). Restoration or convergence was taken as sustained movement of ecosystem towards reference conditions structurally and compositionally. In this study woody species of the *Vachellia* and *Senegalia* genus were used interchangeably with the relevant *Acacia* genus.





**Figure 1.3:** Conceptual diagram showing how novel ecosystems are distinguished from restored, historical and designed ecosystems. (a) Trajectory of self- assembled and designed systems to novel ecosystems. (b) Novel ecosystems are distinguished from restored or historical ecosystems depending on degree of human intervention. The size of each circle approximates the relative level of human intervention. (Diagram adapted from Higgs *et al.*, 2016).



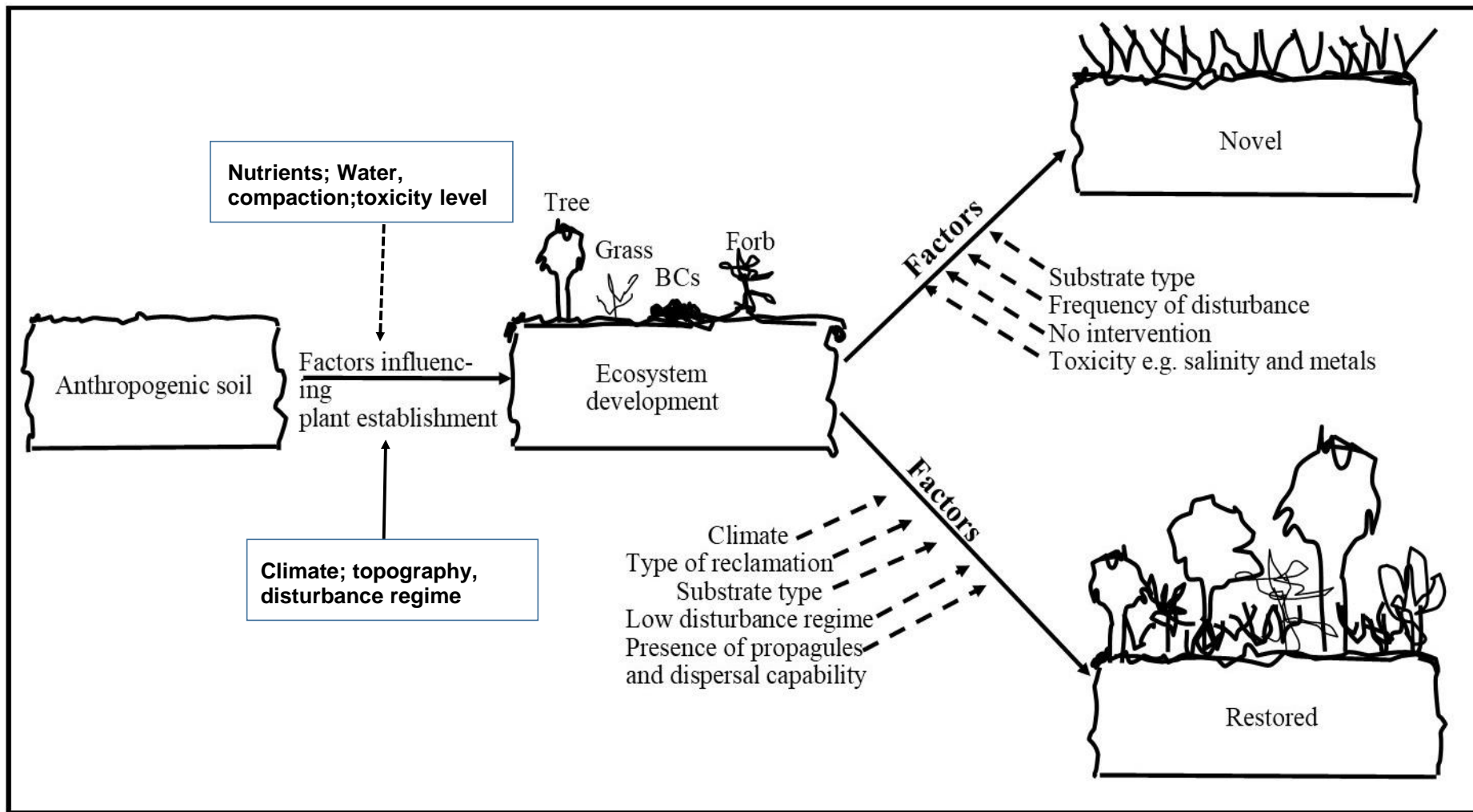
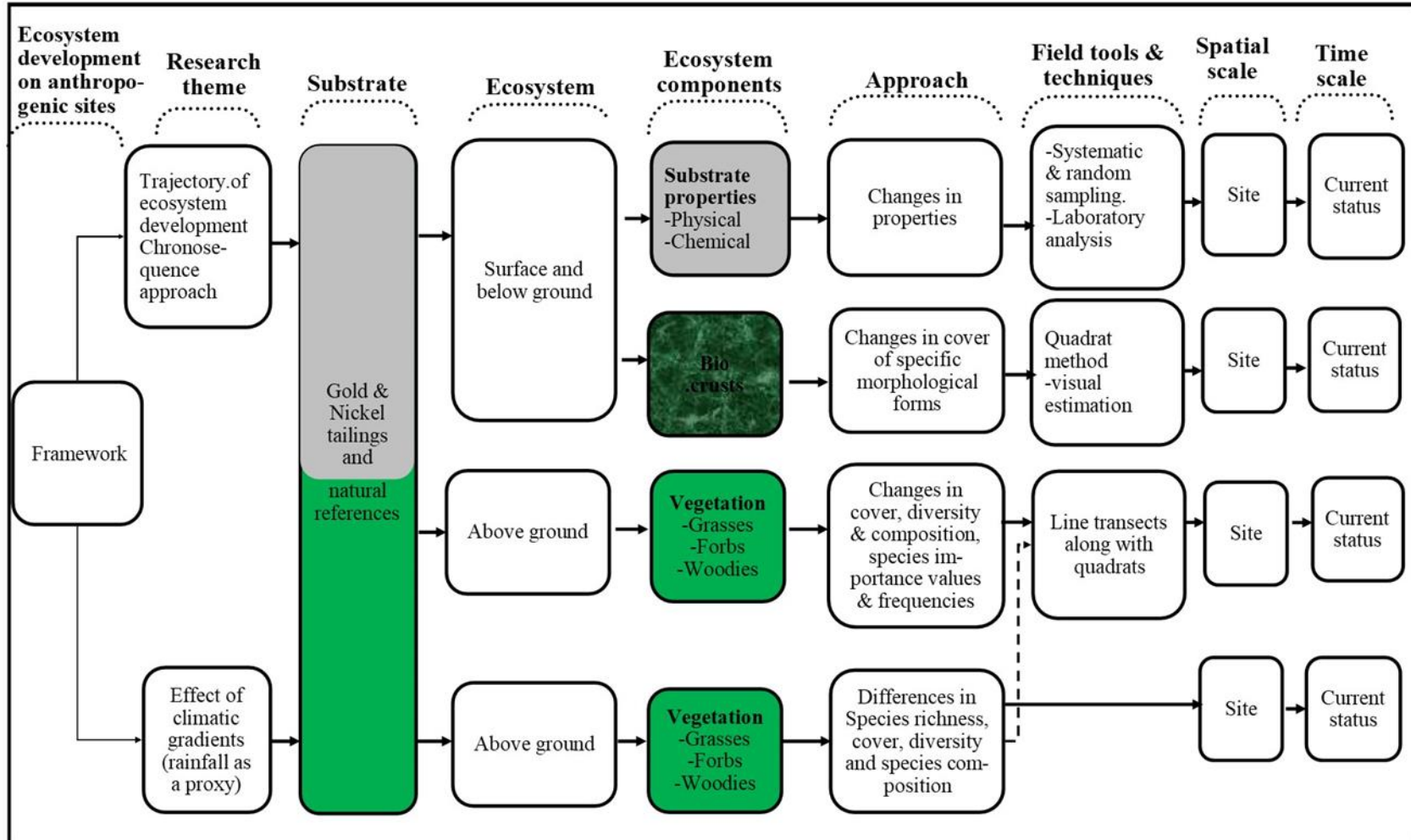


Figure 1.4: Theoretical framework for ecosystem development on mine tailings in Savanna.

### **1.5 Study framework**

Theoretically, revegetation on tailings can be explained using the divergent and convergent trajectories all tracked through state transition models, permanent plots and or chronosequences approaches that substitute time for space. The study adopted a unique approach of jointly investigating individual and interactive effects of substrate, topographic, climatic, biotic factors and management history in a succession. The study used a unique approach that simultaneously tested trajectories of ecosystem development on mine tailings under contrasting reclamation histories, spontaneous revegetation versus assisted revegetation (reclamation or rehabilitation). The study explored ecosystem development through investigating trajectories of multiple ecosystem components such as Soil development, Biological soil

crusts and vascular plants including their interrelationships. On each ecosystem component, the study adopted multiple factor assessment approaches, for instance substrate changes focused on both physical and chemical properties, biocrusts focused on multiple morphological forms while vegetation looked at structural and compositional attributes including plants of all growth forms such as trees, grasses and forbs. The main theme adopted was a chronosequences approach based on tailings of different ages, all tested relative to natural reference sites. To investigate the effect of climatic gradients mine tailings situated in different climatic regions using rainfall as a proxy were used. Main ecosystem components studied were soils using selected parameters as proxies for pedogenesis, biological crusts, herbaceous and woody plants and their interrelationships in a succession. Main vegetation attributes measured were species richness, diversity, composition, vegetation cover. Line transects along with quadrats were the main research tools used. Fig 1.5 shows the framework used.



**Figure 1.5:** Conceptual diagram showing main research themes, approaches, ecosystem components and methods used. General methodology details in Chapter 2; detailed methods in specific chapters.

## 1.3 Research focus

### 1.3.1 Research rationale

Few ecological principles exist that can be used for restoration or rehabilitation of mining-affected areas. However, in order to stand a chance to be successful, mine restoration plans need to incorporate context specificity. Globally, there is a surge in mining activities where a number of mines are expanded while new ones are commissioned regularly, all requiring post-mining restoration plans. Mineral processing yields large amounts of tailings globally estimated to be 7 billion tonnes per annum (Edraki, 2014) which pose great environmental risks such as loss of biodiversity, water pollution related to acid mine drainage, air pollution related to dust and pollution of adjacent sensitive wetlands and agricultural lands due to their susceptibility to erosion. Such environmental risks usually persist due to the hostile physical and chemical properties of the tailings, which often change over time, impeding vegetation colonization and persistence. Trajectories of plant succession and associated temporal changes in substrate properties and their interrelationships on gold and nickel tailings in similar and across climatic gradients have not been widely reported. Empirical studies that inform the local mine tailings restoration efforts are therefore few. While globally, variations in plant composition, diversity and structure have been linked to substrate heterogeneity and climatic variation, little has been reported on the generality of this among different mine wastes. Based on some studies done on both natural and anthropogenic sites, two main contrasting theories on trajectories of vegetation of mine sites exist: (1) the convergence theory which assert progression of ecosystems to pristine conditions and, (2) the divergence theory widely known as the novel ecosystem concept which assert multiple end points that are distinct from the pristine conditions. While, important generalizations about mechanisms driving these succession trajectories have been made, for instance the importance of existence of sources of propagules, seed dispersal capability, substrate factors, climate, topography and species interactions (Makoto and Wilson, 2016), these generalizations have not been tested in the context of gold and nickel tailings. Further, the two contrasting revegetation trajectories have never been simultaneously tested on mine tailing chronosequences under different management regimes, in particular on rehabilitated tailings versus those left to natural succession. Studies that jointly investigate multiple ecosystem components such as soil development, changes in biological crusts and vascular plants of all growth forms and their interrelationship in a primary succession context are very limited. This means the generalization of traditional restoration conceptual frameworks is questionable as they need to be updated by results from empirical studies testing emerging ecological theories in a wide range of contexts.

While restoration goals have been defined in terms of structural and compositional replication, functional success, durability, vigour and organization, these seem to be generalized (Hobbs and Harris, 2001). Certainly, some general ecological principles may be applicable to mining restoration, and there is a

continued quest to derive such generalities. Unanswered questions remain on how to turn these general principles and specific place-based structural and functional issues to effective goals for specific mining restoration projects. The present study thus examined the specific trajectories of ecosystem development on different substrates (gold and nickel tailings), testing generic and emerging conceptual and theoretical frameworks while unearthing site specific feedbacks that will contribute to modification of theories and implementation of successful restoration projects.

### **1.3.3 Primary objectives**

The primary objective of the present study was to establish the trajectory of vegetation structural and compositional attributes on a chronosequence of abandoned gold and nickel tailings with reference to adjacent natural vegetation matrices, and to identify physical, chemical and biological substrate correlates in order to understand restoration of unique anthropogenic sites. The secondary objective was to test the contribution of local site factors such as topography and climatic gradients and their interaction with substrate age on revegetation of the mine tailings.

### **1.3.4 Overall research questions**

1. Do vegetation trajectories of vegetation succession on unrehabilitated gold and rehabilitated nickel tailings resemble convergence to pristine conditions or divergence towards formation of novel ecosystems?
2. How do physicochemical properties of gold and nickel tailings vary over time and how do they relate to vegetation patterns?
3. Are the occurrence patterns of vegetation affected by tailings age, type, local topographic factors and or climatic gradients?
4. What are the occurrence patterns of BCs on gold tailings and what are their relationship with substrate and vegetation attributes?

### **1.3.5 Specific objectives**

The specific objectives of the study were:

1. To assess changes in physicochemical properties on a chronosequence of abandoned gold tailings.
2. To compare physicochemical properties of bio-crusts on tailings and those without.
3. To assess the occurrence patterns of biological crusts and their relationship with vegetation structural and compositional attributes on a chronosequence of abandoned gold tailings.

4. To assess the trajectory of natural vegetation development (structural and compositional attributes) on a chronosequence of abandoned gold tailings, testing the novel ecosystem theory.
5. To assess the trajectory of natural vegetation development (structural and compositional attributes) on a chronosequence of reclaimed nickel tailings, testing the novel ecosystem theory
6. To assess the variation in vegetation structural and compositional attributes on tailings of different ages situated along a climatic gradient along the great Dyke region in Zimbabwe.

### 1.3.6 Research Hypotheses

- Due to pedogenic processes plant macronutrients (N, P, K), organic carbon, organic matter and fine particles content increase with tailings age and approach reference levels and that pH, EC and bulk density decrease with age of mine tailings
- Due to ecological engineering capability of BCs, physicochemical properties of bio-crusts areas are significantly different from those of areas without
- BC cover significantly increased with tailings dump age and was positively correlated to vegetation cover, species richness, density and that vegetation communities significantly varied along a BC cover gradient
- Due to the uniqueness of the substrate, natural revegetation of gold tailings is towards formation of novel plant communities as vegetation attributes do not converge to natural reference conditions
- Vegetation structural and compositional attributes on rehabilitated mine tailings converge to natural references due to the accelerating effect of rehabilitation and,
- Climatic gradients have significant effect in shaping plant structural and compositional attributes on unrehabilitated and rehabilitated mine tailings.

#### 1.4 Merit of scientific contribution of the research

The study is one of the first to test the emerging novel ecosystem concept in a mine tailings restoration context, in particular, employing a factorial approach that investigated individual and interactive effects of substrate age, climatic gradients, local site topography, and local site physical and chemical heterogeneity on both rehabilitated and unrehabilitated mine tailings in a savanna region. The results of this unique approach will increase the generalizability of the scientific results in making inferences about trajectories of ecosystem development on anthropogenically derived substrates. This is an important ecological imperative considering that mine restoration and or rehabilitation is based on manipulation of the natural succession potential of the substrates yet currently there is wide scientific debate on the succession trajectories (Hobbs *et al.*, 2014; Murcia *et al.*, 2014, Simberloff *et al.*, 2015, Milner *et al.*, 2016), with only general ecological grounding within restoration programs. The outcome of the research will contribute to clarifying the confusion caused by the debates and increase the application of scientific lessons to restoration programs by mine managers, a situation which is not currently wide spread (Walker and del Moral, 2009, Chang and Turner, 2019). The factorial approach employed ultimately gives a broader view and potentially a more reliable knowledge base, derived from detailed results and information from different view-points about restoration trajectories and mine tailings floristic composition.

The study is also one of the first to assess the successional trajectories using biota such as biocrusts and vascular plants of all growth forms including their interactions, in a succession that exceeds a century, a scenario that satisfies the multiple-component analysis highly required in ecosystem development modelling, yet often missing in previous studies (Martinez Ruiz and Santos, 2005; Young *et al.*, 2012; Festin *et al.*, 2018). New information gained will positively influence ecological theories on trajectories of primary vegetation succession on specific and unique anthropogenic substrates. Ultimately, lessons of vegetation succession gleaned from studies of unrehabilitated and rehabilitated mine tailing chronosequences will contribute to effectiveness of restoration practices on anthropogenic sites (del Moral and Walker, 2007). This will provide the basis of incorporation of scientific empirical evidence into land rehabilitation or restoration policies that specifically couple ecological and engineering tools to optimize ecosystem recovery, for instance after disturbances of different magnitudes. Ultimately, this will assist in achieving basic restoration goals such as increased plant cover and biodiversity. The approach used in this study is likely give insights into both the natural potential and effect of human intervention including estimate time-frames for achieving restoration.

The results of the occurrence of BCs, their edaphic correlates and their relationship with vascular plants in a succession (Chapter 4 and 5) give insights into the ecological engineering capabilities of biocrusts which can be harnessed in planning revegetation programs. Insights obtained here will inform manipulation of the BCs as substrate ameliorants in tailings rehabilitation. The replication of



compositional studies at many sites across a climatic gradient (Chapters 7 and 8) yielded results that have high external validity. Outcomes can be used to inform restoration programs in areas of varying climatic regimes, and scientific inferences made from such results can aid in planning restoration programs in light of the currently experienced and projected climate changes.

The approach of following trajectories of dominant species in a succession using their importance values (SIVs) and or frequencies along with testing the initial floristic composition succession model (Chapters 6 and 8) will give insights into their response to inhospitable environments. This together with identification of main species colonizing mine tailings in different climatic regions (Chapter 7) will allow the identification of plant species that can tolerate wider ranges of conditions which can be more useful in restoration, than pioneer or ruderals that might have a thin environmental tolerance range (Chang and Turner, 2019). This is critical in the face of inevitable environmental changes.

The simultaneous use of chronosequences, climatic gradients and local landscape factors will allow the identification of physical and physiological requirements of specific plant species, their competitive and facilitative abilities and their responsiveness to temporal changes in substrate fertility, salinity and other factors. Ultimately insights on the nutrient and carbon dynamics, species colonization, establishment and their temporal interactions will be useful in highlighting transitions between plant communities giving invaluable information on vegetation trajectories. This understanding of changes in vegetation is a critical input into the planning of restoration programs (Walker *et al.*, 2007a). Lessons from the study will guide restoration by providing insights into purposeful manipulation of succession (Bradshaw and Chadwick, 1980; Walker *et al.*, 2007). Restoration programs that are benchmarked against some of the research outcomes are most likely to be effective and cheaper when compared to current practices. Ultimately, environmental impacts associated with non-rehabilitated mine wastes will be reduced as rehabilitation success increases.

To mine owners and restoration practitioners, the results will provide baseline monitoring output benchmarks which will be used in future to assess if restoration is moving in the desired direction or not. This knowledge has been widely lacking except for basic cover change determinations (Dowo and Kativu, 2013). These could serve as benchmarks for future studies on other anthropogenic sites or similar ecosystems. Future studies can also use methods and approaches employed in the current study as reference points or modify them based on what they managed to achieve if improvement is desired. The research outcome can be used by environmental management agencies in developing mine restoration standards or guidelines that factor in time and succession principles which is widely lacking in Africa.

## **1.5 Thesis layout and structure**

This thesis is compiled as a series of nine chapters. The first chapter sets the background and describes the theoretical framework, and framework for the study. The second chapter profiles the study area description and general methodology. The chapters numbered three to eight are the data chapters and comprise the main body of the thesis. They have been written in the format of journal articles, each as a stand-alone unit already published and or prepared for publication. As a result, some repetition between the various papers has, therefore, been inevitable especially regarding description of the study area, materials and methods and data analysis, which needed to be restated in some of the chapters. However, I endeavoured to keep repetition to a minimum level. To avoid repetition, references for all chapters are found at the end of the thesis. The thesis follows the following specific structure as summarized below:

### **Chapter 1: Introduction**

The opening chapter provides a general introduction explaining the background to the study explaining physical, chemical and biological properties of mine tailings, theoretical concepts around vegetation succession, and approaches to revegetation and restoration of degraded sites used world –wide. In addition, it highlights the research problem, aims, questions and hypotheses, theoretical and conceptual frameworks underpinning the research. It ends by highlighting the merit of the scientific contribution of the study and describing the outline of the thesis.

### **Chapter 2: Study area and general methodology**

The second chapter provides the background about the study area, covering a description of the main bio-physiographical characteristics of ecological importance. Such features include geographical location, topography, geology, hydrology, soil, flora, fauna, and it describes the main bio-physiographical features that influence the ecological processes. The chapter then describes an account of the tailings deposition and management or rehabilitation history. It ends by giving an overview of the general methodology used in the entire study.

### **Chapter 3: Changes in physicochemical properties on a chronosequence of gold mine tailings.**

The third chapter, and first data chapter, investigated the temporal dynamics of physicochemical properties of unrehabilitated gold tailings ranging from fresh deposited tailings to 110 years after deposition. The main properties that were investigated were: macronutrients, particle size distribution, micronutrients, salinity, pH and compaction at varying depths on a chronosequence of six tailings dumps and freshly deposited tailings, all compared against adjacent reference sites. These few parameters were used as proxies of pedogenesis.

#### **Chapter 4: Biological crusts enhance fertility and texture on gold mine tailings**

The fourth chapter, and second data chapter investigated and compared physicochemical properties of substrate under biological crusts and those without on the two dumps (82 and 92 years), that had highest BC covers. The main parameters investigated were: N, OC, pH, exchangeable bases and texture. Investigations covered the crusts and the underlying top 5 cm layer. This Chapter was published in the journal Ecological Engineering (<https://doi.org/10.1016/j.ecoleng.2019.03.007>).

#### **Chapter 5: Occurrence of biological crusts and their relationship with vegetation on a chronosequence of gold mine tailings**

The fifth chapter, and third data chapter, investigated the morphological forms of biological crusts and their changes in cover along a tailings age gradient along with their substrate correlates. The chapter also investigated vegetation structural and compositional attributes on a BC cover gradient and examined the correlation among BC cover and vegetation attributes on dumps of different ages. This Chapter was published in the journal Ecological Engineering (<https://doi.org/10.1016/j.ecoleng.2019.07.029>).

#### **Chapter 6: Is the trajectory of natural vegetation recovery on a chronosequence of gold tailings towards a novel ecosystem?**

The sixth chapter, and fourth data chapter, examined the changes in structure, composition and diversity of vegetation on a chronosequence of abandoned gold tailings left to spontaneous vegetation succession in relation to adjacent natural vegetation matrices, particularly to test the emerging revegetation theory of possible formation of novel plant ecosystems. This chapter also examined the substrate physicochemical correlates to the vegetation patterns on the gold mine tailings.

#### **Chapter 7: How does floristic composition and structure on gold mine tailings vary along a climatic gradient?**

The seventh chapter, and fifth data chapter, examined the variation of vegetation composition and structure on tailings dumps situated along a climatic gradient throughout the Great Dyke region of Zimbabwe. The chapter tested the individual and interactive influence of tailings age and rainfall gradients on vegetation cover, plant species richness, composition and on different plant growth forms and life cycles. Rainfall was used as a proxy of climate.

#### **Chapter 8: Is the trajectory of vegetation development on a chronosequence of rehabilitated nickel tailings towards or away from a pre-disturbance natural reference?**

The eighth chapter, and final data chapter, examined the changes in structure, composition and diversity of vegetation on a chronosequence of rehabilitated nickel mine tailings in relation to adjacent natural

vegetation matrices, particularly to test the convergence trajectory observed with unrehabilitated tailings in Chapter 6. This chapter also examined the substrate physicochemical correlates to the vegetation patterns on the nickel mine tailings, and also tests the effect of climatic differences on vegetation structural and composition on rehabilitated nickel tailings.

### **Chapter 9: Synthesis and general discussion**

The final chapter integrated and synthesized all the results obtained from the previous chapters, and aimed to come up with general conclusions about the trajectory of vegetation development on mine tailings in Savanna Zimbabwe. The chapter explains the implication of the results obtained to broader theory and restoration praxis, particularly highlighting where results fit into existing theories, expand existing theories and or generated new scientific thinking. This chapter also used the knowledge gained to suggest recommendations for rehabilitation of tailings and other anthropogenic sites. It ends by giving a critical evaluation of the methodological framework used and giving direction for future research.

## CHAPTER 2

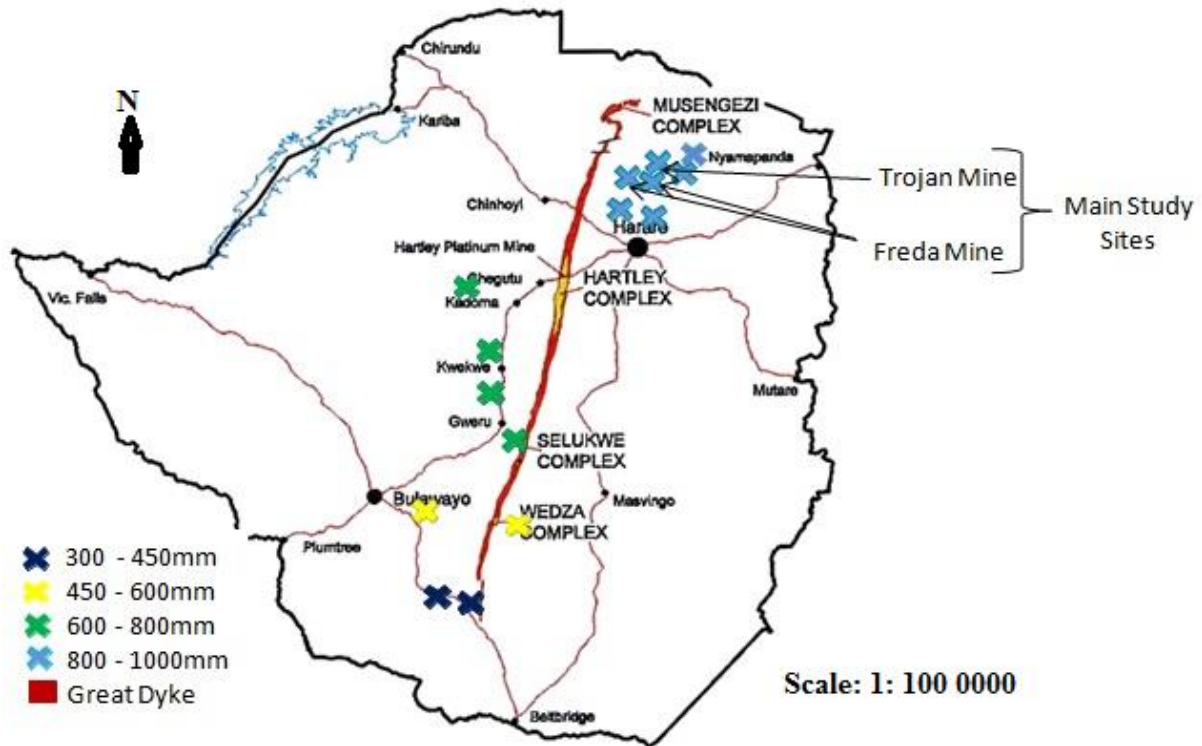
### STUDY AREA AND GENERAL METHODOLOGY

#### 2.1 Introduction

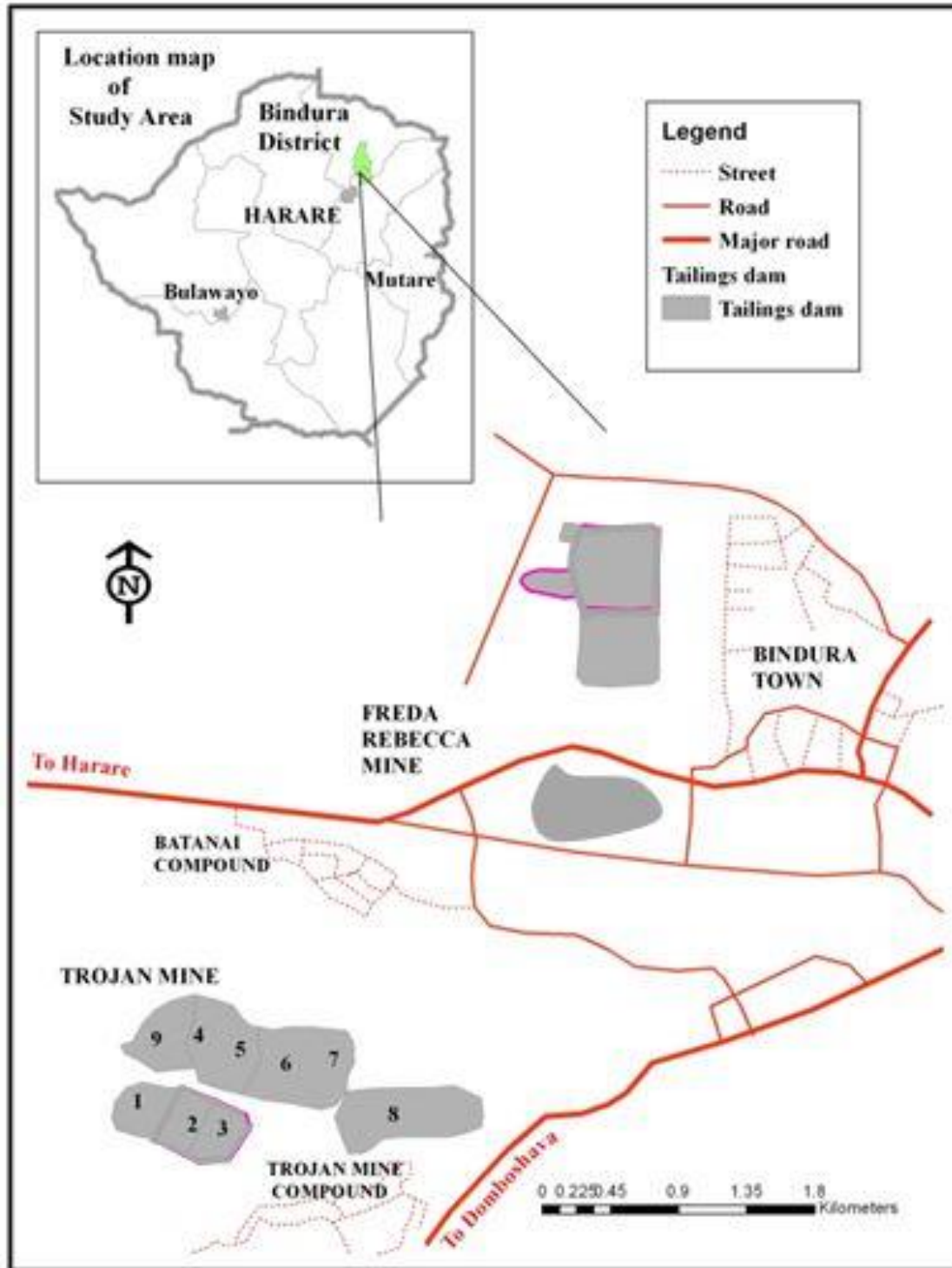
The second chapter provides the background about the study area, describing the main bio-physiographical characteristics of ecological importance. Such features include geographical location, topography, geology, hydrology, soil, flora, fauna, i.e. the main bio-physiographical features that influence the ecological processes. The chapter then gives an account of the tailings deposition and a short overview of the history of reclamation management. The chapter ends with a general overview of the methodology used in this study.

#### 2.2 Location of the study area

The study was carried out at 16 mine sites (14 gold and 2 nickel mines) across Zimbabwe (Figure 2.1). However, the main study sites were Freda Rebecca gold mine and Trojan nickel mine, located approximately 4 km apart in the Bindura district in the north-eastern part of Zimbabwe (Fig 2.2). Freda Rebecca gold mine lies at latitude 17°17' S and longitude 31°18' E, and an altitude of 1070 m, while Trojan nickel mine, lies at latitude 17°19' S and longitude 31°16' E and an altitude of 1080 m, Fig 2.1) in Bindura district. Specific study locations were mine tailings of different ages deposited at the two mine sites (Fig 2.2). The two were selected as the main study sites as they had several mine tailings of different ages (up to 110 years) that provided an opportunity of the study of the trajectory of ecosystem development. The Freda Rebecca mine site had unrehabilitated mine tailings largely subjected to natural succession and was suitable for testing the novel ecosystem concept without human intervention (Chapter 6) while the Trojan mine site had a chronosequence of rehabilitated mine tailings that allowed the testing of the same ecological theories on anthropogenic sites subjected to some human intervention. The main sites were also selected on the basis of their proximity to each other which would ensure similar climatic conditions thus reducing confounding bias when comparing revegetation trajectories. The other secondary mine sites were scattered along the great dyke area and were selected on the basis of them meeting the following criteria: (1) they had mine tailings of different ages, (2) were found in different climatic regions, (3) had no or minimal reclamation.



**Figure 2.1:** Location of study sites in Zimbabwe. Crosses resemble mine site. Different colours if crosses resemble climatic gradients. Complexes are gold complexes along the Great Dyke. Arrows not to scale.



**Figure 2.2:** Map showing the two main study sites: Freda Rebecca and Trojan nickel mine tailings. Numbers on top of tailings denote tailings dump identity at the site.

## 2.2 Climate

The two main study sites (Freda Rebecca and Trojan nickel mines sites) experience a savanna climate characterized by wet summers and dry winters. Based on climatic data of the past 37 years, Bindura receives an average annual precipitation of 879 mm and has an average annual temperature of 28°C (Zimbabwe Meteorological Services, 2018). The rainfall is predominantly received in summer, mainly from November to March. The prevailing wind direction is north westerly.

The other ancillary sites also experience a savanna climate characterized by warm wet summers and cool dry winters. The total annual rainfall for the sites range from 432 mm -879 mm (Meteorological Services, 2018). The climate and geologies for the 14 ancillary study sites are detailed in Table 2.1.

**Table 2.1:** Average annual rainfall data for the main and secondary study sites based on climatic data from 1980- 2017. S in geology denotes Shamvaian while B denotes Bulawayo metasediments.

Site	Geology	Rainfall range (mm)	Average Rainfall (mm)
Vumbachikwe	S&B Meta	300-450	432
West Nicholson	S&B Meta	300-450	432
Sabi	S&B Meta	450-600	546
How Mine	S&B Meta	450-600	559
Chakari	S&B Meta	600-800	760
Connemara	S&B Meta	600-800	644
Kwekwe	S&B Meta	600-800	644
Shurugwi	S&B Meta	600-800	676
Freda	S&B Meta	800-1000	879
Phoenix	S&B Meta	800-1000	879
Ran Mine	S&B Meta	800-1000	879
Shamva	S&B Meta	800-1000	816
Acturus	S&B Meta	800-1000	847
Mazowe	S&B Meta	800-1000	824
Trojan	S&B Meta	800-1000	879
Shangani	S&B Meta	450-600	559

## 2.3 Geology and soils

Freda Rebecca mine site is approximately in the central axis of the Bindura-Shamva Greenstone Belt. Metamorphic mineral assemblage indicates green schist facies to upper amphibolites facies and a range of metamorphic grades across the belt. The metadiorite host the bulk of the mineralization associated with the mining operations. The local geology is typically a greenstone configuration composed mainly of basaltic rocks (gabbro and tholeiitic basalts) combined with banded iron formations and volcanic tuffs (Masvodza *et al.*, 2013). The gold ore that produces the tailings consists of pyrite (FeS<sub>2</sub>), pyrrhotite (FeO<sub>8</sub>S), and arsenopyrite (FeAsS) as the major minerals with chalcopyrite (CuFeS<sub>2</sub>), bornite (Cu<sub>5</sub>FeS<sub>4</sub>)



and pyrolucite ( $\text{MnO}_2$ ) as minors (FRGM, geology report, 2010). The soils surrounding Freda mine are Fersiallitic soils of the Kaolinitic order (Nyamapfene, 1999).

The geology of the Trojan Mine site is typically greenstone configuration comprising of basaltic rocks (tholeiitic basalts and gabbro) coupled with banded iron formations and volcanic tuffs. The ore mainly consist of pyrrhotite ( $\text{Fe, Ni}$ ) S with associated nickel bearing pentlandite ( $(\text{Fe, Ni})_9\text{S}_8$ ) and polydymite ( $\text{Ni}_3\text{S}_4$ ) minerals. Pyrite ( $\text{FeS}_2$ ) and Chalcopyrite ( $\text{Cu, Fe}$ )  $\text{S}_2$  are also found (Trojan Mine, 2007). The site has red fersiallitic soils with some sections of the hills dominated by serpentine soils.

## 2.4 Flora and fauna

The Freda and Trojan Mine areas are in the savanna biome characterized by Miombo woodland with *Brachystegia boemmii* and *Julbernardia globiflora* dominating upper catena positions while remnants of *Senegalia (Acacia) polyacantha* and *Vachellia (Acacia) gerradii* woodland patches dominate low-lying areas. Dominant herbaceous species at Trojan mine include *Aristida* spp., *Diheteropogon amplexens*, *Penisetum setaceum* and *Setaria sphacelata*. Dominant grasses at Freda Rebecca mine are *Hyperrhenia filipendula*, *Brachiaria* spp., *Pogonathria squarrosa*, *Eragrostis* spp. and *Setaria sphacelata*. Near tailings there are marshy areas dominated by *Imperata cylindrica*, *Equisetum ramosissimum*, *Blechnum tabulane* and *Flaveria trinervia*. Reported vegetation on dumps includes *Imperata cylindrica*, *Schizachirium platphyllum*, *Diheteropogon amplexens*, *Cynodon dactylon*, *Andropogon chinensis*, *Cymbopogon caesius*, and *Flaveria trinervia* (Nyenda unpublished). Vegetation on young dumps is patchy while that on older dumps is denser but in all cases herbaceous species dominate. Other notable vegetation in the mine site area are a *Eucalyptus* plantation south of the young dumps and *Leucaena leucocephala* planted on waste rock dumps in the vicinity of the young dumps. Bindura area has a few wild animals such as *Slyvicapra grimmia*, *Tragelaphus sylvaticus*. Birds found in the area include *Polyborades typus*, *Alectoris rufa* and *Streptopelia semitorquata* (Freda Biodiversity report, 2012).

## 2.5 History of mine tailings dumping

Mine tailings produced from ore processing are disposed in systematically constructed dumps as slurry, which upon drying leave heaps of a silt-textured substrate with a very poor structure. At Freda Rebecca mine and other ancillary mines, tailings are openly dumped on open flat to gentle sloping land creating hill-like landforms with flat tops and slopes ranging from 20-25 %. Dumping starts from the base and rise at the rate of 1-2 m per year depending on rates of production and the size of the dump. Dumping is done on the walls in a rotating fashion in order to create a balanced dump less susceptible to breaches. The dumping nozzles have cyclones that usually classify the tailings in accordance to particle size. In this context, coarser particles usually settle at or near the tailings edges while fines flow towards the centre of the dump. This may create particle size and moisture gradients among different dump positions, in

particular moving from the edge inwards. The open dumps usually have at least four sloping faces feeding to a flat top at heights between 7-10 m.

Variation in tailings characteristics is generally expected from changes in milling technologies and use of cyclones at deposition over the century which mainly may affect mainly particle size distribution. At Freda Rebecca mine, as far as can be determined, milling technologies have always been confined to ball mills and or stamp mills which essentially yielded more or less similar particle sizes (Chapter 3). Further, differences could be expected from changes in mineral processing procedures, in particular reagents which could affect tailings chemistry. However, personal communications from mine officials indicated that main gold extraction procedure used was cyanidation resulting in similarities of starting points for different dumps of different ages. Inherent substrate heterogeneity is expected due to slight differences in ores mined which will extend to tailings disposal. This dumping history widely informed the sampling design which was essentially stratified systematic sampling at least to cater for anticipated spatial heterogeneity.

In the case of nickel mines, processing procedures involved concentration and subsequent flotation and tailings disposal procedures similar to those at gold mines although differing in reagents used. The dumping pattern used at Trojan mine was side-hill dumping since the area is generally hilly. This approach resulted in dumps that only had one sloping face and flat tops. In all cases the next dump was constructed attached to an older dump (Fig 2.2). In all cases dump walls and edges are compacted to increase stability, a 1- 2 m step in benches are created on the slopes to aid in stability.

## **2.6 Rehabilitation history of mine tailings**

The tailings from the main sites, Freda Rebecca and Trojan nickel mines had been subjected to two contrasting management regimes. The Freda Rebecca mine tailings were largely left unrehabilitated with revegetation largely happening spontaneously except for an adjacent Gulliver dump that was however excluded from this study and one slope on each of the 10 and 17 year old dumps that had some planted reeds, which were also excluded from sampling. Other gold tailings across a rainfall gradient showed little evidence of human intervention in revegetation.

On the contrary, the nickel tailings from two nickel mine sites were actively rehabilitated by planting leguminous woody species (*Acacia polyacantha*, *Acacia karoo*, and *Acacia tortilis*) on dump tops and *Acacia saligna* and *Cynodon dactylon* on the slopes in the years 2001-2002. These planted trees were fertilized using superphosphate fertilizers and irrigated using recycled process water in the first year of establishment and were left to subsequent natural succession with no further management. Rehabilitation details for the main sites and ancillary sites are detailed in Table 2.2.

**Table 2.2:** Rehabilitation history of the mine tailings

Site	Management type	Details	Study dumps
Freda Rebecca Mine	Unrehabilitated	Left to spontaneous revegetation	6 (Ages: 10, 17, 30, 82, 92 and 110 years)
Trojan Mine and Shangani mine	Rehabilitated	Rehabilitated by planting of <i>Acacia Karoo</i> , <i>Acacia polyacantha</i> and <i>Acacia tortilis</i> in 2001, 2002, broadcasting <i>Sesbania sesban</i> and <i>Chloris gayana</i> on dump tops, <i>Acacia saligna</i> and <i>Cynodon dactylon</i> on slopes; <i>Acacia Polyacantha</i> and <i>Acacia karoo</i> planted on the 10 year old dumps in 2006 -Superphosphate fertilizer application during planting - Dump irrigation in dry season in first year of planting using recycled process water	4 dumps (Ages: 10, 20, 35, 40 years).
Other gold mines – Ancillary sites	Largely spontaneous revegetation	No evidence of active planting of vegetation	Several (See Chapter 7).

## 2.7 Overview of general methodology

The general methodology used was anchored on a chronosequence conceptual framework (time substitution for space concept, Pickett, 1989). Using this approach, I selected mine sites with gold and nickel tailings of different ages across a climatic gradient in accordance to the Zimbabwe agro-ecological classification (Mugandani *et al.*, 2012). This was followed by selection of gold and nickel sites with longer chronosequences with well-known disposal and management history. This was followed by selection of adjacent reference sites based on proximity and absence of significant disturbance. Sampling of the tailings and their references were done. Sampling was done on 4 main components of the ecosystem (1) substrate, (2) biological crusts, (3) herbaceous vegetation, and, (4) woody vegetation. Fig 2.3 is a conceptual diagram summarizing the steps taken, criteria determining that and output as key components of the general methodology. Detailed materials and methods are described in each site chapter (Chapters 3-8).

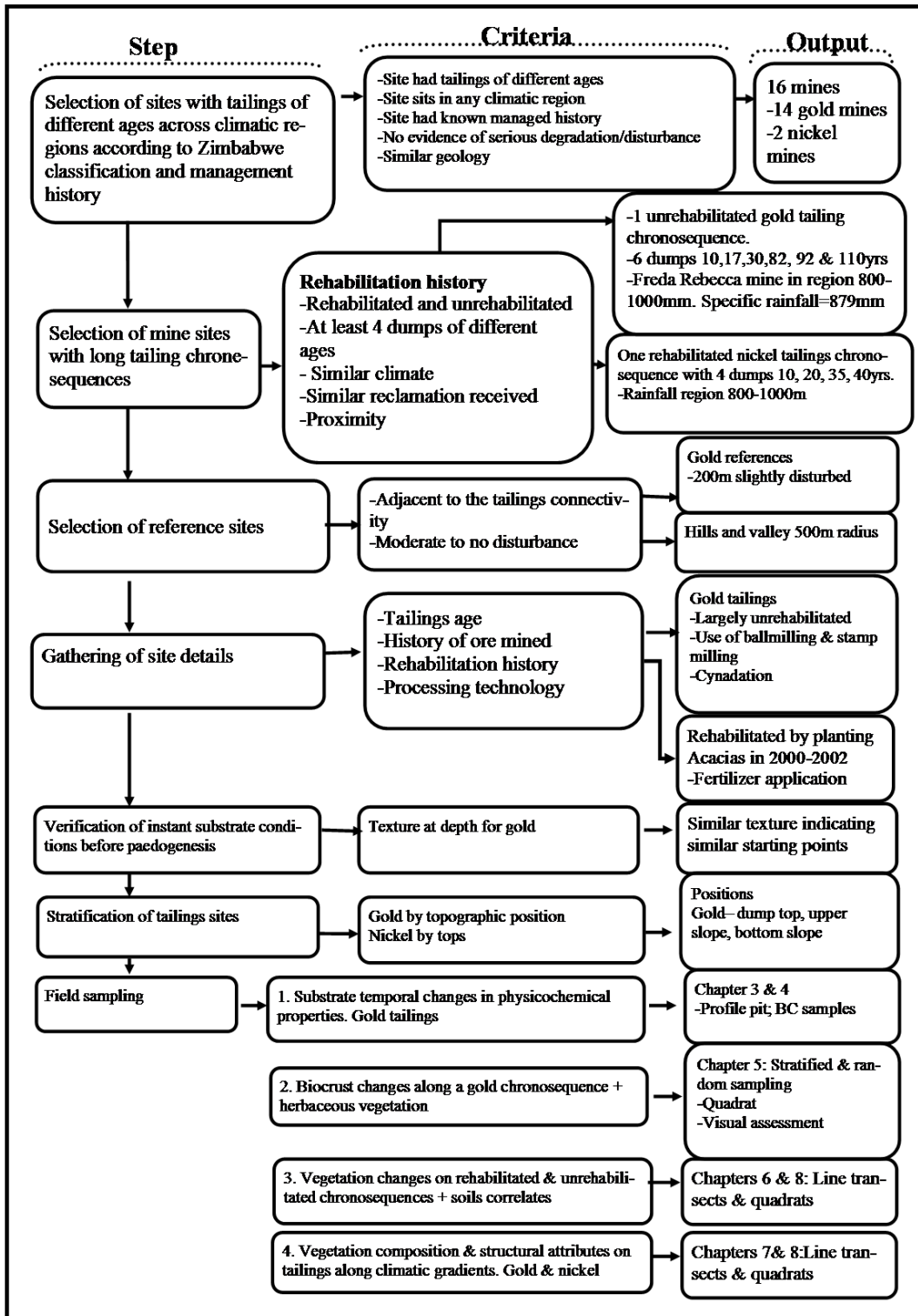


Figure 2.3: Schematic diagram showing general methodological overview linking the steps followed, criteria used for each step and the resultant output.

## CHAPTER 3

### CHANGES IN PHYSICOCHEMICAL PROPERTIES ON A CHRONOSEQUENCE OF GOLD MINE TAILINGS.

#### Abstract

Understanding the trajectory of changes in tailings physicochemical properties is critical for revegetation of mine tailings. The study investigated patterns and direction of change of selected physicochemical properties as proxies of pedogenesis on a chronosequence of six abandoned gold tailings (10, 17, 35, 82, 92 and 110 years) in Zimbabwe. The study hypotheses were: (1) plant macronutrients (N, P, K) and micronutrients (Zn, Mn, Fe, Cu, Cr and Ni), organic carbon (OC) and fine particle content significantly increase with substrate age and approach reference levels, (2) substrate pH, electrical conductivity (EC) and bulk density decrease with tailings age, (3) All parameters significantly increased from the dump top to the base, and significantly decreased with depth. Substrate samples were collected from four depths within the 0- 300 cm layer on the tailings dump tops, upper and lower slope positions and tested for selected physicochemical properties. The main layers sampled were the top 0-5cm and 5-15cm. A two-way ANOVA showed a significant ( $<0.05$ ) effect of substrate age and position on N, P, OC, and EC and interactive effect of age and position on EC. Total N and available P significantly increased with dump age matching reference conditions in the top 5cm on the 110 oldest dump. Organic carbon and pH initially significantly declined between the between disposal time and 10 years but fluctuated thereafter. Bulk density significantly decreased with tailings age, but increased with depth and from dump top to the base. Exchangeable bases, texture and EC did not vary with dump age. Total N significantly decreased with depth and was highest in the 0-5 cm layer. EC and available P increased from the dump top to the base. Available metals (Fe, Cr, Ni, Cu, Mn and Zn) were low mostly less than 5 mg/kg for all dumps. However, total metal fractions significantly decreases with dump age and with depth. A PCA based on all measured parameters showed higher similarity of the older dumps ( 82-110- years to the reference site furthest (2 km away) than the adjacent one (200 m away). Overall, the results suggest that more than 110 years are required for soil nutrients on tailings chronosequences to resemble reference conditions. Nevertheless, changes in tailings properties appeared to be correlated to dynamics in vegetation and biological crusts.

#### Key words

Tailings; chronosequence; physicochemical properties; trajectory, total nitrogen

### 3.1 Introduction

Mineral processing generates and deposits huge amounts (globally estimated at 7 billion tonnes per annum) of tailings on land, destroying pristine ecosystems ((Edraki *et al.*, 2014). The tailings often exhibit adverse physicochemical properties such as poor structure, texture, low macronutrients, extreme pH, high salinity, high concentrations of metals and often contain residuals of processing chemicals (Nothard and Hill, 1973; Bradshaw and Chadwick, 1980; Piha *et al.*, 1995; Mendez and Maier, 2008; Zaranyika and Chirinda, 2011). Such properties inhibit vegetation establishment, making tailings unstable and subject to erosion, leading to environmental pollution (Mendez and Maier, 2008). Land clearance for tailings disposal destroys vegetation, yet their adverse physicochemical properties hinder natural and assisted revegetation. This effect on biodiversity results in disruption of ecosystem function and services. This problem is set to persist in the developing world where existing mines are expanding while new ones are commissioned as mining is becoming pivotal in economic development. While, regulators require the impacts to be urgently addressed in mine closure plans, the prescribed short time-frames are often at odds with the gradual nature of natural pedogenetic processes to ameliorate the bio-physicochemical limitations (Cross and Lambers, 2017). It is therefore imperative to rehabilitate such artificial landforms to minimise the aforementioned challenges. However, ecologically sound management of such unique tailings requires detailed understanding of the pedogenetic trajectories of such substrates, with respect to the direction and rate of change.

Many pedogenetic studies have been done on historic, Holocene and Quaternary chronosequences on several substrates since the 19<sup>th</sup> century (Jenny, 1941, 1980; Burges, 1960; Rode, 1961; Walker, 1966; Stevens and Walker, 1970; Vreeken, 1975; Yaalon, 1971; Bockheim, 1980; Birkeland, 1990; Huggett, 1998; Maharana and Patel, 2013; Ming *et al.*, 2016; Santini and Banting 2016; Ahirwal *et al.*, 2017). The studies yielded two main contrasting theories of pedogenesis: (1) the developmental theory, which stresses the existence of a linear progression or improvement in soil properties towards a natural reference in any time scale ranging from a few decades to centuries and, (2) the evolutionary or divergent theory that points to the existence of multi-directional progression of soil properties on natural and anthropogenic sites resulting in multiple end-points, which are usually substrate and environmentally-driven. Other studies show that sometimes soil development may progress, stay the same or retrogress over time (Huggett, 1998) and that topography is a key determinant due to erosion and deposition factors. In some few exceptional mine chronosequence studies done, soil OC, N and K increased with age of mine spoils, matching with reference sites in 20 to 50 years. The OC and K and were negatively correlated to pH (Ming *et al.*, 2016; Cross and Lambers, 2017). In a study on coal mine spoils, fine particles increased with age (Chartuvedi and Singh, 2017).

However, not all soil forming processes such as salinization negatively affect plant and soil microbes (Gracheva *et al.*, 2001). Studies by Targulian and Krasilnikov (2004) have shown that strong excessive accumulation of salts, weathering and leaching are unfavourable for soil biota. The understanding of this is therefore crucial in planning restoration programs. In light of this, it is therefore imperative to explore dynamics in salinity and Iron on tailings substrate in order to give insights into future vegetation of such substrates. Other soil forming processes such as strong leaching inhibit biodiversity due to formation of hard pans (Gracheva *et al.*, 2001). It is therefore imperative to check temporal dynamics of soil elements down the profile and changes in compaction in light of this possibility. The approach used in this study was informed by this scientific imperative. Weathering, strong leaching and salt accumulation are reported to be mostly biologically induced in soil (Targulian and Krasilnikov, 2004). Many horizons formed by these processes are situated in the top soil giving fertile rooting zones. It is against this background that the current study focused on sampling the top layers most often the rooting zone.

A few efforts to determine the trajectories of soil formation on mine waste was on young chronosequences up to a few decades and following active reclamation of the mine spoils ( Zhao *et al.*, 2013; Mukhopadhyay and Masto, 2014; Ming *et al.*, 2016; Chaturvedi and Singh, 2017; Cross and Lambers, 2017; Yuen *et al.*, 2017). These few studies on mine sites were limited to macronutrients and soil organic carbon without considering other physicochemical properties that can be key proxies of soil development (e.g. Courtney *et al.*, 2013; Kong *et al.*, 2017). Further, pedogenetic studies on mine tailings beyond fifty years are limited. More so, several pedogenetic generalizations have been made, using mainly sand dunes, coal mine spoils, glaciers, disturbed forest and pasture land. Consequently, the pedogenetic theories remain untested in the context of unique mining substrates like mine tailings. In addition, historically, tailings management plans have been limited to containment, with little regard to temporal changes in their bio-physicochemical properties despite their importance in the success of rehabilitation programs.

Mine tailings chronosequences present an opportunity for investigating directions of soil development and therefore testing pedogenetic theories (Santini and Banting, 2016). The chronosequence concept substitutes time for space (Pickett *et al.*, 1989; Walker *et al.*, 2010). The objectives of the study were: (1) to determine the variation of selected physicochemical properties on a chronosequence of abandoned gold tailings as proxies of pedogenesis and, (2) to determine the variation of tailings physicochemical properties along a toposequence of the dumps. The study hypothesized that: (1) plant macronutrients (N, P, K), micronutrients (Zn, Mn, Fe, Cu, Cr and Ni), organic carbon (OC) and fine particle content significantly increase with substrate age and approach reference levels, (2) substrate pH, electrical conductivity (EC) and bulk density decrease with tailings age, (3) all parameters significantly increased from the dump top to the base, (4) all parameters significantly decreased with depth. The results of the

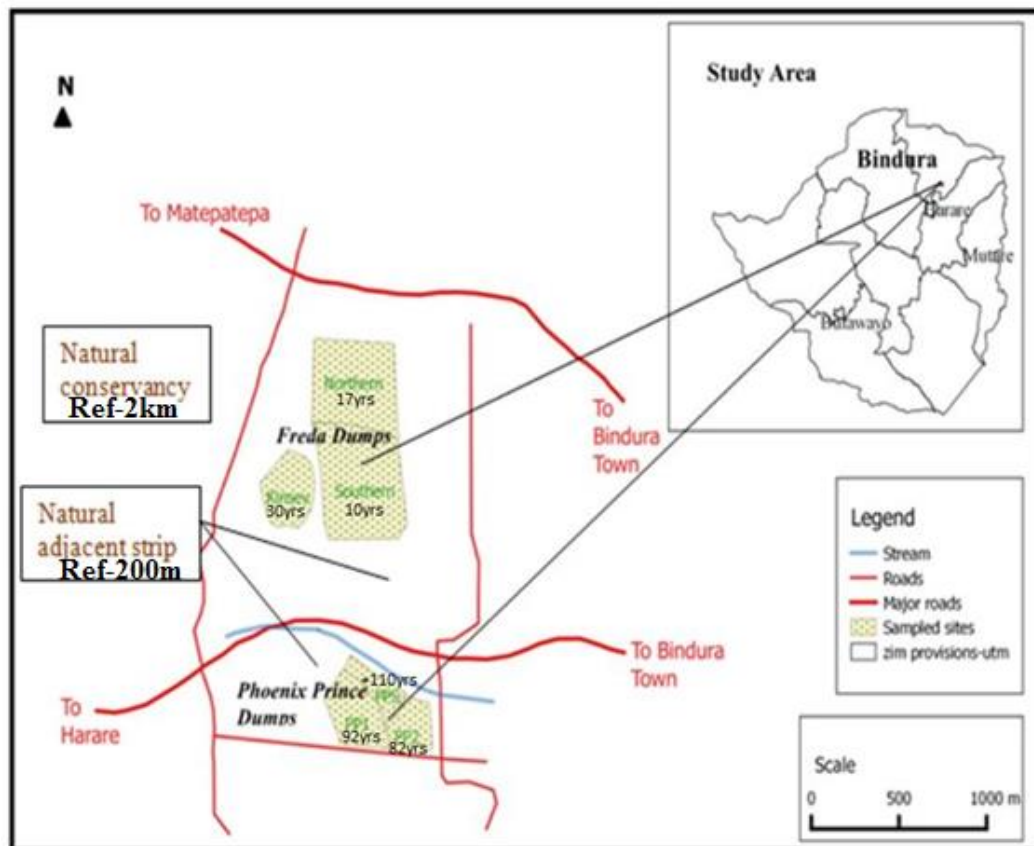


study will be central in identifying potential determinants of the direction and success of rehabilitation of these unique substrates.

### 3.2 Materials and Methods

#### 3.2.1 Description of the study area

The study was carried out on six gold tailings dumps of contrasting ages (10, 17, 30, 82, 92 and 110 years since last deposition) situated at Freda Rebecca Gold mine (latitude 31016'S and longitude 17016'E, altitude , 1070 m) in Bindura district , north east of Zimbabwe (Masvodza *et al*, 2013). The site experiences a savanna climate characterized by wet summers and dry winters. Based on rainfall data for the past 37 years, Bindura receives an average annual precipitation of 879 mm and had an average annual temperature of 28°C (Metereological Services, 2018). To investigate the trajectories of tailings physicochemical properties two adjacent reference sites (Ref 1 - 200 m and Ref 2 - 2 km) were selected. The three youngest tailings (10, 17 and 30 years) are located about 800 m north of the older tailings (82, 92 and 110 years) (Fig 3. 1). Detailed description of the study area is in Chapter 2 of this thesis.



**Figure 3.1:** Map of the study area showing location of tailings dumps at Freda Rebecca Gold mine. The natural adjacent strip (Ref-200 m) was slightly disturbed through mining and tailings disposal. The natural conservancy (Ref - 2 km) remained free of major disturbance from mining.



The general geology of the study area belongs to the Zimbabwe Craton in the Harare-Shamva Greenstone Belt, wedged between the Chinamora (to the south) and Madziwa batholiths (to the north) (FRGM Geology report, 2010). The mine site is approximately in the central axis of the Bindura-Shamva Greenstone Belt. Metamorphic mineral assemblage indicates green schist faces to upper amphibolites facies and a range of metamorphic grades across the belt. The metadiorite host the bulk of the mineralization associated with the mining operations. The local geology is typically a greenstone configuration composed mainly of basaltic rocks (gabbro and tholeiitic basalts) combined with banded iron formations and volcanic tuffs (Masvodza *et al.*, 2013). The gold ore that produces the tailings consists of pyrite ( $\text{FeS}_2$ ), pyrrhotite ( $\text{FeO}_8\text{S}$ ), and arsenopyrite ( $\text{FeAsS}$ ) as the major minerals with chalcopyrite ( $\text{CuFeS}_2$ ), bornite ( $\text{Cu}_5\text{FeS}_4$ ) and pyrolucite ( $\text{MnO}_2$ ) as minors.

The area is in a savanna biome characterized by Miombo woodland with *Brachystegia boemmii* and *Julbernardia globiflora* dominating upper catenary positions while remnants of *Senegalia polyacantha* and *Vachelia gerradii* woodland patches dominate low lying areas. Dominant grasses are *Hypermedia filipendula*, *Brachiaria* spp., *Pogonathria squarrosa*, *Eragrostis* spp., *Setaria sphacelata*. In the vicinity of tailings there are marsh areas dominated by *Imperata cylindrica*, *Equisetum ramosissimum*, *Blechnum tabulane* and *Flaveria trinervia*. Reported vegetation on dumps includes *Imperata cylindrica*, *Schizachirium platphyllum*, *Diheteropogon amplexens*, *Cynodon dactylon*, *Andropogon chinensis*, *Cymbopogon caesius*, *Flaveria trinervia*, *Digitaria eriantha* and *Sporobolus pyramidalis* (Nyenda unpublished). Other notable vegetation in the mine site area are a *Eucalyptus* plantation south of the young dumps and *Leucaena leucocephala* planted on waste rock dumps in the vicinity of the young dumps.

### 3.2.2 Experimental set up

To investigate the effects of age on tailings physicochemical properties, six tailings of similar history, aged 10, 17, 30, 82, 92 and 110 years (in 2015) were sampled. Fresh tailings (herein referred to as age= zero years) were sampled to provide background physicochemical properties of tailings before pedogenetic processes. To investigate the effects of topography each dump was further stratified by slope position yielding three topographic positions; (1) flat tops, (2) upper slope and (3) lower slope (forming a default mini chronosequence due to tailings deposition patterns. On such dumps tailings are deposited starting from the base to the top creating a substrate age gradient. A line transect was laid at an approximate mid-point along of each of the two slope positions, while on the dump top, two diagonal transects were laid from a randomly chosen end. Along each transect, five sampling points were located at regular intervals starting from a randomly selected end (Zhang *et al.*, 2007). At each sampling point, five replicate

points were systematically laid at 1 m intervals (one at centre and four in all major compass directions (Figure 3.2). These were subsamples to be used for one composite sample for that point.

To investigate vertical variation of physicochemical properties, tailings substrate was sampled from five depths (0- 5 cm; 5-15 cm, 30-50 cm and 100 cm and 3m) at each sampling point. In most cases the top 15 cm layer was sampled as this was deemed the root zone for the dominant herbaceous plants. To compare the substrate texture which may be affected by potential differences in mine processing techniques three relatively undisturbed sites on each dump were selected and soil profile pits dug to a depth of 3m and samples extracted for textural analysis. To determine the direction of changes in substrate properties, two adjacent natural woodlands were selected as reference sites: (1) The tailings foot (200m stretch around the tailings (Ref -200m) and (2) the Conservancy (2 km away, Ref- 2km). . Reference sites were selected on the basis of proximity to the dumps and for the conservancy, freedom from human disturbances and similarity in topography. Overall, the experimental set-up catered for verification of substrates before pedogenesis and then the general temporal changes of substrate properties (Figure 3.2)

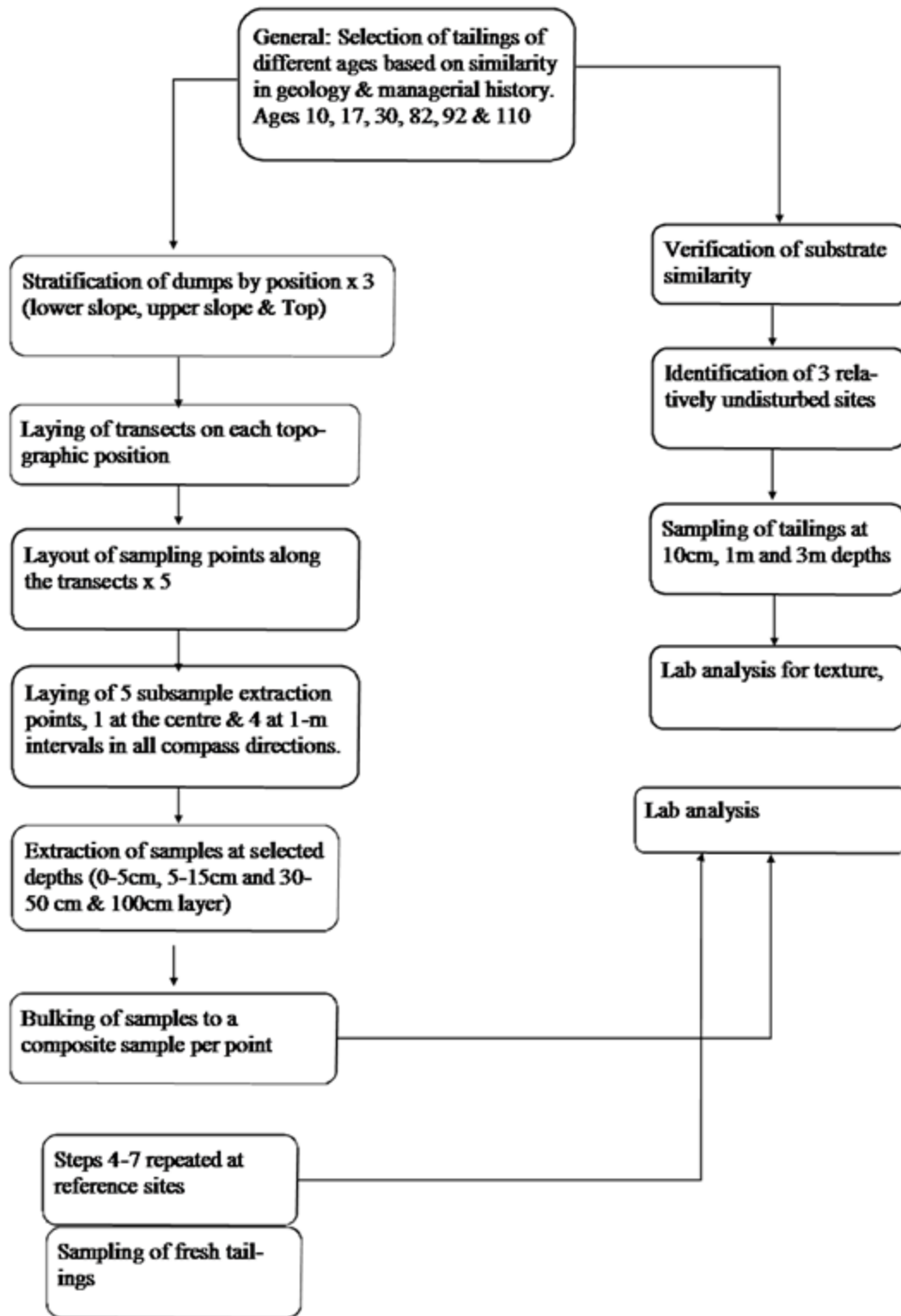


Figure 3.2: Schematic diagram showing steps in experimental set up

### 3.2.3 Soil /Tailings substrate sampling and laboratory analysis

#### 3.2.3.1 General tailings substrate and soil sampling

To determine the general variation of physicochemical properties among dumps and topographic positions, at each sampling point substrate samples were taken from each of the five points at five depths (0-5 cm; 5-15 cm; 15-30 cm, 30-50 cm and 1 m ) using a bucket soil auger, with a diameter of 8 cm and 10 cm height). The five samples at each point were mixed and thoroughly homogenised to make a composite sample for the point in the field. About 500 g of the composite sample was subsequently sealed in a well-labelled plastic bag. Substrate for textural comparisons to confirm the potential variation in texture due to potential changes in processing technologies were extracted from three relatively undisturbed sites on each dump from where three, 3 m-deep profile pits were dug.

#### 3.2.3.2 Laboratory analysis

##### 3.2.3.2.1 Determination of Total N

Total nitrogen (TN) was determined by the Kjeldahl method (Jackson, 1964). The procedure involved transferring an aliquot of sample into a Kjeldahl flask and adding distilled water and allowed to settle for 30 minutes. Subsequently digestion chemicals and catalysts are added, mixture heated and cooled. After digestion the supernatant was taken, acid added and subsequently subjected to distillation. Finally the distillate is titrated against sulphuric acid. Lastly, a blank was run in place of soil. Total Nitrogen (%) was calculated using equation 1 (Maharana and Patel, 2013)

$TN = [(T-B) \times N \times 14.007 \times 100] / W$  ..... (1); where  
T and B are the volume of the titrant used against the sample and blank; N = normality of titrant and W = weight of sample.

##### 3.2.3.2.2 Determination of mineral N and mineralization rate

Mineral N levels were measured using the micro-diffusion method on 2 M KCl extracts (Mylvaney, 1996). The procedure involves distilling the sample with alkaline potassium permanganate solution and determining the ammonia liberated. Exchangeable  $NH_4^+$  is extracted with 2M KCl. Nitrate ( $NO_3^-$ ) is water soluble and therefore was also determined on the same KCl extract. To determine the N mineralization rate, initial N was first determined and samples were incubated for 28 days before a second mineral N test was done. Mineralization rate was then calculated as the difference between the mineral N concentration after incubation and the initial concentration (Okalebo *et al.*, 2002).

### 3.2.3.2.3 Determination of available Phosphorus

Available phosphorus (P) was determined by the Olsen's method (Olsen *et al.*, 1954). In this procedure, a small sample of sieved and air-dried tailings/soil was mixed with  $\text{NH}_4\text{F}$  and  $\text{HCl}$  (1:10: mass (g): volume (mL)), and shaken for 5 minutes and filtered. Subsequent addition of ammonium molybdate, followed by thorough mixing and addition of  $\text{SnCl}$  solution was done. The mixture was allowed to settle for up to 20 minutes. The absorbance was subsequently measured using uv-vis at 660 nm using spectrophotometer (Model: Cintra 3030).

### 3.2.3.2.4 Determination of organic carbon and organic matter

Soil organic carbon (OC) was determined using the Walkley-Black method (Walkley and Black, 1934). In this process, 5 g of oven-dried tailings, 10 ml of 1 N potassium dichromate and 20 ml of concentrated sulphuric acid were added in a 500 ml flask, thoroughly shaken for five minutes and was allowed to settle for 30 minutes. The suspension was diluted with 200 ml of distilled water, followed by 1 ml of 85%  $\text{H}_2\text{PO}_4$  and 1 ml of diphenylamine indicator. The mixture was titrated against 1 N hydrated ammonium sulphate until the colour of the mixture flashed to green. Subsequently, 0.5 ml of 1 N potassium dichromate was added and the titration was completed by adding 1 N ammonium ferrous sulphate till the last traces of blue colour disappeared. Organic carbon (OC) was calculated as described in equation 2:

$$\text{OC} = [(V_1 - V_2)/W] \times 0.003 \times 100 \dots\dots\dots (2),$$
 where  $V_1$  = volume of potassium dichromate,  $V_2$  = volume of hydrated ammonium ferrous sulphate,  $W$  = weight of soil sample. Organic matter was determined by multiplying the OC values with a factor of 1.72 (Tandon, 2009).

### 3.2.3.2.5 Determination of electrical conductivity and pH

To determine electrical conductivity (EC) of the substrate, the substrate was first oven-dried and 1:2 V: V substrate-water mixture was formed for EC determination. The mixture was shaken for 30 minutes before EC determination. The electrical conductivity was recorded with a portable conductivity meter model: Orion 150. To determine the pH of the tailings a 0.01 M  $\text{CaCl}_2$  solution was added to the tailings (2:1, V: V). the mixture was shaken for 30 minutes and pH recorded using a pH meter model: Delta 320, Shanghai.

### 3.2.3.2.6 Determination of exchangeable K, Ca and Mg

Exchangeable K, Ca and Mg were determined in neutral normal ammonium acetate extracts of soils. The extraction was carried out by shaking followed by centrifugation. The K was estimated using a flame spectrophotometer while Ca and Mg were determined by using the AAS. (Okalebo *et al.*, 2002; Tandon, 2009).

#### **3.2.3.2.7 Determination of particle size distribution.**

Texture was determined by sieving and the hydrometer method (Okalebo *et al.*, 2002). The procedure included estimation of clay (< 0.02mm), silt (0.06 mm-0.002 mm) and sand (2mm- 0.06 mm) percentage. In particular, 50 g of the tailings or soil sample were taken in a 500 ml heat resistant bottle, calibrated up to 250 ml. To this 125 ml of water was added and the mixture swirled to wet the tailings thoroughly. 20 ml of 30 % hydrogen peroxide was added to it and the bottle was gently rotated. Few drops of amyl alcohol were added to the mixture and kept in a boiling water bath till the reaction was complete and subsequently, 2 g of sodium hexametaphosphate was added, making up the volume to 250 ml with water and shaken for 28 hrs using a mechanical shaker. The mixture was then transferred to a 1 litre sedimentation cylinder and the volume made up. Samples were placed in a water bath for the appropriate time before Bouyoucos hydrometer readings were taken.

#### **3.2.3.2.8 Determination of dry bulk density**

The core method was used for bulk density determination (Okalebo *et al.*, 2002; Tandon, 2009). Substrate samples were taken using 100 cm<sup>3</sup> cores. The collected sample was oven-dried at 105°C for 24 hrs. Dry weight of the soil was determined. Bulk density (g/cm<sup>3</sup>) was determined as a ratio of dry weight of soil (in g) and volume of core (cm<sup>3</sup>).

#### **3.2.3.2.9 Determination of metals.**

Available metals were determined using the atomic absorption spectrophotometer (AAS) following acid digestion and extraction by a single acid Diethylene Triamine Penta Acetic Acid (DTPA). For each metal standards (calibration curves) were prepared accordingly (Tandon, 2009). Total metals were determined by the same AAS techniques after substrate digestion by a double acid (aqua-regia solution). Specific metal measured were Mn, Zn, Ni, Fe, Cr. These were selected as they are known to dominate mineralogy of gold ores such as sulphides (Zaranyika and Chirinda, 2011) and some such as Zn and Mn are important micronutrients while Fe besides being the main metal in the ore is an important component of soil whose dynamics in pedogenesis is critical. Pyrite concentration was determined by acid titrations (Okalebo *et al.*, 2002).

#### **3.2.4 Data analysis**

Data were analysed in phases involving GLM (ANOVA) with Poisson error distribution, ordination and spearman correlation analysis. Tailings and soil data were first tested for normality using the Kolmogorov-Smirnov test in Statistical Package for Social Sciences (SPSS) version 20 software. All non-normal data were transformed before analysis of variance and correlation analysis (Mckillup, 2012). General linear model ANOVA was used to test effects of dump age, topographic position, depth and their interactions on substrate physicochemical properties. Pair-wise comparisons were made with the post

hoc Turkey's HSD test at the 95% level of significance. To test overall trajectory of soil development against reference sites, a principal component analysis (PCA) was performed using all substrate data. This Linear ordination method was appropriate since gradient length was less than 3 (Lepš and Šmilauer, 2003; Mckillup, 2012).

### 3.3 Results

#### 3.3.1 Substrate base comparisons

To test the potential effect of historical changes in mineral processing technologies such as milling technologies and efficiencies and ore geochemistry on physicochemical properties of tailings, data for tailings extracted from the surface and at 3 m depth of relatively undisturbed tailings sites were analysed using one-way ANOVA. Results showed no significant variation in texture and arsenic (As) concentration of the tailings across the age range (Table 3.1). Pyrite concentration significantly decreased ( $F= 10.32$ ;  $p= 0.04$ ) with substrate age. Results therefore confirm little effect of changes in processing technologies on the substrate properties hence starting points prior to pedogenesis were largely the same. The variation in pyrite concentration may be attributed to temporal loss due to oxidation of pyrites (Zaranyika and Chirinda, 2011).

**Table 3.1:** Textural properties, pyrite and arsenic concentration of undisturbed site on tailings chronosequences—testing effect of potential variation in processing technologies. FS= fine sand; MS= medium sand; CS= coarse sand. NS = Not sampled. All values are Mean  $\pm$  standard deviation.

		0yrs	10yrs	17yrs	30yrs	82yrs	92yrs	110yrs
0-10 cm	Clay (%)	5.4 $\pm$ 1.6	5.2 $\pm$ 1.2	6.3 $\pm$ 1.4	6.1 $\pm$ 1.8	5.3 $\pm$ 1.4	5.8 $\pm$ 1.0.	6.2 $\pm$ 1.6
	Silt (%)	47.7 $\pm$ 5.6	64.0 $\pm$ 6.1	57.8 $\pm$ 5.7	58.7 $\pm$ 3.6	16.0 $\pm$ 3.9	18.9 $\pm$ 2.3	15.3 $\pm$ 4.0
	FS (%)	31.0 $\pm$ 4.43	27.7 $\pm$ 4.3	26.0 $\pm$ 2.9	33.2 $\pm$ 5.3	76.2 $\pm$ 6.4	66.0 $\pm$ 2.5	73.3 $\pm$ 5.3
	MS (%)	5.3 $\pm$ 2.17	3.6 $\pm$ 2.7	0.8 $\pm$ 0.02	2.2 $\pm$ 1.7	1.0 $\pm$ 0.7	10.8 $\pm$ 1.2	4.5 $\pm$ 2.2
	CS (%)	2.2 $\pm$ 0.2	2.3 $\pm$ 0.4	0.01 $\pm$ 0.01	0.6 $\pm$ 0.3	0.7 $\pm$ 0.3	0.3 $\pm$ 0.2	0.3 $\pm$ 0.1
	Pyrite (%)	17 $\pm$ 4.1	13 $\pm$ 5.8	11 $\pm$ 7.2	9 $\pm$ 3.4	7 $\pm$ 2.3	6 $\pm$ 1.9	5.4 $\pm$ 0.8
	AS(mg/kg)	0.02 $\pm$ 0.01	0.02 $\pm$ 0.02	0.02 $\pm$ 0.0	0.02 $\pm$ 0.01	0.02 $\pm$ 0.01	0.01 $\pm$ 0.01	0.01 $\pm$ 0.01
3m	Clay (%)	NS	6.2 $\pm$ 1.2	6.7 $\pm$ 2.1	7.1 $\pm$ 1.8	5.3 $\pm$ 1.4	6.9 $\pm$ 1.0.	6.3 $\pm$ 1.6
	Silt (%)	NS	63.0 $\pm$ 4.1	50.8 $\pm$ 4.1	55.9 $\pm$ 4.1	16.0 $\pm$ 4.06	20.9 $\pm$ 2.3	20.3 $\pm$ 4.0
	FS (%)	NS	26.7 $\pm$ 4.3	29.0 $\pm$ 5.7	33.2 $\pm$ 4.43	78.2 $\pm$ 4.43	60.0 $\pm$ 4.5	68.3 $\pm$ 4.3
	MS (%)	NS	3.4 $\pm$ 2.7	1.0 $\pm$ 0.02	2.2 $\pm$ 1.7	2.1 $\pm$ 0.7	13.8 $\pm$ 1.7	5.5 $\pm$ 2.3
	CS (%)	NS	1.6 $\pm$ 0.4	0.01 $\pm$ 0.01	0.6 $\pm$ 0.3	0.5 $\pm$ 0.3	0.4 $\pm$ 0.2	0.3 $\pm$ 0.1
	Pyrite	NS	17.4 $\pm$ 4.6	14.6 $\pm$ 4.2	12 $\pm$ 5.4	9 $\pm$ 3.0	8 $\pm$ 2.5	7.5 $\pm$ 1.3
	AS(mg/kg)	NS	0.02 $\pm$ 0.01	0.02 $\pm$ 0.01	0.02 $\pm$ 0.02	0.01 $\pm$ 0.0	0.01 $\pm$ 0.01	0.0 $\pm$ 0.0

### 3.3.2 Temporal changes in physicochemical properties of gold tailings

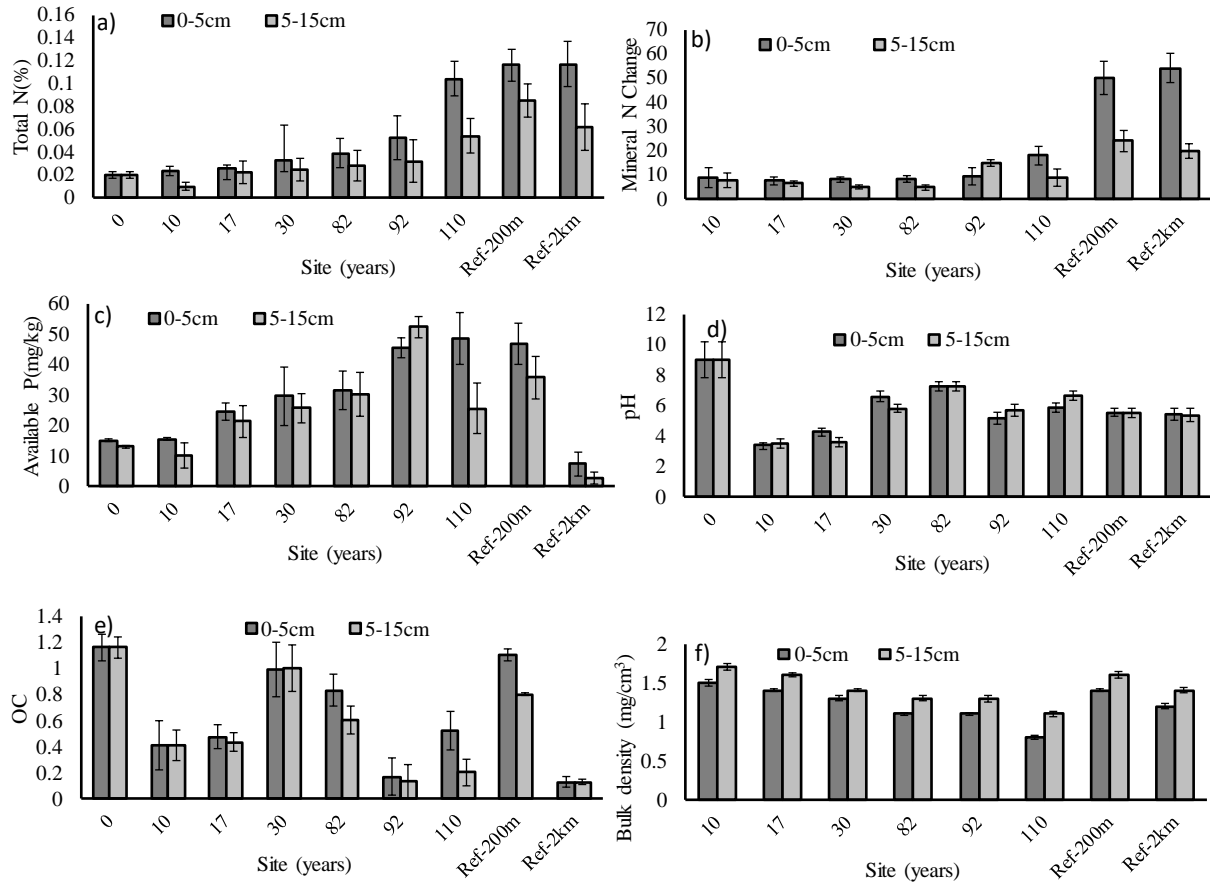
Dump age had a significant effect on tailings substrate total N ( $F= 5.53$ ;  $p= 0.006$ ), N mineralization rate ( $F= 6.56$ ;  $p= 0.032$ ), available phosphorus ( $F= 2.837$ ;  $p= 0.036$ ), and pH ( $F= 16.227$ ;  $p < 0.001$ ). In particular, total N in the surface layer (0-5cm) showed a significant 7-fold increase with age from about 0.022 % for freshly disposed tailings to 0.15 % for the 110-year-old dump whose total N concentration was statistically similar to values observed in the two reference sites (Fig 3.3 a). Similarly, total N in the 5-15 cm depth significantly increased with age, reaching a peak, 5-fold higher at 110 years, but remained significantly lower than values obtained at the two reference sites (Fig 3.3a). Although mineral N did not vary significantly with age, N mineralization rate significantly increased with dump age (Fig 3.3b).

Available P within the top 15 cm significantly increased with age of the dump, reaching statistically similar levels with both reference sites in the 0-5cm depth and exceeding the levels of the soil at the reference sites in the 5-15 cm depths (Fig 3.3 c). Phosphorus levels for the other depths were fluctuating. The pH at the 0-5 cm and 5-15 cm depths significantly dropped by about 300 % in the first 10 years before steadily increasing to reach a peak (mean= 7.25) on the 82-year-old dump and fluctuated between 5.1 and 6.6 below and above reference levels thereafter (Fig 3.3d).

Organic carbon was highest (1.2 %) in fresh tailings, and dropped significantly (about 300 %) in the first 10 years, and exhibited a fluctuating trend thereafter (Fig 3.3e). All dumps had significantly higher OC than Ref-2km, with OC on the 30 and 82-year-old dumps matching values observed at Ref-200m. Bulk density significantly decreased with dump age and depth and reached significantly lower levels than values observed at the reference sites (Fig 3.3f).

Exchangeable Ca showed no distinct trend while exchangeable K and Mg were similar across all age ranges (Table 3.2). Texture was similar for all dumps, but dumps had significantly lower clay content than Ref-200 m but similar to Ref- 2km (Table 3.2). EC fluctuated with dump age, and was always significantly higher on all dumps than Ref -2km while it was highest on the 82-year-old dump where it was statistically similar to Ref-200 m (Table 3.2).





**Figure 3.3:** Variation of chemical properties on a chronosequence of gold tailings (a).Total N (b) mineral N (c) available P (d) pH, (e) OC, (f) bulk density. Only values for the top 15 cm are shown in the graphs (trends for other layers are shown in supplementary tables).

**Table 3.2:** Variation of texture, micronutrients and EC on a chronosequence of gold tailings. FS= Fine sand; MS= Medium sand; CS= course sand. All values are Mean  $\pm$  SD. Different superscripts in same row denote significant difference.

		10yrs	17yrs	30yrs	82yrs	92yrs	110yrs
<b>0-5cm</b>	<b>Clay (%)</b>	4.7 $\pm$ 1.42 <sup>a</sup>	4.3 $\pm$ 1.02 <sup>a</sup>	6.8 $\pm$ 1.24 <sup>a</sup>	6.3 $\pm$ 1.24 <sup>a</sup>	3.1 $\pm$ 0.72 <sup>a</sup>	6.2 $\pm$ 1.24 <sup>a</sup>
	<b>Silt (%)</b>	63.0 $\pm$ 4.06 <sup>b</sup>	58.9 $\pm$ 3.32 <sup>a</sup>	57.7 $\pm$ 4.1 <sup>a</sup>	16.0 $\pm$ 4.6 <sup>a</sup>	18.9 $\pm$ 2.35 <sup>a</sup>	15.3 $\pm$ 4.06 <sup>a</sup>
	<b>FS (%)</b>	26.7 $\pm$ 4.43 <sup>b</sup>	34.0 $\pm$ 3.62 <sup>a</sup>	32.8 $\pm$ 4.4 <sup>a</sup>	76.2 $\pm$ 4.4 <sup>a</sup>	67.0 $\pm$ 2.56 <sup>a</sup>	73.3 $\pm$ 4.43 <sup>a</sup>
	<b>MS (%)</b>	3.3 $\pm$ 2.17 <sup>a</sup>	2.0 $\pm$ 1.77 <sup>a</sup>	2.0 $\pm$ 2.12 <sup>a</sup>	1.0 $\pm$ 2.17 <sup>a</sup>	10.8 $\pm$ 1.25 <sup>a</sup>	4.5 $\pm$ 2.17 <sup>a</sup>
	<b>CS (%)</b>	2.3 $\pm$ 0.37 <sup>a</sup>	0.4 $\pm$ 0.30 <sup>a</sup>	0.5 $\pm$ 0.37 <sup>a</sup>	0.7 $\pm$ 0.37 <sup>a</sup>	0.3 $\pm$ 0.21 <sup>a</sup>	0.3 $\pm$ 0.37 <sup>a</sup>
	<b>EC (mS/cm)</b>	2.1 $\pm$ 0.30 <sup>a</sup>	1.5 $\pm$ 0.25 <sup>a</sup>	2.3 $\pm$ 0.8 <sup>a</sup>	3.02 $\pm$ 1.30 <sup>a</sup>	2.2 $\pm$ 0.6 <sup>a</sup>	0.4 $\pm$ 0.30 <sup>a</sup>
	<b>Ca (me %)</b>	13.6 $\pm$ 4.11 <sup>a</sup>	10.2 $\pm$ 5.2 <sup>a</sup>	12.1 $\pm$ 3.2 <sup>a</sup>	15.41 $\pm$ 4.11 <sup>a</sup>	16.03 $\pm$ 5.31 <sup>a</sup>	12.9 $\pm$ 3.05 <sup>a</sup>
	<b>Mg me %)</b>	0.04 $\pm$ 0.03 <sup>a</sup>	0.05 $\pm$ 0.03 <sup>a</sup>	0.05 $\pm$ 0.02 <sup>a</sup>	0.03 $\pm$ 0.03 <sup>a</sup>	0.04 $\pm$ 0.01 <sup>a</sup>	0.06 $\pm$ 0.03 <sup>a</sup>
	<b>K (me %)</b>	7.6 $\pm$ 4.8 <sup>a</sup>	9.8 $\pm$ 3.6 <sup>a</sup>	10.3 $\pm$ 4.1 <sup>a</sup>	0.35 $\pm$ 0.10 <sup>a</sup>	0.40 $\pm$ 0.08 <sup>a</sup>	0.36 $\pm$ 0.07 <sup>a</sup>
<b>5-15 cm</b>	<b>Clay (%)</b>	5.3 $\pm$ 1.71 <sup>a</sup>	5.2 $\pm$ 1.44 <sup>a</sup>	6.6 $\pm$ 1.24 <sup>a</sup>	6.5 $\pm$ 1.1 <sup>a</sup>	4.1 $\pm$ 0.85 <sup>a</sup>	6.4 $\pm$ 1.43 <sup>a</sup>
	<b>Silt (%)</b>	62.0 $\pm$ 4.6 <sup>b</sup>	57.9 $\pm$ 3.74 <sup>a</sup>	56.6 $\pm$ 8.1 <sup>a</sup>	16.0 $\pm$ 5.12 <sup>a</sup>	17.3 $\pm$ 2.51 <sup>a</sup>	14.3 $\pm$ 4.6 <sup>a</sup>
	<b>FS (%)</b>	26.1 $\pm$ 4.31 <sup>b</sup>	34.0 $\pm$ 3.24 <sup>a</sup>	33.8 $\pm$ 4.7 <sup>a</sup>	72.8 $\pm$ 4.4 <sup>a</sup>	66.1 $\pm$ 2.46 <sup>a</sup>	72.6 $\pm$ 4.43 <sup>a</sup>
	<b>MS (%)</b>	3.1 $\pm$ 2.17 <sup>a</sup>	1.96 $\pm$ 1.55 <sup>a</sup>	2.1 $\pm$ 2.00 <sup>a</sup>	1.0 $\pm$ 0.37 <sup>a</sup>	10.4 $\pm$ 2.05 <sup>a</sup>	4.1 $\pm$ 2.11 <sup>a</sup>
	<b>Co sand</b>	2.2 $\pm$ 0.32 <sup>a</sup>	0.3 $\pm$ 0.20 <sup>a</sup>	0.4 $\pm$ 0.33 <sup>a</sup>	0.7 $\pm$ 0.35 <sup>a</sup>	0.3 $\pm$ 0.21 <sup>a</sup>	0.4 $\pm$ 0.3 <sup>a</sup>
	<b>EC (mS/cm)</b>	2.2 $\pm$ 0.50 <sup>a</sup>	1.6 $\pm$ 0.41 <sup>a</sup>	2.5 $\pm$ 0.9 <sup>a</sup>	2.90 $\pm$ 1.30 <sup>a</sup>	2.3 $\pm$ 0.7 <sup>a</sup>	0.45 $\pm$ 0.30 <sup>a</sup>
	<b>Ca (me %)</b>	13.6 $\pm$ 4.11 <sup>a</sup>	10.2 $\pm$ 5.2 <sup>a</sup>	12.1 $\pm$ 3.2 <sup>a</sup>	15.41 $\pm$ 4.11 <sup>a</sup>	16.03 $\pm$ 5.31 <sup>a</sup>	12.9 $\pm$ 3.05 <sup>a</sup>
	<b>Mg me %)</b>	0.04 $\pm$ 0.03 <sup>a</sup>	0.05 $\pm$ 0.06 <sup>a</sup>	0.04 $\pm$ 0.02 <sup>a</sup>	0.03 $\pm$ 0.03 <sup>a</sup>	0.03 $\pm$ 0.02 <sup>a</sup>	0.07 $\pm$ 0.04 <sup>a</sup>
	<b>K (me %)</b>	6.6 $\pm$ 4.8 <sup>a</sup>	8.8 $\pm$ 3.6 <sup>a</sup>	8.5 $\pm$ 4.1 <sup>a</sup>	0.5 $\pm$ 0.20 <sup>a</sup>	0.40 $\pm$ 0.09 <sup>a</sup>	0.34 $\pm$ 0.08 <sup>a</sup>

### 3.3.3 Changes in metal concentrations on gold tailings.

Younger dumps had higher total concentration of Fe, Mn, Zn, Cr, Cu and Ni in surface layers (0-15 cm) than the older dumps which had higher concentrations in deeper layers (1-3m) (Table 3.3). For most dumps, total Ni, Mn, Cu increased with depth while Cr declined. total Fe showed a steady and significant increase with depth. In most cases, at the surface, the metals occurred in the order Fe > Mn > Cu > Zn > Ni > Cr (Table 3.3). Available metals did not show a significant ( $p < 0.05$ ) distinct trend across the dumps. However, the available metals were generally low on all dumps. Available Mn, Cu, Zn and Fe were significantly higher on the 10 year old dumps than any other dumps. Available metal fractions also did not significantly vary with depth.

**Table 3.3:** Changes in total metal concentrations (Mean  $\pm$  SD) on a chronosequence of abandoned tailings. Values are mg/kg. NS means not sampled. (Only total metal concentrations are shown in table).

		<b>Fe</b>	<b>Mn</b>	<b>Zn</b>	<b>Cr</b>	<b>Cu</b>	<b>Ni</b>
<b>0-15 cm</b>	<b>0yrs</b>	2250 $\pm$ 200	500 $\pm$ 35	230 $\pm$ 21	96 $\pm$ 12	900 $\pm$ 90	101 $\pm$ 8
	<b>10yrs</b>	2105 $\pm$ 300	415 $\pm$ 69	240 $\pm$ 38	93 $\pm$ 14	812 $\pm$ 150	93 $\pm$ 10
	<b>17 years</b>	2060 $\pm$ 100	400 $\pm$ 37	222 $\pm$ 50	84 $\pm$ 16	702 $\pm$ 111	84 $\pm$ 14
	<b>30 years</b>	1775 $\pm$ 205	340 $\pm$ 42	215 $\pm$ 33	85 $\pm$ 10	750 $\pm$ 100	95 $\pm$ 11
	<b>82 years</b>	1090 $\pm$ 107	310 $\pm$ 50	184 $\pm$ 18	76 $\pm$ 19	406 $\pm$ 87	62 $\pm$ 13
	<b>92 years</b>	1150 $\pm$ 110	273 $\pm$ 50	120 $\pm$ 19	70 $\pm$ 11	419 $\pm$ 100	60 $\pm$ 12
	<b>110 years</b>	1050 $\pm$ 90	260 $\pm$ 30	160 $\pm$ 15	66 $\pm$ 13	401 $\pm$ 50	58 $\pm$ 6
<b>1 m</b>	<b>0yrs</b>	<b>NS</b>	<b>NS</b>	<b>NS</b>	<b>NS</b>	<b>NS</b>	<b>NS</b>
	<b>10yrs</b>	2218 $\pm$ 260	370 $\pm$ 80	150 $\pm$ 25	96 $\pm$ 17	500 $\pm$ 88	123 $\pm$ 15
	<b>17 years</b>	2307 $\pm$ 352	310 $\pm$ 50	131 $\pm$ 17	99 $\pm$ 12	602 $\pm$ 100	111 $\pm$ 18
	<b>30 years</b>	2602 $\pm$ 315	275 $\pm$ 20	105 $\pm$ 9	50 $\pm$ 6	300 $\pm$ 148	64 $\pm$ 10
	<b>82 years</b>	2710 $\pm$ 412	281 $\pm$ 66	124 $\pm$ 44	83 $\pm$ 19	447 $\pm$ 120	72 $\pm$ 21
	<b>92 years</b>	2640 $\pm$ 310	200 $\pm$ 53	99 $\pm$ 12	89 $\pm$ 10	318 $\pm$ 54	81 $\pm$ 9
	<b>110 years</b>	2711 $\pm$ 200	201 $\pm$ 37	120 $\pm$ 13	70 $\pm$ 12	253 $\pm$ 29	55 $\pm$ 17
<b>3 m</b>	<b>0yrs</b>	<b>NS</b>	<b>NS</b>	<b>NS</b>	<b>NS</b>	<b>NS</b>	<b>NS</b>
	<b>10yrs</b>	2390 $\pm$ 274	501 $\pm$ 83	111 $\pm$ 20	80 $\pm$ 23	521 $\pm$ 101	83 $\pm$ 18
	<b>17 years</b>	2509 $\pm$ 200	486 $\pm$ 60	100 $\pm$ 9	91 $\pm$ 17	522 $\pm$ 85	92 $\pm$ 19
	<b>30 years</b>	3400 $\pm$ 400	601 $\pm$ 70	101 $\pm$ 6	40 $\pm$ 4	325 $\pm$ 150	90 $\pm$ 15
	<b>82 years</b>	2519 $\pm$ 300	376 $\pm$ 44	113 $\pm$ 18	55 $\pm$ 8	450 $\pm$ 112	84 $\pm$ 16
	<b>92 years</b>	2622 $\pm$ 319	207 $\pm$ 42	91 $\pm$ 8	61 $\pm$ 11	302 $\pm$ 62	90 $\pm$ 10
	<b>110 years</b>	2584 $\pm$ 272	261 $\pm$ 29	96 $\pm$ 12	44 $\pm$ 9	199 $\pm$ 48	72 $\pm$ 11

### 3.3.4 Changes in physicochemical properties along a toposequence.

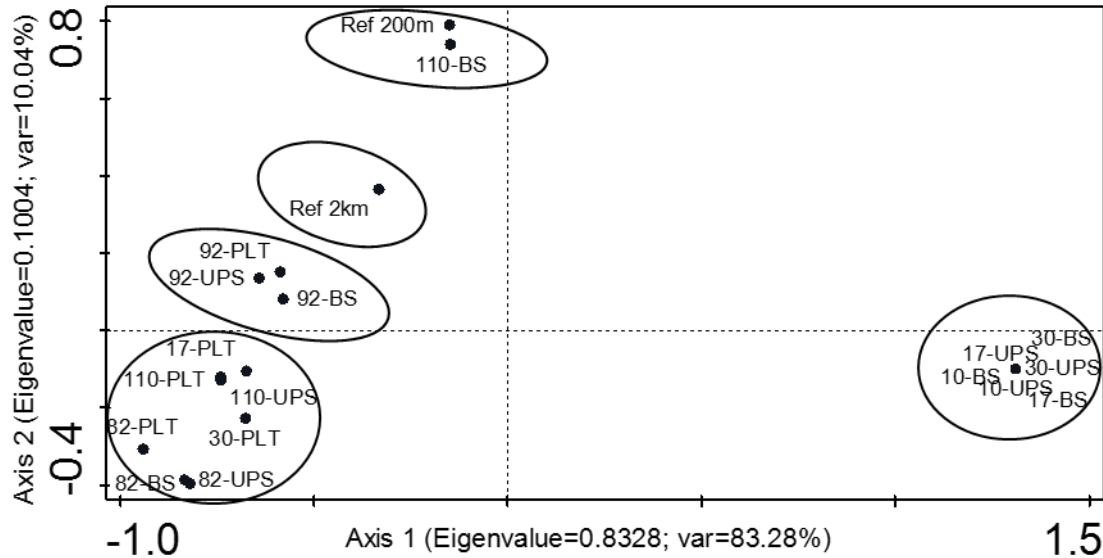
Topographic position had a significant effect on available P ( $F = 3.82$ ;  $p = 0.034$ ), EC ( $F = 3.93$ ;  $p = 0.02$ ), and exchangeable Mg ( $F = 4.82$ ;  $p = 0.02$ .) while the effect of depth was only significant for total N ( $F = 5.046$ ;  $p = 0.001$ ) and bulk density ( $F = 6.7$ ;  $p = 0.02$ ; Table 3.4). In particular, EC and available P significantly increased from the dump top to the base for most dumps (Table 3.4). Exchangeable bases (Ca, K and Mg), pH, dB, and texture were similar across all dump positions. The interactive effect of the three factors (dump age, topographic position and depth) on all parameters was insignificant ( $p > 0.05$ ).

**Table 3.4:** Variation of physicochemical properties (Mean±SE) on a toposequence of gold tailings. LS = lower slope; UPS = upper slope; Top = dump top. All tests were one-way ANOVA at 95 % significance level. Superscripts compare effects of position on each dump and at a specific depth.

	Site (yrs)	0-5cm			5-15cm		
		LS	UPS	Top	LS	UPS	Top
Total N (%)	82	0.04±0.05 <sup>a</sup>	0.03±0.005 <sup>a</sup>	0.14±0.02 <sup>b</sup>	0.29±0.003 <sup>a</sup>	0.27±0.021 <sup>a</sup>	0.03±0.002 <sup>a</sup>
	92	0.07±0.03 <sup>a</sup>	0.03±0.01 <sup>a</sup>	0.09±0.03 <sup>a</sup>	0.03±0.008 <sup>a</sup>	0.026±0.02 <sup>a</sup>	0.04±0.03 <sup>a</sup>
	110	0.08±0.03 <sup>ab</sup>	0.04±0.03 <sup>b</sup>	0.12±0.04 <sup>a</sup>	0.07±0.02 <sup>a</sup>	0.05±0.02 <sup>b</sup>	0.047±0.03 <sup>b</sup>
P(mg/kg)	82	49.3±6.69 <sup>a</sup>	46.5±5.64 <sup>a</sup>	40.5±7.94 <sup>a</sup>	57.7±6.64 <sup>a</sup>	59.0±7.94 <sup>a</sup>	40.0±4.59 <sup>a</sup>
	92	48.0±11.9 <sup>a</sup>	49.0±11.72 <sup>a</sup>	48.9±11.8 <sup>a</sup>	49.0±11.9 <sup>a</sup>	46.0±11.9 <sup>a</sup>	49.6±7.71 <sup>a</sup>
	110	49.0±4.74 <sup>a</sup>	47.5±5.34 <sup>a</sup>	41.71±3.24 <sup>a</sup>	40.5±5.6 <sup>a</sup>	38.3±6.5 <sup>a</sup>	35.7±7.72 <sup>a</sup>
EC(mS/cm)	82	5.04±0.58 <sup>a</sup>	4.0±0.33 <sup>a</sup>	1.34±0.39 <sup>b</sup>	5.12±0.53 <sup>a</sup>	4.78±0.14 <sup>ab</sup>	3.62±0.20 <sup>b</sup>
	92	3.60±0.16 <sup>a</sup>	3.3±0.27 <sup>a</sup>	3.63±0.19 <sup>a</sup>	3.38±0.16 <sup>a</sup>	3.52±0.27 <sup>a</sup>	2.95±0.16 <sup>a</sup>
	110	4.43±0.37 <sup>a</sup>	3.81±0.24 <sup>a</sup>	1.84±0.34 <sup>b</sup>	4.00±0.68 <sup>a</sup>	3.79±0.32 <sup>a</sup>	3.26±0.02 <sup>a</sup>
OC (%)	82	1.32±0.17 <sup>a</sup>	1.52±0.68 <sup>a</sup>	1.46±0.41 <sup>a</sup>	0.95±0.15	1.09±0.12	1.231±0.01 <sup>a</sup>
	92	0.27±0.06 <sup>a</sup>	0.27±0.10 <sup>a</sup>	0.32±0.07 <sup>a</sup>	0.26±0.05 <sup>a</sup>	0.25±0.18 <sup>a</sup>	0.28±0.05 <sup>a</sup>
	110	0.79±0.31 <sup>a</sup>	1.105±0.27 <sup>a</sup>	1.211±0.36 <sup>a</sup>	0.89±0.31 <sup>a</sup>	1.110±0.27 <sup>a</sup>	1.22±0.36 <sup>a</sup>
Ca (me %)	82	12.4±4.12 <sup>a</sup>	15.41±4.11 <sup>a</sup>	18.2±5.01 <sup>a</sup>	22.9±4.11 <sup>a</sup>	15.3±5.21 <sup>a</sup>	19.2±4.17 <sup>a</sup>
	92	11.4±3.11 <sup>a</sup>	17.03±5.11 <sup>a</sup>	18.4±5.13 <sup>a</sup>	20.5±4.20 <sup>a</sup>	16.3±6.11 <sup>a</sup>	20.2±4.15 <sup>a</sup>
	110	12.4±3.94 <sup>a</sup>	12.90±3.05 <sup>a</sup>	12.15±4.28 <sup>a</sup>	3.48±5.74	3.48±5.74	3.48±5.74
K (me %)	82	0.48±0.07 <sup>a</sup>	0.25±0.09 <sup>a</sup>	0.32±0.06 <sup>a</sup>	0.37±0.07 <sup>a</sup>	0.21±0.04 <sup>a</sup>	0.25±0.06 <sup>a</sup>
	92	0.52±0.08 <sup>a</sup>	0.24±0.09 <sup>a</sup>	0.41±0.07 <sup>a</sup>	0.35±0.06 <sup>a</sup>	0.20±0.07 <sup>a</sup>	0.25±0.09 <sup>a</sup>
	110	0.48±0.32 <sup>a</sup>	0.27±0.06 <sup>a</sup>	0.34±0.11 <sup>a</sup>	0.29±0.08 <sup>a</sup>	0.31±0.06 <sup>a</sup>	0.21±0.08 <sup>a</sup>

### 3.3.5 Ordination of sites based on physicochemical properties of the substrate.

Overall, a PCA based on physicochemical properties of the tailings showed that there was a general distinction between young tailings and older tailings as they mostly occupied opposing ends of axis 1 of the PCA monoplots (Figure 3.4). Further, the older plots were closer to references than younger dumps. However, the PCA grouped the sites into five clusters: (1) plots from the two youngest dumps (10 and 17 years), (2) plot from the 17, 30 and 110–years dump tops, all positions of the 82 year dump and upper slope and top of the 110 year-old-dump, (3) plots from the 92-year-old dump, (4) plots from bottom slope of the 110 year-old dump and Ref-200m, and (5) the Ref-2 km site ( Figure 3.4).



**Figure 3.4:** A PCA ordination plot showing separation of tailings dumps based on physicochemical properties. Acronyms UPS= upper slope; BS= Bottom slope; PLT = Dump top.

### 3.4 Discussion

This study is one of the first one to investigate the trajectory of changes in physical and chemical properties on long mine tailings chronosequences, in particular taking a combined assessment of effects of substrate age, local topography and vertical variation of multiple classes of elements and properties (macronutrients, micronutrients, metals and physical properties, salinity and pH dynamics). The study had five main findings: (1) the tailings were likely derived from similar ore which was not significantly affected by variation in temporal changes in physical metallurgical processing technologies, (2) macronutrients such as total N and available P significantly increased with dump age while OC and pH showed initial sharp declines followed by fluctuating trends, (3) substrate compaction and total metals in the surface layers significantly decreased with dump age, (4) position on the dump significantly affected EC and available P and, (5) overall, based on ordination results using all physicochemical properties, the dumps are gradually approaching reference. The results can be attributed to several pedogenetic processes, initial characteristics of the ore, effect of process chemicals and vegetation changes (Chapter 6). Main pedogenetic processes that may account for the results are weathering, oxidation of pyrites, salinization and leaching.

#### 3.4.1 Trajectory of macro and micronutrients

The observed increase in total N with substrate age might be attributed to biogenic additions mainly related to observed corresponding increase in vegetation cover (Chapters 5 and 6). Nitrogen is very low in the fresh tailings as it is seldom a significant component of the ore (Skousen *et al*, 1994). However, the

little N observed in the fresh tailings (Fig 3a) could be coming from residual cyanide (CN) that is used in the gold processing and disposed in tailings. Cyanide is used to leach gold into solution and also to elute it from carbon during the elution stage (Nsimba, 2009). The residual CN contains mineral element N tightly bonded to the carbon atom, which could be contributing to the observed N values. Over time the importance of CN as a source of N declines as CN is not stable in particular when exposed to UV light (Nsimba, 2009). Additional N in fresh tailings might be from decomposed plant matter from raw water extracted from Mazowe River that is used for ore processing. River water is known to contain organic N and inorganic N washed from the river catchment but the determination of the extent of this was outside the scope of this study.

The observed increase in total N over time coincided with increase in vegetation cover and biological crust cover observed in related studies (Chapter 5, Chapter 6; Nyenda *et al.*, 2019b). The increasing vegetation cover could have contributed to the N pool through litter fall and its subsequent decomposition by soil microbes which are known to increase with time during pedogenesis (Skousen *et al.*, 1994; Ahirwal *et al.*, 2017). Similarly, the BCs could also be fixing N into the top layers of the tailings as a related study observed enhanced N in the top layer beneath BCs on the dumps (Chapter 4; Nyenda *et al.*, 2019a). In a related study (Chapter 5), BC cover significantly increased with dump age and this increase may account for more contribution to the N pool as tailings age. Alternatively, some N might also be coming from fixation by free-living microbes that have N-fixing capabilities (Brady and Weil, 2013). Some nitrogen could also be fixed by some leguminous plants such as *Senegalia polyacantha*, *Vachellia karoo*, *Sesbania sesban* and *Crotalaria ochloreuca* that were observed on older dumps (Chapters 6). These legumes are known to improve nitrogen content at microsite level (Brady and Weil, 2013). In a related study enhanced nitrogen levels were observed on tailings substrate under canopies of *planted Senegalia polyacantha* and *Vachellia karoo* than adjacent off-canopy patches (Chapter 8). Further, in a related study, the tailings were observed to be colonized by shallow rooted plants that could contribute more to the observed higher total N levels in the 0-5 cm layer (Chapters 5 and 6, Nyenda *et al.*, 2019a, b). Due to higher compaction, indicated as bulk density in the current study, deeper tailing layers beyond 5 cm had fewer plant roots, unlike in the reference sites where woody plant roots could contribute more to the total N pool. The total N in the 5-15 cm remained markedly below levels observed at the adjacent reference sites, most probably due to less established pedogenetic processes although an increasing (developmental) trajectory towards reference conditions was observed.

Consistent with the study results, other studies on mine sites reported a developmental trajectory of total N, which, however, matched reference sites within a period of 15- 50 years (Skousen *et al.*, 1994, Hugget, 1998; Ahirwaal *et al.*, 2017). The longer time frame to reach reference conditions in the current study can be attributed to differences in starting points and other physicochemical properties of tailings when compared to other mine spoils and sites.

However, the contrasting trend for mineral N, where it did not vary with dump age, could be due to two main factors. Firstly, while mineralization of organic N could have been higher on older dumps, the available N would be quickly taken up by plants and incorporated into their biomass thus keeping the mineral N low (Singh and Singh, 1999). Secondly, mineralized N could be easily leached to lower depths. In the present study the lower positions of some dumps, for instance 82 and 92 years had higher N content than upper position most probably due to leaching. This could have been possible as the tailings had a largely silt –sand texture, a condition known to promote leaching (Brady and Weil, 2013). The similar textures observed among dumps suggests that even the older dumps still were susceptible to such nutrient leaching. Chaturvedi and Singh (2017) reported high susceptibility of N to leaching.

Similar to total N, the observed increase in available P can be attributed to the biogenic additions through decomposition of organic matter. The observed decline in substrate compaction (bulk density) improves aeration of the substrate, a condition which is known to promote mineralization of P from organic matter (Alexander, 1989). However, the temporal increase in P can be attributed to other factors such as the observed pH dynamics. At acidic pH below 5.5, characterizing the 10 and 17 year- old -dumps, P availability is known to be low due to precipitation by Al and Fe and increases as pH increases, reaching optimum values at pH between 6 and 7.5, similar to values observed on older dumps (Pierzynski *et al.*, 1994; Brady and Weil, 2013). The P availability is also very low at pH above 7.5 as was the case with fresh tailings, most probably due to fixation by Ca and this may explain the observed lower available P value (Pierzynski *et al.*, 1994). In particular, the greatest fixation by Fe is at pH 3-4, high fixation by Al at pH 4-5.5 and medium fixation by Ca at pH 7.5-9 (California Fertilizer Association, 1995). Further, P is a component of rock formations (Libertel *et al.*, 2013) and its increase in soils over time might be due to slow release from mineral weathering associated with pedogenetic processes. Unlike N, P is less mobile in soils and less susceptible to leaching. This might also explain its accumulation over time as well as the observed insignificant changes in available P with depth. Consistent with findings of this study, Alexander (1989) reported low leaching of P from the root zone of plants and noted losses were mainly due to erosion and run off. In the present study, observed higher P levels at lower slopes can therefore be attributed to depositions by run-off or erosion from dump tops and upper slopes (Down, 1975). The available P also showed a developmental trajectory that exceeded values observed at Ref-2 km at 82 years most probably due to favourable pH. The Ref-2km site had acidic pH values comparable to those observed on the 10 and 17-year-old dumps and this can also account for the lower available P just like the 10 and 17-year- old dumps. However, the temporal increasing trend of P is inconsistent with findings from a similar study on coal spoils in India where a temporal decrease in P was observed (Ahirwaal *et al.*, 2017). The differences can be attributed to possible variation in substrate geochemistry, biotic, climatic and landscape conditions.

The fluctuating trend for OC can be attributed to: (1) the biogeochemistry of OC in tropical environments (2) the effect of vegetation, (3) the input during gold processing, (4) fluctuating balance between carbon sequestration and replenishment, and, (4) random differences in carbon recovery efficiencies. Firstly, very high OC levels (1.2 %) on fresh tailings can be mainly attributed to residual process reagents such as activated carbon which is added during the CIP stage of gold processing as the medium for gold recovery from solution. This carbon can be eventually disposed in fresh tailings due to recovery inefficiencies, and this may account for the observed higher OC content in fresh tailings. The significantly lower OC values for the 10 and 17- year –old dumps than the fresh tailings can be attributed to early succession carbon losses through either (1) erosion to low lying areas, (2) decomposition by pioneer soil microbes in symbiotic relationships with pioneer plants resulting in reduced the carbon pool. (3) mobilization by free living microbes as a source of energy for growth and nitrogen fixation. This carbon therefore could be the major energy source for organisms during early pedogenesis. The decline in OC suggests that the rate of carbon sequestration was higher than the rate of its replenishment through fixation, litter fall and subsequent decomposition. Despite the gradual additions of OC by vegetation litter, the stabilization of the OC is generally slow in tropical environments, characterized by high temperatures and strong wet and drying cycles which impedes optimum stabilization (Brady and Weil, 2013).

The general significant increase in OC content from 17 years onwards in particular in the top 5 cm can be attributed to the profound effect of established pioneer vegetation either through their eventual death on completing their life cycles or through premature deaths as a result of inhibition by changing substrate factors. On completion of their lifecycles, pioneer species die and contribute to organic carbon built up. Alternatively, as plant species colonise dumps the harsh substrate conditions inhibit their persistence and on turnover they decompose and add organic matter (Feng *et al.*, 2014a; Shen *et al.*, 2014). The net effect of this is replenishment of lost carbon in the substrate. The decomposing litter from the increasing vegetation cover may also account for the increasing trend from 17 years. Observed increases in BC cover from 17 years to 92 years (Chapter 5, Nyenda *et al.*, 2019b) may also have promoted higher carbon fixation particularly in the top 5 cm owing to the ability of components of BC such as mosses and lichens to fix carbon (Chamizo *et al.*, 2012). In a related study enhanced OC content was recorded in areas dominated by lichen –moss crusts than non-bio-crusts patches (Chapter 4, Nyenda *et al.*, 2019a). The decline observed on the 92 years may be attributable to fluctuating sequestration and replenishment rates most attributable to the types of vegetation communities formed. Species with higher life spans such as woodies were increasing (Chapter 6) and would mobilize some of the carbon. However, the increase in OC from 92 -110 years can be attributed to balancing rate of replenishment and assimilation of carbon. Related studies have shown that during this late succession period, some species competitively exclude others as they dominate in cover (Chapter 6), while the high vegetation covers suppress BCs (Chapter 5; Nyenda *et al.*, 2019b). The suppressed vascular species and BCs can decompose and contribute OC to the substrate and that may be mechanism accounting for increases in OC content on the oldest dump.



Alternatively, the fluctuating trends can be attributed to possible random fluctuations in carbon recovery processes that may suggest differences in initial carbon concentration among the dumps. The observed fluctuating trend is inconsistent with findings from other mine chronosequence studies that suggest a progressive improvement in soil OC in the surface layers over time, matching references in periods between 8 – 35 years (Akala and Lal, 2001; Pasayat and Patel, 2015; Ahirwal *et al.*, 2017; Chaturvedi and Singh, 2017). The differences could be that the current study was carried out on unrehabilitated tailings material, unlike the bulk of previous studies that were conducted on rehabilitated mine spoils or overburden that had better initial OC levels and regeneration capacity. The findings thus suggest that the trajectory of OC in pedogenesis may be substrate dependent and may depend on initial substrate characteristics.

### 3.4.2 Changes in Exchangeable bases and other metals

Exchangeable bases (K, Ca and Mg) did not show significant variation with substrate age and did not show a clear trend most probably due to dynamics in weathering, cation exchange in the substrate and their poor mobility. The bases were however generally higher on the dumps than on reference sites owing to their presence in the ground ore as well as the addition of caustic soda (potassium hydroxide) and lime [Ca(OH)<sub>2</sub>] to neutralize pH in the gold recovery process (FRGM, 2015). Caustic soda is an important source of K while lime provides Ca. Similarly, available metals did not vary much contrary to what was expected. This might be mainly due to extent of weathering, pH and vegetation-metal uptake effects. Firstly despite the low pH that must promote heavy metal availability (Zaranyika and Chirinda, 2011), weathering is known to be slow and low and for the short study timeframes metal release could be low resulting in lower metal levels. On older dumps, while weathering might have improved, the higher pH (about 6.5) lowers the solubility of the heavy metals (Zaranyika and Chirinda, 2011). Alternatively, some metals in solution could be absorbed by plants and accumulated in their tissues, reducing the soil concentration. Although this aspect was not investigated in this study, it is well established that several plants take up metals as a mechanism for survival on metalliferous soils ( Wild, 1974; Mendez and Maier, 2008).

Nevertheless, the observation that the surface layers (0-15 cm) of younger dumps had higher concentrations of most metals (Table 3.3) than surface layers of older dumps which had the concentration higher on deeper layers (1-3m) may be attributed to leaching of these metals from top horizons to lower layers (Zaranyika and Chirinda, 2011). Alternatively, this could be due to the fact that the ore for the youngest dumps could have had higher levels of these elements than the ore for the older dumps and or differences in ore for top layers and that for lower layers. While the ore belongs to generally similar geologies as noted (Chapter 2) , local variations in rock formations and mineralogy are a common phenomena in geology which may account for some substrate variation (BGS, 2015). The steady and

significant increase of Fe with depth can be attributed to its precipitation. Zaranyika and Chirinda observed increased Fe precipitation with depth at a gold mine in Zimbabwe (Zaranyika and Chirinda, 2011). The slightly higher available metals on the 10 year-old-dump can be attributed to the strongly very acidic pH (<4) on the dump. Available metals are known to be sensitive to low pH due to increased solubility (Brady and Weil, 2013). However, the general unexpected trend of available metals on most dumps can be due to two main factors, (1) acidity buffering capacity of tailings related to presence of carbonates and or precipitation of metals in the substrate matrix and, (2) alternatively, some solubilized metals may have been quickly leached to lower levels that were not sampled or were taken up by the increasing vegetation, cancelling the effect of metal additions.

### **3.4.3 Changes in pH and salinity**

The pH and EC are originally higher (alkaline) on fresh tailings owing to addition of alkaline gold processing chemicals. Lime ( $\text{Ca}(\text{OH})_2$ ) and potassium hydroxide (KOH) are added during the milling and gold leaching (CIL) steps respectively in order to suppress acidic conditions that may render gold leaching ineffective and suppress the production of HCN which is a health hazard to the workers (ICMI, 2018). The sharp decline in pH from fresh tailings from about 10 to 3 in the top 15 cm can be attributed to oxidation of pyrites. Over time, in particular immediately after disposal, excess water is drained from the tailings and in the presence of oxygen at the surface, coupled with low compaction that promotes aeration, oxidation of pyrite is promoted, releasing sulphuric acid that substantially lowers the pH (Zaranyika and Chirinda, 2011). The observed temporal decline in pyrite levels suggest oxidation rapidly took place after tailings disposal in support of the rapid drop in pH. The steady increase in pH from 17 years onwards can be attributed to decreased rates of pyrite oxidation owing to reduced aeration and drier substrate conditions which are known to discourage oxidation of pyrite. As observed on the 17 and 30 year-old-dumps, the acidity may also be leached to lower layers over time (Zaranyika and Chirinda, 2011; Asoy, 2017). Further, although this aspect was not investigated in the current study, over time the carbonates from the ore minerals in the tailings can be weathered, releasing their acid buffering capability, thus stabilizing the pH (Asoy, 2017). However, the fluctuating pH between 30-110 years could be attributed to continuous disturbances by erosion at the surface which kept on exposing substrate to air and water with subsequent increased rates of acid generation. The results are consistent with findings by Down (1975) who reported a rapid decline in pH after mining followed by a gradual increase with age owing to continued weathering and an increase in leaching of sulphate and acidic cations. Zaranyika and Chirinda (2011) also reported that continued erosion on mine tailings are key determinants of oxidation of pyrites.

The slight decline in EC on surface layers over time might be due to leaching of salts to lower levels and this may also explain the observed relatively higher EC values at the lower slopes of most dumps (Table

3.4). However, the fluctuating EC on substrates of different ages could be related to continued erosion, and moisture dynamics on the dumps.

#### **3.4.4 Changes in physical properties (compaction and texture).**

The observed trends in bulk density can be attributed to natural settling by gravity, raindrop action and effects of vegetation and to some extent particle size. Fresh tailings have relatively low bulk density at dumping as they are not compacted, have high moisture occupying other pore spaces. The initial peak in bulk density in the top layer of the 10-year-old dump when compared to freshly dumped tailings can be attributable to increased compaction as the tailings settle by gravity over time. Fresh tailings are loosely packed and over time there is increased downward movement of fine material resulting in reduced pore space and hence increased compaction. This temporal down-ward movement of material may also account for the observed higher bulk density values at lower depths than on the surface. Rain drop action also increases compaction. The 10-year-old- dump was largely bare (Chapters 5 and 6) and more exposed to compaction effects of rain-drop action. However, the decline in bulk density from 10 to 110 years could be due to development of vertical structure related to vegetation establishment. As tailings age, vegetation increased (Chapter 5 and 6) and the increased vegetation cover could have played a significant role in reducing the compaction effect of rainfall drops by intercepting the drops.

The effect of developing plant roots on older dumps might also lower the bulk density. Increased deposition of plant litter and its subsequent incorporation into the topsoil also may account for temporal decrease in bulk density. Some species, like *Equisetum ramosissimum* that had highest frequency on the oldest dump also lowers bulk density through increased aeration (Young, 2013). Nevertheless, the insignificant changes in texture could be attributed to slow weathering during pedogenesis or the effect of the milling technologies. In the former texture may require several years to change (Brady and Weil, 2013), while in the later the gold milling technologies may have reduced the particle sizes largely silt which appear to be more stable against weathering forces. It is well known that bulk density and texture are closely related (Brady and Weil, 2013). However, the observation that bulk density significantly changed with age and depth while texture did not against the conventional correlation suggests that the other non-substrate factors were more important determinants.

Overall, the PCA discrimination and clustering of sites based on substrate properties do not show a clear trajectory for soils relative to references. However, younger dumps less than 30 years were generally distinct from the older ones. While some parameters followed clear trajectories, the fluctuating trends on others disrupted trajectories. The study findings were consistent with findings by Skousen *et al.* (1988; 1994) where the mine soils developed on 5-15-year-old mined sites appear to be similar in chemical properties, while the mine soils on the 20-30 year-old mined sites were similar to each other. However,

findings from the present study are inconsistent with Skousen *et al.*, (1988) in that tailings of the oldest sites were similar to some younger sites and converged to native references on chemical properties. In the work of Skousen *et al.*, (1988), the oldest (50-year-old mines soil) was different from all other mined areas, and quite different from the native reference soils. Results from the present study show that surface properties, in particular, key macronutrients, show a developmental trajectory which converges and matches reference conditions within 110 years although vertical profiles are not restored. Changes of soil properties on mine tailings is not uniform as topography also plays a role in shaping key trends.

### **3.5 Conclusions and recommendations**

The study concluded that trajectories of physicochemical properties on mine tailings are not uniform, rather element specific. Some macronutrients in particular total N and available P increased with age and approached that of the references in top 5 cm within the 110 year- period but not for the other subsurface layers while K did not show a clear trend. The study noted a different trajectory for mineral N therefore suggesting that observed contrasting total and mineral N trends were influenced by the stoichiometry of N. Organic carbon and fine particles on mine tailings do not increase progressively as hypothesized. Other parameters such as pH, EC and exchangeable bases fluctuate over time concurring with an evolutionary trajectory, contrary to what was hypothesized. Bulk density decreased with age as hypothesized. Topography had limited influence on some tailings physicochemical parameters (P and EC) which increase from dump tops to bases, although age seems the most important determinant. Main determinants of soil trajectories could be oxidation of pyrites, mineral weathering and leaching, salt accumulation, vegetation, and biocrusts.

## CHAPTER 4

### BIOLOGICAL CRUSTS ENHANCE FERTILITY AND TEXTURE ON GOLD MINE TAILINGS

*\* This chapter was published with the journal Ecological Engineering  
(<https://doi.org/10.1016/j.ecoleng.2019.03.007>)*

**Nyenda T<sup>\*abc</sup>; Jacobs SM<sup>a</sup>; Gwenzi, W<sup>d</sup>; Muvengwi J<sup>e,f</sup>**

<sup>a</sup> Department of Conservation Ecology and Entomology, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa.

<sup>b</sup> Department of Environmental Sciences, Bindura University of Science Education, Private, Bag 1020, Bindura, Zimbabwe.

<sup>c</sup> Zimbabwe Mine Environment Research Network (ZIMERN), Agriculture House, No. 1, Adylin Road, Marlborough, Harare, Zimbabwe.

<sup>d</sup> Biosystems and Environmental Engineering Research Group, Department of Soil Science and Agriculture Engineering, University of Zimbabwe, Box MP 167, Mt Pleasant, Harare, Zimbabwe.

<sup>e</sup> Department of Natural Resources, Bindura University of Science Education, Private Bag 1020, Bindura, Zimbabwe.

<sup>f</sup> Restoration and Conservation Biology Research Group, School of Animal, Plant and Environmental Sciences, University of the Witwatersrand, Private Bag 3, Wits 2050, Johannesburg, South Africa.

Corresponding Author email: [tatenyenda@yahoo.com](mailto:tatenyenda@yahoo.com) (Tatenda Nyenda)

#### Abstract

Biological crusts (BCs) are reported to be soil ecological engineers critical in restoration of degraded ecosystems and rehabilitation of anthropogenic substrates, yet their occurrence and influence on such substrates is not well understood. We studied physical and chemical properties of biological crusts and layers immediately beneath them, compared with non-BC covered patches on two gold mine tailings dumps in tropical Zimbabwe. The aim was to determine the influence of biological crusts on fertility and texture of the substrate. We hypothesized that BCs alter tailings' chemical and physical properties, yielding improved fertility and finer texture and that the fertility and finer particle content would decrease with depth. Physicochemical properties of tailings were studied within 36 quadrats, each 30 cm x 30 cm, across two gold tailings dumps from three patches, namely (1) patches consisting of BCs only, (2)

patches with both BCs and vegetation and (3) non-BCs patches, without vegetation. In each patch, we sampled the crust along with two layers immediately below (0- 1 cm and 1-5 cm). Patch type had a significant effect on mineral and total N, exchangeable K, Ca and Mg, OC, available and total Zn and Mn, and available Ni. The interactive effect of patch type and layer was significant for all parameters except OC and EC. Total N, OC, exchangeable Ca, K and Mg and silt content were higher on the BC patches than the bare patches. Overall, a PCA based on soil properties showed that sites in the three patches were distinct. Our results concurred with our hypothesis and point to the existence of significant effect of BCs on the fertility of the underlying substrate. Results revealed a potential role for BCs in the early ecosystem development of mine tailings, notably, in enriching the soil N, OC, and base cations. We recommend close monitoring of the establishment of BCs on gold tailings to develop approaches to effectively remediate such environments, using BCs.

**Key words:** Biological crusts, Exchangeable bases, Mine tailings, Nitrogen, Organic carbon, Texture

#### 4.1 Introduction

Mine tailings usually contain low concentrations of macronutrients such as nitrogen and phosphorus (Melato *et al.*, 2016). They also have high concentrations of micronutrients or toxic heavy metals, for example copper, manganese, zinc, cadmium, nickel, iron and arsenic (Wuana and Okieimen, 2011; Bempah *et al.*, 2013). These unfavorable conditions make natural plant establishment very slow (Melato *et al.*, 2016). Thus mine tailings may remain devoid of vegetation or with sparse vegetation for decades (Melato *et al.*, 2016). Generally, on natural sandy soils, open spaces between the vascular plants are often covered by biological crusts (Zhang *et al.*, 2010; Chamizo *et al.*, 2012). Biological crusts are diminutive but important communities of living organisms (Bowker, 2007) that are a result of an intimate association between bryophytes, lichens, cyanobacteria, micro-fungi, algae and soil particles in different proportions (Belnap, 2006; Chamizo *et al.*, 2012; Bu *et al.*, 2013; Keck *et al.*, 2016).

Biological crusts are primary pioneer colonizers that can survive on soil with extreme pH and salinity (Belnap *et al.*, 2001; Bowker, 2007). Where they colonize a soil substrate, they spread extensively, modifying physical, chemical and hydrological properties in the process (Chamizo *et al.*, 2012). Owing to their ability to alter substrate properties, BCs are considered ecosystem engineers (Belnap *et al.*, 2001; Bu *et al.*, 2013) with potential to greatly contribute to ecosystem restoration. Their effect on soil hydrological properties is largely dependent on their structure and type (Belnap, 2006). Pinnacled BCs roughen soil surfaces thereby promoting infiltration (Zhi *et al.*, 2009). Smooth BCs like cyanobacteria and crustose lichens reduce infiltration and increase run-off due to reduced surface roughness and porosity (Belnap, 2006; Fischer *et al.*, 2014). The BCs enhance soil fertility by fixing carbon and nitrogen (Belnap *et al.*, 2001; Bu *et al.*, 2013), increase soil surface temperatures, hence increasing microbial activity, plant

nutrient uptake rates (Belnap *et al.*, 2001). Surface roughness created by rough BCs, sticky cyanobacteria sheaths and protruding moss stems and lichen thalli, trap airborne fine particles altering texture of surface soils (Belnap, 2003a, Belnap, 2006). Lichens and mosses have most of their biomass above the soil surface which help protect the soil from rain-drop impact (Belnap, 2006). They also stabilize soil as they bind soil particles through cyanobacterial filaments and extracellular polysaccharides (Belnap *et al.*, 2008; Dougill and Thomas, 2014) and promote plant establishment through nutrient supply (Guo *et al.*, 2008; Ochoa-Hueso *et al.*, 2011; Yang *et al.*, 2015). In particular, BCs have been reported to trap small plant seeds and nutrient rich fine particles (Belnap *et al.*, 2001), facilitate seed germination, and promote survival and growth of pioneer plant seedlings (Bowker, 2007; Zhang *et al.*, 2016).

Globally, several studies on biological soil crusts have been conducted (e.g. Belnap, 1996; Li *et al.*, 2006; Bowker, 2007; Büdel *et al.*, 2009; Chamizo *et al.*, 2012; Funk *et al.*, 2014; Bu *et al.*, 2015; Yang *et al.*, 2015). Most of these studies focused on characterization of BCs, effects on soil stability of natural substrate, particularly in arid and semi-arid areas of Asia, USA, Europe and Africa. While several studies reported a significant influence of BCs on fertility, OC and texture of layers beneath them, it remains unknown if similar effects can be observed on geochemically unique anthropogenic substrates like mine tailings. The effect of biological crusts on specific physical and chemical properties of the underlying layers of mine tailings remains poorly understood. A few studies on mine tailings have focused on BC composition, but little on their effect on fertility, texture and metal concentration (e.g. Sun *et al.*, 2004; Orlekowsky *et al.*, 2013; Umba, 2014; Seiderer *et al.*, 2017) . In spite of many studies that have documented the important roles of BCs (e.g. Belnap *et al.*, 2001; Bu *et al.*, 2013; Bu *et al.*, 2015; Stewart and Siciliano 2015), they are rarely included in restoration literature (Bowker, 2007). This has resulted in incomplete tailings rehabilitation solutions, often only targeting promotion of establishment of vascular plants using expensive artificial amelioration approaches. Given the nature of BCs, outlined above, they have the potential to offer a cheap natural solution to tailings rehabilitation.

Understanding the influence of biological crusts on underlying mine tailings layers will help restoration ecologists and practitioners in ascertaining the feasibility of BCs for large-scale ecological engineering in restoration activities. Abandoned unrehabilitated gold mine tailings at Phoenix Prince (Freda Rebecca) Mine in northern Zimbabwe are significantly colonized by lichen-moss dominated biocrusts and present an opportunity to evaluate the soil engineering capability of BCs on such substrates, which require cheap and natural restoration solutions. The aim of the study was to characterize physical and chemical properties of BCs and layers beneath them and compare them with layers from bare patches on the tailings. We hypothesized that BCs alter tailings' chemical and physical properties, yielding improved fertility and finer texture that would however decrease with depth.



## 4.2 Material and methods

### 4.2.1 Study sites and crusts types

The study was carried out on two adjacent abandoned gold tailings (31°16'S; 17°16'E, 1070 m) of the same age range (82 and 92 years) at Phoenix Prince Mine in Bindura, north east of Zimbabwe. The area experiences hot and wet summers, dry and cool winters with mean annual precipitation of over 800 mm and mean annual temperature of 28°C. The general geology of the area belongs to the Zimbabwe Craton in the Harare-Shamva Greenstone belt wedged between the Chinamora (to the south), and Madziwa batholiths (to the north) (FRGM Geology Report, 2010). The specific geology of the study sites belongs to metasediments and metamorphic rocks of the basement schists belonging to the Shamvaian group. The gold ore that produces the tailings consists of pyrite (FeS<sub>2</sub>), pyrrhotite (FeO<sub>8</sub>S), and arsenopyrite (FeAsS) as the major minerals with chalcopyrite (CuFeS<sub>2</sub>), bornite (Cu<sub>5</sub>FeS<sub>4</sub>) and pyrolucite (MnO<sub>2</sub>) as minors. The sampled sites were tailings dump tops with a slope of less than 2 %. The tailings are dominated by herbaceous species, with aerial covers of 52 % ± 8 and 49 % ± 10. The tailings have an estimated total BC cover of 10 % ± 7; 11% ± 7 and about 40 ± 10% and 38 % ± 12 bare ground. The BCs are mainly crustose and fruticose lichen and moss- dominated and occurs in patches particularly between plants. The BCs were moderately developed with a thickness range of 9-15 mm. Areas with high crusts cover (> 50 %) were selected for the study, with and without herbaceous vegetation. Notable herbaceous species on the tailings were *Imperata cylindrica*, *Schizachyrium platphyllum*, *Diheteropogon amplexans*, *Andropogon chinensis*, *Cymbopogon caesius*, *Flaveria trinervia* and *Penisetum setaceum*.

### 4.2.2 Tailings sampling

Sampling was done from three patches, approximately 500 m<sup>2</sup> each, herein referred to as patch types on each tailing dump: (1) BC patch away from vegetation, (2) BCs + vegetation patch and, (3) bare ground. Six samples (30 x 30 cm quadrats) per patch were collected from the following layers on each dump: (1) the crust layer, (2) top layer (1 cm layer beneath the crust) and, (3) lower layer (1-5 cm beneath the crust). In open areas (bare patches), physical crusts were sampled along with two substrate layers beneath them. Selected bare patches were at least 2 m away from the sampled patch to cater for both spatial auto-correlations between patches while minimizing potential topographic and edaphic heterogeneity. To clearly observe BCs, litter was removed and the surface was sprayed with water (Lei *et al.*, 2015). Samples for the determination of BC thickness were collected from four separate points within a 0.25 m<sup>2</sup> quadrat and thickness measured to the nearest mm using a digital veneer caliper. Crust thickness was used as a covariate to ensure crusts in similar age range were sampled at all sites. Morphological features and colour were also considered to ensure similar crusts were sampled across sites. For the comparisons of BC and adjacent non-BC patches, crusts were extracted by placing a knife under the crust while tailings samples in 0-1 cm and 1-5 cm beneath the crusts were extracted using steel



cores. Biological crusts and tailings samples were placed in sterile plastic bags and were immediately taken to the laboratory for analysis.

#### **4.2.3 Determination of physicochemical characteristics of crusts and underlying tailings.**

Laboratory analysis was done for samples from three layers: crusts, underlying top and lower layers. All analyses for the BC layer were done on tailings particles scrapped off the crust herein referred to as crust layer (Chamizo *et al.*, 2012). The sampled crusts and substrate from their underlying layers were air-dried and passed through a 2 mm sieve to obtain fine earth particles. Aliquots of the samples were ground and passed through a 0.5 mm sieve to obtain a fraction necessary for OC determination. Organic carbon was determined using the Walkley and Black method (Walkley and Black, 1934). Texture was determined using the pipette and hydrometer method (Okalebo *et al.*, 2002). Electrical conductivity and pH were measured by an electrical conductivity meter and pH meter respectively in a 1:5 soil-water suspension (Zhan and Sun, 2011; 2012). Total nitrogen was measured using the Kjeldahl method (Jackson, 1964). Available phosphorus was determined using the Olsen method which involved adding 50 ml of Olsen's reagent to 2.5 g of air-dried soil (soil-solution ratio of 1:20) and subsequent shaking for 30 minutes then use the filtrate to determine it calorimetrically. Exchangeable bases (K, Ca and Mg) were extracted in ammonium acetate and K, Ca and Mg were determined using atomic absorption spectrophotometer (AAS). The available metals (Mn, Ni and Zn) were determined by the AAS technique after extraction with 1M CaCl<sub>2</sub> for 2 hrs at 25°C (tailings (mass): water (volume) = 1g: 2 mL). The total metals fraction in the tailings samples were measured by the AAS method after samples were digested with a mixture of hydrofluoric (40%), nitric (68.0%), and perchloric (72 %) acid (Okalebo *et al.*, 2002). Mineral N was determined by the steam distillation method following extraction of NH<sub>4</sub>-N and NO<sub>3</sub>-N with 2 M Kill solution.

#### **4.2.4 Data analyses**

All data were tested for normality using the Kolmogorov-Smirnov test in SPSS version 21 prior to analysis. To determine the effect of patch type, layer and their interaction on physicochemical properties of tailings, we performed general linear models (GLMs) with Poisson error distributions and log link functions for each response variable using crust type and substrate layer as predictors. All analyses were done at 5 % level of significance, with post-hoc LSD tests post -hoc done for pair wise comparisons. In order to determine separation of sites of different patches and depths, a principal component analysis (PCA) linear ordination was performed using measured tailings properties in Conoco for Windows version 5.

## 4.3 Results

### 4.3.1 Physicochemical properties of bio-crust and non-bio-crusted patches on tailings

A patch type had significant effect on mineral nitrogen, exchangeable bases (K, Ca, Mg), Total N, OC, available and total (Zn and Mn, and available Ni (Table 4.1). Mineral N, total N, pH, available P and exchangeable bases (K, Ca, and Mg) were significantly influenced by sample layer (Table 4.1). The interactive effect of patch type and sampling layer was significant for pH, mineral and total N, available P, and exchangeable bases (K, Ca and Mg). Most values of the measured chemical parameters were highest in the BCs only patch followed by the BCs + vegetation patch, then bare patches except available P, EC and available and total metals (Table 4.2). Mineral nitrogen in the crust layer of the BCs only patch decreased significantly with depth while the crusts in the BCs + vegetation patch had lower mineral N than underlying layers. Total N for crusts in the BCs only patch was similar to that observed in the 0-1 cm layer but 2-fold higher than concentrations observed in the lower layer (1-5cm). The lower layer of the BC + vegetation patch had 1.5 times higher total N than the BCs only patch. Available P did not show a distinct trend in all patches. Organic carbon for crusts and underlying layers was similar in all patches (Table 4.2). Exchangeable K decreased from crust to underlying layers in all patches. In the bare and BC + vegetation patches, exchangeable Mg and Ca decreased significantly with depth while it was relatively constant in the BCs only patch (Table 4.2). Substrate layers below crusts in the BC patch had higher pH than those in the vegetated and bare patches (Table 4.2). However, pH decreased with depth in the same patch (Table 4.2). Available and total Mn and Ni were similar across substrate layers in all patches while available Zn increased with depth in the BCs only patch. Available Zn was slightly higher in the lower layer of the BCs+ vegetation patch and 2-fold higher on surface than the 0-1 cm layer beneath in the bare patch (Table 4.2).

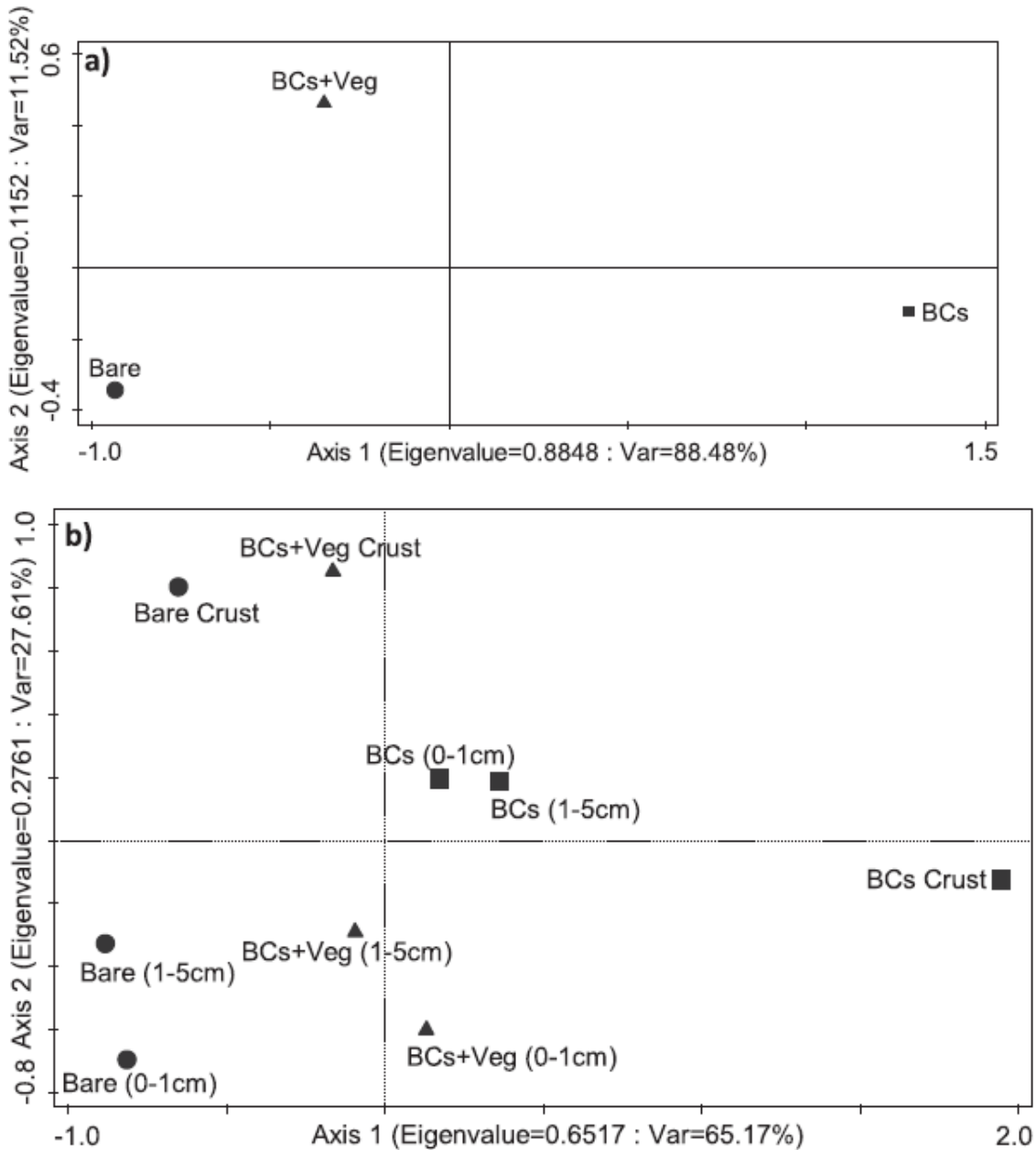
Silt content significantly varied with depth. Clay and silt content in the top and lower layers were highest in the BCs only patch, followed by the BCs + vegetation and then bare patch. Sand content was always higher on the bare patches. Silt content was highest in the 0-1 cm layer of the BCs only and BCs + vegetation layers. Overall, a PCA showed that the sites in the three patches were dissimilar (Fig 4.1a) and that the crust, 0-1 cm and 1-5 cm layers in all patches were to a greater extent also dissimilar (Fig 4.1b).

**Table 4.3:** Results of the GLM showing the effect of the predictor factors (Patch type and layer) on the physicochemical properties of biocrusts tailings at Phoenix Prince gold tailings dumps. Numbers are F and p values (in brackets). The test was performed at 5% significance level. Ava. = available; Exch. = Exchangeable

Predictor	Response Variables					
	pH	Mineral N	Available P	Exch. K	Exch. Ca	Exch. Mg
Patch type	1.2(0.299)	42.9(0.000)	1.0(0.371)	28.1(0.000)	8.9(0.000)	23.2(0.000)
Layer	14.8(0.00)	12.4(0.000)	26.8(0.000)	422.5(0.000)	12.4(0.000)	17.0(0.000)
Patch type*layer	4.9(0.002)	20.9(0.000)	18.6(0.000)	19.2(0.000)	2.7(0.038)	6.9(0.000)
Predictor	Ava. Zn	Total Zn	Ava. Ni	Total Ni	Ava. Mn	Total Mn
Patch type	23.1(0.000)	9.3(0.000)	4.7(0.012)	2.6(0.081)	6.7(0.002)	10.9(0.000)
Layer	0.1(0.932)	0.8(0.450)	0.4(0.671)	0.9(0.433)	0.4(0.683)	1.8(0.184)
Patch type*layer	0.0(0.996)	0.6(0.688)	0.9(0.489)	0.4(0.813)	1.0(0.414)	1.3(0.270)
Predictor	Total N	EC	OC	Clay	Silt	Sand
Patch type	117.7(0.000)	0.0(0.996)	6.7(0.002)	3.6(0.053)	1.0(0.392)	1.7(0.188)
Layer	11.0(0.000)	0.0(0.982)	0.7(0.526)	1.8(0.176)	3.5(0.035)	2.8(0.067)
Patch type*layer	24.9(0.000)	0.0(0.999)	0.5(0.739)	0.9(0.468)	0.7(0.628)	0.6(0.633)

**Table 4 4:** Chemical properties of different soil layers in the two crusts patches compared to the open area. All heavy metal concentrations are mg/kg; All exchangeable bases concentrations are meq/100g; N=36. Tot. = Total

Patch	Crust layer				Top layer (0-1cm)				Lower layer (1-5cm)			
	Mineral N (ppm)	Total N (%)	Available P (ppm)	OC (%)	Mineral N(ppm)	Total N (%)	Available P (ppm)	OC (%)	Mineral N(ppm)	Total N (%)	Available P (ppm)	OC (%)
BCs	48.3±13.6	0.2±0.0	32.3±6.7	0.8±0.7	18.3±5.9	0.2±0.1	39.8±11.8	0.4±0.2	18.5±6.1	0.1±0.0	35.7±7.9	0.7±0.9
BCs+Veg	14.0±0.0	0.2±0.0	52.0±0.0	0.4±0.4	19.0±0.0	0.2±0.0	28.0±0.0	0.4±0.3	16.0±0.0	0.3±0.0	36.0±0.0	0.6±0.4
Bare	11.5±3.6	0.1±0.0	51.8±1.3	0.1±0.0	11.5±3.3	0.1±0.0	25.5±1.2	0.1±0.0	11.1±3.4	0.1±0.0	32.8±3.1	0.1±0.0
Patch	Crust layer				Top layer (0-1cm)				Lower layer (1-5cm)			
	K	Mg	Ca	EC(mS)	K	Mg	Ca	EC(mS)	K	Mg	Ca	EC(mS)
BCs	0.4±0.0	0.6±0.1	2.0±0.3	2.0±1.6	0.3±0.0	0.5±0.1	1.6±0.8	2.0±1.6	0.2±0.0	0.6±0.2	2.0±1.1	1.9±1.6
BCs+Veg	0.4±0.0	0.6±0.0	2.1±0.0	1.9±1.6	0.2±0.0	0.4±0.0	1.0±0.0	2.0±1.6	0.1±0.0	0.3±0.0	1.0±0.0	1.9±1.6
Bare	0.4±0.0	0.5±0.0	1.9±0.1	1.9±1.7	0.1±0.0	0.4±0.0	0.9±0.0	2.1±1.5	0.1±0.0	0.3±0.0	1.0±0.0	2.0±1.5
Patch type	Crust layer				Top layer (0-1cm)				Lower layer (1-5cm)			
	Ava.Zn	Tot. Zn	Ava.Ni	Tot Ni	Ava Zn	Tot Zn	Ava.Ni	Tot Ni	Ava. Zn	Tot Zn	Ava. Ni	Tot Ni
BCs	0.5±0.4	60.5±19.8	3.6±3.3	78.0±17.7	0.6±0.5	52.8±10.0	5.7±6.2	66.4±38.6	0.7±0.9	69.2±22.6	8.7±6.8	81.3±45.6
BCs+Veg	24.9±26.8	65.2±28.8	8.1±7.6	66.3±31.4	23.8±25.9	59.2±30.6	7.9±7.8	60.0±22.7	27.6±29.2	62.0±36.0	6.9±5.0	59.2±21.4
Bare	1.2±0.0	43.0±1.9	2.4±0.0	95.0±0.0	0.6±0.0	34.7±1.0	2.0±0.0	79.2±0.0	1.2±0.0	34.2±0.1	2.8±0.1	76.4±0.0
Patch	Crust layer			Top layer (0-1cm)			Lower layer (1-5cm)					
	Ava Mn	Tot Mn	pH	Ava Mn	Tot Mn	pH	Ava Mn	Tot Mn	pH			
BCs	11.5±8.3	155.4±30.0	5.1±0.4	19.8±7.6	158.8±15.8	5.2±0.2	19.4±9.1	152.9±31.0	5.0±0.8			
BCs+Veg	23.0±18.1	130.2±27.4	5.8±0.0	18.1±12.6	123.2±28.0	4.7±0.0	20.6±17.6	127.8±27.1	4.7±0.0			
Bare	7.2±0.0	153.6±0.4	5.3±0.5	10.2±0.1	120.7±0.5	4.7±0.0	9.1±0.1	126.5±0.5	4.7±0.0			



**Figure 4.1:** PCA scatter plot showing separation of sites based on substrate physicochemical properties: (a) overall site (patch) separation and (b) Substrate layers in the 3 patches; BC denotes biocrust; veg denotes vegetation.

## 4.4 Discussion

### 4.4.1 Contrasting physicochemical properties of bio-crust and non-bio-crusted patches

The current study is one of the first in Southern Africa to assess the influence of BCs on properties on gold tailings. Key findings are higher N, OC and exchangeable bases on BC patches than bare patches with main effects being in the top 1 cm layer rather than the lower layers. The patches with BCs cover and those without were dissimilar based on a PCA using their physicochemical properties. The results suggest the presence of BCs on gold tailings can enhance fertility owing to its significant effect on mineral and total N, OC and exchangeable bases (K, Ca and Mg). The results also indicate that to some extent silt content and pH are also significantly altered by the presence of BCs. The findings highlight the importance of BCs in engineering soil development on anthropogenic substrates.

#### **4.4.1.1 Influence of biological crusts on tailings fertility and texture**

Higher N and OC on BC patches than areas without BCs demonstrate the potential influence of BCs on fertility of the tailings surface and layers immediately below them (Belnap *et al.*, 2001; Sun *et al.*, 2004). Biological crusts, in particular lichen and moss dominated, as was observed on the study site are important in soil nitrogen and carbon cycling in stressful environments (Belnap *et al.*, 2001; Bowker, 2007). Biological crusts have been reported to fix atmospheric nitrogen, through their cyanobacterial component in symbiotic relationship with other microbes such as fungi into (Belnap *et al.*, 2003; Veluci *et al.*, 2006) and mine tailings (Sun *et al.*, 2004; Zhan and Sun, 2011; 2012; Stewart and Siciliano, 2015). This ability could be the mechanism that explains the observed higher mineral and total N levels on BC patches. Non-BC patches may therefore just be depending on free-living microorganisms that may fix and retain nitrogen and this may explain the suppressed nitrogen levels on non-BC patches (Zhan and Sun, 2011). BC patches therefore may have dual nitrogen inputs from the BCs and the free-living N-fixers usually found in soils. Observed higher N on BC patches compared to bare tailings may also be due to the ability of BCs to trap nutrient-rich dust thereby enhancing nutrient input (Chamizo *et al.*, 2012). Further, the observed higher mineral and total nitrogen on biological crusts than the underlying layer suggest the importance of the BCs to the enhancement of fertility of the layers below them (Chamizo *et al.*, 2012).

The higher N in the 0-1 cm than the lower layer in some cases might be due to the ability of BCs to reduce leaching as they are not leaky. This could be mainly due to the polysaccharides secreted by the BC organisms that enhance adherence of soil particles to each other which in turn increase the stability of the substrate and the retention of nutrients in the top layer making it more fertile (Reynolds *et al.*, 2001). This is consistent with findings by Mager and Thomas (2011) who reported higher effect of BCs in nutrient cycling in top layers while effect on lower layers (1-5 cm) was often lower and depend on crust type. Veluci *et al.*, (2006) also reported lower nitrate leaching in lichen dominated BC patches than bare patches. However, lack of variation in total nitrogen between tailings from pure BC patches and that on vegetated patches in this study suggests that the effect of vegetation could be neutral (Sun *et al.*, 2004). The unexpectedly higher total nitrogen in the 1-5cm layer under the BCs + vegetation patch when

compared to the level observed in the top layer (0-1 cm) may be due to the contribution of plant roots to nutrient cycling at that depth. However, the observed enhanced nitrogen on BC patches is consistent with observations on similar mining impacted areas such as tailings (Sun *et al.*, 2004; Stewart and Sicilian, 2015).

Higher OC under BC patches than bare patches suggests the influence of BCs in carbon fixation (Bu *et al.*, 2013). Some studies reported the ability of BCs to fix atmospheric carbon, increasing soil carbon by producing extracellular polysaccharides (Beymer and Klopatek, 1991; Mager and Thomas, 2011). Polysaccharide content of 1.5-3 times higher were reported on BC patches than bare areas (Malam issa *et al.*, 2001; Belnap *et al.*, 2008 ). This may explain the observed higher OC on BC patches than bare patches. The observed higher OC content and total nitrogen on BCs than bare physical crusts were reported in similar studies (Belnap *et al.*, 2001; Sun *et al.*, 2004; Dougill and Thomas, 2014; Gao *et al.*, 2014). However, the observed higher OC in the lower layer might be due to the effect of plant roots that usually exist below the 0-1 cm depth. The higher OC in soils associated with crusts in the vegetated patches than in bare patches shows synergistic effects of biocrusts and the sparse vegetation. However, lack of variation in OC among BC patch layers suggests BCs have not much influence on OC in underlying layers.

The higher exchangeable bases (K, Ca and Mg) on BC than non-BC patches may be attributable to the presence of trapped fine particles of clay and silt which can bind cations such as K, Mg, Ca and heavy metals (Belnap *et al.*, 2001; Bowker, 2007). Cation binding is often enhanced by polysaccharides secreted by BC filaments (Belnap *et al.*, 2003) which in turn enhance exchangeable bases such as K, Ca and Mg in soil as observed in the present study. This may also explain the marked differences in available Zn between different layers and treatments as compared to other metals. Exchangeable bases and Zn are nutrients important in soil fertility and plant growth.

Despite the generally insignificant effect of BC crust cover on tailings pH, higher pH values were observed on BC patches than on bare tailings. This suggests an influence of BCs on substrate pH. This could be attributed to suppressed oxidation of pyrites due to the activities of microorganisms associated with the BCs. The presence of microorganisms that facilitate nutrient fixation and decomposition disrupt oxygen availability in the BC as they utilize oxygen for oxidation of pyrites, hence higher pH values on BC patches (Moon *et al.*, 2013). In other studies, BCs have been reported to increase the pH of the top soil (Belnap, 1996; Bowker *et al.*, 2006) owing to calcium carbonates. Consistent with our findings, marginally higher pH was reported in BC patches than physical crusts of Las Amoladeras in desert soils (Chamizo *et al.*, 2012).

On texture, the slightly higher silt and clay content on BC patches than non- BC patches though not statistically significant could be just be a result of chance. The study noted a different trend from other

studies which reported significantly higher clay content on BC patches when compared to adjacent non-BC patches (Chamizo *et al.*, 2001, Belnap *et al.*, 2001). This discrepancy could be attributed to the intrinsic characteristics of the milled tailings. The tailings generally have a homogenous substrate particle size distribution dominated by sand fractions due to the ore milling process. Such fractions have pores that may allow the movement of finer particles in the clay and silt fraction to lower layers through the pores (Gwenzi, 2011). This therefore might mean that BCs might be trapping fine clay particles as expected but these may not accumulate at the surface as normally observed in natural soils with higher finer particle fractions owing to down-ward mobilization. Some studies report that BCs significantly increase fine particle fractions when compared to adjacent non-BC sites owing to their ability to trap fine particles (Sprote *et al.*, 2010; Chamizo *et al.*, 2012). On the other hand others report the effects depend on substrate, climate and BC composition and structure (Belnap, 2006, Sprote *et al.*, 2009, Fisher *et al.*, 2014). Therefore, it is unclear which mechanisms accounted for the results obtained in the current study. However, it should be noted that these results can also be interpreted as either the improvement of soil properties due to the presence of BCs or as the establishment of BCs on substrate with better physicochemical properties, though little evidence exist for the latter phenomenon as it pertains to post-mining substrates.

#### **4.4 Conclusion and recommendations**

Biological crusts have the ability to enhance tailings N, OC and exchangeable bases with the main effect being concentrated in the top 1 cm compared with lower layers. Therefore, BCs are candidate natural ameliorants to improve nitrogen, OC and exchangeable bases in tailings restoration projects. Effects of BCs on texture of tailings are not apparent although silt and clay were marginally enhanced. The study demonstrate the potential for use of BCs in boosting soil fertility and ecosystem reconstruction on nutrient poor and metalliferous substrates and therefore recommends their development and use in tailings rehabilitation. Future studies should focus on the temporal relationship between BCs and vegetation structural and compositional attributes on mine tailings (Chapter 5).



## CHAPTER 5

# OCCURRENCE OF BIOLOGICAL CRUSTS AND THEIR RELATIONSHIP WITH VEGETATION ON A CHRONOSEQUENCE OF ABANDONED GOLD MINE TAILINGS.

\* *This chapter was published with the journal Ecological Engineering*  
(<https://doi.org/10.1016/j.ecoleng.2019.07.029>)

**Nyenda T<sup>abd\*</sup>; Gwenzi W<sup>c</sup>; Piyo T.T<sup>bd</sup>; Jacobs S.M<sup>a</sup>**

<sup>a</sup> Department of Conservation Ecology and Entomology, Stellenbosch University, Private Bag X1, Matieland, 7602, South Africa.

<sup>b</sup> Department of Environmental Sciences, Bindura University of Science Education, P. Bag 1020, Bindura, Zimbabwe.

<sup>c</sup> Biosystems and Environmental Engineering Research Group Department of Soil Science and Agricultural Engineering, University of Zimbabwe, P.O Box MP 16, Mt Pleasant, Zimbabwe.

<sup>d</sup> Zimbabwe Mine Environment Research Network, No. 1 Adylin Road, Marlborough, Harare, Zimbabwe.

**Corresponding author email:** [tatenyenda@yahoo.com](mailto:tatenyenda@yahoo.com) (Tatenda Nyenda).

### Abstract

Biological crusts (BCs) are soil ecological engineers critical in restoration yet their occurrence, and relationship with vegetation in a primary succession is poorly understood. The objectives of the study were: (1) to determine BC cover changes on a chronosequence and toposequence of tailings dumps and their correlation with vegetation structural and substrate attributes and, (2) to determine vegetation community changes along a BC cover gradient. We hypothesized that: (1) BC cover significantly increased with tailings dump age and that it was positively correlated to vegetation cover, species richness, density, and (2) Vegetation communities significantly varied along a BC cover gradient. Occurrence patterns of BCs and their relationship with vegetation attributes and substrate properties were assessed on six gold tailings of different ages (10, 17, 30, 82, 92 and 110 years). BC cover and vegetation attributes were studied in 1-m<sup>2</sup> quadrats. Texture, electrical conductivity (EC), total nitrogen (N), organic carbon (OC) and available metals (Zn, Ni and Mn) for surface tailings in patches with or without BCs were determined for each dump. Data were analysed using two-way ANOVA, ordination analysis and Spearman correlation analysis. Two- way ANOVA showed that age and topographic position had significant effect on BC cover. BC cover significantly increased with age as hypothesized, to a peak at 92 years and declined thereafter. Cyanobacteria and Algae significantly decreased with age while lichens and mosses increased significantly. A Canonical correlation analysis (CCA) revealed a positive

correlation between BC and vegetation cover, species richness and density on the four youngest dumps (10-82 years) which was however negative on the two oldest dumps (92 and 110 years). Areas of different BC cover classes (high =70-100%, medium = 30-69%, low =6-29 % and very low =  $\leq 5$  %) were associated with different vegetation communities, with high and medium classes forming a similar vegetation community. A principal component analysis (PCA) based on tailings' physicochemical properties showed that BC plots on the three younger dumps separated from those on the three older dumps, mainly based on variation in silt and total Nitrogen content. The results point to existence of a succession stage dependent relationship between BCs and vegetation. This suggests existence of a potential mutual relationship between BCs and vegetation on mine tailings, thus BCs can be used as proxy indicators of vegetation development.

**Keywords:** chronosequence; correlation; cyanobacteria; lichens; mosses; nitrogen; organic carbon; species richness; vegetation cover.

## 5.1 Introduction

Mine tailings are a legacy of environmental impacts of mine operations on ecosystems (Wuana and Okieimen, 2011; Melato *et al.*, 2016). Mine tailings have adverse physicochemical properties, including lack of aggregate structure, low organic matter, low plant macronutrients such as nitrogen and phosphorus (Lei *et al.*, 2015; Melato *et al.*, 2016), high concentrations of toxic heavy metals and metalloids (Wuana and Okieimen, 2011). Due to these adverse physico-chemical conditions, natural plant colonization of mine tailings is slow, thus they usually remain bare or with sparse vegetation patches for decades (Bradshaw, 1983; Melato *et al.*, 2016). This often results in delayed re-establishment of ecosystem structure and function and restoration of ecosystem services.

Biological crusts form a common soil surface community covering about 12 % of the global land surface area mainly in dry land regions (Rodriguez-Caballero *et al.*, 2018). Biological crusts often cover bare patches between vegetation on many soil surfaces as they can survive extreme substrate conditions (Belnap *et al.*, 2001a,b,c; Bowker, 2007; Zhang *et al.*, 2010; Chamizo *et al.*, 2012). Biological crusts are a result of an intimate association between bryophytes, lichens, photosynthetic cyanobacteria, heterotrophic micro-fungi, algae and soil particles in different proportions (Belnap, 2006; Bu *et al.*, 2013; Keck *et al.*, 2016). Biological crusts form encrustations covering the uppermost millimetres of soil, thereby stabilizing it (Bowker *et al.*, 2008). BCs are reported to develop in seres with cyanobacteria dominating in early succession while mosses, lichens, hornworts and liverworts dominate the late succession (Lange *et al.*, 1998; Belnap *et al.* 2001a,b,c; Stewart and Siciliano, 2015). Once they colonize a substrate, BCs spread extensively, modifying the substrate physicochemical and hydrological properties (Belnap *et al.*, 2001 a,b,c; Hodkinson *et al.*, 2003; Bowker, 2007; Lázaro *et al.* 2008; Garcia-Meza *et al.*,

2011; Chamizo *et al.*, 2012), hence are considered as ecosystem engineers (Belnap *et al.*, 2001a,b,c). Due to vegetation and other impediments BCs occur in patches, creating BC cover gradients on substrate where they exist (Bu *et al.*, 2015), a situation that may contribute in vegetation and soil dynamics.

Many studies and reviews on the development of BCs and their relationship with other terrestrial ecosystem components were mainly on natural substrates such as sand dunes and desert soils (Belnap, 1996; Li *et al.*, 2006; Bowker, 2007; Belnap *et al.*, 2008; Kuske, *et al.*, 2011; Chamizo *et al.*, 2012; Funk *et al.*, 2014; Yang *et al.*, 2015; Weber *et al.*, 2018; Rodriguez-Caballero *et al.*, 2018). The studies showed contrasting results with some reporting BC establishment was closely related to vegetation succession (Belnap, 2001a,b,c; Bowker, 2007), while in some their establishment was closely related to substrate factors such as distribution of fine particles (Belnap *et al.*, 2008; Chamizo *et al.*, 2012; Yang *et al.*, 2015), soil pH, moisture and respiration (Rodriguez-Caballero *et al.*, 2018), soil potassium, aggregate stability and surface characteristics such as bare area and litter (Martinez *et al.*, 2006). In other studies conducted on natural substrates, BCs have been reported to facilitate germination, promote survival and growth of pioneer plant seedlings (Bowker, 2007; Zhang *et al.*, 2016) while others report significant inhibition (Belnap *et al.*, 2001a,b,c; Zhang *et al.*, 2010; Ghiloufi *et al.*, 2016; Song *et al.*, 2017). A few others argue the effects are species dependent (Langhans *et al.*, 2008; Maestre *et al.*, 2011), while a few noted no correlation. Some studies reported that BCs increase soil nutrients (Dougill and Thomas, 2004; Guo *et al.*, 2008; Ochoa-Hueso *et al.*, 2011; Yang *et al.*, 2015) and alter other physicochemical properties (Zhang *et al.*, 2010; Chamizo *et al.*, 2012; Bu *et al.*, 2013). Despite the existence of several studies on the ecology of BCs on natural substrates, limited information exists on artificial ecosystems such as mine tailings. However, a few exceptions exist (e.g. Sun *et al.*, 2004; Sprote *et al.*, 2009, 2010; Orlekowsky *et al.*, 2013; Umba, 2014; Stewart and Siciliano, 2015; Seiderer *et al.*, 2017; Nyenda *et al.*, 2019a). The key findings from the few studies conducted on mine tailings were: (1) BCs enhance nitrogen fixation (Sun *et al.*, 2004; Stewart and Siciliano, 2015; Nyenda *et al.*, 2019a) and (2) BCs alter substrate texture and hydraulic properties (Sun *et al.*, 2004; Sprote *et al.*, 2009, 2010).

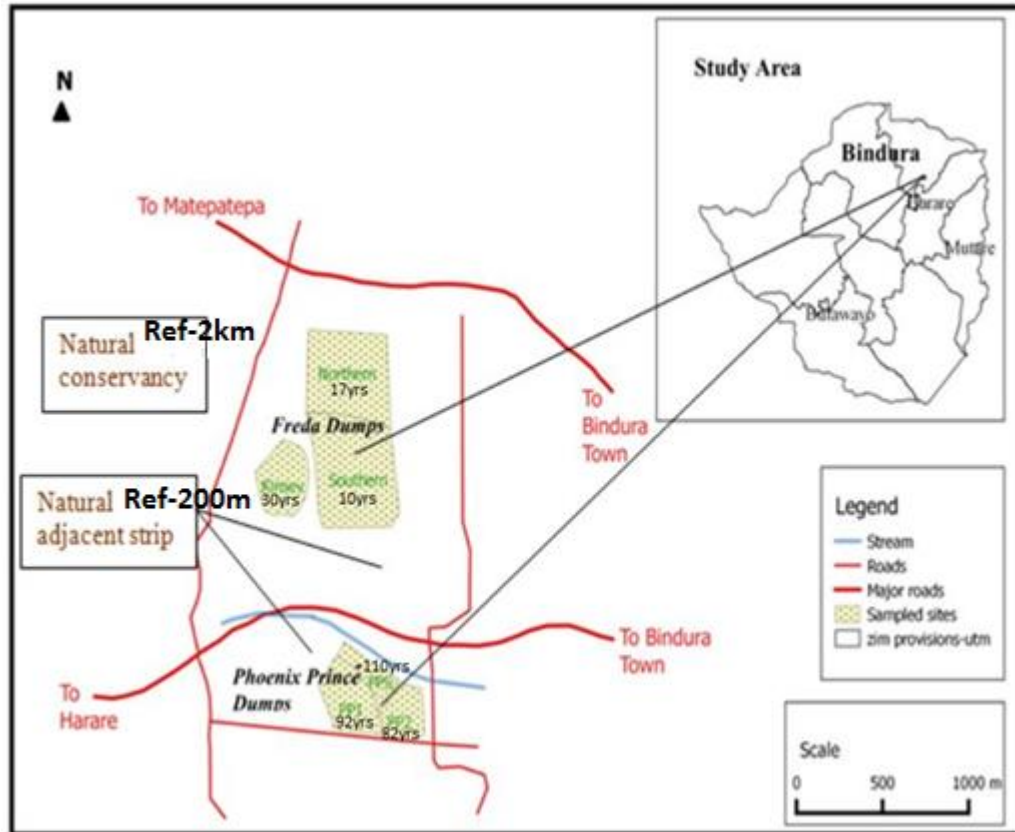
Despite the large body of literature on biological crusts, little is known concerning their distribution patterns and factors driving the patterns of distribution and cover at small spatial scales. Furthermore, evolution of BCs on metalliferous substrates remains poorly understood. Moreover, the temporal relationship between such BCs and structural and compositional attributes of vascular plants has not been widely documented. Specifically, information on morphological forms of biological crusts and their evolution on mine tailings, the temporal correlation of BCs and vegetation and substrate properties are scanty. This has often resulted in omission of BCs in restoration programs and literature (Bowker, 2007), resulting in confined use of artificial amendment solutions in tailings rehabilitation which is often expensive and incongruent to the current global restoration practices that emphasize multifactor analysis approaches and optimizing natural self-sustaining rehabilitation programs.

Chronosequences of mine tailings provide ideal sites for investigating development patterns of biological crusts and their relationship with vascular plants (Pickett *et al.*, 1989; Walker *et al.*, 2010). Six abandoned gold tailings of different ages with similar disposal and management history at Freda Rebecca Gold mine in Zimbabwe were studied. The objectives of the study were: (1) to determine BC cover changes on a chronosequence of gold tailings dumps and their correlation with vegetation structural attributes substrate properties, and (2) to determine vegetation community changes along a BC cover gradient. The study hypothesized that: (1) BC cover significantly increased with tailings dump age, was positively correlated to vegetation cover, species richness, density, fine particles, OC and total N and (2) vegetation communities varied along a BC cover gradient. Understanding the relationship between biological crusts and vascular plants will assist in developing cheap and self-sustaining options for rehabilitation of disturbed ecosystems. The results will help policy makers in the formulation of policies and inform future restoration research. Further, the results will provide further insights on the early ecosystem development trajectories on unique artificial substrates such as mine tailings, which often have previously produced contradictory results.

## **5.2 Materials and Methods**

### **5.2.1. Description of the study area**

The study was carried out on six gold tailings dumps of contrasting ages situated at Freda Rebecca Gold mine (latitude 17°16' E latitude and longitude 31°16'S, altitude 1070 m) in Bindura district, in north-east Zimbabwe (Masvodzi *et al.*, 2013). The site experiences a savannah climate characterized by wet summers and dry winters. Based on rainfall data for the past 37 years, Bindura receives an average annual precipitation of around 879 mm and had an average annual temperature of 28°C (Zimbabwe Meteorological Services; 2018). To investigate the trajectories of BC cover change on mine tailings, six dumps of contrasting ages (10, 17, 30, 82, 92 and 110 years since last deposition) and two adjacent reference sites (Ref 1- 200 m) and Ref 2-2km away) were studied. The three youngest tailings (10, 17 and 30 years) are located about 800 m north of the older tailings (82, 92 and 110 years; Fig. 5.1). The dumps of different ages provided an opportunity for studying establishment and succession patterns of BCs, but there was no chance for dump age replication due to the dumping patterns.



**Figure 5.1:** Map of the study area in north-east Zimbabwe showing location of tailings dumps at Freda Rebecca Gold mine. The adjacent natural strip (Ref 1-200 m) was slightly disturbed through mining and tailings disposal. The natural conservancy (Ref 2- 2 km) remained free of major disturbance from mining.

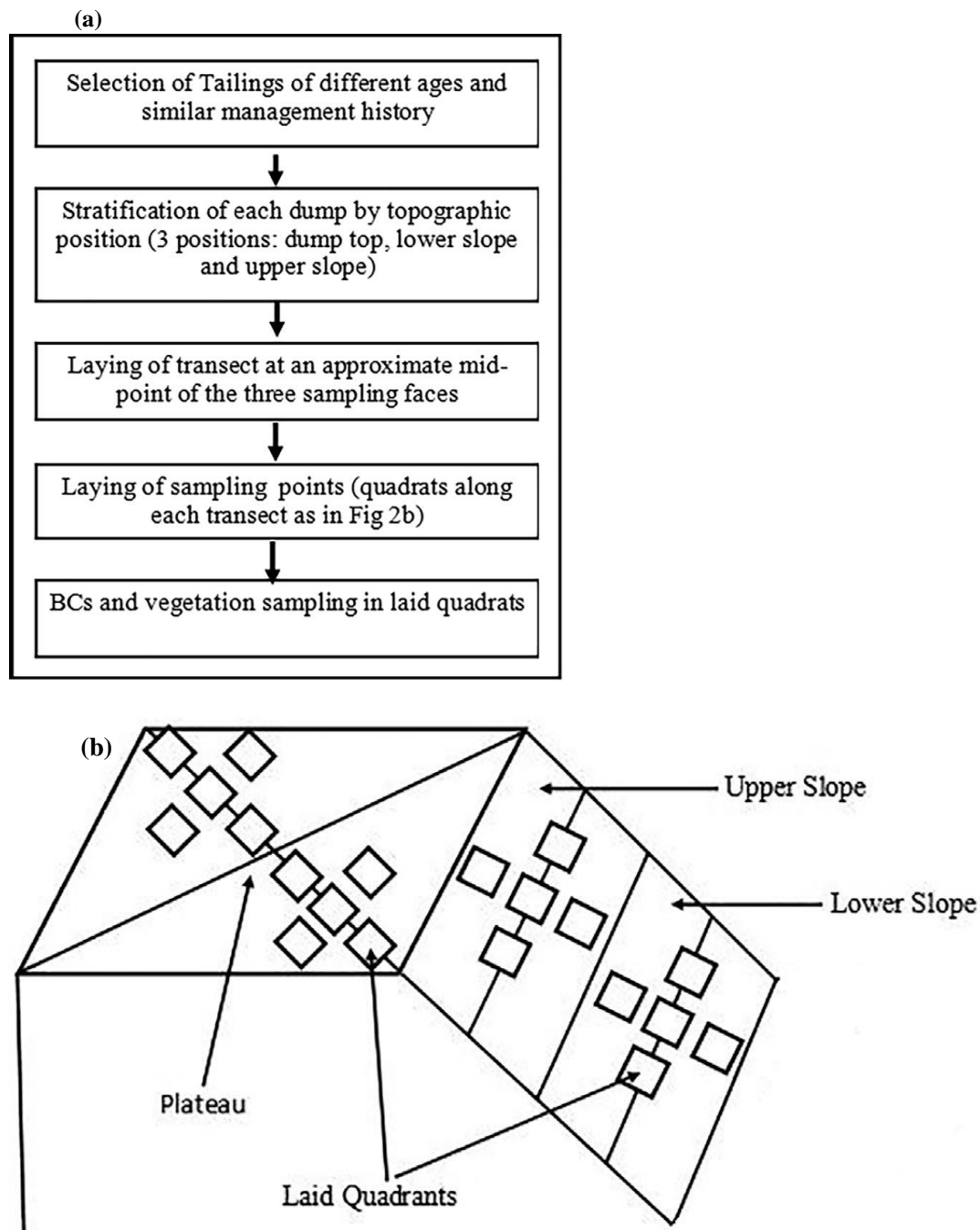
The mine site is approximately in the central axis of the Bindura-Shamva Greenstone Belt (FRGM Geology report, 2010). Metamorphic mineral assemblage indicates green schist facies to upper amphibolites facies and a range of metamorphic grades across the belt. The metadiorite host the bulk of the mineralization associated with the mining operations. The local geology is typically a greenstone configuration composed mainly of basaltic rocks (gabbro and tholeitic basalts) combined with banded iron formations and volcanic tuffs (Masvodza *et al.*, 2013). The gold ore that produces the tailings consists of pyrite ( $\text{FeS}_2$ ), pyrrhotite ( $\text{FeO}_8\text{S}$ ), and arsenopyrite ( $\text{FeAsS}$ ) as the major minerals with chalcopyrite ( $\text{CuFeS}_2$ ), bornite ( $\text{Cu}_6\text{FeS}_4$ ) and pyrolucite ( $\text{MnO}_2$ ) as minors.

The vegetation of the area is predominantly Miombo woodland with *Brachystegia boemmii* and *Julbernardia globiflora* dominating upper catena positions while remnants of *Senegalia polyacantha* and *Vachellia gerrardii* woodland patches dominate low-lying areas. Dominant grasses are *Hyperrhenia filipendula*, *Brachiaria spp.*, *Pogonathria squarrosa*, *Eragrostis spp.* and *Setaria sphacelata*. Close to tailings there are marshy areas dominated by *Imperata cylindrica*, *Equisetum ramosissimum*, *Blechnum*

*tabulane* and *Flaveria trinervia*. Vegetation on dumps includes *Imperata cylindrica*, *Schizachirium platphyllum*, *Diheteropogon amplexans*, *Cynodon dactylon*, *Andropogon chinensis*, *Cymbopogon caesius*, and *Flaveria trinervia*, (Nyenda unpublished). Other notable vegetation in the mine site area are a small *Eucalyptus* plantation south of the young dumps and *Leucaena leucocephala* planted on waste rock dumps in the vicinity of the young dumps.

### 5.2.2 Experimental set up

To investigate the effects of age on BC cover, six tailings of various ages were selected. To investigate the effects of topography each dump was further stratified by slope position, yielding three topographic positions: (1) flat tops, (2) upper slope and (3) lower slope. On such dumps tailings are deposited starting from the base, in effect also creating a chronosequence; Figure 5.2a). A transect was laid at each topographic position, at an approximate mid-point along the face while on the dump top two diagonal transects were laid from a randomly chosen end (Fig 5.2a). Along each transect and at 10-20 m intervals starting from a randomly selected end (Zhang *et al.*, 2007), five replicate quadrats were systematically laid, one at centre and four at 1-m interval in all major compass directions (Figure 5.2b). To cater for possible influence of aspect on observed BC and vegetation patterns the slopes were replicated in all cardinal directions for each tailings dump. The procedure was also done at the two reference sites. Reference sites were selected based on proximity to the dumps and for the conservancy, freedom from human disturbances and similarity in topography. A total of 602 sampling points were laid on all dumps and natural reference sites.



**Figure 5.2:** Diagrams showing experimental set-up and sampling point layout: (a) Schematic diagram showing experimental set-up; (b) Layout of quadrats at each sampling point. Five 1-m<sup>2</sup> size quadrats were laid out at each sampling point, with one at the centre and one, 1 m apart in each major compass cardinal direction (N, S, E, and W).



### 5.2.3 Assessment of biological crusts

To clearly observe biological crusts, litter was removed (Dettweiler-Robinson *et al.*, 2013a) and the surface was sprayed with water (Lei *et al.*, 2015). BCs cover in each 1 m<sup>2</sup> quadrat was visually estimated as a percentage of the whole quadrat (Dougill and Thomas 2004; Ochoa-Hueso *et al.*, 2011). A graduated metal framed quadrat (10 cm x 10 cm) was used to enable actual surface cover estimations. All morphological forms of BCs in the quadrat were identified and quantified as percentage cover (to the nearest percent) in accordance with shape, colour and general appearance with the aid of 10 x hand lens and a field microscope and photos taken using a digital camera (Belnap *et al.*, 2001a,b,c; Dougill and Thomas, 2004; Chaudhary *et al.*, 2009). The main morphological forms identified were cyanobacteria, algae, mosses and crustose and fruticose lichens. For further analysis, crust cover was classified into four groups: (1) Very low ( $\leq 5\%$ ), (2) Low (6-29%), (3) Medium (30-69%) and, (4) High ( $\geq 70\%$ ). Biological crust samples were placed in sterile plastic bags and taken to the National Herbarium and Bindura University laboratory (within 1 week of collection) for identification to morphological form level.

### 5.2.4. Determination of physicochemical properties of tailings

To correlate BCs and substrate properties, tailings samples at 5 cm depth below crusts were sampled from five randomly chosen points in areas of BCs and adjacent non-crusted patches on each dump using steel cores. The samples were tightly sealed in the cores to avoid cross-contamination and taken to the laboratory for determination of texture, EC, pH, OC, total N and available metals (Zn, Mn and Ni) as ancillary parameters. In the laboratory, the tailings samples were passed through a 2 mm sieve to obtain fine particles. Aliquots of samples were crushed in a mechanical mortar to obtain a 0.5 mm fraction necessary for OC determination. Organic carbon was determined using the Walkley and Black method (Walkley and Black, 1934). Texture was determined using the pipette and hydrometer methods (Okalebo *et al.*, 2002). Electrical conductivity and pH were measured by an electrical conductivity and pH meter respectively in a 1:1 solid: water suspension (Chamizo *et al.*, 2012). Total N was measured using the Kjeldahl method (Jackson, 1964). Samples for available metals (Zn, Ni and Mn) were digested in 1 M CaCl<sub>2</sub> while the total fraction was digested using a double a double acid, Aqua-regia solution and measured using an AAS (Okalebo *et al.*, 2002). All tests were done using sterilized laboratory apparatus to ensure quality control. To ensure validity of results, tests were repeated three times and the average of the three was used in reporting results. Zn, Ni and Mn were chosen as they were reported in a related study to be key components of the tailings substrate (Chapter 3) and are key trace elements required for plant growth (Brady and Weil, 2013). Detailed laboratory methods for testing elements are covered in Chapter 3.

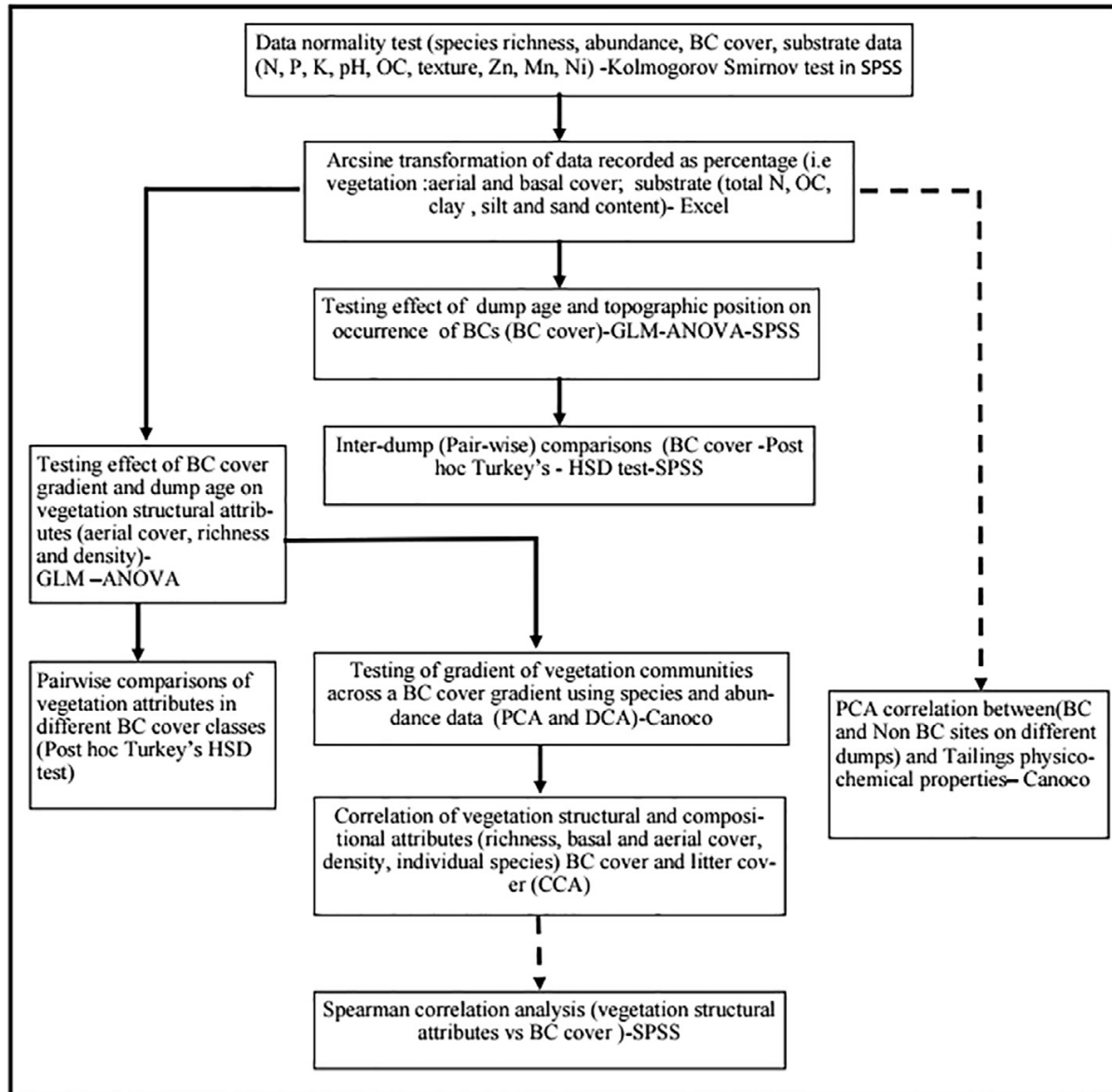


### 5.2.5 Assessment of vegetation structural and compositional attributes.

All herbaceous plants and woody seedlings (height less than 50 cm) observed in each quadrat were identified to species level using field guides (Van Outshoorn, 2014) and their abundances determined by physical counting of tufts or stems. For each quadrat, species richness, species abundances, total and individual species aerial and basal covers for all vegetation and individual plant species were determined. Those that could not be identified in the field were taken to the National Herbarium in Harare for identification and those that could not be identified to species level were identified to genera level. Aerial and basal covers were visually estimated to the nearest percent in terms of the proportion of the part of quadrat being covered (Ochoa-Hueso *et al.*, 2011). When estimating cover, the quadrat was divided into 100 x 100 cm<sup>2</sup> squares with each representing 1% cover using wire frames (Dettweiler-Robinson *et al.*, 2013b). Total basal cover was taken as the measure of the proportion of the plants in a quadrat which extends into the soil (Dettweiler-Robinson *et al.*, 2013b). Basal cover of each tuft in each quadrat were estimated and then added to obtain the total basal cover (Ochoa-Hueso *et al.*, 2011). Litter cover (%) was visually determined as an ancillary parameter.

### 5.2.6 Data analyses

Data were analysed in three phases involving two-way analysis of variance and multivariate general linear model analysis, multivariate ordination analysis and Spearman correlation analysis (Fig 4.3). Plant species abundance, plant species richness, BC cover and substrate data were tested for normality using the Kolmogorov-Smirnov test of homogeneity of variance in Statistical Package for Social Sciences (SPSS) version 20 software. All vegetation and BC cover data recorded as percentages were arcsine transformed before analysis of variance and correlation analysis (Mckillup, 2012). General linear model ANOVA was used to test effects of dump age and topographic position and their interactions on BCs. Pair wise comparisons were made with post hoc (HSD) test at the 5% level of significance (Fig 4.3). The HSD test was used due to its ability to minimise distortions of the alpha level of the test. To test effect of BC cover on vegetation community development, a linear principal component analysis (PCA) was performed since data gradient length was less than three (Lepš and Šmilauer, 2003; Mckillup, 2012). A PCA was used to correlate sample sites to tailings physicochemical properties. A Canonical correspondence analysis (CCA) was used to assess the relationships between BCs and vegetation attributes (Ter Braak, 1986) since it accounts for the non-linearity that is caused by the zero values characterizing vegetation composition data (Ter Braak and Verdonschot, 1995; Morgenthal and Rensburg, 2004). All ordination analyses were done using Canoco for Windows (Version 5). Finally, a Spearman correlation analysis was done to quantify the magnitude of the correlation between BCs and vegetation attributes (Cañadas *et al.*, 2010). Overall, a multivariate analysis approach was used in order to summarize in a few number of variables a group of characteristics that are connected.



**Figure 5.3:** Schematic diagram showing steps in data analysis

## 5.3 Results

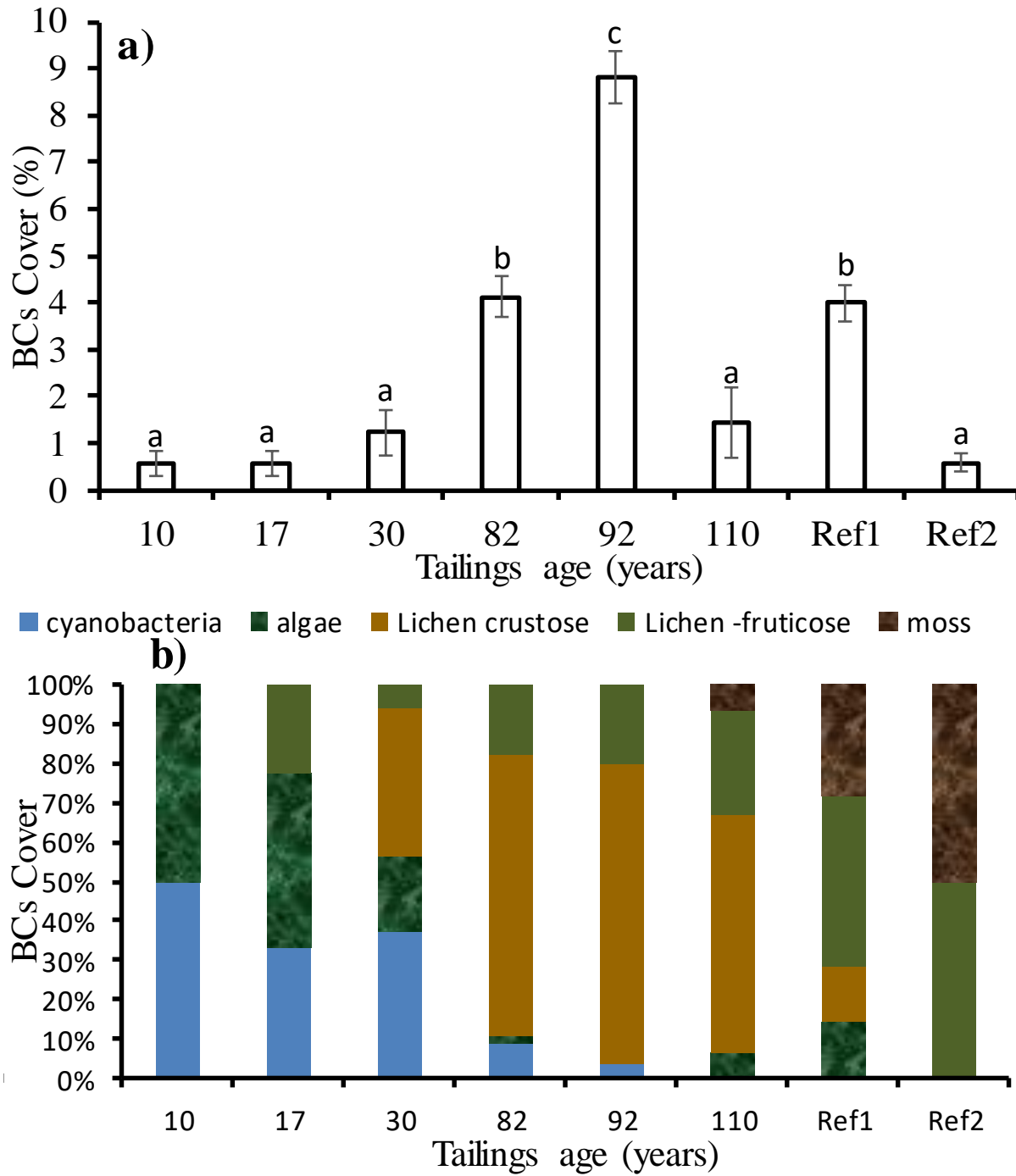
### 5.3.1 Patterns of occurrence of biological crusts

General linear model (GLM) analysis showed that tailings age ( $F = 150.92$ ;  $p < 0.001$ ), topographic position ( $F = 11.2$ ;  $p = 0.001$ ) and their interaction ( $F = 21.83$ ;  $p < 0.001$ ) had significant effect on BC cover. In particular, BC cover significantly increased with age reaching a peak at 92 years but significantly decreased thereafter (Fig 5.4a). Turkey's HSD post-hoc test revealed that the three youngest dumps (10, 17, 30 years) and the oldest dump (110 years) had statistically similar ( $p > 0.05$ ) BC covers, which were

however, significantly lower ( $p < 0.05$ ) than those observed on the 82 and 92-year-old dumps (Fig 5.4a). Although BC cover increased with age, the three youngest and oldest dumps had similar BC cover as Ref -2 km while the 82-year-old dump and the adjacent reference site (Ref-200 m) were similar.

In terms of morphological classes present, cyanobacteria and algae significantly decreased with age of dump, while lichens increased reaching a peak at 92 years and declined thereafter (Fig 5.4b). In terms of BC cover classes, the three oldest dumps (82, 92 and 110-year-old) had high cover classes (i.e. 61% - 100 %) with only the 92-year-old dump reaching above 90% cover. Five dumps namely (17, 30, 82, 92 and 110 years) had very low to moderate BCs covers (i.e. 1% - 60 %).

Although overall BC cover varied significantly along a toposequence, in particular, significant variations were observed on the 92 year-old ( $F = 29.13$ ;  $p < 0.001$ ) and the 110-year-old-dump ( $F = 7.44$ ;  $p = 0.007$ ) while all positions on the four youngest (10, 17, 30 and 82 -year- old) dumps had similar BC covers (Table 5.1). However, on four out of the six dumps, lower slopes had significantly higher BCs than upper slopes (Table 5.1). Only the 30 and 92-year-old dump tops had significantly higher BC cover than their slopes (Table 5.1).



**Figure 5.4:** Changes in BC cover on a chronosequence of gold mine tailings compared to natural reference sites (a) Overall BCs (b) proportion of specific BC types. Bars with different letters indicate significant differences ( $P < 0.05$ ); Ref 1= adjacent reference site- Ref- 200m; Ref 2 = conservancy reference site –Ref- 2km.

**Table 5.1:** Variation of BC cover (%) among topographic positions on a chronosequence of gold mine tailings. Same superscripts across a row denote no significant difference ( $p > 0.05$ ). Different superscripts in same row denote significant difference ( $p < 0.05$ ). Ref 200 m is the adjacent reference site within 200 m radius of the tailings, which was slightly disturbed by mining activities, while Ref 2 km is the second reference site (conservancy), located about 2km away from the dumps and generally free from mine disturbances. All statistics performed were GLM and post-hoc Turkey's HSD at 95% significance level ( $p < 0.05$ ).

Site	Lower slope Mean $\pm$ SE	Upper slope Mean $\pm$ SE	Plateau Mean $\pm$ SE
10 years	1.16 $\pm$ 0.31 <sup>b</sup>	0.37 $\pm$ 0.36 <sup>a</sup>	0.00 $\pm$ 0.00 <sup>a</sup>
17 years	1.24 $\pm$ 0.53 <sup>b</sup>	0.407 $\pm$ 0.36 <sup>a</sup>	0.02 $\pm$ 0.00 <sup>a</sup>
30 years	0.38 $\pm$ 0.21 <sup>b</sup>	0.14 $\pm$ 0.06 <sup>c</sup>	6.65 $\pm$ 1.12 <sup>a</sup>
82 years	5.10 $\pm$ 0.94 <sup>a</sup>	4.94 $\pm$ 0.51 <sup>a</sup>	4.89 $\pm$ 1.01 <sup>a</sup>
92 years	18.51 $\pm$ 1.85 <sup>a</sup>	6.53 $\pm$ 0.89 <sup>b</sup>	20.40 $\pm$ 3.08 <sup>a</sup>
110 years	0.00 $\pm$ 0.00 <sup>a</sup>	4.25 $\pm$ 1.47 <sup>b</sup>	1.38 $\pm$ 0.60 <sup>a</sup>
Ref-200m	4.00 $\pm$ 0.39	4.00 $\pm$ 0.39	4.00 $\pm$ 0.39
Ref-2km	0.576 $\pm$ 0.14	0.576 $\pm$ 0.14	0.576 $\pm$ 0.14

### 5.3.2 Vegetation structural and community attributes along a BC cover gradient

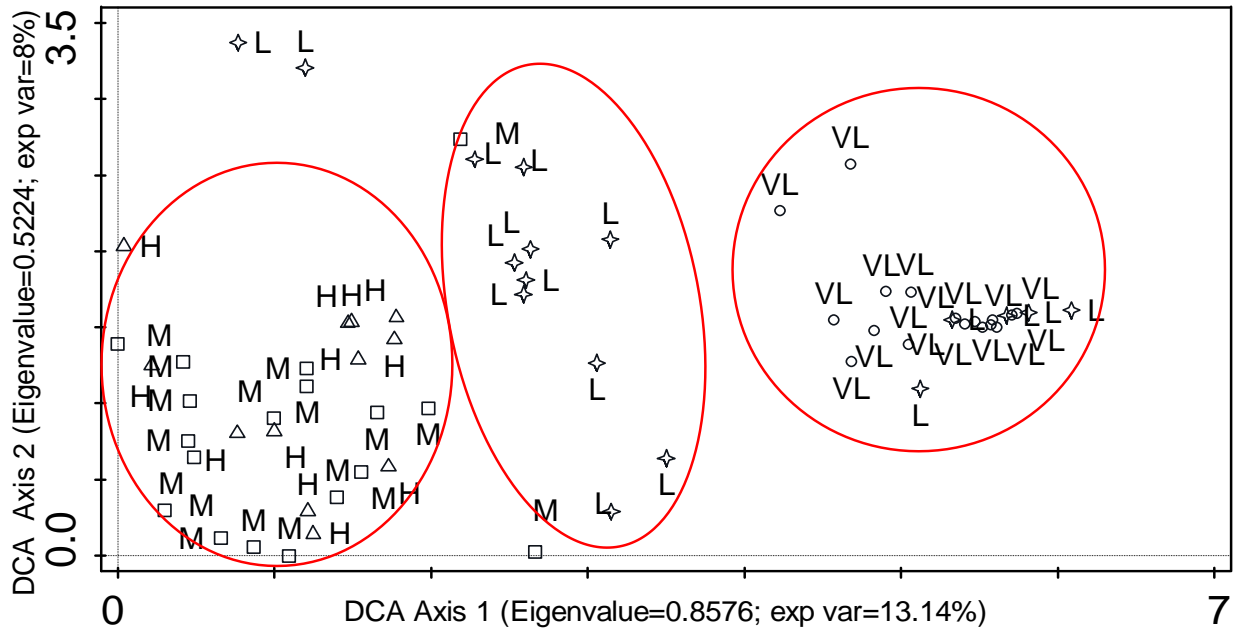
Generally, areas of medium and high BC cover had significantly higher vegetation aerial cover, basal cover and species richness (Table 5.2). Contrary, areas of medium and high BC cover had significantly lower plant densities than areas of lower BC covers (Table 5.2). The same vegetation structural attributes however significantly increased with tailings age for all BC cover classes (Table 5.2).

A detrended correspondence analysis (DCA) monoplots of sites based on species composition and abundance data yielded three broad categories of vegetation communities (Figure 5.5). Medium (30-69 %) and high ( $\geq 70\%$ ) BC cover sites dominated the first cluster. Low (6-29%) and very low ( $\leq 5\%$ ) BC cover sites separated significantly, forming the second and third clusters (Figure 5.5).

Only 13 plant species occurred on all the four BC cover classes, namely *Imperata cylindrica*, *Pennisetum setaceum*, *Asteraceae* spp., *Coryza* spp., *Blechnum tabulare*, *Acanthaceae* spp., *Cynodon dactylon*, *Polygala* spp., *Acacia polyacantha*, *Cobichonia decumbens*, *Andropogon chinensis*, *Corigiola litoralis* and *Coryza albida*. Of all 19 plant species that occurred on high BC cover patches, only *Blumea brevipes* did not occur on very low BC cover areas as it only appeared on the 5-29 % BC cover class.

**Table 5.2:** Changes in vegetation attributes across a BC cover gradient. Superscripts (in uppercase row comparisons, Superscripts (in lower case) column comparisons; all different letters denote significant difference at  $p < 0.05$ . Ref 200m is the adjacent reference natural strip within 200 m radius of the tailings, slightly disturbed by mining activities. BC cover classes were  $\leq 5\%$ , 6-29%; 30-69% and 70-100% for very low, low, medium and high respectively. All statistics performed were GLM and post hoc Turkey's HSD at 95% significance level.

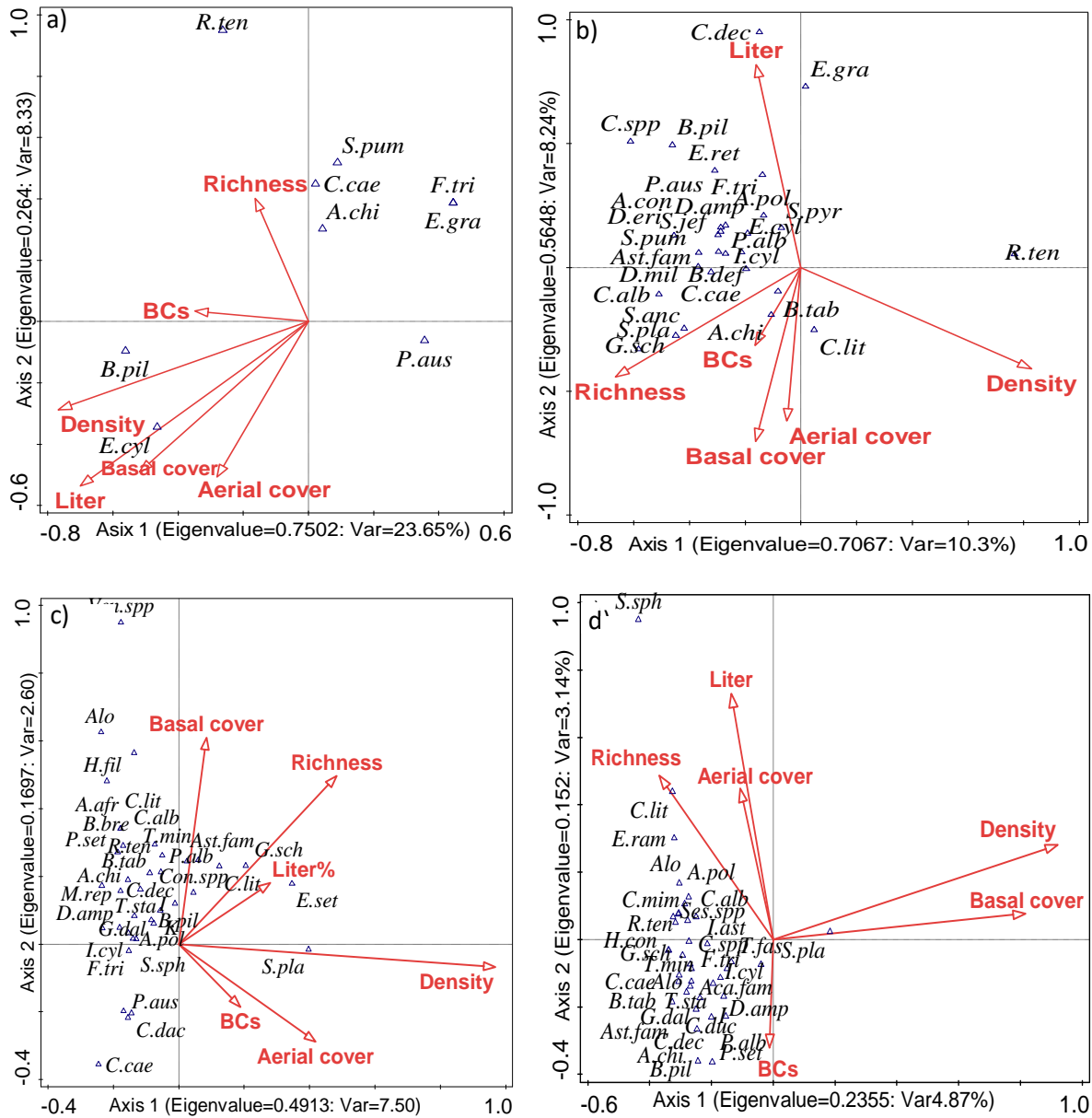
Variable	BC class	Very low	Low	Medium	High
	Dump age ↓				
		mean $\pm$ SE	mean $\pm$ SE	mean $\pm$ SE	mean $\pm$ SE
Aerial cover (%)	10 years	16.79 $\pm$ 0.86 <sup>Aa</sup>	39.18 $\pm$ 6.63 <sup>bA</sup>	70.0 $\pm$ 20.82 <sup>cA</sup>	-
	17 years	18.62 $\pm$ 0.91 <sup>Aa</sup>	39.18 $\pm$ 6.63 <sup>6A</sup>	70.0 $\pm$ 20.82 <sup>cA</sup>	-
	30 years	22.14 $\pm$ 1.05 <sup>aA</sup>	48.71 $\pm$ 3.84 <sup>bB</sup>	52.22 $\pm$ 9.97 <sup>bA</sup>	-
	82 years	45.20 $\pm$ 1.40 <sup>Ab</sup>	48.15 $\pm$ 2.17 <sup>aB</sup>	61.67 $\pm$ 6.35 <sup>bA</sup>	70.00 $\pm$ 7.58 <sup>bA</sup>
	92 years	43.49 $\pm$ 2.45 <sup>Ab</sup>	55.16 $\pm$ 1.94 <sup>bB</sup>	55.68 $\pm$ 3.24 <sup>bA</sup>	61.33 $\pm$ 4.15 <sup>bA</sup>
	110 years	87.58 $\pm$ 1.00 <sup>aC</sup>	74.33 $\pm$ 5.21 <sup>bC</sup>	78.00 $\pm$ 7.00 <sup>abA</sup>	-
	Ref-200m	83.57 $\pm$ 0.91 <sup>Ac</sup>	84.62 $\pm$ 1.96 <sup>aC</sup>	79.44 $\pm$ 6.15 <sup>aA</sup>	76.00 $\pm$ 6.70 <sup>aA</sup>
Richness (species/m <sup>2</sup> )	10 years	0.56 $\pm$ 0.02 <sup>Aa</sup>	1.41 $\pm$ 0.21 <sup>bA</sup>	1.33 $\pm$ 0.33 <sup>bA</sup>	-
	17 years	0.63 $\pm$ 0.03 <sup>aA</sup>	1.41 $\pm$ 0.21 <sup>bA</sup>	1.33 $\pm$ 0.33 <sup>abA</sup>	-
	30 years	2.04 $\pm$ 0.07 <sup>Ab</sup>	4.47 $\pm$ 0.32 <sup>bB</sup>	4.89 $\pm$ 0.75 <sup>bB</sup>	-
	82 years	3.88 $\pm$ 0.11 <sup>aC</sup>	4.54 $\pm$ 0.19 <sup>bB</sup>	4.40 $\pm$ 0.54 <sup>bB</sup>	4.80 $\pm$ 0.74 <sup>abAB</sup>
	92 years	4.04 $\pm$ 0.20 <sup>aC</sup>	5.67 $\pm$ 0.17 <sup>bB</sup>	6.23 $\pm$ 0.33 <sup>bC</sup>	5.93 $\pm$ 0.55 <sup>bA</sup>
	110 years	5.19 $\pm$ 0.15 <sup>aD</sup>	6.08 $\pm$ 1.24 <sup>aB</sup>	7.00 $\pm$ 1.00 <sup>aC</sup>	-
	Ref-200m	4.74 $\pm$ 0.11 <sup>aD</sup>	5.08 $\pm$ 0.17 <sup>aB</sup>	4.33 $\pm$ 0.33 <sup>aB</sup>	3.67 $\pm$ 0.33 <sup>aB</sup>
Density (individuals/ m <sup>2</sup> )	10 years	8.26 $\pm$ 0.69 <sup>aA</sup>	13.24 $\pm$ 2.64 <sup>aA</sup>	40.67 $\pm$ 26.43 <sup>bA</sup>	-
	17 years	10.21 $\pm$ 1.20 <sup>aA</sup>	13.24 $\pm$ 2.64 <sup>aA</sup>	40.67 $\pm$ 26.43 <sup>bA</sup>	-
	30 years	16.71 $\pm$ 1.20 <sup>aB</sup>	123.5 $\pm$ 28.51 <sup>bB</sup>	121.22 $\pm$ 41.8 <sup>bB</sup>	-
	82 years	53.66 $\pm$ 3.75 <sup>aC</sup>	49.75 $\pm$ 4.55 <sup>aC</sup>	112.42 $\pm$ 41.06 <sup>bB</sup>	71.0 $\pm$ 32.69 <sup>abA</sup>
	92 years	103.3 $\pm$ 19.29 <sup>aD</sup>	145.76 $\pm$ 17.55 <sup>bB</sup>	169.15 $\pm$ 39.84 <sup>bB</sup>	88.9 $\pm$ 17.03 <sup>aA</sup>
	110 years	325.1 $\pm$ 20.62 <sup>aE</sup>	310.17 $\pm$ 63.47 <sup>aD</sup>	382.0 $\pm$ 124.43 <sup>aC</sup>	-
	Ref- 200m	147.2 $\pm$ 9.86 <sup>aF</sup>	137.12 $\pm$ 18.9 <sup>aB</sup>	192.22 $\pm$ 54.99 <sup>aB</sup>	70.3 $\pm$ 11.98 <sup>bA</sup>



**Figure 5.5** : A DCA monoplot showing grouping of BC plots based on vegetation compositional and abundance data differences. The first axis (Eigenvalue = 0.8576) explains 13.14% of the variation while the second axis (Eigenvalue = 0.5224) explained 8.0 % of the variation. Gradient length for the analysis was 3.9 SD units. For cover classes: high (H= triangle), medium (M= square), low (L= star) and very low (VL= circle).

### 5.3.3 Relationship between biological crust cover and plant attributes.

A CCA showed an increasingly strong positive correlation between BC cover and vegetation aerial and basal covers, density and species richness up to the 82-year-old dump, with a negative correlation observed on the two oldest dumps (92 and 110 years) and the reference sites (Fig 5.6, Fig S5.1). Similarly, the correlation between BC covers and litter was strongly positive on the three youngest dumps (10, 17 and 30 years) and was negative on the two oldest dumps (92 and 110 years) and the natural reference. A CCA plot showed that the correlation between specific plant species and BC cover was dependent on age of tailings as *Bidens pilosa* was highly positively correlated to BCs on the two youngest dumps, the 30 year old to the following species: *Andropogon chinensis*, *Blechnum tabulare*, *Schizachyrium platyphyllum*, *Setaria pumilla*, the 82-year-old to: *Corigiola litoralis*, *Schizachyrium platyphyllum*, *Cynodon dactylon* and *Phragmites australis*, the 92-year-old to: *Pennisetum setaceum*, *Polygala albida*, *Polygla* spp., *Bidens pilosa*, *Diheteropogon amplexans*, the 110-year-old to *H. contortus* and *Cyperus esculentis*, the Reference site to *A. chinensis*, *C. litoralis*; Fig 5. 6).



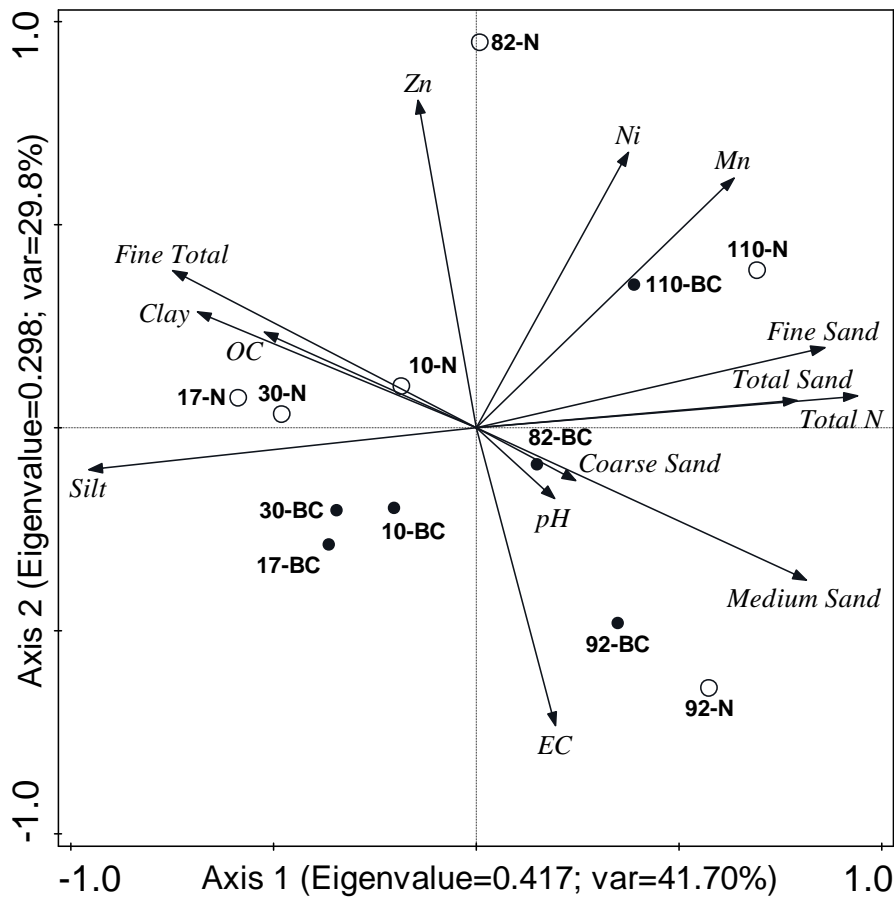
**Figure 5.6:** Correlation between BCs and vegetation structural and compositional attributes (a) 17 (b) 30 (c) 82 (d) 92 years (Graphs for the 10, 110 and reference sites and Full species names in Appendices).

### 5.3.4 Correlation of BC sites and physicochemical properties of the surface tailings

Principal components analysis showed that the sites grouped by age along axis 1 and by patch type along axis 2 (Fig 5.7). Regardless of patch type, plots from the three youngest dumps (10, 17 and 30 years) separated noticeably from plots from the three oldest dumps, forming two main clusters along axis



1. BC plots from the three youngest dumps formed a separate cluster from their adjacent non-BC patches (Fig 5.7). The BC plots on the two oldest dumps (92 and 110-years-old) grouped with their non-BC counterparts although plots from the two dumps markedly separated (Fig 5.7). The 82- year -old dump was intermediate along an age gradient but had BC plots separating from non-BC plots along Axis 2. The BC plots on the three youngest dumps were positively correlated to silt and sand content (Fig 5.7; Fig S5.2), while BC plots on older dumps (82, 92 and 110 years) were positively correlated to Total N, EC and medium sand. Both BC and non-BC plots on younger dumps were positively correlated to clay content and OC. The first axis (Eigenvalue= 0.417) explained 41.7 % of the variation while the second axis (Eigenvalue= 0.298) explained 29.8% of the variation.



**Figure 5.7:** PCA biplot showing correlation of BC and non-BC plots and physicochemical properties on the top 5 cm of gold tailings of different ages (solid circles represent BC plots; hollow circles= Non- BC plots; BC= biological crust, N= non-BC; Number per plot denotes the age of the dump; Fine total = clay + silt content).

## 5.4 Discussion

### 5.4.1 Patterns of occurrence of BCs and relationship with substrate properties

Observed BC cover trends were correlated to age dependent physicochemical properties of surface tailings, in particular texture, pH, EC, OC and total N (Figure 5. 7). Substrate properties seemed to have more influence on specific BC types than total BC cover. The very low BC cover on the two youngest dumps could be due to harsh chemical nature of the substrate, in particular strongly acidic pH of between 3 and 4 when compared to higher pH between 5 and 6 observed on the four older dumps (Table S5.1). In general, the correlation of BC cover and substrate physicochemical properties (texture, fertility, OC, pH) was age dependent. Silt content was more strongly positively correlated to BC cover on relatively younger dumps while total N was more positively correlated to BC cover on older dumps.

The dominance of cyanobacteria and green algae on the two youngest dumps suggest their higher tolerance to more hostile substrate conditions than lichens and mosses that dominated on the older dumps, which had relatively higher pH and nitrogen content. Observed higher pH under BC patches than those without (Table S5.1) may also explain the observed BC patterns. The suppressed BC cover on strongly acidic young dumps and on other acidic environments on all dumps, suggests a pH dependent occurrence patterns of BCs although the observed higher pH and other properties can be due to the influence of BCs on the substrate chemistry. The presence of BCs disrupt oxygen and water availability, limiting the amount of oxygen and water for oxidation of pyrites, thereby reducing acidity (Moon *et al.*, 2013).

The observed general increase in BC cover with age of tailings may be attributed to the observed increase in total N. As was found in the present study macronutrient concentrations are known to increase with age in a succession and this promotes BC covers (Belnap *et al.*, 2003; Büdel *et al.*, 2009). Lower nitrogen concentration on younger dumps make them support only adaptive high nitrogen-fixing cyanobacteria and carbon fixing green algae. Consistent with our findings, Belnap *et al.*, (2001a, b, c), reported that cyanobacteria dominate in nutrient impoverished soils owing to its ability to fix nitrogen. Lichens and mosses that developed later most probably due to improvement in substrate N, and pH contributed to the observed increase in total cover over time. Cyanobacteria have higher N fixing capability than mosses that dominated the later succession (Belnap *et al.*, 2001a, b, c). However, the comparable total BC cover between the oldest and the three youngest dumps, despite varying physicochemical properties, suggests influence of non-substrate factors, in particular vegetation cover (Section 5.4.2).

BC covers were however generally low owing to low clay and high sand content. These parameters have been reported in similar studies to discourage development of biological crusts (Schroeder *et al.*, 2005;

Shu *et al.*, 2005; Lei *et al.*, 2015). Such coarser textural substrate support less developed BCs such as cyanobacteria and green algae dominating young dumps as noted in similar studies in Spain (Chamizo *et al.*, 2012) and Germany (Sprote *et al.*, 2007; 2010).

Our findings are consistent with studies reporting that as tailings age, nutrient content increase (Lei *et al.*, 2015), chemical toxicity decrease (Schroeder *et al.*, 2005), heavy metal content decreases (Melato *et al.*, 2016) and fine particles increase (Shu *et al.*, 2005), which in turn favour development of BCs as well as increased vegetation cover. Vegetation will in turn conserve moisture and promote development of BCs (Bowker, 2007; Zhang *et al.*, 2010). However, suppressed BC cover under higher vegetation cover on the oldest dump suggests they may also be competing for moisture.

#### **5.4.2 Relationship between biological crusts and vascular plant attributes**

The results showed age-dependent correlation of BC cover and vegetation structural and compositional attributes. The observed positive correlation between BCs, vegetation cover, species richness and density on all younger dumps (10, 17, 30, 82 years) suggest mutual facilitative role between BCs and vegetation in early succession. Due to harsh tailings conditions related to edaphic properties in early tailings succession as observed in a related study (Chapter 4), colonization of BCs may be creating micro-sites for seed reception and plant nourishment, hence the positive relationship (Fischer *et al.*, 2014). Alternatively, pioneer vegetation colonizing tailings may be also creating micro-sites suitable for BC colonization. For instance, shading and moisture retention were observed to facilitate BC establishment (Bowker, 2007). However, the decrease in BCs on the oldest dump against the general trend suggests that the relationship is positive until a certain threshold, where continued increase in vegetation cover may suppress BCs (Fig 5.6). This could be due to reduced light penetration (Bowker, 2007; Dettweiler-Robinson *et al.*, 2013a,b) and competition for space. High vascular plant cover such as observed on the oldest dump also reduces the free soil surface area for colonization by BCs (Thompson *et al.*, 2005; Martinez *et al.*, 2006).

The observed BC and vegetation trajectory may however be an usual expected succession pathway where pioneer BCs are replaced by vascular plants at a certain stage, which may be after ~100 years in this particular case (Zellman, 2014). The findings concur with results of a similar study in Channel Islands National Park, California where more BCs were observed in areas with sparse vegetation than areas with dense vegetation (Zellman, 2014). However, to the contrary, occurrence of BCs on the reference sites suggest that, although BCs are pioneer species due to their biological nitrogen fixation and photosynthesis capacity, they may persist in mature ecosystems though suppressed by vegetation. Results therefore suggest that BCs play an important role in early succession, but their importance decline over time (after 90-100 years) and thus are a small but important part of the tailings ecosystem. The observed substrate-age-dependent correlation between BCs and vegetation suggests existence of a

threshold vegetation cover where facilitation ends, and suppression starts. However, the exact timing of these processes could not be determined in the current study. The findings from this study thus bring new knowledge on time dependent relationship between vegetation and BCs on artificial substrates like mine tailings.

Based on literature, vegetation cover reduces temperature due to shading effect that in turn improves moisture, which in turn enhance BC colonization and development (Belnap *et al.*, 2001a,b,c; Ochoa-Hueso *et al.*, 2011; Lei *et al.*, 2015). Cyanobacteria and other poorly developed BCs that dominated younger tailings dumps have been reported to colonize poor nutrient environments and fix atmospheric nitrogen, making it available for vascular plants and other organisms playing a key role in pedogenesis (Veluci *et al.*, 2006; Bowker *et al.*, 2007; Buddel *et al.*, 2009; Bu *et al.*, 2013). The BCs also provide habitat for microorganisms, thus further enhancing nutrient cycling between soil and vegetation, promoting vegetation development (Pickett., *et al* 2001). The BCs are also known to trap nutrient-rich dust, enhancing nutrients on the surface and promoting plant cover in early succession (Belnap *et al.*, 2003). This may partially explain the observed improvement in the fertility of tailings e.g. total N on BCs patches that could have promoted the establishment of vascular plants on the dumps. The trapped fine silt and clay were reported to bind cations such as Mg, Ca and metals (Chamizo *et al.*, 2012). Such associated cation binding is often enhanced by polysaccharides secreted by BC filaments, enhancing CEC and metal immobilization, which may promote vegetation response (Belnap *et al.*, 2003). Consistent with this, the present study observed suppressed Zn, Ni and Mn availability on BC patches, which could explain observed increase in vegetation cover in particular on the 10-82 year old dumps. Consistent with findings by other studies (Sun *et al.*, 2004; Chamizo *et al.*, 2012), the plants in turn provide suitable microsites for further BC colonization through litter deposits, shading and moisture conservation ((Bowker, 2007; Zhang *et al.*, 2010). The results therefore suggest mutual facilitative relationship between BCs and vegetation.

Compositionally, the results suggest taxa-specific effects of BCs with some species such as *Corigiola litoralis*, *Schizachyrium platyphyllum* and *Bulbostylis contexta* and *Polygala spp.* seemingly facilitated while others such as *Imperata cylindrica* and *Sporobolus pyramidalis* were inhibited or conversely. Findings from this study are in accordance with those from similar studies that reported species-specific effects (Callaway and Walker, 1997; Langhams, 1998; Martinez *et al.*, 2006; Maestre *et al.*, 2011; Song *et al.*, 2017; Rodriguez-Caballero *et al.*, 2018). The observed negative correlation between BCs and plant species richness, particularly on older dumps may be due to soil surface sealing effects of BCs, consistent with findings from a similar study (Gao *et al.*, 2014). BCs are known to inhibit the germination, emergence and survival of some vascular plants either through competition for space and or changes in edaphic properties (Belnap *et al.*, 2003, Bowker, 2007) and this may also explain observed lower vegetation densities in areas of higher BC cover.

BCs may enhance germination of seeds of some species on younger dumps by regulating temperature and moisture conditions that mostly influence metabolism of plant seeds (Funk *et al.*, 2014). This may also be related to plant seeds traits such as size (Lei *et al.*, 2015; Song *et al.*, 2017). High BC covers could have promoted a few species that tolerate such thick crust conditions during establishment owing to their morphological characteristics. Small seeds such as those for *Bulbostylis contexta* and *Corigiola litoralis* are most likely to fall between BC cracks where moisture is high, thereby promoting germination (Funk *et al.*, 2014). BCs with rough surfaces such as mosses and lichens that had higher covers on older dumps enhance the entrapment of vascular plant seed than smooth cyanobacteria crusts that dominated on younger dumps (Belnap *et al.*, 2001a, b, c).

The observed negative correlation between BCs and plant litter may be due to the shading effect by litter, which reduces light penetration (Facelli and Pickett, 1991; Peintinger and Bergamini, 2006). Litter from some species that produce allelochemicals has also been reported to produce leachate which is toxic to germination and growth of vascular plants (Xiong and Nilsson, 1999). The same effect may be recorded on biological crusts (Facelli and Pickett, 1991). Litter also acts as a mechanical barrier to the emergence of buried BCs even if there are favourable environmental conditions (Facelli and Pickett, 1991). Further, the BCs could also have been improving substrate fertility by accelerating litter decomposition and soil development in addition to nitrogen and carbon fixation, in turn promoting growth of vascular plants (Belnap *et al.*, 2001; Bowling *et al.*, 2011; Kuske *et al.*, 2011; Bu *et al.*, 2015).

Overall, observed higher plant species richness on patches with higher BC cover is consistent with results from similar studies where BCs facilitated multi-species germination and hence richness (Soudzilovskaia *et al.*, 2011; Ghiloufi *et al.*, 2016). Findings from this study are however inconsistent with species inhibition theories observed in some studies (Zhang *et al.*, 2010; Funk *et al.*, 2014). The study has uncovered new knowledge, in particular: (1) the age-dependent relationship between BCs and vegetation structural and compositional attributes and (2) the differential effects of BCs on different plant taxa on unique artificial pedogenetically poor substrates like mine tailings.

#### **5.4.3 Changes in vegetation communities along a BC cover gradient**

Observed variation of vegetation communities in areas of contrasting BC cover classes confirm the influence of BCs on vegetation composition as modified substrate properties attracted different combination of plant species (Zellman, 2014). In a desert study in China, BCs induced a shift of shrub vegetation community to one dominated by shallow-rooted herbaceous species by reducing infiltration (Li *et al.*, 2010). Sparse communities characterizing high BC patches may be a result of moisture related seed germination of some vascular plants (Gao *et al.*, 2014). This effect on germination was not directly

measured in the current study although assessments of composition on BC cover gradients showed marked variations in plant communities.

The presence of some 13 plant species common to all BC cover classes suggest that BCs facilitate or at least do not affect germination and growth of some plant species, for example *Schizachirium platphyllum*. Such facilitation might be through moisture conservation and improved temperature regulation (Belnap *et al.*, 2001a,b,c) and mycorrhizal associations related to N and carbon fixation (Belnap *et al.*, 2005). Rainfall interception and inhibition of infiltration of water to deeper layers beneath crusts (Chamizo *et al.*, 2012) might explain an increase in shallow-rooted plant species such as *Diheteropogon amplexans*, *Cymbopogon caesius*, *Polygala* spp., *Corigiola litoralis*, and *Schizachyium platyphyllum* on older dumps that contributed to separation of plant communities. Similar to their findings annual forbs and grasses were noted on BC patches in a parallel study and this may explain the crust-related compositional variations observed. Results showed that moderate to high BC covers are key in shaping plant communities on mine tailings.

## 5.5 Conclusion and recommendations

The current study investigated the occurrence patterns and changes of BC cover and type on an age sequence of gold tailings and their correlation with vegetation structural and compositional attributes. The key findings were: (1) Total BC cover increased with age of tailings and was positively correlated to substrate pH, total N, and OC, (2) Young tailings are initially dominated by cyanobacteria and green algae which decrease with dump age as over time they are replaced by lichen and moss dominated BCs and (3) the relationship between BCs and vegetation structural attributes is tailings-age dependent where it is a positive correlation in early succession but becomes negative or neutral in late succession and (4) the effect of BCs on plants was species-specific, which in turn affected species associations and hence communities on dumps. The differential effects on different plant taxa may explain the changes in species richness with cover change and the existence of varying plant communities under areas of contrasting BC cover classes.

The increase in BC cover coincided with substrate changes due to pedogenetic processes including improvement in fertility typical of soil formation in a succession. The decline in BC cover on the oldest dump revealed existence of a threshold for vegetation facilitation beyond which BC inhibition starts. Findings from this study therefore do not support the hypothesis that BC cover increases with age as it was observed that this increase is up to a certain threshold before a decline mainly related to suppressive effects of vegetation cover is experienced. The findings are however in support of the hypothesis that different BC cover classes form different vegetation communities owing to taxa-specific effects. The study therefore concluded that BCs are important components of tailings ecosystems and that their relationship with vegetation is more important in early succession and decline later. However, the generally low

percentage explained variation accounting for the correlation between BCs and vegetation structural and compositional attributes especially on older dumps suggests that other factors outside the scope of this study might be key determinants of the observed patterns. Nevertheless, the results show potential of BCs in ecosystem reconstruction on mine tailings. The study therefore recommends: (1) the inclusion of BCs in mine tailings restoration programs, (2) detailed compositional studies of BCs and their changes in a succession and (3) the investigation of vegetation development and relationship with other non-BC factors on mine tailings (Chapters 6, 7 and 8).

## CHAPTER 6

### IS THE TRAJECTORY OF NATURAL VEGETATION RECOVERY ON A CHRONOSEQUENCE OF GOLD TAILINGS TOWARDS A NOVEL ECOSYSTEM?

#### Abstract

Understanding the trajectory of natural vegetation recovery on mine tailings is critical in planning rehabilitation programs. Contrasting theories exist on revegetation trajectories yet specific natural revegetation trajectories on such unique anthropogenic metalliferous sites have been scantily studied. Six unrehabilitated mine tailings ranging in age from 10 - 110 years were sampled to evaluate the trajectory of changes in vegetation structural and compositional attributes compared to adjacent reference sites and identify substrate correlates. The study hypothesized that novel plant communities are formed as vegetation attributes do not converge to natural references. Plant taxa, cover, abundances and species richness were assessed along transects laid on dump tops, slopes and reference sites. The ten-year-old tailings dump had very sparse vegetation dominated by *Cyperus spp* and *Flaveria trinervia* and herbaceous plant cover increased significantly with age of tailings dump matching values observed at reference sites at 82 years. Woody species were observed on tailings as early as 17 years but did not become substantial until 82 - 92 years. Plant species richness significantly increased with dump age but remained lower than values observed at reference sites after 110 years. A non-metric dimensional scaling ordination analysis grouped plant communities on tailings and reference sites into four groups: (1) the younger dumps (10 and 17 years), (2) the intermediate age dump (30 years) that was different from both the young and the oldest dumps (82, 92 and 110 years), (3) the three oldest dumps that grouped with adjacent reference site, 200m radius and (4) the second reference site (2 km away) that was distinct from the rest of the sites. The results do not support the hypothesis that vegetation trajectory is towards formation of a novel plant ecosystem. The study observed that vegetation structural and compositional attributes may develop towards references but composition changes may be gradual and may require more than 110 years. The trajectories of vegetation structural attributes were closely related to changes in substrate properties, in particular, positively correlated to pH, available P, organic matter (O.M) and total N and negatively correlated to bulk density and electrical conductivity (EC). Results appear to dispel the emerging theory of formation of novel ecosystem and may contribute to adding context –specificity in redefining ecological restoration theories.



## 6.1 Introduction

Mining and mineral ore processing cause significant loss of biodiversity due to tailings disposal. The deposited tailings occupy large tracts of land that remain devoid of vegetation for very long periods due to their low fertility, high metal and salt toxicity, extreme pH, poor physical structure and high compaction (Piha *et al.*, 1995; Bradshaw, 1997; Shu *et al.*, 2005; Renault *et al.*, 2007; Young *et al.*, 2013; Chen *et al.*, 2015). This has caused air, water and soil pollution impacts to extent into the post- mining phase. To minimize such impacts policy makers have crafted strict regulations for the rehabilitation of tailings, in particular emphasizing revegetation with native vegetation to restore pre-disturbance ecosystem composition and function. To achieve this, mines have adopted a number of approaches to introduce vegetation cover on tailings, generally with little success. The most common techniques used are substrate amelioration involving fertilizer and organic amendments coupled with planting of non-native fast growing species (Piha *et al.*, 1995; Hadacova and Prach, 2003; Martinez and Fernandez, 2005; Chartuvedi and Singh, 2017c; Festin *et al.*, 2018). These approaches are usually expensive and often do not meet the desired ecosystem restoration goals, targeting composition, diversity and function. Finding effective natural long lasting and cheap methods of achieving the restoration goals remain a challenge as natural succession on metalliferous sites is poorly studied. Despite this challenge, the importance of knowledge of natural succession in rehabilitation cannot be underestimated (Bradshaw, 2000).

Natural revegetation involves the spontaneous development of vegetation communities, entailing colonization, persistence and succession of plant species (Bradshaw, 1983). The rate of plant colonization on any disturbed site depends mainly on the presence of sources of propagules such as adjacent vegetation patches (Prach, 2006; Young *et al.*, 2013; Prach, *et al.*, 2014; Prach *et al.*, 2015; Urbanova *et al.*, 2016). Succession following colonization usually is driven by edaphic changes (Chartuvedi and Singh, 2017c) and biogenic factors such as competition and species traits (Urbanova *et al.*, 2016; Chan and Turner, 2019). The trajectory of plant succession, often expressed with reference to undisturbed reference sites is described by a number of contrasting theories and or hypotheses. Firstly, the Clementian theory asserts that succession will see pioneer species being linearly replaced by mid and late succession species over time, reaching a climax (Clements, 1916). Secondly, the 'initial floristic composition hypothesis' asserts that climax or late succession plants are pioneer species which just persist and co-exist with incoming late succession species (Hobbs *et al.*, 2006). Thirdly, a few studies report constant species richness for over a century (Kalin and Everdingen, 1988; Kimmerer, 1996). In light of the evidence, four restoration trajectories relative to the reference have been reported, namely; (1) linear, (2) unimodal, (3) asymptotic and (4) stochastic (Bullock *et al.*, 2011). For each trajectory, substrate properties play a role in observed vegetation patterns (Bullock *et al.*, 2011). Recently, the concept of novel ecosystems has emerged (Hobbs *et al.*, 2006; Miller and Bestelmeyer, 2016). This concept suggests that some disturbed sites support a specific assemblage of plant species, completely distinct from the surrounding vegetation (Bradshaw, 1987; Wu, 1990; Hobbs *et al.*, 2006). The concept has

however received some criticism from some scholars (Marris, *et al.*, 2013; Simberloff *et al.*, 2015) who suggest ecosystems will always converge towards pristine reference conditions. The existence of such conceptual and theoretical contradictions makes planning of self-sustaining tailings revegetation programs difficult. Therefore, there is need for more empirical studies that test existing theories and provide context specific trajectories.

A number of ecosystem development studies have been done on natural and artificial substrates (Hobbs and Harris, 2003; Martinez & Fernandez., 2005; 2007; Charturvedi *et al.*, 2017c). Most studied substrates are mine soils and coal spoil heaps (Skousen *et al.*, 1994; Andrews, 1998; Boerner *et al.*, 1998; Jochmisen, 2001; Holl, 2002; Sourkova *et al.*, 2005; Frouz *et al.*, 2007; Yao *et al.*, 2010; Alday *et al.*, 2011; Mukhopadhyay and Maiti, 2011; Payasat and Patel, 2015). Key findings from these studies are: (1) a positive correlation between tailings age and vegetation structural attributes (e.g. Hodkinson and Webb, 2003; Wang *et al.*, 2004; Huang *et al.*, 2011; Herzberger *et al.*, 2015; Lei *et al.*, 2015a), (2) the importance of adjacent references in shaping plant composition on disturbed sites (Shu *et al.*, 2005; Weiersbye *et al.*, 2006; Young *et al.*, 2013) and, (3) Varying physicochemical properties are key determinants of characteristics of plant communities (Huang *et al.*, 2004; Mendez and Maier, 2008; Alday *et al.*, 2011; Huang *et al.*, 2011). However, specific natural revegetation trajectories on such unique anthropogenic metalliferous sites have been scantily explored. A few studies on mine tailings were either once-off or short term vegetation surveys with no emphasis on succession trajectories (e.g. Wild, 1965; Hill and Nothard, 1973; Wild, 1974; Piha *et al.*, 1995; Wang *et al.*, 2004; Shu *et al.*, 2005; Weiersbye *et al.*, 2006; Young *et al.*, 2013; Mukaro *et al.*, 2017; Festin *et al.*, 2018). As such ecological restoration theories remain untested on unique substrates like mine tailings. Further, studies exploring the influence of age and topographic position on succession are limited. While permanent plots have been used in a few studies e.g. on coal spoils in Spain (Martínez *et al.*, 2001); these however, have been on a very short period. Spontaneous revegetation studies on mine waste stretching to over 100 years are limited.

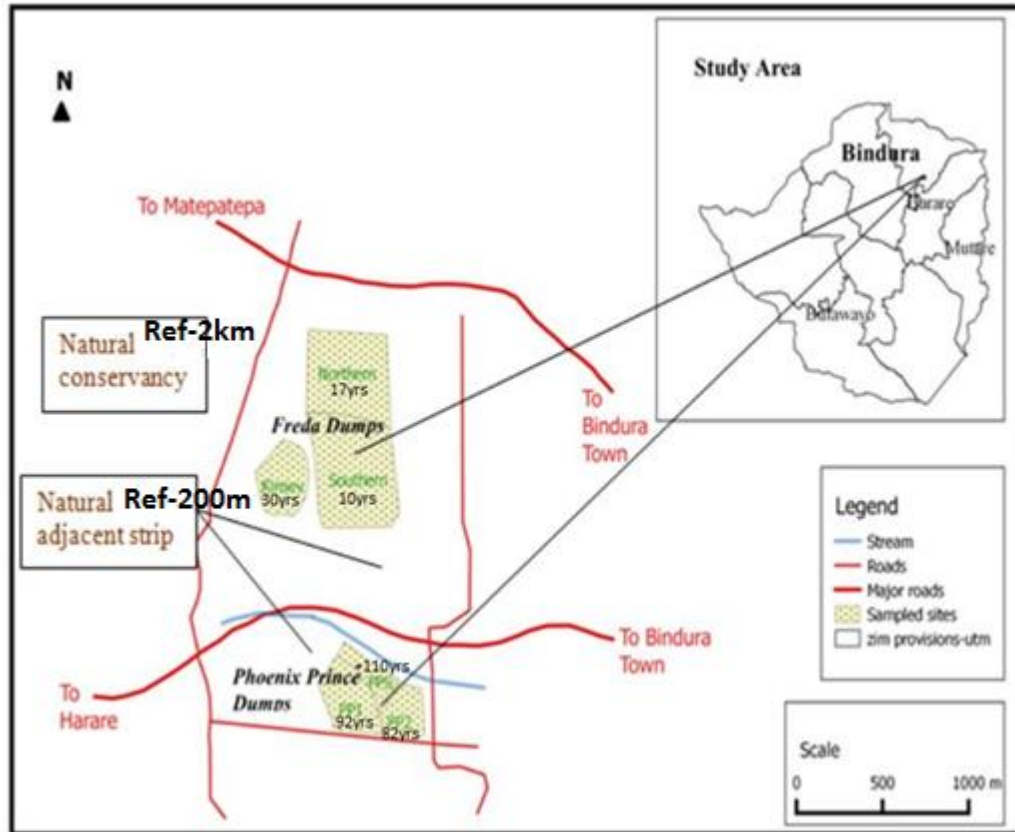
In light of several contrasting revegetation theories, and lack of long-term succession studies on mine tailings, field studies are needed to test these theoretical frameworks. The study assessed trajectories of vegetation development, mainly testing the emerging novel ecosystem theory, the traditional convergent theory and supporting models such as the initial floristic composition model or floristic relay model. Findings from this study will contribute to the understanding of restoration of mine sites in the savanna region which may differ from those in other biomes. The study will contribute towards closing the current knowledge gap on the link between the generic conventional succession conceptual framework and the specific empirical experience. Mine tailings are suitable for primary succession research as they are distinctive, definable and often of known age and are ecologically simple (Marris and Bradshaw, 1993).

The specific objectives of the study were: (1) to determine the trajectory of changes in plant structural and compositional attributes on a chronosequence of gold tailings and, (2) to determine substrate and topographic factors correlated to observed vegetation trajectories. Due to the uniqueness of tailings substrates, the study hypothesized that: (1) vegetation cover, species richness and diversity increase with tailings age but do not converge towards the natural reference over time, (2) plant communities formed on tailings do not converge to natural references (novel ecosystems are formed) over time and, (3) local topography significantly influenced patterns of occurrence of vegetation structural and compositional attributes. Knowledge of trajectories of plant community development may enhance the ability to manipulation of natural succession processes to accelerate restoration (Palmer *et al.*, 1997). Understanding the processes that occur during natural colonization and succession on mine wastes is important in guiding restoration programs ( Mathew *et al.*, 2009; Alday *et al.*, 2011; Baasch *et al.*, 2012).

## **6.2 Materials and methods**

### **6.2.1 Description of the study area**

The study was carried out on six gold tailings dumps of contrasting ages, situated at Freda Rebecca Gold mine (latitude 31°16'S and longitude 17°16'E, altitude, 1070m) in Bindura district, north east of Zimbabwe. The site experiences a savanna climate characterized by wet summers and dry winters. Based on weather data for the past 37 years, Bindura receives an average annual precipitation of 879 mm and has an average annual temperature of 28°C (Zimbabwe Meteorological Services, 2018). To investigate the trajectories of vegetation structural and compositional attributes, six dumps of contrasting ages (10, 17, 30, 82, 92 and 110 years since last deposition) and two adjacent reference sites, one 200 m away from dumps (Ref- 200m) and another 2 km away (Ref-2km) were studied. The three youngest tailings (10, 17 and 30 years) are located about 800 m north of the older tailings (82, 92 and 110 years; Figure. 6.1). The dumps of different ages provided an opportunity for the natural revegetation study, but there was no chance for dump age replication due to dumping patterns and different management of mining operations over time.



**Figure 6.1:** Map of the study area in northeast Zimbabwe. The study area comprises six gold tailings dumps. The adjacent natural strip (Ref 200 m) was partly disturbed through mine activities. The natural conservancy (Ref- 2 km) remained free of major disturbance from mining.

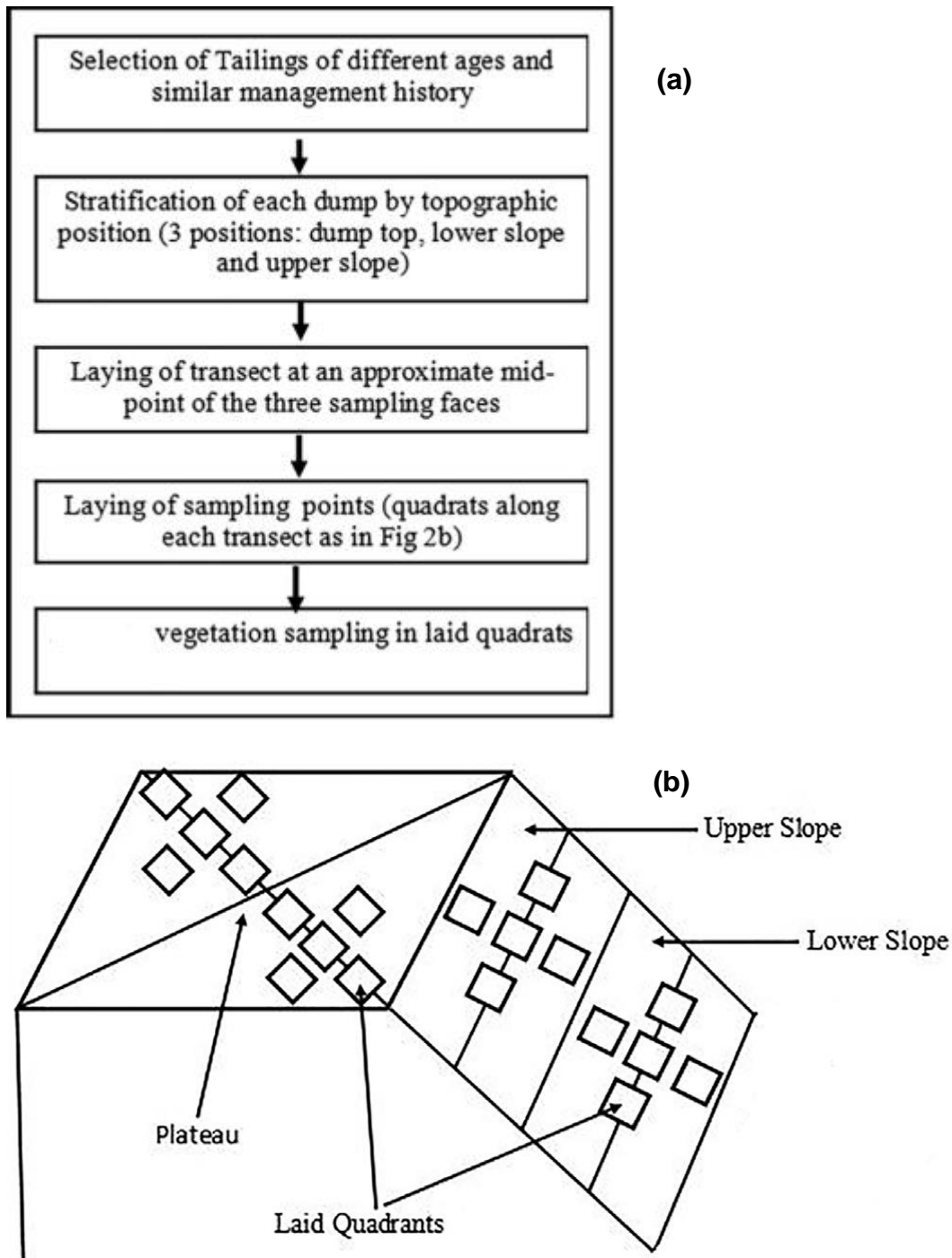
The general geology of the study area belongs to the Zimbabwe Craton in the Harare-Shamva Greenstone Belt, wedged between the Chinamora (to the south) and Madziwa batholiths (to the north) (FRGM Geology report, 2010). The mine site is approximately in the central axis of the Bindura-Shamva Greenstone Belt. Metamorphic mineral assemblage indicates green schist facies to upper amphibolites facies and a range of metamorphic grades across the belt. The metadiorite host the bulk of the mineralization associated with the mining operations. The local geology is typically a greenstone configuration composed mainly of basaltic rocks (gabbro and tholeiitic basalts) combined with banded iron formations and volcanic tuffs (Masvodza *et al*, 2013). The gold ore that produces the tailings consists of pyrite ( $\text{FeS}_2$ ), pyrrhotite ( $\text{FeO}_8\text{S}$ ), and arsenopyrite ( $\text{FeAsS}$ ) as the major minerals with chalcopyrite ( $\text{CuFeS}_2$ ), bornite ( $\text{Cu}_5\text{FeS}_4$ ) and pyrolucite ( $\text{MnO}_2$ ) as minors.

The area is in the savanna biome characterized by Miombo woodland with *Brachystegia boemmii* and *Julbernardia globiflora* dominating upper catenary positions while remnants of *Senegalia (Acacia)*

*polyacantha* and *Vachellia (Acacia) gerrardii* woodland patches dominate low-lying areas. Detailed composition is described in Chapter 2.

### **6.2.2 Experimental set up**

To investigate the effects of age on vegetation structural and compositional attributes, six tailings of similar history, aged 10, 17, 30, 82, 92 and 110 years (in 2015) were selected. To investigate the effects of topography, each dump was further stratified by slope position, yielding three topographic positions; (1) flat tops (2) upper slope and (3) lower slope (i.e. on such dumps tailings are deposited starting from the base, in effect also creating a chronosequence). A transect, was laid at an approximate mid-point, along the bottom and upper slopes, while on the dump top, two diagonal transects were laid. Along each transect sampling points were located at 10-20 m intervals starting from a randomly selected end (Zhang *et al.*, 2007; Fig 6.2a). At each sampling point, five replicate quadrats were systematically laid at one-metre intervals (one at centre and four in all major compass directions; Fig 6.2b). To cater for possible influence of aspect on observed vegetation patterns the slopes were replicated in all cardinal directions for each tailings dump. Two natural woodlands were used as reference sites (controls): (1) the tailings foot (200 m stretch around the tailings and (2) the conservancy (2 km away). Reference sites were selected based on proximity to the dumps and for the conservancy, freedom from human disturbances and similarity in topography. A total of 602 sampling points were laid on all dumps and natural reference sites.



**Figure 6.2:** Diagram showing steps taken in sampling: (a) Schematic diagram showing steps in experimental set up; (b) Layout of quadrats at study sites. Five 1-m<sup>2</sup> quadrats were placed at each sampling point, one at the centre and four arranged on each major compass cardinal direction (N, S, E, and W) and with the edge 1 m away from the edge of the central quadrat.

### 6.2.3 Assessment of vegetation attributes

All plant taxa observed in each quadrat were identified to species level using field guides (Van Oudtshoorn, 2014) and their abundances determined by physical counting of tufts and stems for woody seedlings (height  $\leq 50$ cm) . Those that could not be identified in the field were sent to the National Herbarium of Zimbabwe in Harare for identification. Quadrat and site species richness were determined for different taxa observed. Aerial and basal cover of total and individual herbaceous species were visually estimated to the nearest percent in terms of the proportion of the quadrat being covered (Ochoa-Hueso *et al.*, 2011). To estimate cover, a 1-m<sup>2</sup> quadrat was divided into 100 grids of 100 cm<sup>2</sup> each with each square, representing 1% cover, using wire frames (Dettweiler-robinson *et al.*, 2013b). Total basal cover was taken as the measure of the proportion of the plants in a quadrat which extends into the soil (Dettweiler-Robinson *et al.*, 2013b). Basal covers of each tuft in each quadrat were estimated and then added to obtain the total basal cover for such quadrat (Ochoa-Hueso *et al.*, 2011). Plant density in each quadrat was determined using abundance data per m<sup>2</sup>. Total counts for all trees and shrubs (> 50 cm height) were determined per dump position since they were very few. For further analysis, vegetation was classified according to growth form (i.e. forbs, grasses and woody seedlings) and life cycle (annuals and perennials). To establish trends for individual species during primary succession, the species were categorized into succession stages based on their frequencies (a frequency > 1% in a category of first occurrence). The following categories were used: (1) early succession (10 and 17 years), (2) mid-succession (30 years), (3) late succession (82 and 92 years) and, (4) very late succession (110 years). Alpha diversity was analysed using Shannon and evenness indices below:

$$\text{Shannon diversity index } (H') = -\sum p_i \ln p_i \dots \dots \dots (1)$$

where  $p_i$  is the relative abundance of species  $i$ .

$$\text{Evenness} = H' / \ln [\text{Richness}] \dots \dots \dots (2)$$

Sorensen indices of similarity (S) and species importance value (SIV) were determined using the formulae below:

$$\text{Sorensen } (SI) = 2c / (a + b) \dots \dots \dots (3),$$

where  $c$  is the number of shared species between two sites,  $a$  and  $b$  are the total number of species at each site.

### 6.2.4 Substrate sampling and analyses

Tailings samples were collected from five randomly selected points from those used for vegetation sampling on all topographic positions of the dumps. Where appropriate sampling points were selected from areas of contrasting vegetation cover. At each sampling point, sampling was done at 0-5 cm, 5-15 cm, and 15–30 cm depths using a bucket soil auger (8 cm diameter). At each sampling point samples were collected from the centre of each of the five quadrats used for vegetation assessments. The



samples were thoroughly homogenized and bulked to make a composite sample for that point and a 500 g sample sealed in a sample bag and transported to the department of soil research in Harare for laboratory analysis. In the laboratory samples were air-dried and passed through a 2 mm sieve before being analysed for texture, pH, EC, total and mineral N, available P, exchangeable (Ca, K and Mg), OC, and bulk density using methods described by Tandon (2009). Brief methods for determination of each element are given below and detailed in Chapter 3.

Total nitrogen was determined by the Kjeldahl method (Jackson, 1964). Mineral N levels were measured using the micro-diffusion method on 2 M KCl extracts. Available P was determined by the Olsen method (Olsen *et al.*, 1954). Soil organic carbon was determined using the Walkley and Black method (Walkley and Black, 1934). Organic matter was determined by multiplying values for OC with a factor of 1.72 (Tandon, 2009). Texture was determined by the pipette and hydrometer method. The procedure included estimation of clay (< 0.02 mm), silt (0.06 mm - 0.002 mm) and sand (2 mm- 0.06 mm) percentage. Bulk density was determined by the core method. Tailings or soil samples were extracted by driving a 100 cm<sup>3</sup> core into the ground. The collected sample was oven-dried at 105°C for 24 hrs. Dry weight of the soil was determined. Bulk density (g/cm<sup>3</sup>) was calculated as dry weight of soil (in g)/ volume of core (cm<sup>3</sup>). An electronic digital pH meter (PHS-3BW series) was used to measure pH in a 1:2: V: V Substrate: water suspension. The electrical conductivity of the oven-dried tailings was recorded with a portable conductivity meter (Orion 150) using a (1: 1 V: V) water slurry method. Exchangeable Ca and Mg were determined in ammonium acetate extracts of soils obtained as by using the AASICE 3000 series.

### 6.2.5 Data analysis

Data were analysed in two phases involving two-way analysis of variance and ordination. Species abundance, richness, diversity and substrate data were tested for normality using the Kolmogorov Smirnov test in Statistical Package for Social Sciences (SPSS) software version 20. All vegetation and substrate data recorded as percentages were arcsine transformed before analysis of variance (Mckillup, 2011). Two way-ANOVA was used to test effects of dump age and topographic position, and their interactions on vegetation covers, species richness and plant densities. Pair-wise comparisons were done with post-hoc (LSD) test at 95 % level of significance.

To test effect of age and position on vegetation community development, a linear principal component analysis (PCA) was performed since data gradient length was less than 3 (Lepš & Šmilauer, 2003; Mckillup, 2011). The same effects were tested using the non-metric dimensional scaling (nMDS) and detrended correspondence analysis (DCA) as they were also suitable. All tests were done without down-weighting of rare species (species with very low frequencies in the study). Redundancy analysis (RDA) and Canonical correspondence analysis (CCA) were employed to assess relationships between tailings



attributes and vegetation structural and compositional attributes (Ter Braak, 1986). All ordination analyses were done using Conoco for windows version 5. Non-metric dimensional analyses were done in Past 3 software. In this study a regression approach was not possible due to high percentage of zero values that characterized vegetation composition data (Morgenthal and Rensburg, 2004). A CCA solves this problem while it also takes care of the non-linearity that is caused by the zero values (Ter Braak and Verdonschot, 1995).

## 6.3 Results

### 6.3.1 Changes in vegetation structural attributes on an age sequence of gold dumps

Herbaceous plant aerial cover significantly ( $F= 490.5$ ;  $p < 0.01$ ) increased with age of tailings (Fig 6.3a), with vegetation cover on the oldest dump (110 years) matching covers observed at Ref 200 m ( $p = 0.124$ ). The oldest dump had significantly higher aerial cover than the furthest reference (2 km). Despite the general significant increase in herbaceous vegetation aerial cover with tailings age, the post-hoc LSD test showed that aerial cover for the 10 and 17-year-old dumps were similar (Fig 6.3a). Similarly, the 82 and 92-year-old dumps had similar aerial cover (Fig 6.3a). Herbaceous basal cover significantly increased ( $F=52.050$ ;  $p < 0.01$ ) with age reaching a peak on the 92-year-old dump but recorded a 102 % decline on the oldest (110 year) dump. A post-hoc LSD test showed that the 110-year-old dump and adjacent reference site (Ref-200 m) had similar basal cover which were significantly lower than those observed on the 82 and 92-year-old dumps (Fig 6.3b) but significantly higher than that observed on the three youngest dumps (Fig 6.3b).

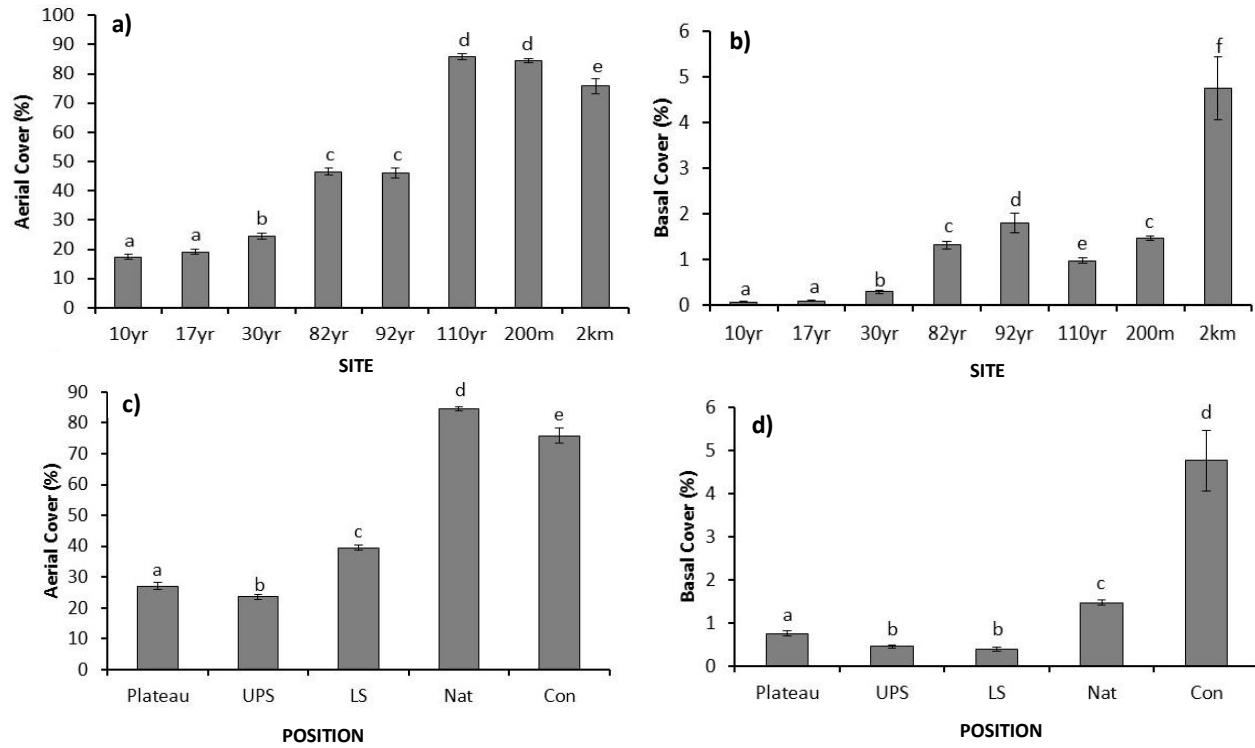
Aerial cover significantly varied with topographic position in the order: lower slopes (LS) > dump tops (PLT) > upper slopes (UPS; Fig 6.3c). Basal cover was significantly higher ( $p = 0.024$ ) on dump tops than slopes which had similar values for both lower and upper slope positions (Fig 6.3d). However, basal cover on dumps was significantly lower than on both reference sites (Fig 6.3d).

Plant species richness was significantly affected by dump age ( $F= 695.10$ ;  $p < 0.001$ ), topographic position ( $F= 12.52$ ;  $p < 0.001$ ) and their interactive effect ( $F= 28.62$ ;  $p < 0.001$ ). In particular, species richness per  $m^2$  significantly increased with dump age, exceeding values observed on the adjacent reference site at 92 years though significantly lower than the second reference site (Fig 6.4a). Although total species richness recorded a similar trend, it reached a peak on the 92-year-old dump and declined thereafter (Fig 6.4b). In all cases total species richness was markedly lower on dumps than on both reference sites.

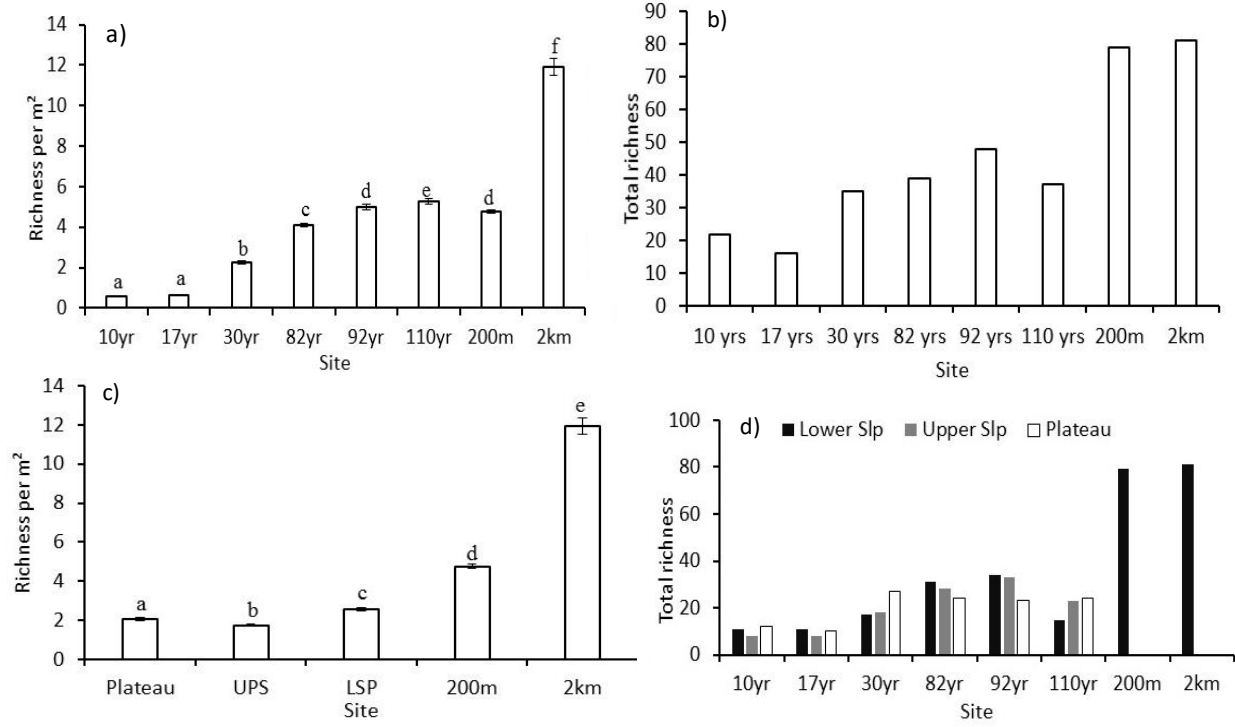
Species richness per m<sup>2</sup> significantly varied with topographic position in the order: lowerslope > dump tops > upper slopes (Fig 6.4c). Total species richness followed a similar trend except on the 30-year-old dump where richness was highest on the dump tops (Fig 6.4d). In most cases plant species richness of the two youngest dumps was statistically similar.

In terms of trends for functional types, species richness and abundances of forbs, grasses, ferns and woody seedlings increased with dump age. In particular, forbs and fern species richness increased up to 92 years and declined on the oldest dump (110 years) while grasses and woody seedlings richness continuously increased up to the oldest dump (**Table S6.1**). In most cases, all plant growth forms on the 82, 92 and 110-year-old dumps had richness exceeding values obtained on the adjacent reference site (Ref-200 m) but was markedly lower than values obtained at the further away reference site (Ref-2km). Species richness for most growth forms was significantly higher on slopes than dump tops while the opposite was observed for abundances (**Table S6.2**). Woody seedlings generally fluctuated below and above the references with abundances on 30-110-year-old dumps matching values obtained at the adjacent reference site. However, a few shrubs began showing on the 17-year-old dump and increased with age (**Table S6.2**). The 92 and 110-year-old tailings dumps had markedly higher trees/shrubs densities that were however significantly lower than those observed at both reference sites. Dominant woody species on the dumps were *Senegalia polyacantha* and *Rhus tenuinervis*.

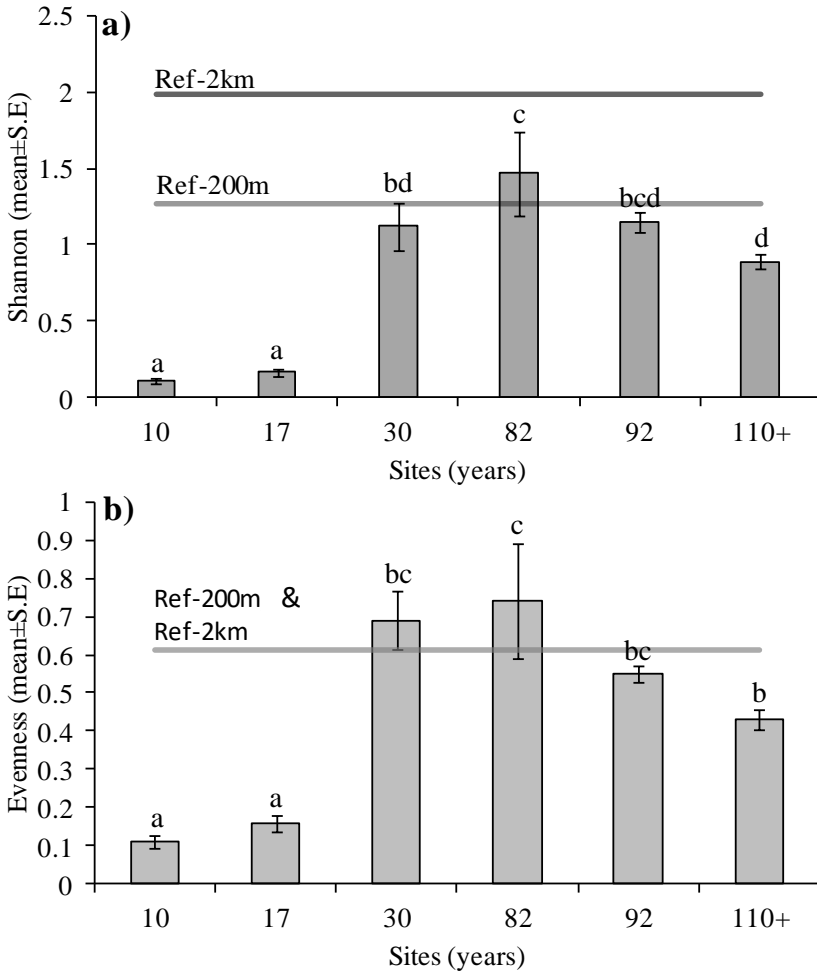
Although Shannon species diversity and evenness for the two youngest dumps were statistically similar, these variables significantly increased with dump age, reaching a peak at 82 years and steadily declined thereafter (Fig 6.5a and b). Shannon diversity index surpassed the values for the adjacent reference site at 82 years, but was significantly lower on the reference site furthest away (Fig 6.5a). Similarly, evenness increased with age reaching a peak at 82 years but first exceeded both reference sites on the 30-year-old dump (Fig 6.5b).



**Figure 6.3:** Changes in vegetation cover on a chronosequence and toposequence of gold tailings dumps and reference sites: (a-b) cover changes on an age sequence, (c-d) cover changes on a toposequence: (Nat = adjacent reference -200m; Con = Conservancy; UPS = upper slope; LS = Lower slope; Plateau = Dump top).



**Figure 6.4:** Changes in plant species richness on the dumps (a-b) age sequence (c-d) toposequence; (UPS= upper slope; LSP = upper slope, plateau= dump top, 200m = adjacent reference, 2 km= conservancy reference site).

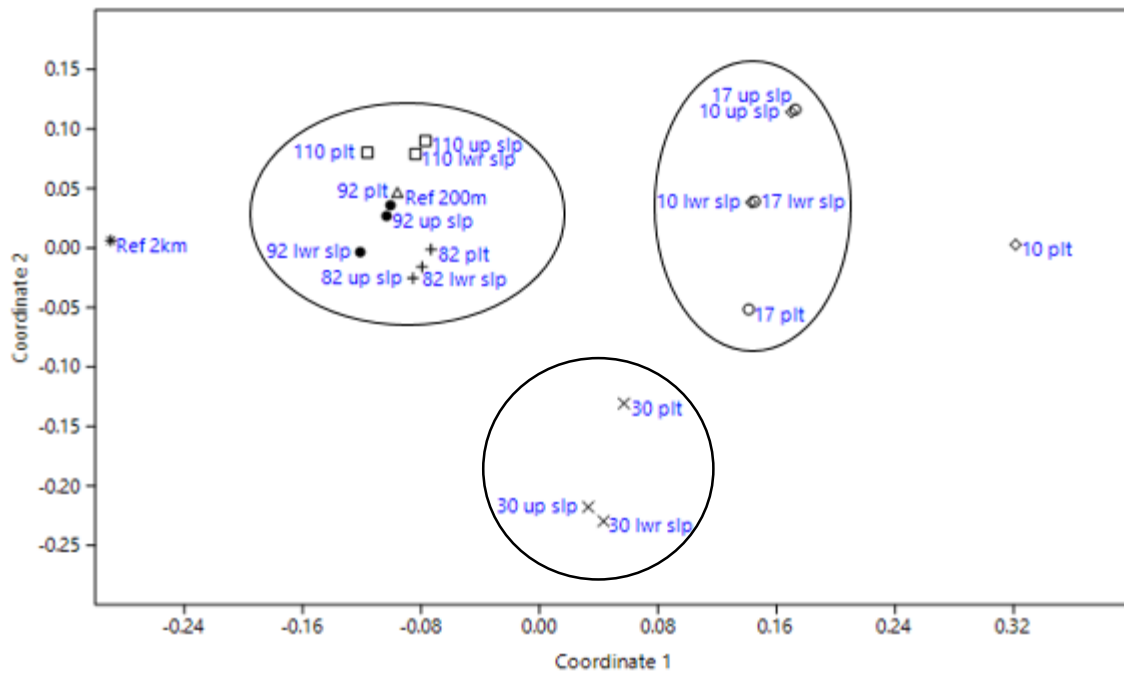


**Figure 6.5:** Changes in plant species diversity on a chronosequence of gold tailings dumps. (a) Shannon diversity index (b) evenness. (Ref -200 m = adjacent reference site; Ref-2km = conservancy).

### 6.3.2 Trajectory of Plant communities

Nonmetric dimensional scaling (nMDS) and Detrended correspondence analysis (DCA) using species abundance data both grouped the tailings dumps into three broad clusters. The first cluster had plots from the two youngest tailings dumps (10 and 17 years). The second cluster had plots from the intermediate age tailings dump (30 years) while the third cluster comprised plots from the three oldest dumps (82, 92 and 110 years) and the adjacent (R-200 m) reference site (Fig 6.6;S6.1). Plots from all dumps separated from the 2 km reference site although the trajectory was towards it. Similar results were obtained from an NMDS plot when herbaceous and woody species (seedlings, trees and shrubs) were combined (Fig S6.2). However, despite clustering together, plots from the oldest (110 -year- old dump) slightly separated from the 82 and 92-year- old dump plots ( Fig 6.6).

Ordination analysis showed little separation of plots from different topographic positions on the dumps except for the youngest (10 years). In most cases plots from dump tops slightly separated from those from slopes (Fig 6.6; Fig S6.1). However, Sorensen index of similarity (Table 6.1) showed steady progression of plant communities on tailings towards the adjacent natural vegetation community with Sorensen indices of 0.3 and 0.52 for the youngest (10 years) and oldest (110 years) respectively. All dumps were markedly dissimilar (Sorensen indices < 0.25) to Ref-2 km (Table 6.1). The similarity between plant communities on dump slopes and tops increased with dump age and higher similarity among dump faces was observed than between dump faces and the adjacent reference site (Table 6.2).



**Figure 6.6:** nMDS ordination monoplot of sites based on species composition and abundance data Stress = 0.078, Axis 1= 0675, Axis 2 = 0.0790 (Numbers denote tailings age; plt= plateau-dump top; lwr slp= lower slope; up slp= upper slope; Ref 200 m= adjacent reference slightly disturbed by dumping; Ref-2km= conservancy reference site- largely undisturbed).

**Table 6.1:** Sorenson similarity index (number in bold) between sites (number in brackets shows number of common species between sites) (R200m- adjacent reference; R 2km- conservancy reference site).

	10yr	17yr	30yr	82yr	92yr	110yr	R200m	R2km
10yr	1(22)	<b>0.68</b> (13)	<b>0.74</b> (21)	<b>0.46</b> (14)	<b>0.37</b> (13)	<b>0.41</b> (12)	<b>0.30</b> (15)	<b>0.16</b> (8)
17yr	<b>0.68</b> (13)	1(16)	<b>0.55</b> (14)	<b>0.33</b> (9)	<b>0.25</b> (8)	<b>0.23</b> (6)	<b>0.23</b> (11)	<b>0.10</b> (5)
30yr	<b>0.74</b> (21)	<b>0.55</b> (14)	1(35)	<b>0.51</b> (19)	<b>0.43</b> (18)	<b>0.42</b> (15)	<b>0.39</b> (22)	<b>0.21</b> (12)
82yr	<b>0.46</b> (14)	<b>0.33</b> (9)	<b>0.51</b> (19)	1(39)	<b>0.69</b> (30)	<b>0.53</b> (20)	<b>0.42</b> (25)	<b>0.18</b> (11)
92yr	<b>0.37</b> (13)	<b>0.25</b> (8)	<b>0.43</b> (18)	<b>0.69</b> (30)	1(48)	<b>0.56</b> (24)	<b>0.46</b> (29)	<b>0.17</b> (11)
110yr	<b>0.41</b> (12)	<b>0.23</b> (6)	<b>0.42</b> (15)	<b>0.53</b> (20)	<b>0.56</b> (24)	1(37)	<b>0.52</b> (30)	<b>0.24</b> (14)
R200m	<b>0.30</b> (15)	<b>0.23</b> (11)	<b>0.39</b> (22)	<b>0.42</b> (25)	<b>0.46</b> (29)	<b>0.52</b> (30)	1(79)	<b>0.24</b> (19)
R2km	<b>0.16</b> (8)	<b>0.10</b> (5)	<b>0.21</b> (12)	<b>0.18</b> (11)	<b>0.17</b> (11)	<b>0.24</b> (19)	<b>0.24</b> (19)	1(81)

**Table 6.2:** Sorensen similarity indices between sites (number in brackets shows number of shared species) (PLT= plateau- dump top; UPS= upper slope; LSP= lower slope);

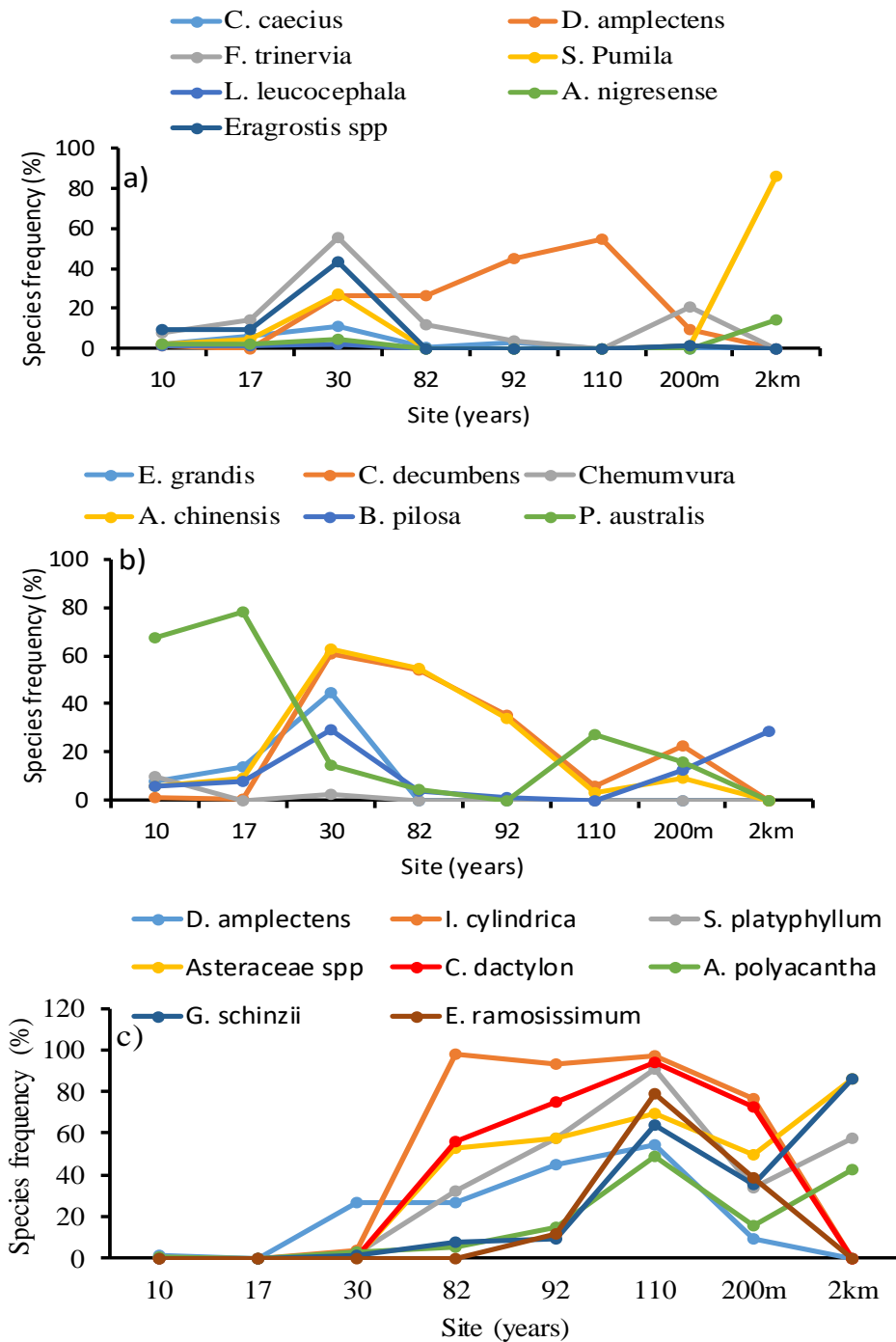
Dump face	10yr	17yr	30yr	82yr	92yr	110yr
Slope vs. plateau	<b>0.24</b> (3)	<b>0.61</b> (7)	<b>0.67</b> (16)	<b>0.68</b> (20)	<b>0.5</b> (16)	<b>0.59</b> (15)
Slope vs. R200m	<b>0.22</b> (10)	<b>0.22</b> (10)	<b>0.3</b> (15)	<b>0.42</b> (24)	<b>0.48</b> (29)	<b>0.41</b> (21)
Plateau vs R200m	<b>0.18</b> (8)	<b>0.13</b> (6)	<b>0.36</b> (19)	<b>0.39</b> (20)	<b>0.31</b> (16)	<b>0.43</b> (23)
Position						
PLT vs. UPS	<b>0.1</b> (1)	<b>0.56</b> (5)	<b>0.62</b> (14)	<b>0.73</b> (19)	<b>0.54</b> (15)	<b>0.55</b> (13)
PLT vs. LSP	<b>0.26</b> (3)	<b>0.67</b> (7)	<b>0.59</b> (13)	<b>0.69</b> (19)	<b>0.46</b> (13)	<b>0.41</b> (8)
UPS vs. LSP	<b>0.63</b> (6)	<b>0.63</b> (6)	<b>0.8</b> (14)	<b>0.81</b> (24)	<b>0.78</b> (26)	<b>0.53</b> (10)
UPS vs. NAT	<b>0.09</b> (4)	<b>0.11</b> (5)	<b>0.29</b> (14)	<b>0.37</b> (20)	<b>0.46</b> (26)	<b>0.37</b> (19)
LSP vs. NAT	<b>0.2</b> (9)	<b>0.2</b> (9)	<b>0.23</b> (11)	<b>0.44</b> (24)	<b>0.44</b> (25)	<b>0.3</b> (14)

### 6.3.3 Evolution and classification of key plant species on the dumps

There were 13 pioneer species (7 grasses, 3 forbs, 1 sedge and 2 woody species) present on two youngest dumps (early succession). Of the pioneer species, eight (*Cymbopogon caesius*, *Setaria pumila*, *Eragrostis* spp., *Andropogon chinensis*, *Phragmites australis*, *Cyperus* spp, *Flaveria trinervia* and *Bidens pilosa* were most frequent (Table S6.1). Only *Diheteropogon amplexans* increased in all succession stages attaining frequencies higher than those observed from both reference sites (Fig 6.7a and b). *Flaveria trinervia*, *Setaria pumila*, *Andropogon chinensis*, *Leucaena leucocephala*, *Cymbopogon caesius* and *Bidens pilosa* increased significantly to a peak at 30 years then declined thereafter (Fig 6.7a and b). Five species (*Leucaena leucocephala*, *Setaria pumila*, *Senegalia nigrescens*, *Eragrostis* spp., *eucalyptus grandis* and *Cyperus* spp) were limited to the early and mid-succession phases (Fig 6.7).

*Phragmites australis* showed a fluctuating trend. Twenty-eight new species were observed in the mid-succession phase (30 years), a further 28 in the late succession stage (82 and 92 years) and only 7 in the very late succession stage (110 years). However, most pioneer species were either missing (8 species) or had sharply declined (3 species) in the very late succession stage (Fig 6.7a, b). Seven out of eight dominant species in the very late succession stage (*Imperata cylindrica*, *Schizachyrium platyphyllum*, *Gigeria schinzii*, *Equisetum ramosissimum*, *Asteraceae spp*, and *Cynodon dactylon*) emerged in the mid-succession phase and progressively attaining frequencies higher than those observed in the two reference sites (Fig 6.7c).

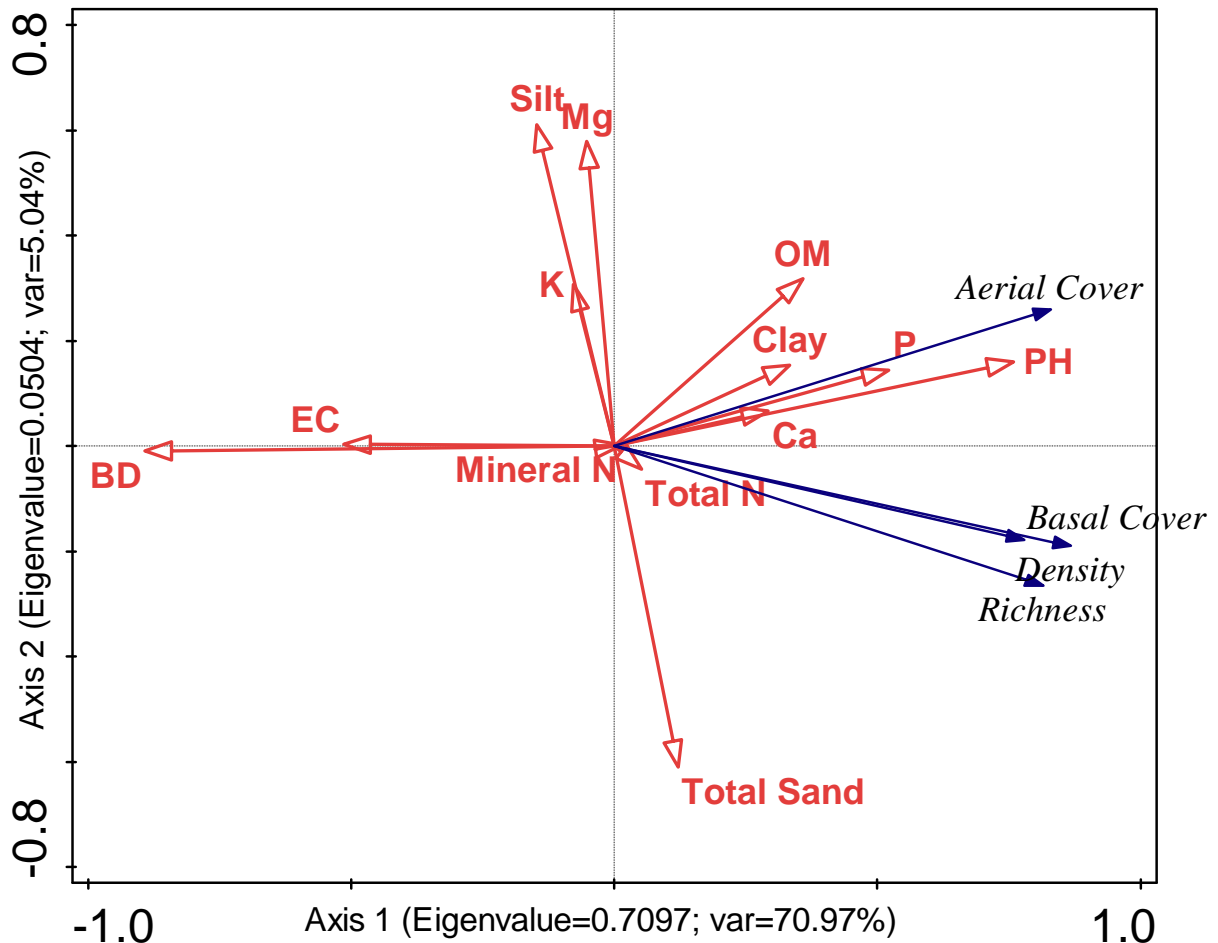




**Figure 6.7 :** Evolutionary trajectory of pioneer and dominant late successional species on gold dumps: (a-b) pioneer species (c) species dominating (Frequency ≥ 45%) the very late succession stage (110 year – old- dump).

### 6.3.4 Correlation between vegetation structural attributes and substrate properties

A redundant detrended analysis (RDA) showed a strong positive correlation between vegetation structural attributes (aerial cover, basal cover, species richness and density) and substrate (in the order of importance) pH, available P, organic matter, clay content, exchangeable Ca and total N (Fig 6.8). Bulk density (BD) and Electrical conductivity (EC) were strongly negatively correlated to all vegetation structural attributes (Fig 6.8).



**Figure 6.8:** Correlation among vegetation structural attributes and tailings physicochemical properties. Data SD length = 1.9 units; Axis 1 explains 70.97% of the variation; Axis 2 explains 5.04% of the variation.

## 6.4 Discussion

The study had four key findings: (1) Vegetation structural attributes significantly increased with age of tailings towards and at times exceeding conditions for the reference sites, (2) Vegetation composition gradually moved towards reference conditions but remained below the conditions of the undisturbed reference site within the 110 years, (3) Some plant taxa showed differential trajectories with some few pioneer plants thriving to the very late successional stages while some were replaced by others, suggesting dominance of the floristic relay mechanisms of revegetation rather than the initial floristic composition model and, (4) Vegetation structural attributes were mainly positively correlated to substrate pH, available P, total N, O.M and clay content but negatively correlated to bulk density and EC. Results do not support the hypothesis of formation of novel plant ecosystems, rather appear to uphold the conventional convergence theory.

### 6.4.1 Trajectory of vegetation structural attributes

The observed significant increase in herbaceous cover that equalled or exceeded values observed at reference sites at 92 years can be attributable to changes in substrate physicochemical properties mainly, macronutrients (N and P), pH, EC, O.M, and substrate compaction represented by bulk density in the present study. In a related study such parameters showed differential trends over time (Chapter 3; Table S6.3; Fig S6.3) and had strong correlation with vegetation structural attributes (Fig 6.8).

Firstly, the very sparse vegetation on the 10 and 17-year-old dumps can be attributable to lack of macronutrients such as N and P. Freshly disposed and young tailings lack these macronutrients as they seldom occur in the gold ore minerals, thus are poor substrates for plant establishment. Such nutrients can increase over time due to enhanced pedogenetic processes. The increase in N and P concentrations would in turn promote leaf and root growth for colonizing plants which in turn improve vegetation covers (Brady and Weil, 2013; Leghari *et al.*, 2016). The temporal improvement of these macronutrients would also support the persistence of some mid-succession plants that were otherwise inhibited in early succession stages with a net increase in species richness and diversity as observed in the present study. Consistent to findings of this study, Wang *et al.* (2018) observed nutrient-dependent vegetation cover and diversity improvement on a chronosequence of gold tailings in China.

The trajectory of vegetation structural and diversity attributes can also be attributed to dynamics in substrate pH. Acidic pH (3-4.5) characterizing the younger dumps (10 and 17 years) appears to inhibit vegetation establishment on such dumps. Despite the highly alkaline pH (10-11) at disposal (Chapter 3), the pyrites in tailings are quickly oxidized, generating acidity (Zaranyika and Chirinda, 2011). The very high pH at disposal and very low pH owing to pyrite oxidation discourages the germination of dispersed seeds and nutrient uptake by few tolerant plants resulting in stunted growth (Chan and Turner, 2019).

This can account for the observed low plant species richness and cover on these dumps. At acidic pH below 5.5, characterizing the 10 and 17 year- old -dumps, P availability is known to be low and increases as pH increases, reaching optimum values at pH between 6 and 7.5, similar to values observed on older dumps (Pierzynski *et al.*, 1994; Brady and Weil, 2013). The acidic pH also increases the bioavailability of heavy metals, creating toxic conditions for establishment of metal intolerant species (Conesa *et al.*, 2006; Zaranyika and Chirinda, 2011; Chaturvedi and Singh, 2017). Due to reduced weathering, probably starting at 30 years, pH significantly increased, attaining a range (5-7) more conducive for plant growth. This pH range characterizing the older dumps (30- 110 years) can explain the increase in cover, density and species richness. To some extent changes in substrate salinity represented by EC values can also account for the observed vegetation trends. Bradshaw and Chadwick (1980) noted that plants do well at an EC range 0- 0.9 dS/m as observed on the older dumps and that some species are severely inhibited by EC ranges of 1.8-3.6 dS/m as observed on younger dumps (Williams *et al.*, 1982).

Changes in substrate compaction represented by bulk density in this study could also have influenced the vegetation trajectory. A related study observed a temporal decrease in tailings compaction (Chapter 3). In the present study the vegetation attributes were negatively correlated to tailing bulk density (Fig 6.8) demonstrating a close relationship between the factors. Bulk density values greater than 1.4 mg/cm<sup>3</sup> are reported to inhibit root and overall plant growth on silt and sand soils similar to mine tailings (Chaudhari *et al.*, 2013). Higher bulk density on younger dumps (> 1.4mg/ cm<sup>3</sup>; Chapter 3) might have directly inhibited emergence of plant seedlings and discouraged root penetration causing lower structural attributes and stunted growth (Onweremadu *et al.*, 2008; Kormanek *et al.*, 2015; Wang *et al.*, 2018). Indirectly, bulk density has a negative influence on water infiltration, holding capacity and aeration of the soil. This in turn hinders microbial activity resulting in lower nutrient release and lower plant productivity (Wang *et al.*, 2018). Over time, bulk density decreased due to root action and organic matter deposition by spreading pioneer plants, creating favourable conditions for establishment of previously inhibited plant species. Low bulk density has been reported to be a key determinant of vegetation development on mine wastes (Wali, 1999; Borden and Black, 2005; Wang *et al.*, 2018).

Dynamics in organic matter can also account for the observed vegetation trends. Temporal improvement in OM as observed in a related study (Chapter 3) might have reduced compaction of the substrate and improved soil hydrology by retaining moisture. Further, the O.M input from the turnover of early succession pioneer plants may help to stabilize the tailings surface and allow for improved wind-borne sediment and seed interception (Bradshaw, 2000). The subsequent decomposition and mineralization of deposited organic matter promotes development of microbial communities that in turn promote plant establishment and growth due to their positive effects on soil structure and nutrient cycling (Shrestha and Lal, 2006). At early stages of vegetation colonization, O.M is known to be correlated to biological crust (BC) cover that in turn may enhance nutrient cycling with a net positive effect on vegetation

establishment. In a related study (Chapter 5), BC cover was observed to significantly increase with tailings dump age and that BC cover was positively correlated to vegetation cover, species richness and herbaceous plant densities on 10-82 –year- old dumps (Chapter 5; Nyenda *et al.*, 2019b). In another related study (Nyenda *et al.*, 2019a) areas of high BC cover were noted to have higher total N, OC due to their N and C fixation capability (Nyenda *et al.*, 2019a; Chapter 4).

However, the higher vegetation structural attributes on lower slopes can be attributable to complementary effects of dump age and topography on substrate nutrient and hydraulic properties. As observed in a related study (Chapter 3) lower slopes are the oldest part of the dump and were observed to be more fertile (higher N and P) owing to more established pedogenetic processes (Chapter 3). Such portions of the dump may be sinks to nutrients and seeds washed from higher positions resulting in enhanced vegetation growth and higher species richness. Lower slopes also receive leached water as tailings drain and which in turn could have promoted establishment and growth of ferns such as *Blechnum tabulare* that had higher covers on such positions. The higher species richness on the lower slopes is also likely to be due to their proximity to the reference sites that eases dispersal of seeds and spread of rhizomes from the adjacent reference site. Results are consistent with some findings by Young *et al.*, (2012) who noted colonization of gold tailings to start from margins connected to reference sites. The higher vegetation richness on flat tops of younger dumps than relatively older upper slopes suggest the effect of topography. Flat tops are less susceptible to erosion hence may retain dispersed seeds which will germinate and establish while on upper slopes, these are eroded to lower positions.

However, despite the increasing trend in many structural attributes, attainment of similar values of vegetation attributes on these dump pairs; (10 and 17 years) and (82 and 92 years) suggests the vegetation changes are gradual and that 10 years may be a minimum time for significant changes in vegetation attributes to be noted on gold tailings. This is a new insight into the rate and direction of plant structural changes on unique metalliferous sites such as gold tailings.

Overall, the vegetation parameters approached the reference conditions but remained largely below them coinciding with trends observed for substrate factors in a related study (Chapter 3). The results partly concur and are inconsistent with findings from other studies. First, the observed temporal increase in vegetation cover that exceeded reference covers in adjacent reference sites at 92-110 years is consistent with findings by (Pietrzykowski, 2008). The results are to a large extent inconsistent with results obtained at other mine sites (Skousen *et al.*, 1988; 1994), where vegetation cover increased with mine site age but shorter periods (25 years) were required to attain peak herbaceous covers, which also unlike in the present study declined without reaching reference levels. The discrepancy could be due to differences in the substrates between the sites. In the present study herbaceous cover increased continuously up to 110 years and exceeded the natural reference values beyond 82 years. These differences might be because in the Skousen *et al* cases, the mined sites were relatively natural soils and not tailings which

had more woody species that suppressed herbaceous species, unlike the present study which had very few woody species on the tailings. Consistently, this study observed suppressed herbaceous cover at Ref- 2 km which had higher tree densities observed and further confirms the suppressive effects of tree species on understory vegetation, with possible thresholds that could not be ascertained in the current study.

#### 6.4.2 Mechanisms driving trends for key plant species

Overall, the observed absence of many pioneer species on the oldest dumps (late succession and very late succession stages) suggest the dominance of the floristic relay model when compared to the initial floristic composition model. Results appear to show that pioneers establish by tolerance, followed by successive facilitation, coexistence among species and lastly competitive exclusion in the late succession stage. However, the patchy existence of pioneer species such as *Flaveria trinervia*, *Cynodon dactylon* and *Phragmites australis* on young dumps can be attributed to their tolerance to extreme pH, saline and low-nutrient environments. Piha *et al* (1995a) observed that *Cynodon dactylon* is tolerant to saline and nutrient stressful environments such as coal spoils and mine tailings. Similarly, Pelralta (2000) classified *Flaveria* species as salt-tolerant. Alternatively, dispersal capability related to the traits of these species may account for the early presence of these species on dumps (Chan and Turner, 2019). The three species produce very light small seeds that are easily dispersed and may be the mechanism that contributed to the temporal increase in vegetation cover (Van Outshdoom, 2014). The rhizomatous strategy might have also assisted the spread of some pioneer species. *Cynodon dactylon* and *Phragmites australis* spread through rhizomes where the main plants feed the tillers even under nutrient stress (Shu *et al.*, 2005), contributing to the observed increases in cover and stem densities. Over time, these pioneer species could have facilitated the establishment of less tolerant species through creation of micro-sites with improved fertility and reduced compaction (Chapter 3), better moisture retention, capable of trapping seeds and nutrients. Such micro-conditions could have promoted the establishment of other species that contributed to the observed increase in cover and species richness. According to Game *et al.*, (1982), pioneer plants on mine sites in Missouri and Texas grew in patches that gradually enlarged, coalesced and covered the surface as micro-conditions improve. This may be the mode by which cover of pioneer plant species increased in the present study.

However, the decline in overall species richness after 92 years following a steady increase could be due to competitive exclusion by late succession species such as *Imperata cylindrica* and *D. amplexans* which increased in cover and importance values while early succession species like *Flaveria trinervia* and *Polygala albida* disappeared. This competitive exclusion is again related to species traits. For instance, *Imperata cylindrica* spreads by both seeds and rhizomes outcompeting other species (Van Outshdoom,

2014). *D. amplexans* and *H. filipendula* attain heights that can suppress shorter species (Van Outshoorn, 2014). Further, the contrasting trends in species richness for forbs, ferns, grasses and woody species mainly beyond 92 years suggest that trajectories of plant succession are functional type-specific. Forbs and ferns appeared to be easily suppressable by perennial plants such as *Imperata cylindrica* that dominated the older dumps hence the decline in richness after 92 years. This may also account for the observed late-succession decline in species diversity. Nevertheless, the results suggest more than 110 years are required to attain herbaceous richness of reference sites. The dumps, though improving, still had physicochemical limitations to support certain species that were noted in reference sites only.

### 6.4.3 Trajectory of plant community composition

The grouping of the six sites of different ages based on plant community composition into three groups indicates development of varying vegetation communities in a succession is gradual. The clustering of the oldest dumps along with the adjacent reference site (Ref-200 m) in the direction of the further away reference site on the nMDS and PCA ordination plots (Fig 6.5) dispels the theory on divergency towards a novel ecosystem. Instead, results appear to suggest that plant communities on tailings gradually develop towards adjacent references but within the 110 years remain significantly different from the distant natural reference sites .

The first part of the succession represented by 10 and 17-year-old dumps had plant communities dominated by pioneer species such as *Flaveria trinervia*, *Phragmites australis* and *Cynodon dactylon* that are either tolerant or are capable of adapting to hostile conditions such as low fertility, extreme pH and high bulk density , forming communities clearly dissimilar to reference sites. The second successional phase (30 years) was characterized by plant communities dissimilar to the first succession phase but moving in the direction of the reference sites. This phase had both: (1) pioneer species that were increasing in frequencies most probably due improved substrate properties and, (2) mid -succession species such as *Imperata cylindrica*, *Polygala albida*, *Andropogon chinensis* and *Schizachyrium platyphyllum* and other other forb and graminoid species that could have been facilitated by pioneer species. This phase could have been driven by the co-existence of pioneer species and those coming from reference sites as the the main biogenic mechanism shaping plant communities at this stage. The third successional phase consisted a plant community that was similar to the adjacent reference site and was characterized by species that emerged in the second succession stage and probably through rhizomatous and other strategies competitively excluded a number of pioneer species. Results therefore suggest the dominance by a few species from the adjacent reference site e.g. *H.filipendula* resulted in exclusion of pioneer species.

The absence or sharp decline of most pioneer species on the oldest dumps dismisses the 'Initial composition hypothesis and appear to confirm the Floristic relay theory as key succession mechanisms at play. This further suggests vegetation development may not be towards a novel ecosystem, rather gradually move towards reference conditions. However, the contrasting steady increase in a single species (*D. amplexans*) over time suggests the trajectory could be taxa-specific. This brings in a new insight into the need to consider the taxa context in generating or applying general revegetation theories. The occurrence of many new species in the mid-succession stage (30 years) suggests the importance of the facilitation model in shaping vegetation communities on mine tailings. The sharp decline in new species and their covers in the late succession (oldest dump) demonstrate the importance of dominance and competitive exclusion in shaping plant communities at this stage. The models that seemed at play are: (1) the tolerance model in the early succession (Gleason, 1976) and, (2) relay floristic ( facilitation ) model (Clements, 1916) in the mid and late succession phase. The results are consistent with findings from a related study at Gunnar mine where colonization was initially by woody and herbaceous species which were eventually succeeded by climax species (Shu *et al.*, 2005).

However, regardless of trajectory and succession stage, plant communities on the gold tailings were dominated by species belonging to the Poaceae (Graminae), Asteraceae and Compositae families suggesting their high dispersal capacity and tolerance to unique substrates. Most Asteraceae and Compositae species have small and wind-borne seeds, but Asteraceae species were lower than Poaceae species at all the sites. This suggests that Poaceae (Gramineae) plants have higher tolerance to the hostile substrate conditions such as fluctuating pH, soluble salts and low nutrients than Asteraceae and other families. Also a number of colonizing species used the rhizomatous strategy e.g. *P. australis*, *Cynodon dactylon* and *Imperata cylindrica*.

However, the similarity of dump communities with adjacent references could on one hand show progression to references while on the other end, this may indicate the influence of the dumps to nearby communities. Erosion of mine tailings, leaching of salts and metals may be altering the physicochemical properties of the adjacent soils into tailings-like properties (Chapter 3, Table S6.3). This in turn may have promoted the proliferation of adaptive species such as *Equisetum ramosusimum* and *Imperata cylidrica* just like on mine tailings.

Overall, the study results therefore do not fully support the hypothesis that the trajectory of natural vegetation recovery on gold tailings is towards a novel ecosystem. The study however brings in new insights: (1) the natural potential of unique anthropogenic substrates to support a trajectory towards plant ecosystem restoration contrary to wide pessimism in literature, (2) trajectories for vegetation structural and compositional attributes may differ in time frames hence the need to consider such facts in



developing revegetation theories and, (3) the need to consider potential influence of mine tailings to the adjacent references which may distort interpretation of revegetation trajectories both in direction and time.

## **6.5 Conclusion and recommendation**

The study concluded that structural and compositional attributes move towards reference conditions although structural attributes take shorter periods. The results do not support the hypothesis that the tailings revegetation follows a divergent trajectory towards formation of novel plant ecosystems. In particular, the results supported the hypotheses that vegetation cover and species richness increase with tailings age but observed that species richness takes time to reach undisturbed reference level. It was however noted that within 100 years tailings vegetation communities may be similar to adjacent references most probably due to the proximity to sources of propagules for tailings colonization. The study did not support the hypothesis that stressed pioneer species persist to late succession phases through coexistence with mid and late succession plants and embraced the “floristic relay theory” of species succession as most pioneer species were absent or had significantly low covers on late succession dumps. The vegetation changes were mainly correlated to changes in substrate pH, available P, EC, OM, bulk density and total N. The results may be limited though with the length of the chronosequence. The study recommends replication of similar studies with different mine tailings substrate and across many sites resembling longer chronosequences. Further, this chapter focused on unrehabilitated sites, but the novel ecosystem concept need to be also tested on rehabilitated sites (Chapter 8).

## CHAPTER 7

### HOW DOES FLORISTIC COMPOSITION AND STRUCTURE ON GOLD MINE TAILINGS VARY ALONG A CLIMATIC GRADIENT?

#### Abstract

Studies that investigate variation of plant species composition and structure on mine tailings along a climatic gradient are limited. The current study investigated variation of floristic composition and structure on gold tailings along a climatic gradient in savanna Zimbabwe. The investigation was done on 14 mine sites grouped into 4 climatic groups using total annual rainfall as a proxy of climate: 432-432 mm, 546-559 mm, 644-760 mm and 816-874 mm. The objectives of the study were: (1) to determine the variation of plant species richness of various functional types along a climatic gradient, (2) to assess the interactive effect of rainfall and substrate age on plant structural attributes, and, (3) to determine plant taxa assemblages and their variation along a climatic gradient. Plants growing on tailings dumps situated along a climatic gradient were identified to species level. Data were subjected to two-way analysis of variance and ordination analysis. The tailings were colonized by 141 plant species (53 forbs, 47 grasses and 41 woody species). Overall plant, forbs and gramminoid species richness significantly ( $p < 0.05$ ) increased with rainfall, while woody species richness did not. Annuals were more frequent in drier regions while perennials did not vary significantly along a rainfall gradient. Species richness significantly increased with tailings age, but the interactive effect of tailings age and rainfall was not significant. Dominant species in terms of frequency were gramminoids. Dominant families were *Poaceae*, *Asteraceae*, and *Fabaceae*. Only 19 of the 42 most frequent (> 45%) species occurred in all the four climatic regions suggesting their tolerance to substrate characteristics and a range of climatic conditions. Contrary to the study hypothesis, principal component analysis (PCA) showed overlap of plant assemblages across rainfall regions. The study concluded that the effect of rainfall gradients on vegetation was taxa, growth form and life cycle-specific. Effect of rainfall gradient on plant structural and compositional attributes vary. Results also suggest tailings age may be influencing composition more than rainfall due to the possible improvement in fertility and reduced chemical toxicity. Enhanced species richness with rainfall increase is most probably due to enhanced microbial activity and nutrient cycling under higher substrate moisture.

**Keywords:** Forbs, Gold mine Tailings, gramminoids, Plant community assemblages, principal component analysis, Rainfall gradient, species richness

## 7.1 Introduction

Mining and subsequent mineral processing are associated with a number of adverse environmental impacts such as air, surface and ground water pollution, and loss of biodiversity mainly due to tailings disposal (Duruibe *et al.*, 2007; Mendez and Maier, 2008). The tailings are ecological islands deposited in heaps on pristine land (Umba, 2014). These heaps of freshly exposed geological material pose adverse physical and chemical constraints to plant establishment (Shu *et al.*, 2005). The main chemical constraints associated with mine tailings are low levels of N and P (Shu *et al.*, 2005), adverse pH, and high levels of bioavailable metals, particularly Fe, Zn, Mn and As (Wild, 1974; Zaranyika and Chirinda, 2011). Main physical constraints are high compaction, low water holding capacity, steep slopes and salinity (Weiersbye *et al.*, 2006). Tailings thus often remain devoid of vegetation for long periods, subjecting human communities to water and air pollution. Active reclamation therefore has been proposed as a solution to facilitate revegetation on such substrates (Piha *et al.*, 1995a; Mendez and Maier, 2008). The reclamation efforts are however, likely to be hampered by lack of universal understanding of specific determinants of natural recovery of vegetation on these unique anthropogenic substrates particularly in light of varying and changing climatic conditions.

Globally, most studies on vegetation of mine tailings focused on single sites (Alday *et al.*, 2011; Young *et al.*, 2013; Ahirwal *et al.*, 2017; Festin *et al.*, 2018) or at several sites in similar climatic regions (Shu *et al.*, 2005; Weiersbye *et al.*, 2006). In Zimbabwe past studies focused on early stages of reclamation on tailings (Hill, 1977; Piha *et al.*, 1995; Mulizane *et al.*, 2005; Nyakudya *et al.*, 2011; Dowo *et al.*, 2013; Mukaro *et al.*, 2017). Such studies mainly reported that survival and growth of plants are influenced by substrate characteristics such as N, P, metals and pH. A few chronosequence studies reported substrate age dependent vegetation structural and compositional attributes (Maharana and Patel, 2014; Chaturvedi and Singh, 2017; Mukaro *et al.*, 2017). Despite the existence of several studies on natural and assisted vegetation on mine tailings, plant taxa capable of naturally establishing on gold tailings have not been widely documented. Exceptions are (Weiersbye *et al.*, 2006; Weiersbye and Witkowski, 2009; Rossouw, 2009; Young *et al.*, 2013; Young *et al.*, 2015; Stewart and Siciliano, 2015; Schimmer, 2018; Tardiff *et al.*, 2019) and more recently, (Nyenda *et al.*, 2019b, Chapters 5 and 6) who also observed that floristic composition dependent on substrate age and type. While the studies have given invaluable insights, their major drawback is their lack of inclusion of effects of climatic gradients on vegetation occurrence patterns. Therefore, empirical studies that investigate variation of vegetation on mine tailings along a climatic gradient are limited yet very important.

Ecosystem development has been reported to be influenced by climate (Hobbs and Harris, 2005; Rajakaruna, 2014) and substrate age (Maharana and Patel, 2014; Chapters 5 and 6). Many studies on vegetation and climate relationships have been done on natural arid and semi-arid environments

throughout the world (Venter and Getenbach, 1986; Scholes *et al.*, 2002; Cornwell and Grubb, 2003; Adler *et al.*, 2005; Hobbs and Harris, 2005; Davidar *et al.*, 2007; Giladi *et al.*, 2011; Adler and Levine, 2013; Rajakaruna *et al.*, 2014; Bocksberger *et al.*, 2016). Key findings from such studies were: (1) a positive relationship between species richness and rainfall e.g. one species per m<sup>2</sup> per every 100 mm change in rainfall particularly in grasslands (Cornwell and Grubb, 2003; Adler *et al.*, 2005; Adler and Levine, 2013; Bocksberger *et al.*, 2016) which is often a result of indirect effects of rainfall on a range of biotic and abiotic variables, and (2) significant differences in plant species composition in areas of contrasting rainfall (Scholes *et al.*, 2002). However, a few exceptions done on artificial substrate seem to also suggest edaphic factors related to time and pedogenesis are the key determinants of plant communities on tailings (Weiersbye *et al.*, 2006; Nyenda *et al.*, 2019b, Chapters 5, 6 and 8).

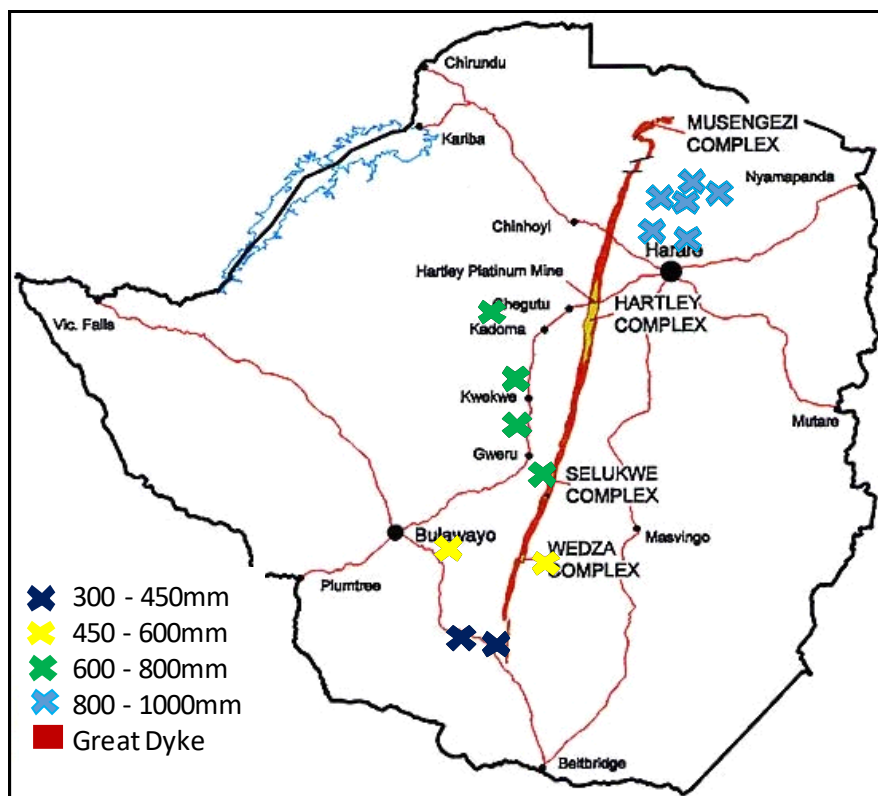
Despite the reported relationships between rainfall and vegetation on natural soils, it still remains unknown if this is true for unique substrate such as mine tailings. While substrate age and rainfall have been reported to independently influence plant attributes, their interactive effect has never been widely tested on artificial and unique substrates such as mine tailings. To the best of my knowledge, no study on variation of vegetation structural and compositional attributes on tailings substrate along a climatic gradient was done. This therefore means generalizations about responses of plants to climatic and other environmental gradients remains difficult. Comparing plant communities developing across climatic gradients may yield valuable outcomes in the face of global demands for mine site rehabilitation. In light of the present climate change, assessing the role of climatic gradients in shaping plant communities is therefore crucial. Since plant species composition and functional traits are key in maintaining ecological net primary production under different conditions, (Tilman, 1999), predicting the effects of climatic variations in ecosystems requires understanding how plant community structure and functional traits exist along environmental gradients such as rainfall (Baez *et al.*, 2013). The Zimbabwe's Great Dyke region presents an opportunity for the study of climate-vegetation relationships as it has several abandoned mine tailings situated along a rainfall gradient ranging from 300– 1000 mm. In this study rainfall was used as a proxy for climate.

The study aimed to identify and classify plant taxa naturally colonizing gold tailings and their variation along a rainfall gradient. Specific objectives of the study were; (1) to determine the variation of plant species richness of various functional types along a rainfall gradient, (2) To assess the interactive effect of rainfall and substrate age on plant structural attributes, and, (3) to determine plant taxa assemblages and their variation along a climatic gradient. The study hypothesized that plant composition and structure varied significantly along a climatic gradient and that the interactive effect of climate and substrate age on vegetation was significant.

## 7.2 Materials and methods.

### 7.2.1 Description of study sites

A total of 53 gold tailings from 14 mine sites situated along a climatic gradient in Zimbabwe were selected (Figure 7.1, Table 7.1). The mines were situated in four climatic regions with total annual rainfall ranging from 300-450 mm for the lowest to between 800 and 1000 mm for the highest (Table 7.1). The climatic clusters of sites based on rainfall are: (1) Sites receiving annual rainfall between 300- 450 mm (West Nicolson and Vumbachikwe), (2) sites receiving 450-600 mm (How Mine and Sabi), (3) sites receiving 600-800 mm (Kwekwe, Connemara, Shurugwi and Chakari) and (4) Sites receiving 800-1000 mm (Freda, Phoenix, Ran, Shamva, Mazowe, and Acturus). All dumps had similar designs with flat tops and four slopes facing all four major compass directions.



**Figure 7.1:** Map showing location of gold tailings sites along a rainfall gradient in the great Dyke Region of Zimbabwe. Crosses (X) denote location of sampled sites and colour denote climatic region.

**Table 7.1:** Description of the gold tailings sampled for this study, including the geology, average annual rainfall received from 1980- 2017, estimated age of the dumps. S in geology denotes Shamvaian while B denotes Bulawayo metasediments.

Site	Geology	Rainfall range (mm)	Average Rainfall (mm)	No. of dumps	Approx. Ages (Years)
Vumbachikwe	S&B Meta	300-450	432	8	>60
West Nicholson	S&B Meta	300-450	432	3	>60
Sabi	S&B Meta	450-600	546	3	0, 28, 50
How Mine	S&B Meta	450-600	559	3	0, 28, 60
Chakari	S&B Meta	600-800	760	4	0, >100
Connemara	S&B Meta	600-800	644	3	>60
Kwekwe	S&B Meta	600-800	644	3	>50
Shurugwi	S&B Meta	600-800	676	3	>50
Freda	S&B Meta	800-1000	879	6	0,6,16,26;28,35
Phoenix	S&B Meta	800-1000	879	3	80,90,110
Ran Mine	S&B Meta	800-1000	879	4	50, 60, 100
Shamva	S&B Meta	800-1000	816	5	0, 15, 80, 120
Acturus	S&B Meta	800-1000	847	3	0, 30, 50
Mazowe	S&B Meta	800-1000	824	2	0, 50

\*Rainfall data in fourth column was obtained from Zimbabwe Meteorological Services department. Dump ages obtained from mine records and key informants.

The geology of the study sites generally belongs to metasediments, specifically serpentine and metamorphic rocks of the basement schists belonging to the Shamvaian, Bulawayan and Sebakwian group (Table 7.1; BGS, 2015). The gold ore for the study mines generally consists of pyrite ( $\text{FeS}_2$ ), pyrrhotite ( $\text{FeO}_8\text{S}$ ), arsenopyrite ( $\text{FeAsS}$ ), chalcopyrite ( $\text{CuFeS}_2$ ), bornite ( $\text{Cu}_6\text{FeS}_4$ ) and pyrolucite ( $\text{MnO}_2$ ) as minors. The sites in natural region 2 (Freda, Phoenix Prince and Ran, Shamva, Mazowe and Acturus tailings are surrounded by red clay soils of the fersiallitic group, with a few patches of fine sands to clayey loamy soils. Soils of the region 3 sites (Kwekwe and Shurugwi) are clay-loamy of the fersiallitic group of the Kaolinitic order. The region 4 (Sabi and How mine), region 5 (Vumbachikwe and West Nicolson) sites are surrounded by loamy soils and some patches of weakly sodic soils belonging to the sodic group of the Natric order (Nyamapfene, 1999).

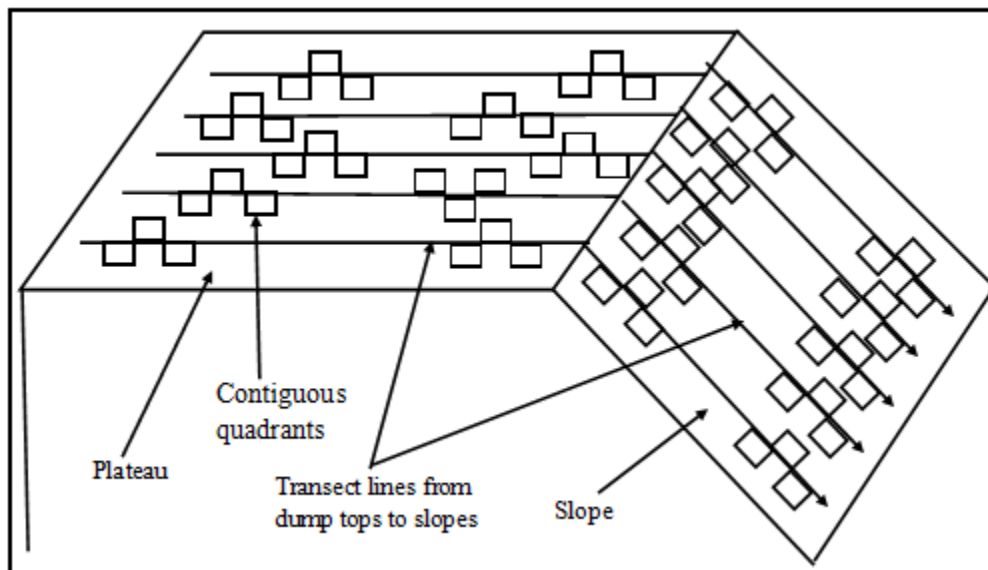
In terms of vegetation, sites in regions 2 and 3 are surrounded by Miombo woodlands with low catena positions dominated by *Senegalia polyacantha*. Sites in regions 4 and 5 are dominated by mixed

woodlands with *Combretaceae* and *Colophospermum mopane*, *Vachellia* and *Senegalia* patches forming dominant stands.

### 7.2.2 Experimental set up

Overall, 14 sites were selected on the basis of the following criteria in order of importance (1) site is a gold mine with unrehabilitated or very minimally rehabilitated tailings, (2) Site has abandoned tailings below the age of 50 and/ or some above 50 years where possible, (3) site receives annual rainfall in any one of the four rainfall regions described in Table 7.1.

At each site in each climatic cluster, tailings dumps were classified into two- age classes namely; young (<50 years) and old (> 50 years) in accordance to information provided by key informants. This yielded a design with rainfall received and substrate age as experimental factors. Line transects, in conjunction with the quadrat method were then used to determine floristic composition (Walker *et al.*, 1987, Young *et al.*, 2012). In particular, six line transects were laid at 10-30 m intervals, running from the dump tops down the slopes on each tailings dump (total n= 318), to capture variability presented by topographic gradients (Young *et al.*, 2012). Contiguous 1 m<sup>2</sup> quadrats were laid along each transect and used to sample any plant species encountered (Fig 7.2).



**Figure 7.2:** Schematic diagram showing layout of transects and contiguous quadrats on each tailings dump.

### 7.2.3 Assessment and classification of vegetation.

All plants encountered in each quadrat were identified to species level using a field guide (Van Outshodrom, 2014) and their frequency on each dump and overall site noted. Plant taxa not positively identified in the field had a whole plant pressed and later identified at the National Herbarium in Harare. Frequency of occurrence was calculated as in equation 1:

$$\text{Frequency} = \frac{n}{N} \times 100 \dots\dots\dots (1),$$

where *n* is the number of quadrats in which a species occurred and *N* is the total number of quadrats surveyed.

For complete determination of species richness, the researcher randomly walked across the dump tops and slopes, outside the established transects, and identified additional species encountered without noting their frequencies. These species were used on species composition list but were not included in the statistical data analysis.

All plant species encountered along the transects were classified into three growth forms: (1) woody, (2) forbs, and (3) grasses, and two life cycle categories (annuals and perennials). Their frequency of occurrence were noted for each dump. All individual species in each growth form category were further classified by photosynthetic pathway (i.e. C3 and C4) in accordance to literature (e.g. [www.flora of Zimbabwe.com](http://www.floraofzimbabwe.com)). Frequency of occurrence was used to classify plant species into three categories namely; (1) dominant (frequency ≥ 50%), (2) occasional (frequency = 10-49%) and (3) rare (frequency < 10% (Walker, 1999.)

### 7.2.4 Data Analysis

To test the effect of climate and age on species richness for all plant categories, a two- way ANOVA was performed at 95 % level of significance. This test was preceded by testing data for normality using the Kolmogorov-Smirnov Test in SPSS version 21. Data that were not normal were log-transformed before analysis of variance was carried out. Pair- wise comparison was done using a post-hoc Least squares difference (LSD) test (Mckillup, 2012). To test the relationship between plant species richness for all growth forms, rainfall and age of substrate, a spearman correlation analysis was performed in SPSS version 21. An unconstrained linear ordination technique, principal component analysis (PCA) was used to test the variation of plant species composition along a rainfall gradient using species frequency data in Canoco version 5. The linear method was used since the data gradient length was 2.5 (Ter Braak, 1994; Lepš and Šmilauer, 2003). For this technique, analysis was done employing four axes while a plot of



samples was constructed using two main axes. The analysis was done using both absolute frequencies of each species per site and by down-weighting rare species (rare species as determined by the analysis software). In order to determine species-sites relationships, a PCA bi-plot showing samples and species was computed and species associated with particular regions were noted. In order to determine the correlation between environmental variables (rainfall and tailings age) and vegetation structural attributes a canonical correspondence analysis (CCA) was carried out.

## 7.3 Results

### 7.3.1 Plant species richness along a rainfall gradient

Two-way ANOVA showed that total species richness, graminoid and forbs richness significantly increased with rainfall increase while woody species richness was not significantly affected by climatic gradients (Table 7.2, Table 7.3). In particular, woody species richness was highest in the moderate rainfall region (600-800 mm) followed by the 800-100 mm, then 300-450 mm and lastly 450-600 mm. Total, grass and woody species richness at the various mine sites significantly increased with dump age (Tables 7.2, Table 7.3). The interactive effect of rainfall and tailings dump age on species richness was insignificant (Table 7.2). However, for all growth forms, the wettest region had significantly higher species richness than the other regions except for woody species (Table 7.2; Table S7.1). In most cases, species richness was statistically similar for either the two wettest regions (600-800 and 800-1000 mm) or driest regions (300- 450 and 450-600 mm). A spearman correlation analysis showed a strong positive correlation between rainfall and overall herbaceous species richness ( $r > 0.85$ ,  $p < 0.001$ ) while age had no significant relationships with herbaceous species richness ( $r < 0.5$ ;  $p > 0.05$ ; Fig 7.3). Overall, dump age had a positive correlation with woody species richness and a negative correlation with forb species richness (Fig 7.3).

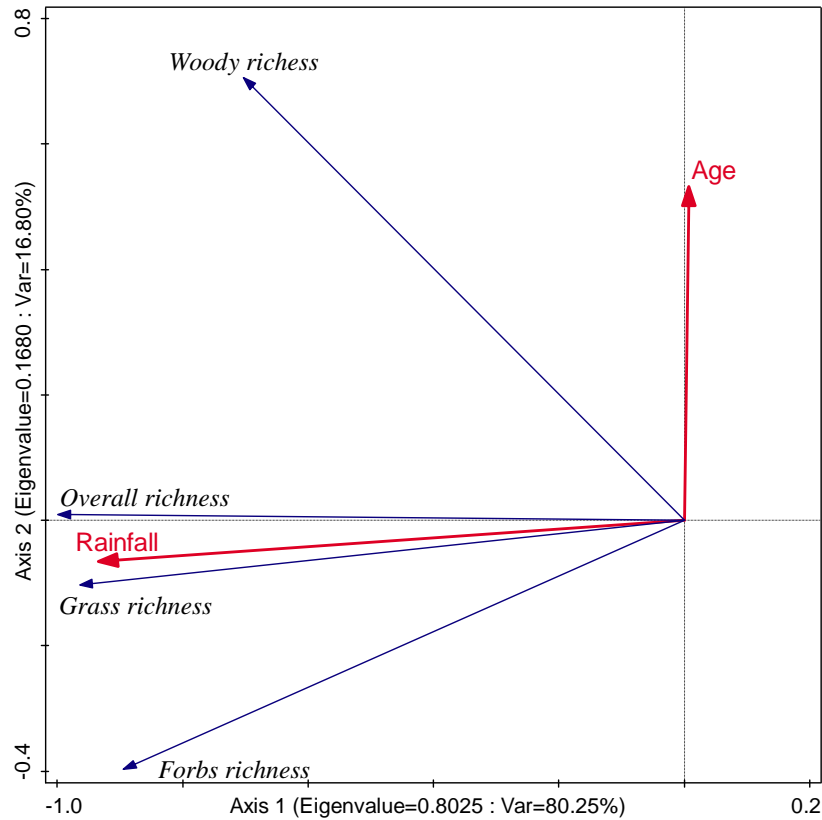
In terms of measured life cycle attributes, drier regions (300-450 mm and 450-600 mm) had higher annual species richness than wetter regions (650 -800 mm and 800-1000 mm) while perennial species richness was similar across the sites (Table 7.3; Table S7.2). However, in all regions perennial species richness was significantly higher than annual species richness (Table 7.3). Highest annual and perennial species were observed in regions 4 (rainfall =450-600 mm) and 3 (rainfall = 600-800 mm) respectively (Table 7.3).

**Table 7.2:** Two way-ANOVA results for the effect of rainfall and dump age on species richness

Variable		Total richness	Forbs	Grass	Woody
Rainfall	F-value	333.7	39.7	50.3	6.3
	p-value	0.000	0.006	0.004	0.079
Dump Age	F-value	84.9	17.6	0.5	4.5
	p-value	0.003	0.025	0.541	0.124
Age*Rainfall	F-value	117.8	115.6	149.4	0.4
	p-value	0.068	0.068	0.060	0.800

**Table 7.3:** Mean number of species per growth form and life cycle on gold tailings along a rainfall and an age gradient (values are mean± standard deviation). All tests performed were two- way ANOVA at 95 % level of significance. Superscripts in lower cases compare total richness across rainfall regions; Superscripts in upper case compare richness on young and old tailings in same column; different superscripts denote significant differences.

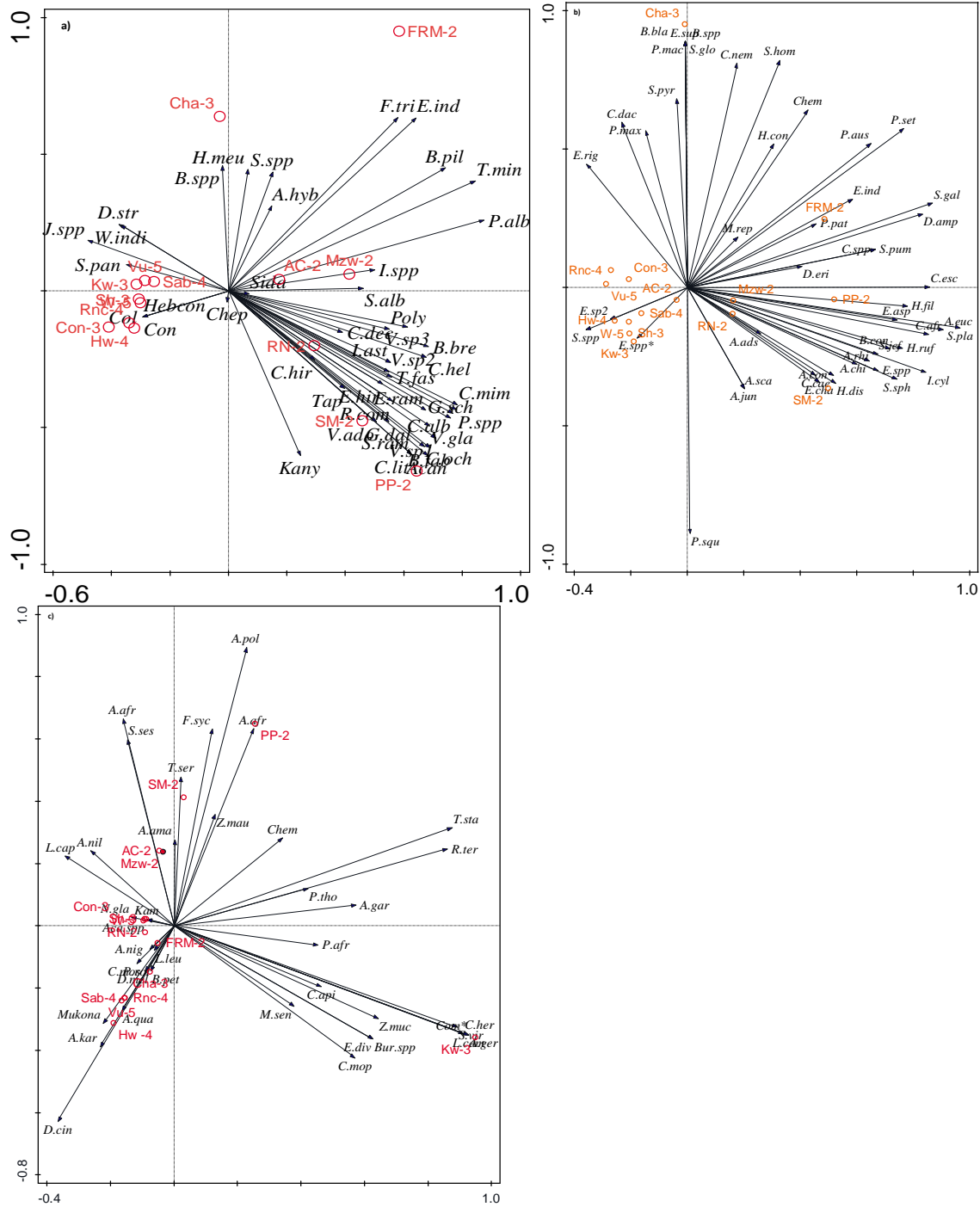
		Species richness	300-450 mm N=2	450-600 mm N=2	600-800 mm N=4	800-1000 mm N=6
<b>Growth form</b>	Overall	Total	23.0±1.4 <sup>a</sup>	31.7±7.6 <sup>bc</sup>	48.5±17.8 <sup>cd</sup>	77.0±11.7 <sup>d</sup>
		<50 years	22.1±4.6 <sup>A</sup>	20.3±6.0 <sup>A</sup>	20.3±12.6 <sup>A</sup>	22.1±3.6 <sup>A</sup>
		>50 years	24.0±5.1 <sup>A</sup>	29.2±4.1 <sup>B</sup>	42.4±9.5 <sup>B</sup>	70.0±12.2 <sup>B</sup>
	Grasses	Total	7.5±2.1 <sup>a</sup>	11.7±4.6 <sup>bc</sup>	15.5±4.5 <sup>cd</sup>	30.8±3.3 <sup>d</sup>
		<50 years	9.2±2.4 <sup>A</sup>	12.1±2.4 <sup>A</sup>	15.0±3.3 <sup>A</sup>	11.4±2.2 <sup>A</sup>
		>50 years	6.3±2.3 <sup>A</sup>	17.6±4.3 <sup>B</sup>	13.2±3.6 <sup>A</sup>	33.6±4.2 <sup>B</sup>
	Forbs	Total	1.4±1.0 <sup>a</sup>	3.7±1.6 <sup>bd</sup>	8.6±4.0 <sup>bc</sup>	33.0±5.7 <sup>bd</sup>
		<50 years	7.0±1.9 <sup>A</sup>	8.3±1.4 <sup>A</sup>	10.3±2.0 <sup>A</sup>	9.2±2.4 <sup>A</sup>
		>50 years	9.2±2.3 <sup>A</sup>	8.9±2.0 <sup>A</sup>	8.3±3.2 <sup>A</sup>	31.3±5.6 <sup>B</sup>
Woody	Total	7.0±2.8 <sup>a</sup>	4.7±1.2 <sup>a</sup>	18.3±7.4 <sup>b</sup>	12.7±3.8 <sup>ab</sup>	
	<50 years	5.1±1.2 <sup>A</sup>	4.0±1.1 <sup>A</sup>	15.2±4.5 <sup>A</sup>	2.5±0.6 <sup>A</sup>	
	>50 years	9.0±1.5 <sup>B</sup>	4.6±1.3 <sup>A</sup>	21.2±7.1 <sup>B</sup>	6.3±0.9 <sup>B</sup>	
<b>Life cycle</b>	Annuals	9.4± 1.7 <sup>a</sup>	13.1± 0.6 <sup>b</sup>	3.6 ± 3.6 <sup>a</sup>	6.2 ± 0.5 <sup>a</sup>	
	Perennials	90.6±1.7 <sup>ac</sup>	86.9 ± 0.6 <sup>a</sup>	96.4 ± 3.6 <sup>bc</sup>	88.9 ± 0.6 <sup>a</sup>	



**Figure 7.3** : A CCA ordination monoplot showing correlation among rainfall, age and plant species richness on abandoned gold mine tailings.

### 7.3.2 Plant community assemblages along a rainfall gradient.

Most forb and grass species were positively correlated and had higher relative frequencies in high rainfall (800-1000 mm) areas (Fig 7.4a and b). Woody species were not clearly correlated to rainfall (Fig 7.4c). In terms of comparisons of sites based on forb and grass species assemblages, a PCA yielded two distinct groups from the 14 mine sites (Fig 7.4a and b). A cluster of all high rainfall sites (total annual rainfall =800-1000 mm) was distinct while sites from the other rainfall regions (3, 4 and 5: rainfall range 300-800 mm) formed the second cluster while a contrasting pattern was observed for woody species where no distinct differences were observed (Fig 7.4c).



**Figure 7.4:** Plant species assemblages and correlation across a rainfall gradient (red are sites, angle between species indicate degree of similarity). (a) Forbs (b) Grasses (c) woody species: (Suffix (total annual rainfall codes, 2= 800-1000 mm; 3=600-800 mm; 4= 450-600 mm; 5= 300-450 mm) in savanna Zimbabwe. Site codes: Chakari (Cha), Acturus(AC), Shamva (SM), Ran Mine (RN), Freda Rebecca Mine (FRM), Mazowe (Mzw), Phoenix Prince (PP), Kwekwe (Kw), Connemara (Con), Shurugwi (Shu), Sabi (sab), How Mine (Hw); Vumbachikwe (Vu); West Nicholson (W). Full names of species in Table S7.3.

### 7.3.3 Occurrence of dominant plant species along a rainfall gradient

Forty-two (42) species occurred as occasional and /or dominant species in terms of frequency in at least one site (Table 7.5). Of these species, 9 were forbs, 20 graminoids and 13 woody species. In particular, some species, namely; *Schizachyrium platyphyllum*, *Schizachyrium jefreysii*, *Imperata cylindrica*, *Blumea brevipes*, *Penisetum setaceum*, *Polygala albida var albida*, members of the *Hyparrhenia* genera significantly increased in frequency with increase in rainfall. Some species such as *Dicrostachys cineria*, *Vachellia karoo* and *Cynodon dactylon* significantly decreased in frequency with rainfall increase. Some forbs (e.g. *Flaveria trinervia*, *Bidens pilosa* and *Tagetes minuta*), grasses (*Pogonathria squarrosa*, *Melinis repens*, *Aristida adscensionis*, *Andropogon chinensis* and *Heteropogon contortus*) woody species (*Rhus tenuinervis*, and *Lonchocarpus capassa*) had generally similar frequencies along the rainfall gradient.

**Table 7.4:** Frequency (%) of dominant plant species on gold tailings along a rainfall gradient. Rainfall values in table are mean annual rainfall for values computed using 37 year Meteorological services data (Zimbabwe Meteorological Services, 2018). A denotes annual life cycle while P denotes perennial life cycle.

<b>Species</b>	<b>Life Form</b>	<b>Photo Path</b>	<b>Life cycle</b>	<b>R 5 300-450 mm</b>	<b>R4 450-600 mm</b>	<b>R3 600-800 mm</b>	<b>R2 800-1000 mm</b>
<i>Flaveria trinervia</i>	Forb	C4	A	30	16.7	26.2	42.9
<i>Polygala albida</i>	Forb	C3	A	0	10	0	32.1
<i>Bidens pilosa</i>	Forb	C3	A	10	10	10	36.4
<i>Blumea brevipes</i>	Forb	C3	A/P	0	0	0	20.7
<i>Tagetes minuta</i>	Forb	C3	A	10	10	10	42.9
<i>Conyza albida</i>	Forb	C3	A/P	10	1.4	1.4	24.3
<i>Venonia glabra</i>	Forb	C3	P	0	10	10	15.7
<i>Ricinus communis</i>	Forb	C3	P	10	6.7	1.4	15.7
<i>Solanum spp.</i>	Forb	C3	A/P	10	1.4	1.4	12.9
<i>Imperata cylindrica</i>	Grass	C4	P	0	10	20	42.1
<i>Penisetum setaceum</i>	Grass	C4	P	0	23.3	10	46.4
<i>Andropogon chinensis</i>	Grass	C4	P	10	23.3	10	27.1
<i>Diheteropogon amplexans</i>	Grass	C4	P	0	0	3.3	30
<i>Setaria sphacelata</i>	Grass	C4	P	0	6.7	3.3	20
<i>Schizachyrium platyphyllum</i>	Grass	C4	A/P	0	0	0	45
<i>Schizachyrium jeffreysii</i>	Grass	C4	A/P	0	0	0	17.9
<i>Hyparrhenia filipendula</i>	Grass	C4	P	0	0	10	40
<i>Cynodon dactylon</i>	Grass	C4	P	75	30	23.3	36.4
<i>Melinis repens</i>	Grass	C4	P	30	6.7	20	30
<i>Eragrostis aspera</i>	Grass	C4	A	0	6.7	3.3	14.3
<i>Sporobolus pyramidalis</i>	Grass	C4	P	10	10	0	11.4
<i>Pogonathria squarrosa</i>	Grass	C4	P	10	10	10	8.6
<i>Heteropogon contortus</i>	Grass	C4	P	10	23.3	13.3	27.1
<i>Hyparrhenia rufa</i>	Grass	C4	P	0	0	6.7	21.4
<i>Aristida adscensionis</i>	Grass	C4	A	10	10	3.3	14.3
<i>Aristida congesta</i>	Grass	C4	A	0	3.3	0	14.3
<i>Bulbostylis contexta</i>	Grass	C4	P	0	0	0	20.7
<i>Cyperus esculentis</i>	Grass	C4	P	0	6.7	0	27.9
<i>Phragmites australis</i>	Grass	C3	P	0	0	3.3	25

<i>Acacia polyacantha</i>	Woody	C3	P	10	3.3	10	27.9
<i>Acacia karoo</i>	Woody	C3	P	30	16.7	6.7	12.9
<i>Terminalia sericea</i>	Woody	C3	P	0	0	3.3	19.3
<i>Vachelia nilotica</i>	Woody	C3	P	10	3.3	6.7	5.7
<i>Sesbania sesban</i>	Woody	C3	P	3.3	3.3	8.6	14.3
<i>Tecoma stans</i>	Woody	C3	P	0	0	13.3	12.9
<i>Rhus Trecuineris</i>	Woody	C3	P	5	0	13.3	11.4
<i>Venonia glabra</i>	Woody	C3	P	0	0	6.7	7.1
<i>Dichrostachys cineria</i>	Woody	C3	P	30	30	10	4.3
<i>Piliostigma thoningii</i>	Woody	C3	P	0	0	3.3	7.1
<i>Lonchorchopus cappasa</i>	Woody	C3	P	5	3.3	3.3	8.6
<i>Asparagus africanus</i>	Woody	C3	P	5	0	6.7	7.1

## 7.4 Discussion

The study had five key findings: (1) overall plant and herbaceous species richness significantly increased with rainfall increase while woody species richness did not show a distinct trend (Tables 7.2 and 7.3; Fig 7.4), (2) the interactive effect of age and rainfall on plant species composition and richness was insignificant but the individual effect of age was significant for grass and woody species only (Tables 7.2 and 6.3), (3) plant species richness on tailings along a climatic gradient was life cycle- dependent with drier regions (300-450 mm and 450-600 mm) having higher annual species richness than wetter regions (650 -800 mm and 800-1000 mm), (4) different species exhibited different trends in relation to climatic gradients with some increasing, decreasing and some similar and, (5) based on forb and grass species composition the 14 sites in four climatic clusters formed two major clusters while no distinct variation in species composition across a rainfall gradient was observed for woody species (Fig 7.4).

The significant increase of overall species richness with rainfall increase may be attributable to a number of factors. The positive relationship between rainfall and species richness could be as a result of indirect effects of rainfall on a range of biotic and abiotic substrate variables. High rainfall promotes the decomposition of litter through increased microbial activity and nutrient cycling. This in turn boosts soil fertility which in turn may facilitate plant establishment and can account for the various plant species observed on the tailings dumps. Higher rainfall also increases leaching of salts from the tailings surfaces which creates suitable sites for species colonization and subsequent establishment. High rainfall can also help in dispersing plant seeds through run off. This may have assisted the dispersal of forb and grass species which were higher on tailings in wetter regions. In addition, high rainfall also helps in translocation of soil nutrients and improve fertility on the tailings dumps which in turn promotes the establishment of

otherwise limited species. Higher rainfall promotes rapid growth of adaptable species which in turn through their increased cover can lower bulk density (substrate compaction), intercept nutrients and plant seeds. This therefore may account for the observed increase in grass and forb species richness with increase in rainfall. The observed trends in species richness are consistent with findings of a study in Central American grasslands where a net increase of one species per m<sup>2</sup> per every 100 mm change in rainfall was reported (Adler and Levine, 2006). A similar trend was reported in other central American grassland studies (Cornwell and Grubb, 2003; Adler and Levine, 2013; Bocksberger *et al.*, 2016) and in natural woodlands (Davidar *et al.*, 2007; Giladi *et al.*, 2011).

The other key finding was that different species exhibited different trends in relation to climatic gradients with some increasing, decreasing and some similar (Table 7.5). This differential existence of plant species on tailings across rainfall regions seem to be associated with known plant physiological tolerances to moisture regimes. For instance some species that increased with rainfall increase such as *Imperata cylindrica*, *Blumea brevipes* and *Cyperus esculentis* (Table 7.5) naturally require high moisture for their establishment (Van Outshodrom, 2014), hence their confinement to wetter regions (total annual rainfall-600-1000 mm). This therefore may also explain the higher herbaceous species richness in wetter regions than in drier regions. In addition, the decrease in frequency of some species with rainfall increase suggests their adaptation to lower moisture levels. For instance, *Sporobolus pyramidalis*, *Eragrostis* and *Cynodon* species are known to tolerate dehydration of foliage to the point of air dryness (Gaff, 1971; Gaff and Ellis, 1974). Moisture limitations of otherwise edaphically adaptable species may be therefore key in shaping plant compositional attributes on gold tailings. This may also explain the distinction between plant communities in particular the separation of sites in the wettest regions from the rest.

The grouping and separation patterns of the mine sites in four climatic clusters can be attributable to observed differential behaviour of individual species, plants in different growth forms and life cycle categories. First, the general clustering of the sites from different climatic regions may be attributable to a range of species that showed tolerance to wide rainfall variations by maintaining their frequencies across the rainfall gradient (Table 7.5). As observed, these include forbs (e.g. *Flaveria trinervia*, *Bidens pilosa* and *Tagetes minuta*), grasses (*Pogonanthria squarosa*, *Melinis repens*, *Aristida adscensionis*, *Andropogon chinensis* and *Heteropogon contortus*) woody species (*Rhus tenuinervis*, and *Lonchocarpus capassa*). The results suggest these species are both tolerant to hostile tailings substrate and a wide climatic range. The similarities in compositions along a climatic gradient may also be explained by characteristics of dominant plant taxa. Observed dominant plants across the climatic regions were grasses of the *Poaceae* family that have been reported to tolerate a wide range of environmental and climatic conditions (Shu *et al.*, 2005; Weiersbye *et al.*, 2006; Festin *et al.*, 2018). Such dominant grass species are C4 plants that are known to thrive in drier regions through the photosynthetic pathway mechanism which further suggests the importance of this trait in shaping plant communities. Possible



adaptive mechanisms accounting for the prevalence of C4 relative to C3 plants include; higher water use efficiency due to higher stomatal conductance (Voga and Sage, 2011).

However, the separation of sites in the wettest region from the rest can be attributed to traits of some few species that thrived only in such wetter conditions (Table 7.5). Such water loving species such as *Imperata cylindrica*, *Schizachyrium platyphyllum*, *Equisetum ramosissimum* and *Conyza species* occurred only in the wettest region and at significantly high frequencies (Table 7.5). The clustering of the other eight sites in the rainfall range 300-800 mm based on herbaceous composition and of all the 14 sites based on woody species composition show that boundaries of natural ecological regions based on climate do not directly influence species composition on unique anthropogenic substrates like gold tailings. The grouping patterns suggest wider rainfall range thresholds exist to influence herbaceous composition on gold tailings dumps. The converse trend on woody species where sites did not clearly separate may be attributable to their root morphology. In this context woody species are deep-rooted plants that can withstand dry conditions better than shallow-rooted herbaceous species (Van Outshodrom, 2014). For instance *Acacia* species have long roots up to 60 m (van Wyk and van Wyk., 2013). Such species have been reported to occur on a number of mine tailings in Africa (Festin *et al.*, 2018).

The aggregation of some sites in different geographic regions receiving different precipitation is inconsistent with results of a survey in a natural setting reported in North America where geographically dispersed sites recorded significant differences in species composition (Adler and Levine, 2006). The results are also inconsistent with findings from a similar study in the natural setting in Southern Africa (O'Brien, 1993) and Kalahari desert (Scholes *et al.*, 2002), where a positive relationship between woody species richness and precipitation was reported. The differences can be attributed to suppressive effects of grasses on woody species as the sites in higher rainfall regions were dominated by grasses such as *Imperata cylindrica*. The differences could also be attributed to varying substrates and the fact that the current study was conducted at a smaller scale than that of these studies. The results, therefore generate a new hypothesis that suggests that edaphic similarities could be more important in shaping plant communities on gold tailings than climatic gradients.

The finding that species richness was life cycle- dependent, with drier regions (300-450 mm and 450-600 mm) having higher annual species richness than wetter regions (650 -800 mm and 800-1000 mm) can be attributed to a number of factors. The growing period is shorter in drier regions and annuals make use of the shorter favourable period for completing its life cycle. However, observed intra-climatic region separation of sites, particularly the Freda site that separated from the other sites in the highest rainfall region is most probably attributed to tailings dump age effects. The site had only younger dumps (<50 years as noted in Chapter 5) than others in the same region and this, confirms the influence of age on

plant structural attributes. In addition the observed significantly lower woody and grass species richness on younger tailing dumps (<50 years) than those on older dumps also confirms the significance of substrate age in shaping plant structural attributes. The lower species richness on younger sites can be attributed to inhibitory substrate properties. These physicochemical properties include high bulk density, extreme pH, low N, and OC that can inhibit germination, and survival of some plant species. These are known to improve with time and therefore promote establishment of more plant species as observed in related studies (Chapters 3, 6 and 7). The results are consistent with findings from a few chronosequence studies on mine tailings that reported substrate age dependent vegetation structural and compositional attributes (Maharana and Patel, 2014; Chaturvedi and Singh, 2017).

In summary, the study did not completely support the hypothesis that different rainfall regions form different plant communities, as the clustering of sites in three drier regions (300-800 mm) suggests that rainfall affects plant species communities to certain thresholds that however could not be ascertained in the present study. The study therefore generates a new hypothesis of the existence of threshold rainfall amount to separate composition on mine tailings and that these are usually different from those for natural sites. In addition the study confirms the hypothesis of the existence of a significant positive relationship between rainfall and species richness but due to differential trends between herbaceous and woody species, generates a new hypothesis that on unique anthropogenic sites, the relationship is plant growth form dependent. The clustering of several sites despite significant variation in rainfall received suggests a new hypothesis that substrate properties or other factors may be key determinants of floristic composition on mine tailings. The separation of sites receiving similar rainfall amounts and their differences in plant species richness further confirms the significant influence of substrate age on vegetation compositional and structural attributes as observed in related studies (Nyenda *et al.*, 2019b; Chapters 5 and 7). The overall implication of the study results to rehabilitation practice is the insights for possible universal application of grasses and woody species in different climatic conditions. The results also further give insights into the importance of specific plant taxa traits and substrate age in tailings rehabilitation programs. To a greater extent, the results show that similar revegetation programs can be employed in areas of ranging climatic variations if they are of similar geologies.

## **7.5 Conclusion and recommendations**

The main objective of the study was to assess the variation of plant species richness and community assemblages on gold mine tailings along a rainfall gradient and investigate the interactive effect of dump age and climate. Forbs and grass species richness significantly increased with rainfall and tailings age while effect on woody species richness was not significant. Contrary to the hypothesis that tailings in the four rainfall regions form distinct plant communities, only the wettest (800-1000 mm) sites, separated from the three drier sites that clustered together. The results therefore suggest that wider rainfall differences influenced plant communities' separation on gold tailings that could not coincide with the natural

ecological region boundaries. Observed dissimilarities in species composition and richness are driven by species traits that either cannot thrive in dry or wet conditions. Annuals were more associated with drier sites than wetter sites while perennials were independent of rainfall. In addition to rainfall gradients, substrate age is also a key determinant of species richness. Older dumps may be less toxic in that nutrient levels are higher, bulk density and salinity lower while pH is tolerable when compared to nutrient poor, extremely alkaline and acidic and highly compacted younger dumps. Younger dumps therefore inhibit species establishment while temporal improvement in the substrate owing to biotic action, leaching and other pedogenetic processes promote less tolerant species resulting in increased species richness and creation of distinct plant communities. Overall, the effect of climate on floristic composition on gold tailings was dependent on taxa, growth form and life cycle. The interactive effect of age and climate on floristic composition and species richness on gold tailings is not significant. The study recommends the conduct of similar research using other anthropogenic substrates. Since this chapter investigated climatic influence on vegetation of largely unrehabilitated mine tailings, similar tests must be done on rehabilitated mine tailings in order to increase the chances for generalizations (Chapter 7).

## CHAPTER 8

### IS THE TRAJECTORY OF VEGETATION DEVELOPMENT ON A CHRONOSEQUENCE OF REHABILITATED NICKEL TAILINGS TOWARDS OR AWAY FROM A PRE-DISTURBANCE REFERENCE ECOSYSTEM?

#### Abstract

Understanding the trajectory of vegetation recovery on rehabilitated mine tailings is critical in evaluating the effectiveness of rehabilitation programs, but is still largely unknown. A chronosequence of rehabilitated nickel mine tailings at Trojan mine, as well as other tailings in a different climatic region (Shangani mine) in the savanna region of Zimbabwe were studied to: (1) evaluate the trajectory of changes in vegetation structural and compositional attributes compared to an adjacent reference site, (2) identify substrate correlates to observed vegetation structural attributes and, (3) to determine the influence of climatic gradients on vegetation structural and compositional attributes. The study hypothesized that: (1) vegetation cover, species richness and diversity increase with age of tailings, converging towards the natural reference condition within 40 years, (2) plant communities that are formed converge to natural references (novel ecosystems are not formed), and, (3) plant communities formed on rehabilitated nickel mine tailings in contrasting climatic regions are different but both converge to natural reference 15 years after reclamation. Plant taxa, aerial and basal cover, abundances and species richness were assessed along transects laid out on four nickel mine tailings aged 10, 20, 35 and 40 years and adjacent reference sites, while soils samples were taken for basic soil analyses. Vegetation cover for naturally colonizing species significantly increased with dump age reaching reference conditions at 20 years and exceeding them at 35 years. Species richness significantly increased with dump age, exceeding reference sites at 35 years. Shannon species diversity equalled that of reference sites at 10 years, but evenness remained significantly lower than values obtained at reference sites even after 40 years. A principal component analysis (PCA) showed that the 10 year-old site was significantly different from the reference site but over time, the plant communities diverge more from the reference site. In addition, 15 years after reclamation, plant communities on tailings in contrasting climatic regions were similar but both were apparently distinct from their adjacent references. On younger dumps (10 and 20 years) *Cynodon dactylon*, *Imperata cylindrica* and *Andropogon chinensis* had higher species importance values (SIV) while on the oldest, *Hyparrhenia filipendula* was more important. A PCA showed that species richness and vegetation cover were positively correlated to total N, OM, clay and silt content and negatively correlated to bulk density, total sand content, electrical conductivity (EC) and pH. The findings indicate a divergent vegetation community trajectory following reclamation although structural attributes converge and exceed reference levels. The results therefore suggest that: (1) the trajectory of vegetation

community composition on rehabilitated nickel tailings move towards formation of novel plant ecosystems, although structural attributes converge and exceed reference levels and, (2) climatic differences have less apparent influence on vegetation composition on unique rehabilitated mine tailings contrary to its effect on natural substrates.

**Keywords:** Mine tailings; reclamation, chronosequence; revegetation trajectory; total N; climatic gradient; vegetation community; species richness.

## 8.1 Introduction

Mine tailings contain high levels of phyto-toxic elements such as heavy metals (Babau *et al.*, 2017; Rola and Osyczka, 2017; Woch *et al.*, 2017; Pan *et al.*, 2017; Uddin and Robinson, 2017; Slingerland *et al.*, 2018; Festin *et al.*, 2018). They also lack macronutrients such as nitrogen and phosphorus (Stewart and Siciliano, 2015) and may contain traces of process chemicals that often contribute to extreme pH and salinity (Gumbo *et al.*, 2009). In some cases, mine tailings contain sulphides from their ore which on oxidation present acidity problems (Singh *et al.*, 2016). As a result, tailings remain devoid of vegetation for very long periods (Festin *et al.*, 2018), posing a threat of air, water, surface and groundwater pollution as they are subject to water and wind erosion, and leaching (Mendez and Maier, 2008; Sheoran *et al.*, 2010; Li *et al.*, 2014; Zhang *et al.*, 2015; Chen *et al.*, 2016; Chaturvedi, 2017; Rola and Osyczka, 2017; Courchamp and Bradshaw, 2018). The reported pollution often is associated with human and environmental health risks (Babau *et al.*, 2017) as well as destruction of biodiversity (Sheoran *et al.*, 2010; Cardinale *et al.*, 2012; Madonsela *et al.*, 2018).

Traditionally, tailings were left to naturally revegetate, a process that is slow due to their edaphic limitations. In order to overcome these challenges and minimize the associated environmental problems, assisted tailings revegetation has been widely adopted (Piha *et al.*, 1995a; Mendez and Maier, 2008; Wang *et al.*, 2016; Chaturvedi, 2017; Festin *et al.*, 2018). Assisted revegetation is a reclamation approach that actively introduces vegetation in order to facilitate natural re-establishment of vegetation. This approach targets improving biodiversity, ecological processes, soil quality and reduce erosion and hence environmental pollution by initially planting adaptable plant species whose establishment would engineer the substrate and facilitate subsequent natural plant colonization (Mench *et al.*, 2006; Kumar and Maiti, 2013; Pardo *et al.*, 2014; Mukaro *et al.*, 2017; Ahirwal and Maiti, 2018). The approach usually involves use of organic or inorganic ameliorants along with planting of vegetation (Das and Maiti, 2007; Mukhopadhyay *et al.*, 2013; Lintangah *et al.*, 2016; Chen *et al.*, 2016; Chaturvedi, 2017; Ahirwal and Maiti, 2018). The most common techniques used are substrate amelioration involving fertilizer and organic amendments with planting of fast growing plant species (Piha *et al.*, 1995; Hadacova and Prach, 2003; Martinez and Fernandez, 2005; Chaturvedi and Singh, 2017c; Festin *et al.*, 2018). These

approaches are usually expensive and often do not meet the desired ecosystem restoration goals, which generally target restoring composition and diversity and function. Finding effective natural, long lasting and inexpensive methods of achieving the restoration goals remain a challenge as natural succession on anthropogenic and unique metalliferous sites is poorly studied.

A number of revegetation studies have been done on natural and artificial substrates (e.g. Hobbs and Harris, 2003; Martinez and Fernandez., 2005; 2007; Chartuvedi *et al.*, 2017c). Most studied substrates are near natural mined sites and coal spoil heaps (Skousen *et al.*, 1994; Andrews, 1998; Boerner *et al.*, 1998; Jochmisen, 2001; Holl, 2002; Sourkova *et al.*, 2005; Frouz *et al.*, 2007; Yao *et al.*, 2010; Mukhopadhyay and Maiti, 2011; Alday *et al.*, 2011; 2012; 2014; Moreno *et al.*, 2012; Payasat and Patel, 2015). Generally, these studies found that there was a positive correlation between tailings age and vegetation structural attributes (e.g. Hodkinson and Webb, 2003; Wang *et al.*, 2004; Huang *et al.*, 2011; Herzberger *et al.*, 2015; Lei *et al.*, 2015a). Another common observation was that the adjacent reference sites were important sources of propagules colonizing and shaping composition on disturbed sites (Shu *et al.*, 2005; Weiersbye *et al.*, 2006; Young *et al.*, 2013; Chan and Turner, 2019). Several studies investigating plant establishment patterns on disturbed sites reported that physicochemical properties are key determinants of plant community characteristics (Huang *et al.*, 2004; Mendez and Maier, 2008; Alday *et al.*, 2011; Huang *et al.*, 2011) and that climatic gradients drive vegetation communities (Prach and Walker, 2019; Chapter 7). Moreover, some studies that examined trajectories of vegetation development report that in most cases plant communities on rehabilitated sites were divergent from the natural reference sites although diversity and structural attributes were restored or similar to that of reference sites (Holl, 2002, Martinez and Santos, 2007; Holl and Moreno *et al.*, 2011; Alday *et al.*, 2011, 2012, 2014). In most cases, such studies were however done in temperate Mediterranean dry climatic regions.

Mine tailings are unique, differing from other mine soils in that they have a very silt texture due to milling, contain residual process chemicals, lack any soil or biological properties, appear in different landforms and are highly susceptible to erosion and related disturbances. A considerable number of revegetation studies were done on such mine tailings (Mendez and Maier, 2008; Sracek *et al.*, 2010; Boateng *et al.*, 2012; Liefferink and Liefferink, 2015; Lintangah *et al.*, 2016; Wang *et al.*, 2016; Zhang *et al.*, 2016; Chaturvedi, 2017; Pan *et al.*, 2017; Festin *et al.*, 2018; Yuan *et al.*, 2018; Zapico *et al.*, 2018). The bulk of the studies focused on growth performance, heavy metal uptake by candidate rehabilitation species and comparing the efficacy of different ameliorants in promoting growth of planted species (Piha *et al.*, 1995a; Mulizane *et al.*, 2005; Nyakudya *et al.*, 2011). Common findings from these studies were: (1) slow recovery in vegetation which was limited by nutrients and heavy metal toxicity (Piha *et al.*, 1995), (2) good growth performance of the introduced plant species (Nyakudya *et al.*, 2011). In spite of the several studies done, very few have evaluated the success of introduced adaptable species in promoting subsequent natural plant communities recovery in composition, and diversity on such unique substrate

over time (Dowo and Kativu, 2013; Mukaro *et al.*, 2017). A few exceptions on mine tailings were either once-off or short term vegetation inventories on rehabilitated tailings with no emphasis on trajectories of vegetation development (e.g. Piha *et al.*, 1995a; Mukaro *et al.*, 2017; Festin *et al.*, 2018). A related study (Chapter 6) recently investigated the trajectory of natural revegetation on unrehabilitated gold mine tailings, in particular testing the novel ecosystem concept, which it largely dispelled. It showed that species richness significantly increases with tailings age and that vegetation development on unrehabilitated mine tailings is gradual but towards reference conditions in terms of both structural attributes and species composition. Moreover, restoration of composition was not achieved within 110 years. Ecological revegetation theories therefore remain largely untested on rehabilitated unique anthropogenic substrates like nickel mine tailings. Therefore, the rationale for the current study is to answer the following research question, “Do contrasting initial points: natural revegetation (Chapter 6) versus reclamation (Current chapter) result in the same end-point?”

The emerging concept of novel ecosystems (Hobbs *et al.*, 2006; Miller and Bestelmeyer, 2016), suggests that disturbed sites support a specific assemblage of plant species, completely distinct from the surrounding vegetation (Bradshaw, 1987; Wu, 1990; Hobbs *et al.*, 2006). The concept has received criticism from some scholars (Marris, *et al.*, 2013; Simberloff *et al.*, 2015). The contradictions along with lack of testing of the novel ecosystem concept on mine sites make it difficult to plan self-sustaining mine tailings revegetation programs. Therefore, there is need for more empirical studies that test such emerging theories to provide context specific trajectories. The present study sought to interrogate this emerging theory.

A chronosequence of mine tailings that were rehabilitated by planting woody species present an opportunity for testing the novel ecosystem concept. The specific objectives of the study were: (1) to determine the trajectory of plant structural and compositional attributes on a chronosequence of rehabilitated nickel tailings, (2) to identify substrate correlates to observed vegetation attributes, and (3) to determine the influence of climatic differences on vegetation structural and compositional attributes on rehabilitated nickel tailings. The study hypothesized that: (1) vegetation cover, species richness, and diversity increase with age converging towards the natural reference, (2) plant communities formed converge to natural references (novel ecosystems are not formed), and, (3) plant communities formed on rehabilitated nickel mine tailings in contrasting climatic regions are different but both converge to natural reference, 16 years after reclamation.

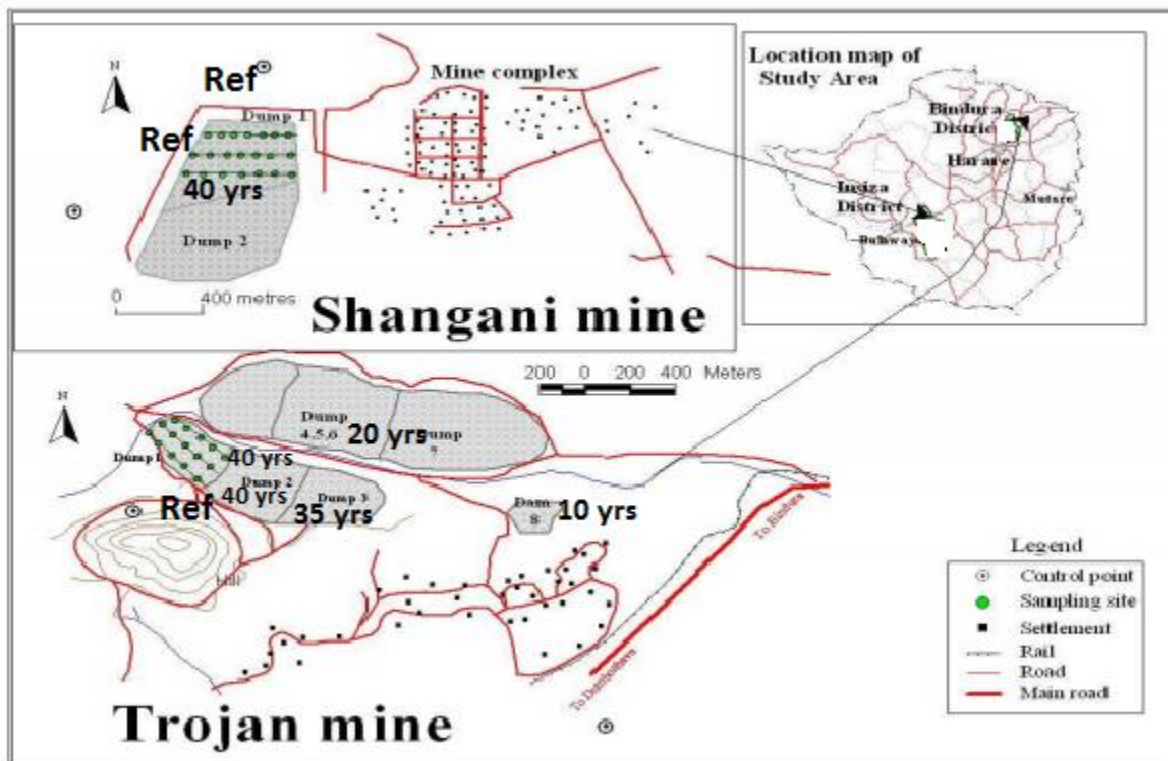
## **8.2 Materials and methods**

### **8.2.1 Description of the study area**

The study was carried out at two mine sites, Trojan Mine (31°16'E; 17°19' S) in Bindura district, in north east of Zimbabwe and Shangani mine (29°21'E; 19°46' S) in the southern region. The Trojan mine site



experiences a savanna climate characterized by wet summers and dry winters. Based on rainfall data for the past 37 years, Bindura receives an average annual precipitation of 879 mm and has an average annual temperature of 28°C (Zimbabwe Meteorological Services, 2018). Shangani mine receives an annual rainfall of 550 mm. To investigate the trajectories of vegetation structural and compositional attributes, four tailings dumps of contrasting ages (10, 20 35 and 40 years) and two adjacent reference sites were studied at Trojan nickel mine (Fig. 8.1). To investigate the influence of climatic differences on vegetation structural and compositional attributes, one dump at Shangani and Trojan mine aged 40 years and 16 years after reclamation were selected (Fig 8.1). The dumps were subjected to similar rehabilitation procedures as they were owned by one company. The dump tops were rehabilitated by planting three leguminous tree species, *Senegalia polyacantha*, *Vachellia karoo*, *Vachellia tortilis* and broadcasting *Sesbania sesban* in 2001. The dumps were irrigated using recycled process water up to 2002 and left for successive natural recovery thereafter.



**Figure 8.1:** Map of the study area in Zimbabwe. The study area comprises four nickel tailings dumps at Trojan mine (10, 20, 35 and 40 years) and one at Shangani mine (40 years). The adjacent natural woodlands were used as reference sites. Layout of sampling points are shown for only the two dumps (40 years at each site) used for comparison of vegetation attributes for sites in different climatic regions.



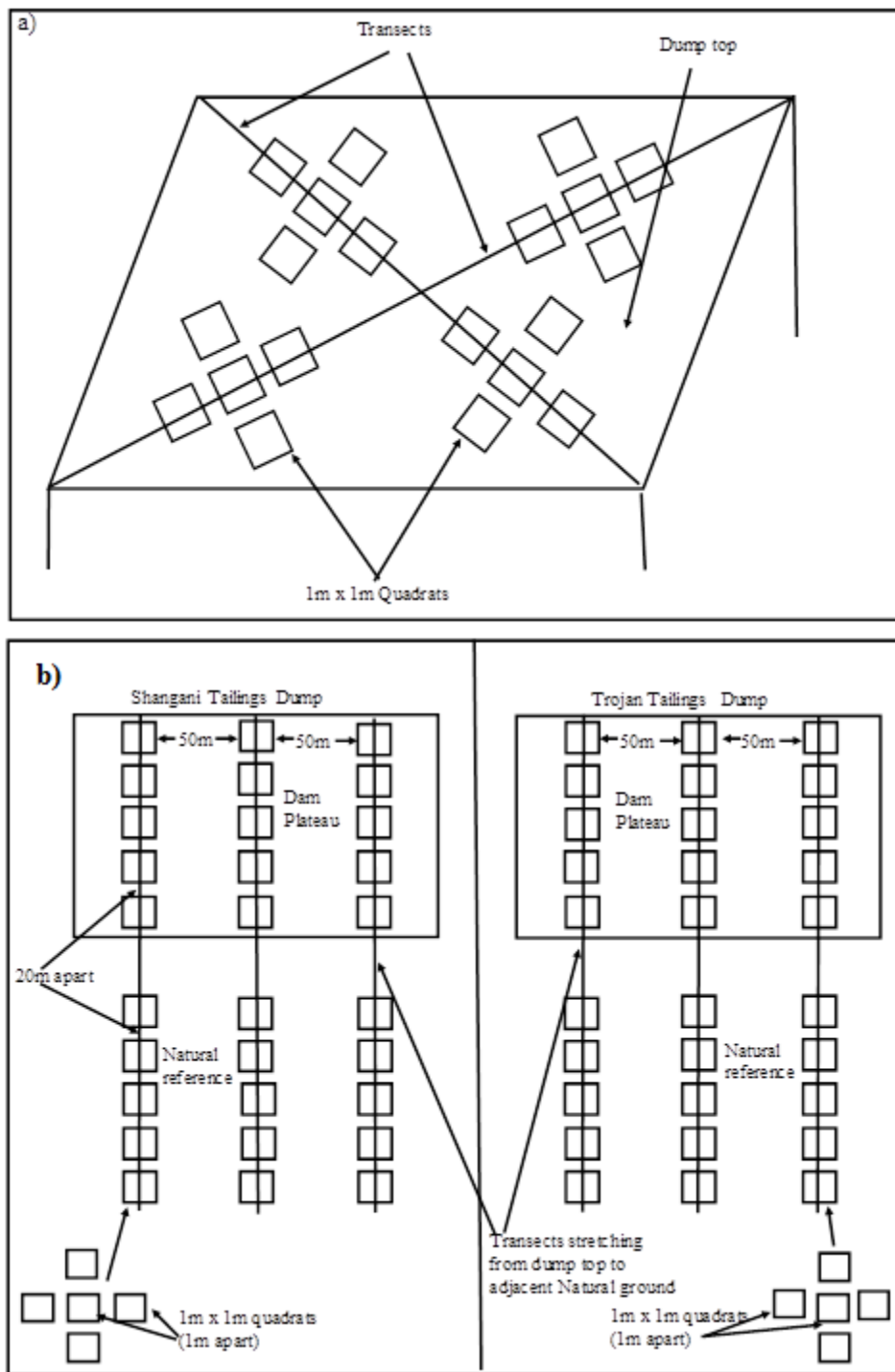
The geology of the sites is typically greenstone configuration comprising of basaltic rocks (tholeiitic basalts and gabbro) coupled with banded iron formations and volcanic tuffs. The ore of nickel mainly consist of pyrrhotite  $\text{Fe}_8\text{S}$  with associated nickel-bearing pentlandite ( $(\text{Fe}, \text{Ni})_9\text{S}_8$ ) and polydymite ( $\text{Ni}_3\text{S}_4$ ) minerals. Pyrite ( $\text{FeS}_2$ ) and chalcopyrite ( $(\text{Cu}, \text{Fe})\text{S}_2$ ) are also found (Bindura Nickel Corporation, 2007).

The Trojan mine area is in the savanna biome characterized by Miombo woodland with *Brachystegia boemmii* and *Julbernardia globiflora* dominating upper catenary positions while remnants of *Senegalia polyacantha* and *Vachellia gerrardii* woodland patches dominate low-lying areas (Bindura Nickel Corporation, 2006). Dominant herbaceous species include *Aristida* spp., *Diheteropogon amplexans*, *Pennisetum setaceum* and *Setaria sphacelata*. Shangani mine vegetation is mixed woodland dominated by *Vachellia*, *Dichrostachys*, *Diospyros* and *Combretum* spp. Dominating herbaceous species belong to the *Aristida* genera (Bindura Nickel Corporation, 2006).

### 8.2.2 Experimental set up

To investigate the effects of age on vegetation structural and compositional attributes, four tailings (10, 20, 35 and 40 years) were selected. The dumps were reclaimed approximately 16 years before the time of sampling except for the 10 year old dump that was reclaimed 10 years prior to sampling (Chapter 2). On each dump top, two diagonal transects were laid out (Fig 8.2a). Along each transect, 20 sampling points were located at 10 m intervals starting from a randomly selected end (Zhang *et al.*, 2007). At each sampling point, five replicate quadrats were systematically laid out at 1 m intervals (one at the center and four in all major cardinal directions; Fig. 8.2a). Two adjacent natural woodlands 200 m stretch around the tailings at each site) were used as reference sites, from where 80 sampling points were laid out. The natural site was largely the bottom slope of adjacent hills and some hill valleys. The slopes of the hills were open woodlands dominated by *Brachystegia boehmii*, *Bauhinia petersiana*, *Diplorhynchus condylocarpon* trees and *Heteropogon contortus*, *Diheteropogon amplexans* and *Aristida* spp. The valleys were wooded grasslands dominated by *Senegalia polyacantha*, *Aristida* spp., *Superba gloriosa* and some *Eragrostis* spp. The sites were selected as references because of their proximity and connectivity to the dumps, thus were expected to be sources of propagules (Prach *et al.*, 2016). The sites were also free from significant human disturbances as they were in a protected mine site area. To assess the influence of rainfall differences on success of rehabilitation and trajectory relative to a reference site, one dump aged 40 years (but sampled 16 years after reclamation) was selected at each site (the annual rainfall at Trojan was 879 mm and at Shangani 550mm). The two dumps had similar reclamation history as they were rehabilitated by planting *Senegalia polyacantha*, *Vachellia nilotica*, *Vachellia karoo* and broadcasting of *Sesbania sesban* in 2001. Only the tops were comparable as they had the same species planted on them, thus slopes were left out. Three transects, 50 m apart running from dump tops into the adjacent reference sites were laid at each site. At Shangani, the reference site was again a 300 m flat

area around the dump. Sampling points were again located at 20 m intervals as in procedure above (Fig. 8.2b).



**Figure 8.2:** Layout of sample points at sampling sites on tailings and reference sites, (a). Quadrats laid out for the chronosequence study at Trojan mine (b) Sampling points for the dumps at Trojan and Shangani dumps (contrasting climate sites). The sampling design in b was slightly adjusted in order to

facilitate easy access to reference sites at Shangani mine as diagonals would get into a disturbed area and another tailings dump

### 8.2.3 Vegetation assessments

Species richness, abundance, aerial and basal cover were measured. All plant taxa observed in each quadrat were identified to species level using a field guide (Van Oudtshoorn, 2014) and their abundances determined by counting of tufts. Those that could not be identified in the field were sent to the National Herbarium of Zimbabwe for identification. Quadrat and site richness were determined for different taxa observed. Aerial and basal cover of total and individual herbaceous species were visually estimated to the nearest percent in terms of the proportion of the quadrat being covered (Ochoa-Hueso *et al.*, 2011). To estimate cover, a 1 m<sup>2</sup> quadrat was divided into 100 grids of 100 cm<sup>2</sup> each with each square, representing 1 % cover using wire frames (Dettweiler-Robinson *et al.*, 2013b). Total basal cover was taken as the measure of the proportion of the plants in a quadrat which extends into the soil (Dettweiler-Robinson *et al.*, 2013). Basal cover of each tuft of herbaceous species in each quadrat were estimated and then added to obtain the total basal cover (Ochoa-Hueso *et al.*, 2011). Plant density in each quadrat was determined using abundance data. For further analysis, vegetation was classified according to family.

Shannon diversity index was calculated as follows:

$$\text{Shannon } (H') = -\sum p_i \ln p_i \dots \dots \dots (1)$$

where  $p_i$  refers to relative abundance of species  $i$ .

Species importance value (SIV) was computed as:

$$SIV = \text{Relative Density} + \text{Relative Frequency} + \text{Relative Dominance} \dots \dots \dots (2)$$

$$\text{Relative Density} = \frac{\text{Density of one species}}{\text{Total density of all species}} \times 100 \dots \dots \dots (3)$$

$$\text{Relative frequency} = \frac{\text{Frequency of a species}}{\text{Total frequency of all species}} \times 100 \dots \dots \dots (4)$$

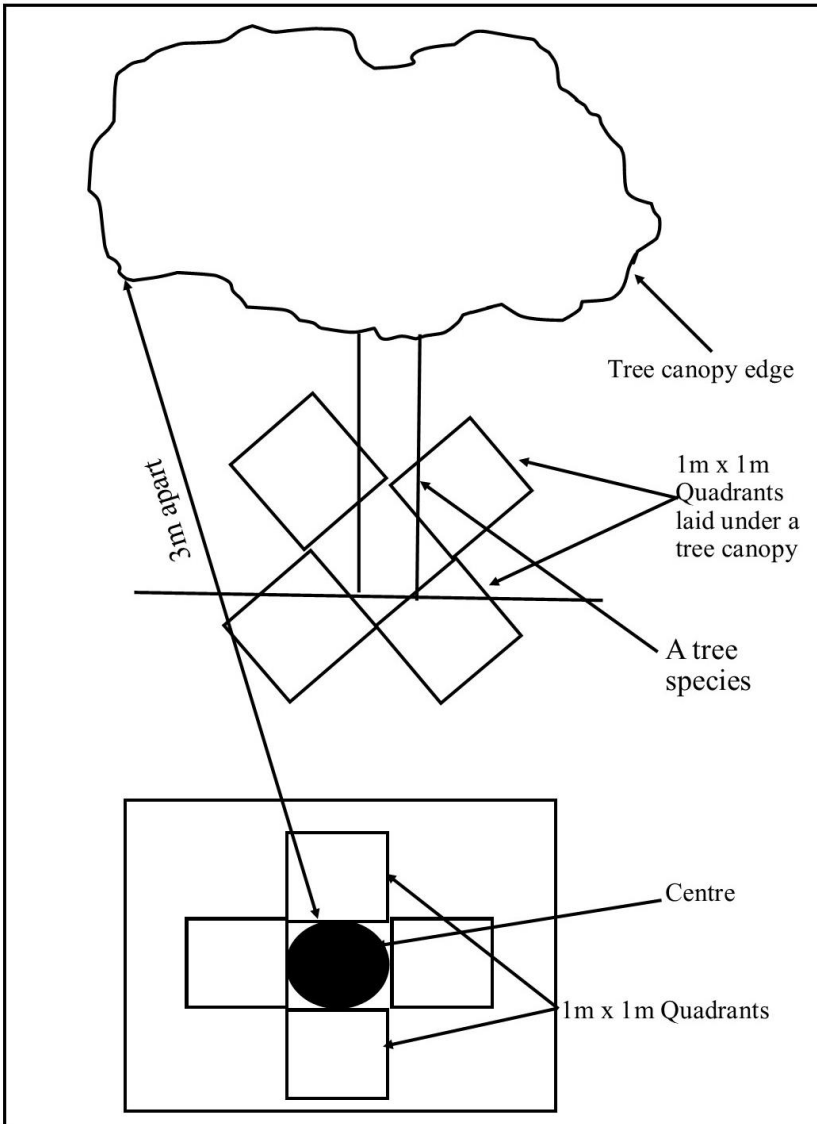
$$\text{Relative Dominance} = \frac{\text{Basal area of one species}}{\text{Total basal area of all species}} \times 100 \dots \dots \dots (5)$$

Sorensen index of similarity (S) was calculated as:

$$SI = 2C / (A+B) \dots\dots\dots (6)$$

where C is number of common species between sites, A and B are the total number of species for each site.

To determine the micro site (canopy versus inter-canopy) influence of planted species on vegetation, two dumps aged 20 and 40 years were selected. Ten trees of *Senegalia polyacantha* and *V. Karoo* of height > 2.5 m and canopy diameter > 4 m were selected. Four 1 m x 1 m quadrats were laid out under the canopy of each of the ten planted trees per species and adjacent inter-canopy patches for vegetation and substrate assessments (Fig. 8.3). Vegetation attributes determined were species richness, abundances and biological crusts. Biological crusts cover was estimated in quadrats used for vascular plants assessments following methods used in related studies (Chapter 4; Nyenda *et al.*, 2019b).



**Figure 8.3:** Sampling point layout under and off planted tree canopies

#### 8.2.4 Sampling of tailings substrate and laboratory analyses

To determine variation of tailings physicochemical properties across dumps of different ages at Trojan mine, four bulk samples were collected from 10 randomly located points in each quarter of each dump top. At each point 10 subsamples were collected to a 10 cm depth using a bucket soil auger (8 cm diameter). The sub-samples were thoroughly homogenized in the field before a 500 g sample was packed into plastic sampling bags. To test the micro-scale effect of planted trees on tailings properties, four tailings samples were collected from underneath the planted trees and adjacent patches, particularly from quadrants used for vegetation assessments on the 20 and 40 year-old dumps. At each sampling point, sampling was done at 0-10 cm depth using a bucket soil auger (8 cm diameter). The sub-samples were

bulk and homogenized in the field to make one composite sample per tree and one for the adjacent control point. Samples were analyzed for texture, pH, EC, total and mineral N, available P, exchangeable (Ca, K and Mg), OC, OM and bulk density using methods described by Okalebo *et al.* (2002), summarized in Chapter 3, 4 and 5 and Nyenda *et al.* (2019 a, b).

### 8.2.5 Data analysis

Data were analyzed in two phases involving one-way analysis of variance and multivariate ordination. Species abundance, richness, diversity and substrate data were tested for normality using the Kolmogorov Smirnov test in the Statistical Package for Social Sciences (SPSS) software version 20. All vegetation data recorded as percentages were arcsine transformed before analysis of variance (McKillup, 2011). A one-way ANOVA was used to test variation of vegetation structural attributes across dumps and climates. In all cases, pair-wise comparisons were made with a post-hoc test, least significant difference (LSD) at 5 % level of significance.

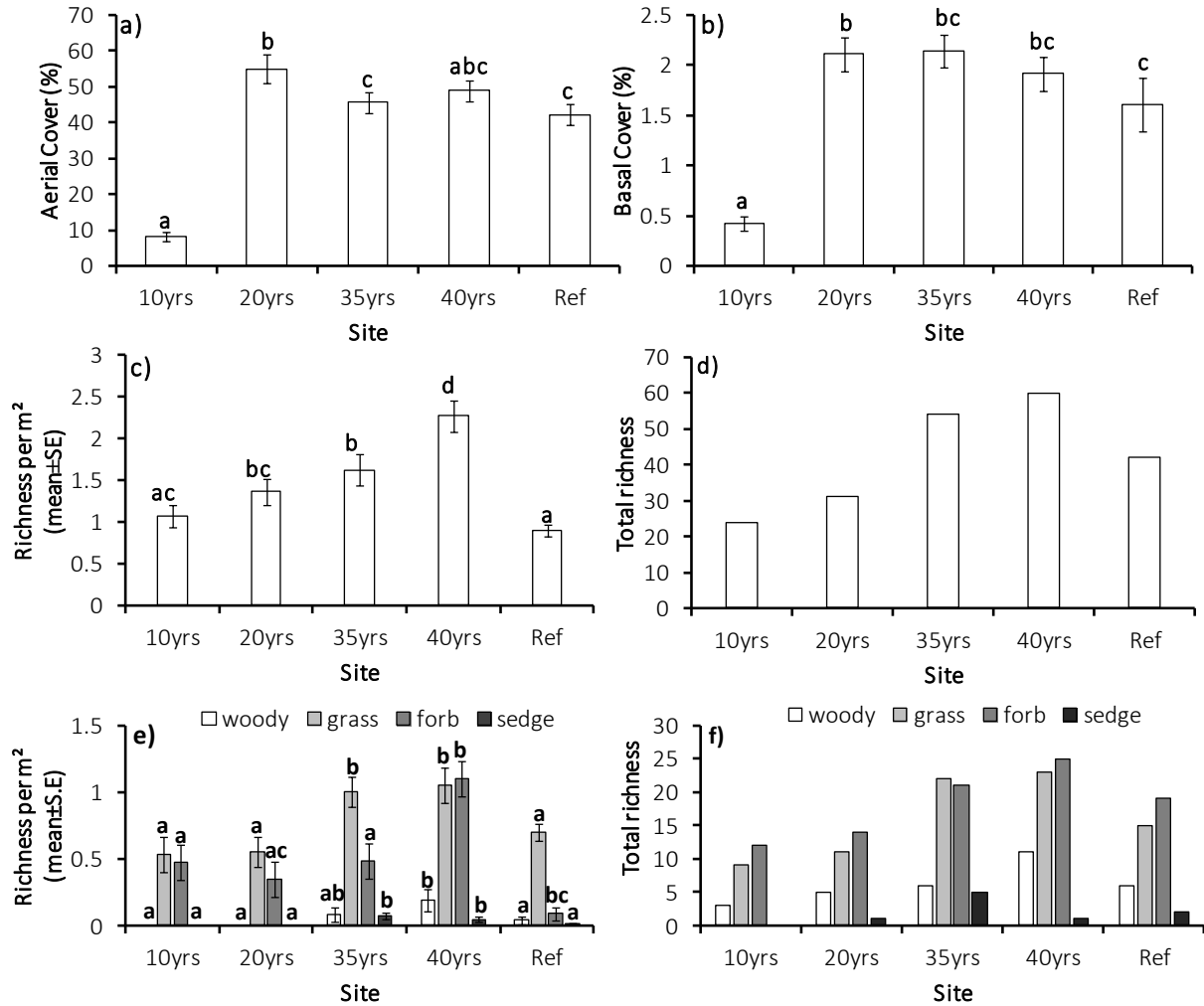
A principal component analysis (PCA) was used to test the effects of tailings age on vegetation community development, and the relationships between tailings attributes and vegetation structural and compositional attributes (Ter Braak, 1986). A PCA was performed since data gradient length was less than 3 (Lepš & Šmilauer, 2003; Mckillup, 2011). All tests were done without down weighting of rare species based on frequencies. To test the specific effects of planted trees at micro-scale, a PCA was further performed using vegetation attributes for canopy and inter-canopy patches. A canonical correspondence analysis (CCA) was performed to test the relationship between vegetation and tailings physicochemical data (Cañadas *et al.*, 2010). All ordination analyses were done using Canoco for Windows version 5.

## 8.3 Results

### 8.3.1 Changes in vegetation structural attributes

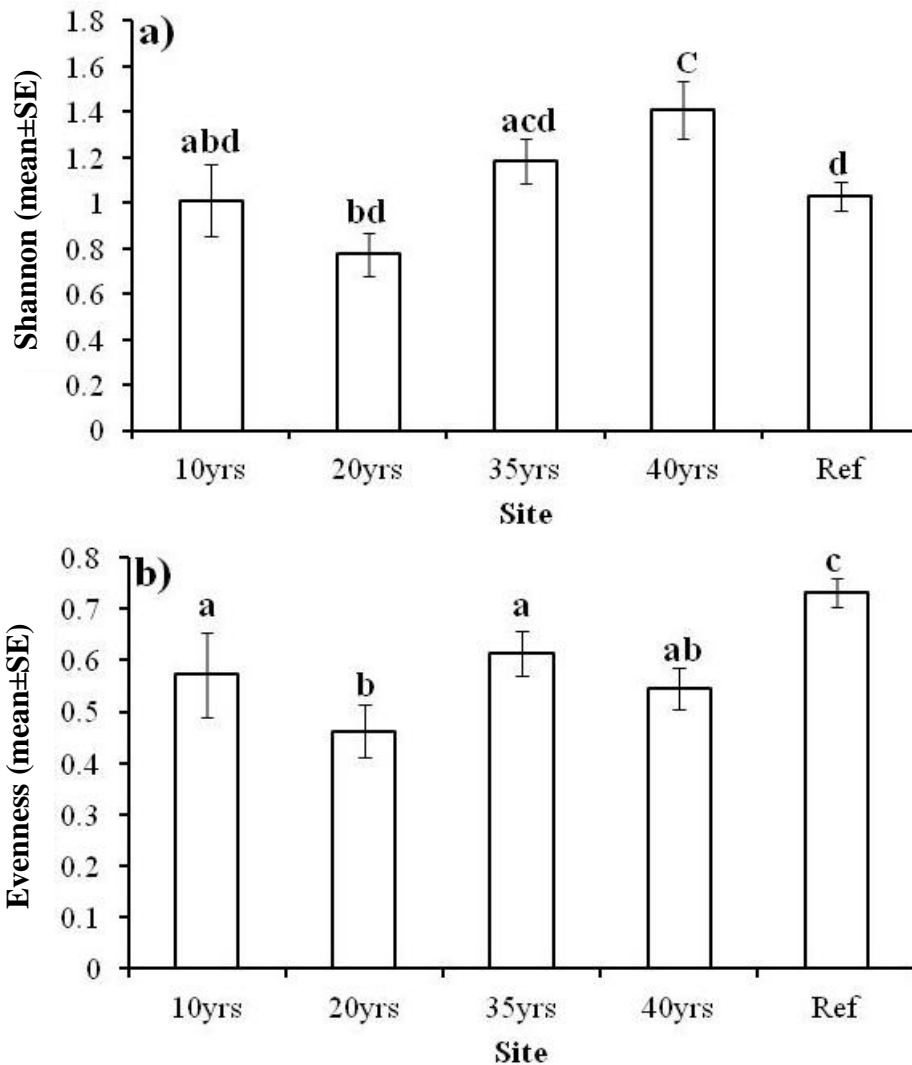
Herbaceous plant aerial cover ( $F = 33.84$ ;  $p < 0.01$ ), basal cover ( $F = 15.59$ ;  $p < 0.01$ ) and species richness ( $F = 26.7$ ;  $p < 0.001$ ) significantly increased with age of tailings, exceeding values observed at the reference site at 20 years (Fig. 8.4a, b and c). In spite of the generally significant increase in aerial covers with dump age, the post-hoc LSD test showed that herbaceous cover for the 35-year-old dump was significantly lower than values observed on the 20 and 40-year-old dumps. Similarly, the species richness on the 10 and 20-year-old dumps was statistically similar. Overall plant species richness increased almost three-fold, from 24 on the 10-year-old dump to 60 on the 40-year-old dump but first exceeded values observed at the reference on the 35-year-old dump (Fig. 8.4d). In terms of growth forms, on most dumps, grass species richness was significantly higher than forb, sedge and woody

species richness although differences were less apparent on the youngest dumps (10 and 20 years; Fig. 8.4e). Overall species richness for all growth forms increased significantly with tailings age except woody species ( $F = 2.25$ ;  $p = 0.05$ ). On all dumps and reference site, species richness occurred in the order: sedge < woody < forbs < grasses ( Fig. 8.4f). Shannon species diversity index significantly increased ( $F = 4.74$ ;  $p = 0.001$ ) with dump age, matched the reference site on the 10-year-old dump, and significantly exceeding it from 35 years thereafter (Fig. 8.5a). The 20-year-old dump was the least diverse while the Shannon diversity index for the 35 and 40-year-old dumps were similar. However, evenness was similar across all dumps but was significantly lower on all dumps than the reference site (Fig. 8.5b).



**Figure 8.4:** Changes in vegetation cover and species richness (Mean  $\pm$  SE) on a chronosequence of rehabilitated nickel tailings dumps compared to reference sites: (a) aerial cover; (b) basal cover; (c) plant species richness per m<sup>2</sup>; (d) total species richness; (e) mean richness/ m<sup>2</sup> for different growth forms; (f) total species richness for all growth forms. Letters on top of error bars compare means across dumps for (a, b and c) and growth forms per each year in the case of Fig 4e. All different letters between dumps denote significant difference. Ref = reference site.





**Figure 8.5:** Changes in species diversity on a chronosequence of nickel tailings dumps. (a) Shannon diversity index (b) evenness. Different letters on top of bars show significant difference in mean. Ref = reference site .

### 8.3.2 Changes in plant community composition on a chronosequence of nickel tailings.

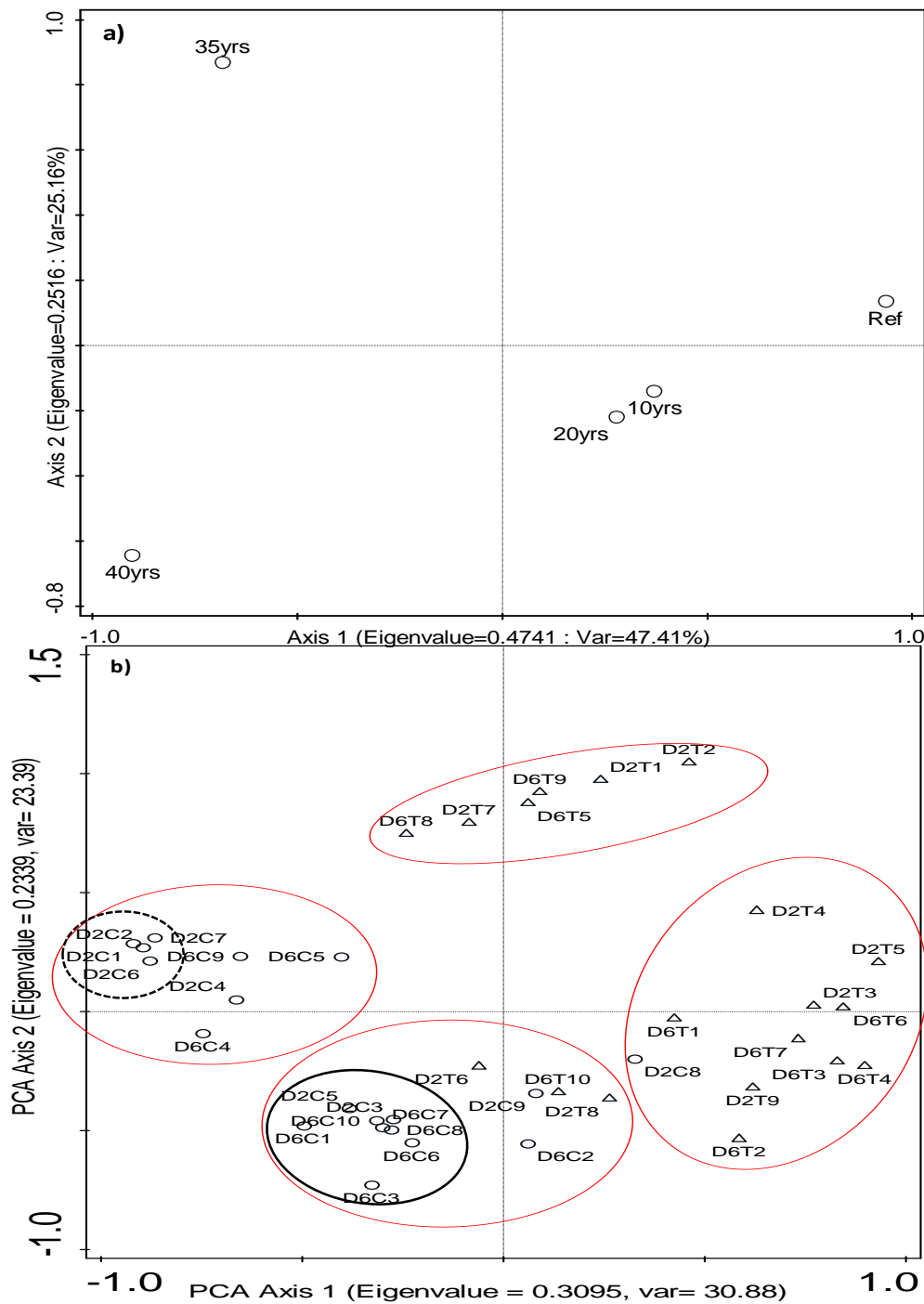
Principal component analysis (PCA) using species abundance data separated the tailings and the reference site but grouped the two youngest dumps (10 and 20 years) together (Fig. 8.6a). The younger dumps were close to the centre of the first axis, the reference site to the far right of the first axis (eigenvalue = 0.474; explained variation = 47.4 %) while the 35 and 40 year-old -dumps were at the far left end of the first axis, representing a divergent trajectory. The 35 and 40 years dumps however were at opposing ends of the second axis (eigenvalue = 0.252; explained variation = 25.2 %).

The Sorensen index of similarity (Table 8.1) showed slight progression of plant communities on tailings towards the reference community with Sorensen indices of 0.24 and 0.37 for the youngest (10 years) and oldest (40 years) respectively. The number of common species on dumps and the reference site increased significantly by a factor of 2.5 from 8 for the 10-year-old dump to 19 for the 40-year-old dump (Table 8.1). The oldest dumps (35 and 40 years) and reference sites however, remained dissimilar despite increasing number of common species (8.6a).

The PCA showed that plant communities under canopies of planted trees were different from those from the adjacent control patches regardless of dump age (Fig 8.6b). The ordination diagram yielded four main groups of sites which generally had (1) a mixture of plots from canopies of trees on the 20 and 40-year-old dumps and (2) a mixture of plots from the inter-canopy spaces (herein referred to as controls) of both dumps (Fig 8.6b). The sites from the tree canopies generally occupied the right side of axis 1 of the ordination plot while those from the intercanopy spaces occupied the opposite end of axis 1. Despite broadly clustering together, plots from the control sites were closely aggregated showing higher similarity when compared to sites from the canopy which were relatively further apart (Fig 8.6 b). Further, the PCA ordination yielded sub-clusters within the broad clusters showing significant separation of inter-canopy plots of the 20 year-old dump from those from the older dump (Fig 8.6 b).

**Table 8. 1:** Sorensen similarity index (number in bold) between sites (number in brackets shows the number of common species between sites).

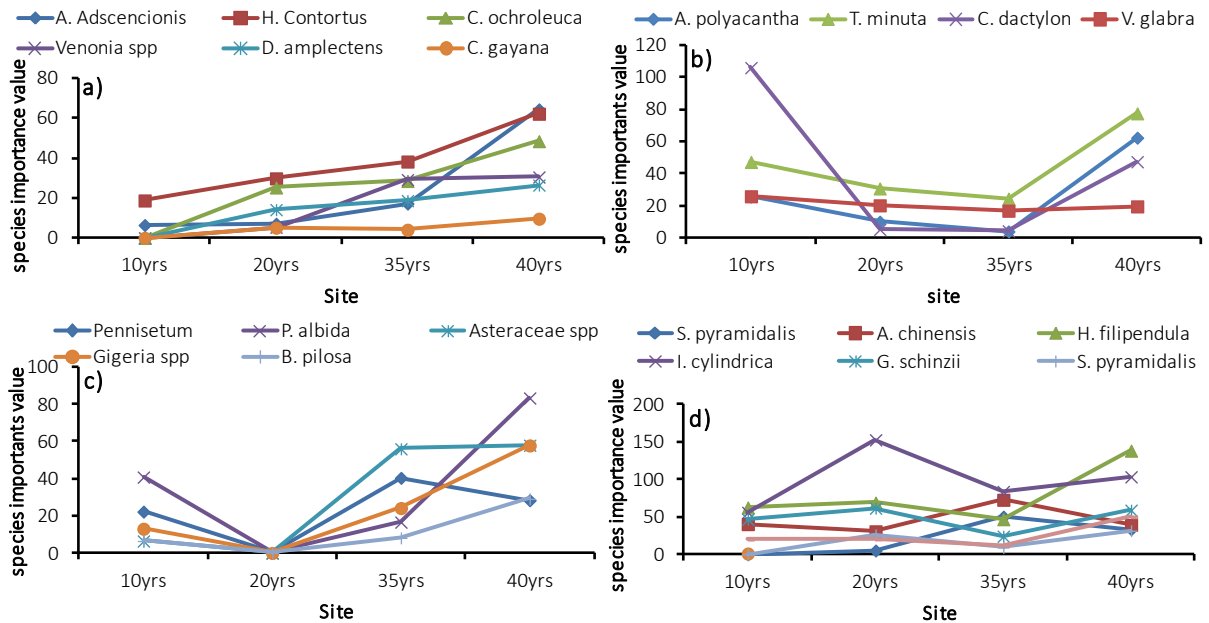
	<b>10 years</b>	<b>20 years</b>	<b>35 years</b>	<b>40 years</b>	<b>Ref</b>
<b>10 years</b>	<b>1</b> (24)				
<b>20 years</b>	<b>0.41</b> (11)	<b>1</b> (30)			
<b>35 years</b>	<b>0.39</b> (19)	<b>0.43</b> (18)	<b>1</b> (54)		
<b>40 years</b>	<b>0.43</b> (18)	<b>0.42</b> (19)	<b>0.60</b> (34)	<b>1</b> (60)	
<b>Ref</b>	<b>0.24</b> (8)	<b>0.25</b> (9)	<b>0.38</b> (18)	<b>0.37</b> (19)	<b>1</b> (42)



**Figure 8.6:** PCA ordination plots of sites based on species composition and abundance data; (a) tailings of different ages and reference sites, (b) plots under canopies of planted trees(DT) and adjacent intercanopy controls (DC); D2= 40 year-old tailings; D6= 20 year-old tailings. The number at the end denotes plot replicate; Ts denotes tree number. Red outlines show four main groups; Black dashed and solid outlines in side main groups show further separation of control plots by substrate age.

### 8.3.3 Changes in species importance values (SIVs) on a chronosequence of nickel tailings dumps

Species importance value (SIV) showed four distinct trends: (1) a significant increase with tailings age (e.g. grasses *Aristida adscensionis*, *Chloris gayana*, *Venonia* spp., *Diheteropogon amplexans*, *Heteropogon contortus* and a forb *Clotalia ochlorea*; (Fig 8.7a), (2) declining to 35 years and increasing thereafter (e.g. *Senegalia polyacantha*, *Cynodon dactylon* and *Tagetes minuta*; Fig 8.7b), (3) appeared at 10 years, absent at 20 years and reappeared and increased thereafter (e.g. the forbs: *Polygala albida* var *albida*, *Bidens pilosa*, *Asteraceae* spp., *Gigeria* spp. and *Pennisetum setaceum*; Figure 8.7c), and (4) fluctuating trends for species such as *Diheteropogon amplexans*, *Imperata cylindrica*, *Hyparrhenia filipendula*, *Andropogon chinensis*, *Gigeria schinzii* (Fig 8.7d). All in all, species with highest importance values on the youngest dump were *Cynodon dactylon* (SIV= 62.0), *Imperata cylindrica* (SIV= 40.3), *Hyparrhenia filipendula* (SIV= 35.2), *Andropogon chinensis* (SIV= 18.2) and *Penisetum setaceum* (SIV = 12.4). Five species that had the highest importance values on the oldest dump (40 years) were *Hyparrhenia filipendula* (SIV= 74.2), *Heteropogon contortus* (SIV= 20.9), *Imperata cylindrica* (SIV= 13.3), *Andropogon chinensis* (SIV= 12.2) and *Penisetum setaceum* (SIV= 11.5). Most pioneer forbs were absent at 20 years but reappeared and at high SIV values thereafter while grasses either increased or significantly fluctuated. Overall, grasses had higher importance values on both young and older tailings dumps than forbs.



**Figure 8.7:** Changes in species importance values on a chronosequence of nickel tailings : (a) Species showing an increasing trend, (b) Species declining with age to 35 years and increasing thereafter, (c) species present at 10 years and disappear at 20 years before reappearing and increasing thereafter and (d) Species showing a fluctuating trend.

### 8.3.4 Physicochemical properties of tailings and their relationship with vegetation structural attributes

Clay content was similar ( $P > 0.05$ ) for all dumps except the youngest (10 years) that had a significantly lower value ( $P < 0.05$ ; Table 8.2). Silt content had no distinct trend while sand content, EC and pH were similar across all tailings dumps (Table 8.2). Total N, mineral N and OM significantly increased ( $p < 0.05$ ) while bulk density significantly decreased with tailings age (Table 8.2). Available P was similar for the three youngest dumps (10, 20 and 35 years) but was significantly higher on the oldest dump (40 years). Exchangeable Ca and K were similar across all tailings dumps (Table 8.2).

The sites under canopies of planted trees had significantly ( $p < 0.05$ ) lower bulk density, higher clay and silt content than the inter-canopy control sites. Mineral N, Total N, available P, and O.M were significantly higher on sites under tree canopies than inter-canopy plots. However, EC, pH and exchangeable K did not vary between canopy and inter-canopy sites while exchangeable Ca and BC cover were significantly higher on inter-canopy sites (Table 8.3).

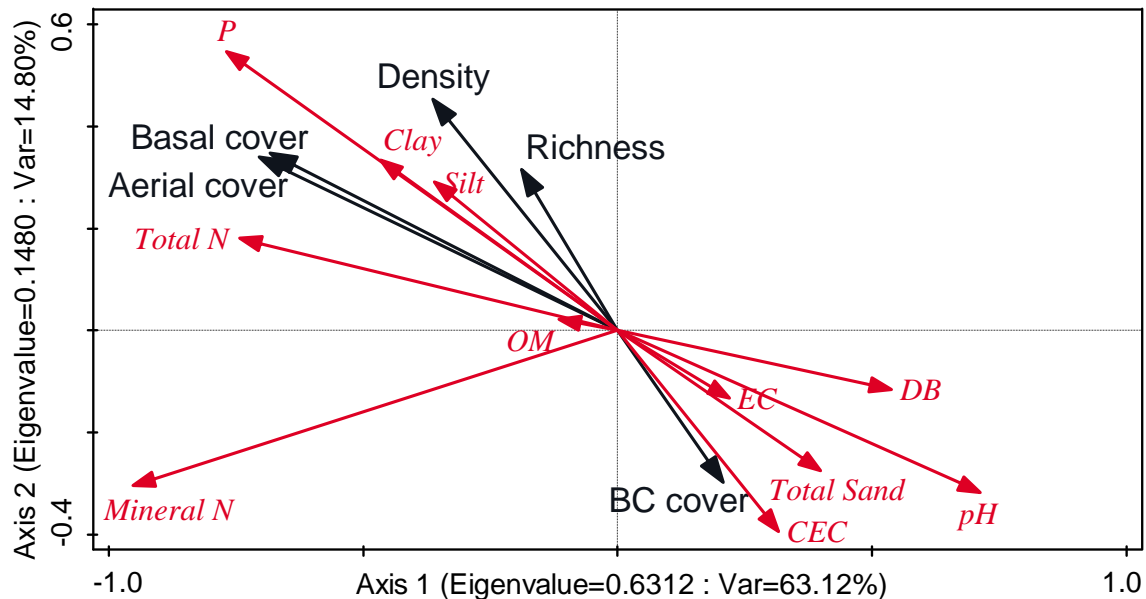
A PCA showed a strong positive correlation between vegetation structural attributes (aerial cover, basal cover, species richness and density) and substrate total N, mineralizable N, OM, clay and silt content. Vegetation structural attributes were however strongly negatively correlated to pH, EC, CEC, bulk density and sand content (Fig 7.8). Biological crust cover was negatively correlated with vascular plant cover and richness but positively correlated to pH, EC and bulk density (Fig 8.8).

**Table 8. 2:** Variation of physicochemical properties on a chronosequence of rehabilitated nickel tailings (N=16). Bars with different letters indicate significant differences ( $P < 0.05$ ). All test were one way ANOVA at 95 % level of significance

	<b>10 years</b> <b>(Mean±SE)</b>	<b>20 years</b> <b>(Mean±SE)</b>	<b>35 years</b> <b>(Mean±SE)</b>	<b>40 years</b> <b>(Mean±SE)</b>
Clay (%)	2.80±0.37 <sup>a</sup>	4.60±0.87 <sup>b</sup>	5.20±0.58 <sup>b</sup>	5.60±1.21 <sup>b</sup>
Silt (%)	12.20±1.77 <sup>a</sup>	12.60±1.08 <sup>a</sup>	19.00±1.23 <sup>b</sup>	18.80±2.58 <sup>b</sup>
Sand (%)	85.80±2.20 <sup>a</sup>	79.80±2.65 <sup>a</sup>	76.80±2.76 <sup>a</sup>	75.80±2.13 <sup>a</sup>
Bulk density (g/cm <sup>3</sup> )	1.8±0.27 <sup>a</sup>	1.6±0.32 <sup>b</sup>	1.1±0.18 <sup>c</sup>	1.0±0.32 <sup>c</sup>
pH (CaCl <sub>2</sub> )	8.00±0.00 <sup>a</sup>	7.60±0.25 <sup>a</sup>	7.80±0.20 <sup>a</sup>	8.00±0.00 <sup>a</sup>
EC(mS/cm)	4.00±0.00 <sup>a</sup>	3.80±0.20 <sup>a</sup>	4.80±0.37 <sup>b</sup>	4.00±0.00 <sup>a</sup>
Organic Matter (%)	0.8±0.25 <sup>a</sup>	1.42±0.64 <sup>b</sup>	1.90±0.20 <sup>c</sup>	1.80±0.25 <sup>c</sup>
Total N (%)	0.04±0.02 <sup>a</sup>	0.08±0.02 <sup>b</sup>	1.18 ± 0.22 <sup>c</sup>	1.68 ± 0.16 <sup>d</sup>
Mineral N (ppm)	9.20±4.07 <sup>a</sup>	19.00±3.70 <sup>b</sup>	11.00±4.81 <sup>a</sup>	16.20±2.92 <sup>ab</sup>
Available P(ppm)	4.40±0.75 <sup>a</sup>	5.80±1.20 <sup>a</sup>	5.40±0.93 <sup>a</sup>	10.80±2.35 <sup>b</sup>
K (mg/100g)	1.00±0.00 <sup>b</sup>	2.00±0.32 <sup>a</sup>	1.40±0.24 <sup>a</sup>	1.60±0.31 <sup>a</sup>
Ca (mg/100g)	10.20±1.16 <sup>a</sup>	8.80±1.36 <sup>a</sup>	8.80±1.20 <sup>a</sup>	8.20±1.16 <sup>a</sup>

**Table 8.3:** Variation of physicochemical properties on sites under canopies of planted trees and adjacent-off-canopy sites. Bars with different letters indicate significant differences ( $P < 0.05$ )

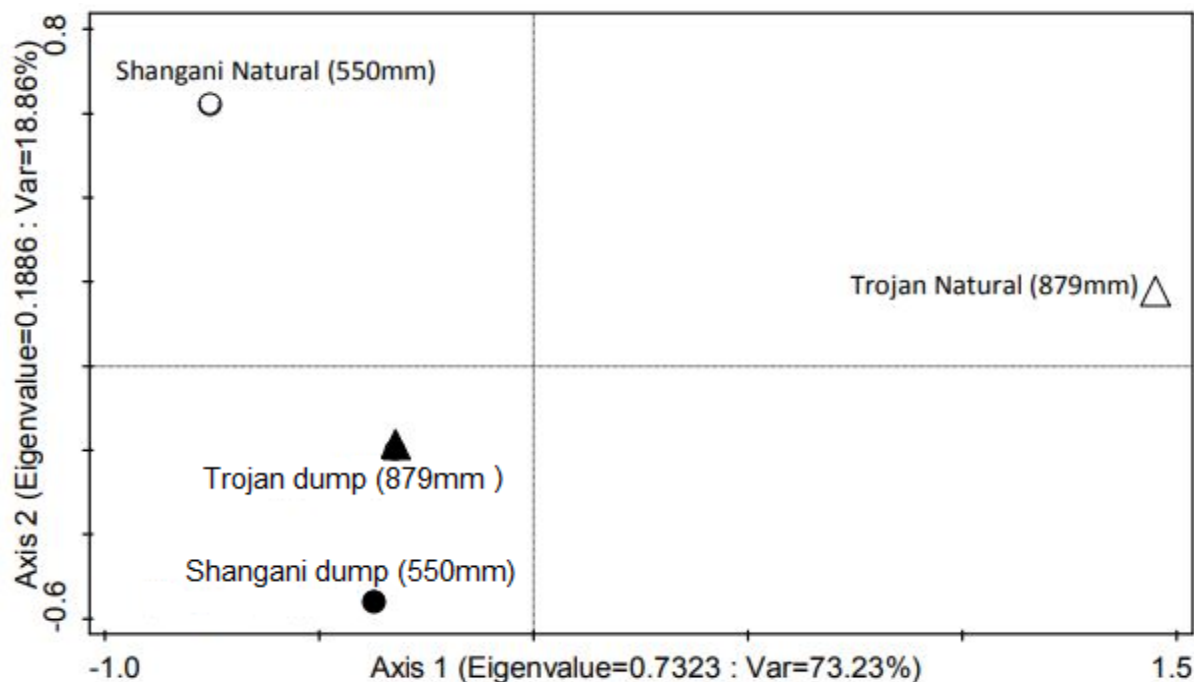
PARAMETER	20 years		40 years	
	Canopy (Mean±SE)	Inter-canopy (Mean±SE)	Canopy (Mean±S.E)	Inter-canopy (Mean±SE)
Clay (%)	5.8±1.3 <sup>a</sup>	3.1±0.7 <sup>b</sup>	5.6±1.2 <sup>a</sup>	2.8±0.4 <sup>b</sup>
Silt (%)	24.8±4.1 <sup>a</sup>	19.0±4.6 <sup>a</sup>	18.8±2.6 <sup>a</sup>	12.2±1.8 <sup>b</sup>
Fine sand (%)	60.8±4.4 <sup>a</sup>	27.8±4.4 <sup>a</sup>	66.8±2.1 <sup>a</sup>	73.8±2.2 <sup>a</sup>
Medium sand (%)	10.0±0.6 <sup>a</sup>	98±0.1 <sup>a</sup>	7.8±1.8 <sup>a</sup>	10.8±2.7 <sup>a</sup>
Coarse sand (%)	0.5±0.4 <sup>a</sup>	0.3±0.2 <sup>a</sup>	0.4±0.4 <sup>a</sup>	0.2±0.0 <sup>a</sup>
Bulk density	1.4±0.4 <sup>a</sup>	1.7±0.6 <sup>b</sup>	1.3±0.2 <sup>a</sup>	1.6±0.6 <sup>b</sup>
pH (CaCl <sub>2</sub> )	7.7±0.3 <sup>a</sup>	8.3±1.2 <sup>a</sup>	7.8±0.5 <sup>a</sup>	8.5±0.6 <sup>a</sup>
EC(mS/m)	4.00±0.00 <sup>a</sup>	3.80±0.20 <sup>a</sup>	4.80±0.37 <sup>a</sup>	4.00±0.00 <sup>a</sup>
OM (%)	1.4±0.4 <sup>a</sup>	0.8±0.5 <sup>b</sup>	1.8±0.2 <sup>a</sup>	1.3±0.3 <sup>a</sup>
Mineral N (mg/kg)	8.1±1.3 <sup>a</sup>	5.4±1.5 <sup>b</sup>	15.1±3.1 <sup>a</sup>	9.3±3.5 <sup>b</sup>
Total N (%)	0.2±0.04 <sup>a</sup>	0.1±0.02 <sup>b</sup>	0.36±0.20 <sup>a</sup>	0.22±0.18 <sup>b</sup>
Ava P (mg/kg)	8.2±1.2 <sup>a</sup>	5.4±0.7 <sup>b</sup>	11.2±0.2 <sup>a</sup>	5.2±0.7 <sup>b</sup>
K (mg/100g)	4.3±0.9 <sup>a</sup>	4.7.8±0.6 <sup>a</sup>	2.3±0.2 <sup>a</sup>	3.0±0.6 <sup>a</sup>
Ca (mg/100g)	10.3±3.5 <sup>a</sup>	9.6±3.8 <sup>a</sup>	8.6±1.4 <sup>a</sup>	10.4±1.3 <sup>a</sup>
Mg (mg/100g)	0.06±0.02 <sup>a</sup>	0.05±0.03 <sup>a</sup>	1.7±0.3 <sup>a</sup>	1.3±0.0 <sup>a</sup>
BC cover (%)	6.1.4±0.65 <sup>a</sup>	8.7±0.4 <sup>b</sup>	5.4±1.8 <sup>a</sup>	10.8±3.5 <sup>b</sup>



**Figure 8.8:** PCA ordination biplot showing correlation among vegetation structural attributes and tailings physicochemical properties. Total variation= 24.1; Gradient length= 0.4 SD units.

### 8.3.5 Plant structural and compositional attributes on tailings in contrasting climate

A PCA ordination plot based on plant species composition showed that rehabilitated tailings sites in contrasting rainfall regions grouped together to the left of the first axis, showing high similarity. However, the tailings in both climatic regions were distinct from their adjacent reference sites, which occurred on the upper part of the second axis (Fig. 8.9). On the contrary, reference sites in contrasting climatic regions were distinct in terms of plant communities as the sites occurred on opposing ends of the first axis (Fig. 8.9).



**Figure 8.9:** A PCA monoplot based on species composition showing grouping of rehabilitated nickel tailings sites relative to adjacent reference sites in contrasting climatic regions.

### 8.4 Discussion

This study had a unique approach, in that it examined the combined trajectory of plant structural and compositional attributes and substrate physicochemical properties on a chronosequence of mine tailings, in conjunction with examination of micro-scale effects of the planted species as well as interrogating the influence of climate on revegetation trajectory. The study had six main findings: (1) herbaceous plant cover, species richness and diversity significantly increased with age of tailings, at 20 years exceeding values observed at the reference sites, with grasses significantly dominating other growth forms; (2) ordination analysis showed that from 10 to 40 years, plant communities increasingly diverge from reference conditions in terms of composition in support of the novel ecosystem hypothesis. Trends of species importance values were taxa-dependent; (3) plant communities under canopies of planted trees



were different from those from adjacent control sites, although those under canopies were similar despite differences in dump age, (4) Total N, mineral N and OM significantly increased while bulk density significantly decreased with tailings age, while texture, exchangeable bases and EC were generally similar across dumps but sites under canopies of planted trees had higher plant cover, finer particles, total N, available P and OM and significantly lower bulk density and BC cover than inter-canopy control plots, (5) A PCA showed a strong positive correlation between vegetation structural attributes and substrate total N, available P, OM, clay and silt content and a negative correlation with bulk density, pH, EC and BC cover, and, (6) climate differences did not influence vegetation communities on rehabilitated tailings, unlike on natural reference sites.

#### **8.4.1 Trajectory of vegetation structural and diversity attributes**

The significant increase in herbaceous cover and species richness that equaled or exceeded values observed at reference sites at 20 years might be attributed to the observed temporal changes in tailings physicochemical properties. In particular, the PCA results suggest temporal increases in substrate total N, available P and fine particles and decrease in bulk density were the main determinants of the observed vegetation attributes.

The significant increase in plant species richness and vegetation cover on the tailings dumps can be attributed to observed dynamics in N concentration in the substrate. Nitrogen is an essential macronutrient for plant growth (Nyamangara, 2011; Brady and Weil, 2013), however, it is not a typical constituent of mineral ores and is therefore nearly absent in young tailings like the 10-year-old dump which are essentially ground parent material with residual chemicals from processing. The low N levels in the tailings as observed on the 10-year-old dump are insufficient to support establishment and growth of a variety of plant species and therefore this could explain the lower species richness, diversity and lower plant cover on the youngest dump. This means only a few species such as *Imperata cylindrica* and *Cynodon dactylon*, which can thrive in such conditions would colonize the tailings, as observed, and contribute to the plant cover. The observed increases in species richness and plant cover over time can therefore be attributed to a gradual build-up of N pools, most probably due to biotic additions by nitrogen fixation from growing planted trees, naturally colonizing vegetation, decomposition of deposited plant litter, free-living microorganisms and atmospheric deposition. The introduced plants were mainly leguminous members of the *Vachellia* genus and some naturally colonizing legumes such as *Sesbania sesban* that have the ability to fix nitrogen and transfer that to the soil through litter production and decomposition (Chang and Turner, 2019). This improvement in substrate N in turn boosts growth of other colonizing plants which then increase their cover and therefore this is likely to have contributed to the observed increases in overall aerial cover with tailings age. In addition, over time, the planted trees and

naturally colonizing plants shed plant material such as leaf litter or incorporate dead roots into the soils. The decomposition of such material also releases N into the substrate matrix which will in turn be taken up by plants, contributing to higher cover (Wang *et al.*, 2018; Chang and Turner, 2019). In the present study it was observed that some frequencies of pioneer species such as the forbs *B. pilosa*, *T. minuta* and *Asteraceae* spp. declined up to 20 years, however, it is likely that their remains and subsequent decomposition adds N to the substrate. The higher N concentration also would promote the establishment of plant species that require higher N levels to establish which in turn may increase species richness over time as observed in the present study. Higher N, along with low compaction as observed on older dumps are known to promote species richness and plant establishment (Nyamangara, 2000). In a related study on a chronosequence of unrehabilitated gold tailings at a mine adjacent to the current study site (Chapter 3), N and P were found to increase with tailings age and were significantly positively correlated to plant cover. The results are also consistent with reports by Khumar and Patel (2013) who observed N-related increases in vegetation cover and species richness on mine wastes in India. Consistent with our findings, Wang *et al.*, (2018) observed nutrient-dependent vegetation cover improvement on a chronosequence of gold tailings in China owing to nutrients increasing over time, which is attributable to enhanced pedogenetic processes.

The observed negative correlation between substrate bulk density and vegetation attributes along with the observed decrease in bulk density with the increase in tailings age suggests changes in substrate compaction might also have influenced the observed trajectory of vegetation attributes. Higher bulk density observed on younger dumps and on inter-canopy patches of the 20 and 40- year-old dumps can inhibit emergence of plant seedlings and discourage root penetration, resulting in poor vegetation structure and stunted growth (Onweremadu *et al.*, 2008; Kormanek *et al.*, 2015; Wang *et al.*, 2018). Higher bulk density discourages soil aeration and water infiltration, which in turn hinders microbial activity, resulting in low nutrient release and plant productivity (Wang *et al.*, 2018). Over time, bulk density decreased, most probably owing to root action and organic matter deposition by spreading pioneer plants and the planted plants, creating favourable conditions for establishment of previously inhibited species. This may also explain the higher species richness associated with older dumps and sites under canopies of planted trees that had lower bulk density values. Consistent with our findings, temporal decrease in bulk density has been reported to be a key determinant of vegetation development on mine wastes (Wali, 1999; Borden and Black, 2005; Wang *et al.*, 2018). In particular, bulk density values greater than 1.4 mg/cm<sup>3</sup> as observed on the 10 and 20 year tailings dumps are reported to inhibit root and overall plant growth on silt and sandy soils, similar to the nickel mine tailings (Chaudhari *et al.*, 2013). The observed vegetation trends can also be attributed to observed OM dynamics; plant OM can help in moisture retention, shading, cation exchange, harbor microbes, contribute to nutrient cycling, and provide microbes with energy, which in turn can promote plant growth (Duruibe, 2007).

The observed increase in species richness and vegetation cover over time is consistent with findings from a related study on a chronosequence of gold tailings at an adjacent mine (Chapter 6) where these vegetation structural attributes on dumps of similar age ranges (10, and 30 years) increased although longer periods were required to match vegetation structural attributes in reference conditions. Higher values of vegetation cover and species richness were however obtained on the 40-year chronosequence on rehabilitated tailings in this study than on a similar chronosequence of unrehabilitated gold tailings from an adjacent gold mine (Chapter 6). The relatively shorter period obtained to match structural attributes of the reference site in the present study could be attributable to the positive effect of planted leguminous trees on natural revegetation related to their proven effect on hydrological and nutrient fluxes (Van Wyk and Van Wyk, 2013). In particular, concentrations of key macronutrients, N and P were higher on the nickel tailings than the gold tailings dumps (Chapter 3). More so, the rehabilitated tailings in this study had pH ranges of 7-8 for the 10-40-year-old dumps while on the gold dumps, the observed pH ranges from tailings dumps of similar ages were acidic (3-6 range). The more neutral pH on nickel tailings are known to support nutrient uptake by plants, resulting in better growth (Brady and Weil, 2013). This therefore might alternatively account for the shorter periods to reach reference structural attributes on the nickel chronosequence compared to the gold tailings. The results are consistent with findings by Skousen *et al.* (1988; 1994), where shorter periods of around < 30 years were shown to attain peak vegetation cover on rehabilitated substrates. However, observed continuous increase in species richness and cover, which exceeded values in natural reference sites, is to a large extent inconsistent with results from Skousen *et al.* (1988), who reported an increase in herbaceous vegetation structural attributes with mine site age up to 25 years but declined thereafter before reaching reference levels. In the present study, herbaceous cover increased continuously up to 40 years and exceeded the natural reference values beyond 20 years. These differences might be because in the case of Skousen *et al.* (1988), the mined sites had a soil cover layer different from mine tailings that supported the establishment of woody species that suppressed herbaceous species, unlike the present study which had only the planted woody species.

However, despite the increasing trend in many structural attributes, attainment of statistically similar values of vegetation structural attributes on the 20, 35 and 40 year-old- dumps suggests vegetation recovery following reclamation by planting leguminous *Acacia* species is accelerated and can converge with reference levels regardless of starting point. In effect results underline the importance of active reclamation by planting trees in breaking temporal barriers in revegetation of unique anthropogenic sites. This is a new insight into the rate and direction of plant structural changes on unique metalliferous sites such as mine tailings which can greatly contribute to the development of revegetation theories. The observed delayed attainment of species richness comparable to reference sites at 35 years suggest colonization by different species may be slow and that at 35 years substrate factors would be significantly different: higher nutrient values (N, P) and OM content and lower bulk density values are attained. The

increase of herbaceous species richness beyond reference values from 35 years demonstrates the capability of the reclamation process to drive ecosystem composition to beyond pristine conditions. This is a key insight that can contribute to expansion of existing theories.

#### 8.4.2 Trajectory of plant composition and diversity

Although the Shannon diversity index for all dumps either equalled or exceeded those for references, the low evenness on all dumps can be attributed to higher species dominance effect across all dumps most likely related to traits specific to certain species, increasing tolerance to adverse substrate factors. Firstly, only a few species (*Cynodon dactylon*, *Imperata cylindrica* and *Andropogon chinensis*) out of the 24 that colonized the youngest dump managed to increase in frequencies as others were inhibited by hostile substrate conditions. These species have been reported to withstand low nutrient, dry and saline environments such as mine wastes and other disturbed sites (Piha *et al.*, 1995a, Shu *et al.*, 2005; Van Oudtshoorn, 2014; Festin *et al.*, 2018). Their dominance can therefore be attributed to their tolerance of low nutrient environments typical of relatively fresh tailings as observed. Such traits make them key pioneer species which could thrive in environments that are normally hostile (in this case low N, P and high bulk density) to other species that emerged later. The dominance of such species also could be attributable to their dual means of reproduction (Van Oudtshoorn, 2014). *Andropogon chinensis*, *Imperata cylindrica* and *Cynodon dactylon* produce small and very light seeds that are easily dispersed, making them easier to spread, and that might have contributed to the observed temporal increase in vegetation cover. The rhizomatous strategy might also have assisted the spread of *Cynodon dactylon* and *Imperata cylindrica*; the main plants feed the tillers even under nutrient stress (Shu *et al.*, 2005), and that may have contributed to the observed temporal increases in cover and stem densities, and hence importance values. This allows them to outcompete other species that only spread following maturation and seed production. *Imperata cylindrica* has sharp thorny shoots, a trait that likely to make them withstand emergence in compacted substrates more than other species.

Species composition on older dumps (35 and 40 years) shifted to dominance by *Hyparrhenia filipendula* and *H. contortus* and to a greater extent, *Imperata cylindrica* which had higher species importance values. Two mechanisms that can explain such dynamics are facilitation and competitive exclusion. Firstly, as observed in the present study, some pioneer species persisted until 20 years while others colonized and increased in importance value most probably due to the facilitation effect of pioneer species. Conventional floristic relay models assert that pioneer species improve substrate conditions and facilitate the establishment of mid-succession species which may explain the separation of the sites on an ordination plot. However, the decline in importance values of *Andropogon chinensis* and *Cynodon dactylon* on the older dumps suggest they were competitively excluded by other species such as *H.*

*filipendula* and *H. contortus*, which had higher SIVs over time. This in turn may as well explain the observed differences in plant communities among the dumps.

Nevertheless, the patterns of separation of the sites on an ordination plot where increased dissimilarity with references increased with age (Fig 8.6a) demonstrate the importance of reclamation and planting of trees in determining the trajectory of vegetation development on mine tailings. As observed the reclamation and planting of trees accelerated nutrient accumulation and herbaceous species establishment attaining levels beyond pristine conditions in terms of richness and diversity. This however must not be entirely taken as a pure improvement as woody species were largely missing on the mine tailings contrary to the reference site. However, the separation of the older dumps (35 and 40 years) from the younger dumps (10 and 20 years) on the PCA plot, despite receiving similar reclamation suggests the influence of substrate to response to reclamation. While the dumps were rehabilitated at generally similar times, the results suggest the effects of tree planting on facilitating natural revegetation is seemingly a gradual process which does not yield similar results for relatively fresh and older substrates. This is most probably due to gradual effect on nutrient fluxes through the substrate. Such effects could be more apparent in older substrate (35 years and 40 years). Moreover, according to the Sorensen indices of similarity, most species colonizing the dumps were not found in the adjacent reference site, further contributing to the observed dissimilarity among all dumps and the reference site. This may also suggest the species from the adjacent reference that could not colonize the tailings either do not tolerate the substrate conditions or had dispersal limitations (Chan and Turner, 2019). The dispersal capability and or specific substrate tolerances were however outside the scope of the present study.

Further the observed separation of the 35 and 40 year-old- dumps along PCA axis 2 despite being in the same age range further dispels the theory of compositional convergence. The results appear to suggest the influence of other factors (not related to substrate age), which were however not covered within the scope of this study. Such factors could be the effect of invasive species such as *Lantana camara* and *Acacia saligna* that colonized the 35- year-old dump more extensively than the 40-year-old-dump. While such species add organic matter, they are known to have allelopathic effects on other plants, a situation that may have contributed to compositional differences. This difference from observations in an unrehabilitated gold chronosequence (Chapter 6) can be attributed to the absence of such invasive species on the gold tailings. The higher similarity of younger dumps and the reference than the older dumps seem to suggest the references may provide propagules for initial colonization but these will not persist, most probably due to initial hostile conditions. Consistently, the study noted the disappearance of some pioneer species after 10 years, suggesting they could not persist, although the trends can also be suggestive of a natural process where pioneer species naturally disappear and replaced by others.

However, considering the fluctuating frequencies and importance values of some species, it cannot be concluded with certainty that the plant communities had ceased to develop, or development had slowed

down. Hence the plant communities may still be heading towards a reference site owing to continued changes in substrate substrate and biogenic factors. This may suggest that the concept of novel ecosystems as end-points may not be confirmed with certainty though evidence suggests that trajectory. Longer chronosequences would assist in confirming this theory. In light of this, results suggested that either more than 40 years are required to attain plant communities similar to that of reference sites or novel ecosystems are likely be formed. Earlier studies used chronosequences ranging in ages from 20 years to decades. In some shorter chronosequences studied e.g. 35 years, formation of plant communities distinct from references were observed from 35 years and above in USA (Holl and Cairns, 1994; Holl., 2002). Results therefore seem to suggest assisted and natural recovery within 10-40 years (Chapter 6) follow same revegetation trajectories on structural attributes but different trajectories compositionally relative to natural reference sites.

Further, the grouping of tailings sites from contrasting climatic regions and their failure to converge with reference sites in both regions suggests the importance of substrate and reclamation type in shaping plant species composition on mine tailings. Nickel substrates may be distinctive and regardless of climatic differences they can support only specific plant species. These nickel tailings had pH and magnesium values that are higher than in most soils. On the other hand, the introduction of plants on dumps have ameliorative effects that may break the barriers introduced by climatic factors, since in a related study (Chapter 7) such climatic differences yielded different plant communities on unrehabilitated gold tailings dumps. The study therefore brings the following new insights into restoration ecology: (1) the need to consider influence of reclamation types in revegetation trajectories both in direction and time and, (2) trajectories for structural and compositional attributes may differ and hence the need to consider such factors in developing revegetation theories. Traditionally, where novel ecosystems are discussed compositional attributes are mainly used, such as species presence and absence data without paying much attention to structural attributes. This study therefore underlines the importance of considering structural attributes in developing revegetation theories. A new hypothesis that, "rehabilitation through tree planting creates nutrient and biodiversity hotspots on tree planting stations", has been generated.

#### **8.4.3 Influence of climate on revegetation of rehabilitated mine tailings**

PCA ordination results showed that based on plant species composition, rehabilitated tailings in contrasting climatic regions grouped together, showing high similarity, but both were clearly distinct from their adjacent reference sites. The results suggest that a climatic difference of more than 300 mm difference in rainfall may not be enough to separate plant communities. The tailings could have unique physicochemical properties that are overriding a climatic effect, owing to similarities in the ore and mineral processing methods. These could be very hostile for a number of plants whose seeds may arrive within

the tailings dump area and only species with adaptive traits would be able to colonize these tailings dumps. The same reclamation procedures could also have countered the potential effects of climatic gradients. The study results are inconsistent with findings from a related study on unrehabilitated gold tailings where plant communities on tailings in the same region receiving a total annual rainfall of 550 mm were distinct from those receiving 879 mm (Chapter 7). The results are also inconsistent with what was reported by earlier studies that reported the importance of substrate factors on unique sites than climate and general landscape factors (Rajakaruna *et al.*, 2014; Prach and Walker, 2019). The differences could be due to the unique nature of the tailings substrate as other studies were done on non-anthropogenic substrates, i.e. soils.

#### **8.4.4 Comparison of understory and inter-canopy vegetation and substrates**

At micro-scale, the higher plant cover, finer particles, total N, available N and OM and significantly lower bulk density and BC cover on under –canopy plots than inter-canopy control plots can be attributed to the positive effect of planted leguminous species on tailings substrate, which in turn promoted plant establishment. The planted *Vachellia Karoo*, *Senegalia polyacantha* and *Vachellia tortilis* trees can create suitable micro-sites for plant establishment due to their influence on nutrient fluxes and soil hydrology (Mukaro *et al.*, 2017). In particular, such species are legumes known to fix nitrogen in the soil which in turn promotes vegetation growth (Vandrs, 2002). Decomposition of deposited leaf litter also adds N, P and carbon which in turn promote microbial activities, nutrient cycling and nutrient availability for uptake by plants (Shrestha and Lal, 2006). Incorporation of leaf litter into the surface tailings coupled with the interception of raindrops by tree canopies reduce compaction of the tailings, resulting in the observed low bulk density, that in turn promote seed emergence and plant growth (Alday *et al.*, 2012). Over time, the planted trees, could also have facilitated the establishment of less tolerant species through creation of micro-sites with reduced surface temperature and better moisture retention, and is capable of trapping seeds and nutrients. Further, the organic matter input from the litter of planted trees may help to stabilize the tailings surface and allow for improved wind-borne sediment and seed interception (Bradshaw, 2000). Such micro-conditions could have promoted the establishment of other plant species that contributed to the observed higher species richness and understory vegetation cover. In support, the study results show enhanced N, P and OM and declining bulk density under tree canopies. Consistent with our findings, Alday *et al.* (2012; 2014) observed improved nutrients and species richness and cover following reclamation by tree planting on coal waste in Spain.

Overall, findings from the study showed that rehabilitation has an acceleratory effect on vegetation development when compared to spontaneous revegetation. Nevertheless, reclamation does not alter the trajectory of structural attributes but, rather composition. In light of existing literature and findings from a



related study on rehabilitated gold tailings, the study generated a new hypothesis: “revegetation trajectories in relation to reference sites is dependent on substrate age and reclamation type”.

## **8.5 Conclusion and recommendation**

The study concluded that rehabilitation accelerates recovery of vegetation structural attributes relative to spontaneous revegetation but does not necessarily alter the divergent trajectory. On the contrary, the study suggests rehabilitation by planting *Vachellia* and *Senegalia* trees and early artificial nutrient application may promote a divergent trajectory compositionally. The study therefore suggests that vegetation structural and compositional attributes do not completely follow the same trajectory during succession on rehabilitated mine tailings. In particular, the results support the hypothesis that structural attributes converge to conditions at reference sites as tailings age. On the contrary, ordination results for species composition do not support the hypothesis that plant communities converge towards a reference conditions, but rather appear to uphold the emerging theory of formation of novel ecosystems. Climatic differences may also be overridden by reclamation in shaping vegetation community composition on nickel tailings. The vegetation changes were mainly correlated to total N, OM, silt content, clay content and bulk density. The results may be limited though with the short length of the chronosequence. In light of existing literature and findings from a related study on unrehabilitated gold tailings, the study generated a new hypothesis that revegetation trajectories in relation to reference sites is dependent on substrate age and reclamation type. The study recommends carrying out similar studies with different mine tailings substrate and across many sites, representing longer chronosequences.



## CHAPTER 9

### GENERAL DISCUSSION AND SYNTHESIS

#### 9.1 Introduction

Understanding trajectories of vegetation and soil development is critical for ecosystem restoration on mine tailings. Despite the existence of significant literature on succession and restoration trajectories, which have generated contrasting views on convergence to natural references or divergence to novel ecosystems, such studies have been widely tested in secondary succession, with only a few testing these contrasting theories in a primary succession on anthropogenic soils (Chan and Turner, 2019). A key knowledge gap is which trajectories apply to unique substrates like mine tailings, and, whether the trajectories vary for tailings completely left for spontaneous revegetation and those actively rehabilitated, rendering the generalization of these theories questionable. Although the few studies acknowledge the individual influence of factors such as substrate age, climate, nutrients, toxicity, dispersal capability (Walker and del Moral, 2009; Higgs *et al.*, 2016; Chan and Turner, 2019), there is little empirical evidence based on multifactorial approaches on unique anthropogenic sites. Studies that test succession theories within a restoration framework on unique anthropogenic substrates, simultaneously investigating individual and interactive effects of substrate, time, topographic, climatic, biotic factors and management history in a succession remain limited. Further, studies that simultaneously investigate the trajectory of multiple ecosystems components such as all growth forms of vascular plants, biota such as BCs and soil in a succession on mine tailings are limited. This hinders the generalization and adoption of lessons learnt into the restoration of unique anthropogenic sites. The current study was conducted against this background and attempted to address these knowledge gaps.

The study investigated: (1) changes in selected substrate physicochemical properties on a chronosequence of abandoned gold tailings in relation to adjacent reference conditions, as proxies of soil development in Chapter 3, (2) physicochemical properties of biocrusts and layers beneath them in comparison with non-bio-crusted patches in Chapter 4, (3) occurrence patterns of biological crusts and their relationship with vegetation attributes on a chronosequence of gold tailings in Chapter 5, (4) the trajectory of natural revegetation on a chronosequence of gold mine tailings, testing the emerging novel ecosystem theory and identification of key substrate correlates (Chapter 6), (5) the trajectory of assisted revegetation on a chronosequence of rehabilitated nickel tailings and identifying substrate correlates (Chapter 8) and, (6) The influence of substrate age and climatic gradient on revegetation of unrehabilitated and rehabilitated mine tailings (Chapters 7 and 8).

The study tested seven main hypotheses: (1) plant macronutrients (N, P, K), OC, organic matter and fine particles content increase with tailings age and approach reference levels and that pH, EC and bulk density decrease with age of mine tailings, (2) physicochemical properties of bio-crusts areas are significantly different from those of areas without, (3) BC cover significantly increased with tailings dump age and was positively correlated to vegetation cover, species richness, density, (4) vegetation communities significantly varied along a BC cover gradient, (5) Due to the uniqueness of the substrate, natural revegetation of gold tailings is towards formation of novel plant communities as vegetation attributes do not converge to natural reference conditions, (6) vegetation structural and compositional attributes on rehabilitated mine tailings converge to natural references faster due to the accelerating effect of rehabilitation and, (7) climatic gradients have significant effect in shaping plant structural and compositional attributes on unrehabilitated and rehabilitated mine tailings.

## 9.2 Key findings of the study

Key findings from the study are:

(1) Trajectories of physicochemical properties during pedogenesis on mine tailings are not uniform, rather element specific (Chapter 3). Macronutrients (total N and available P) in the top 15 cm layers increased with age of tailings and approached reference conditions within a 110 year- period but not for the deeper layers. Bulk density decreased with tailings age as hypothesized. Contrary to what was hypothesized, texture on mine tailings does not significantly change. Other parameters such as pH, EC and exchangeable bases fluctuated over time, consistent with a divergent trajectory. (2) As hypothesized, areas covered by BCs had higher pH, total N, OC, exchangeable bases and fine particles than those without (Chapter 4).

(3) Tailings were colonized by four morphological forms of BCs (algae, cyanobacteria, lichens and mosses whose total cover significantly increased with age of tailings up to 92 years and decreased thereafter (Chapter 5). Young tailings are initially dominated by cyanobacteria and green algae-dominated BCs, which decrease with dump age as they are replaced by lichen and moss-dominated BCs, (4) the relationship between BCs and vegetation structural attributes is succession stage dependent, where it is a positive correlation (facilitative) in early succession but becomes negative (inhibitive) or neutral in late succession, and (6) vegetation communities varied along a BC cover gradient (Chapter 5).

(7) Vegetation structural and compositional attributes on tailings left to natural succession move towards reference conditions; structural attributes take shorter periods, dispelling the novel ecosystem theory (Chapter 6). (8) The findings from the study did not support the initial floristic composition hypothesis that assert that pioneer species persist to late succession phases through coexistence with mid and late-succession plants, rather, appear to support the “floristic relay model” of species succession as most pioneer species were absent or had significantly low covers in the late succession stages (Chapters 6

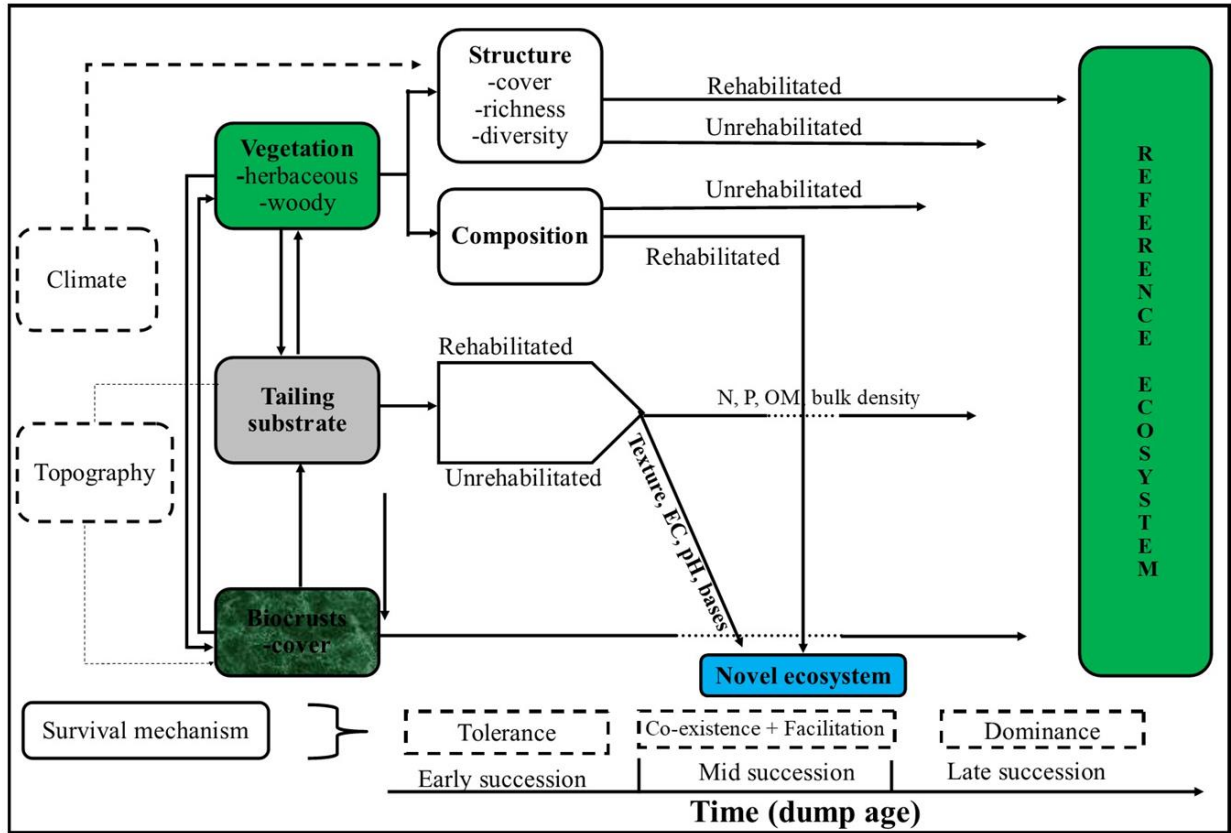
and 8). (9) Vegetation structural attributes were closely correlated to changes in substrate properties, in particular pH, total N, available P, OM, total, bulk density and EC (Chapters 6 and 8). (10) Contrary to what was observed on unrehabilitated gold dumps, the trajectory of vegetation community composition on rehabilitated tailings is towards formation of novel plant ecosystems (Chapter 8). However, consistent with observations with natural succession, vegetation structural attributes on rehabilitated tailings converge and exceed reference levels but relatively faster. Species richness and vegetation cover were positively correlated to total N, OM, clay and silt content and negatively correlated to bulk density, total sand content, EC and pH.

(11) The effect of climatic gradients on vegetation was taxa, growth form and life cycle-specific and can vary for plant structural and compositional attributes (Chapter 7). Results suggest tailings age (Chapter 7) and reclamation (Chapter 8) may be influencing vegetation composition on mine tailings more than climatic gradients. Climatic differences may also be overtaken by reclamation in shaping vegetation community composition on mine tailings (Chapter 8). The interactive effect of substrate age and climate on floristic composition and species richness on gold tailings is not significant (Chapter 7).

Overall, the study revealed that trajectories of vegetation development on mine tailings is not unidirectional. It can be either towards reference points or novel ecosystems are formed. Main determinants of this seem to be substrate age, extent of human intervention (rehabilitated versus spontaneous revegetation), and to a lower extent climatic gradients and type of substrate. Mine tailings seem to support unique plant communities that are more sensitive to the substrate more than small to moderate climatic differences for both unrehabilitated and rehabilitated tailings. Changes in pH, macronutrients (N and P) and compaction seem to be the main drivers of trajectories of vegetation development on mine tailings. Biogenic factors related to plant-plant interactions (Chapters 6 and 8), interaction between BCs and vascular plants (Chapter 5) appear play a critical role in shaping vegetation structure and composition on mine tailings. Plants colonizing tailings at any time may come from the adjacent matrix or further away sites, both suggesting the importance of dispersal capability. The trajectory of vegetation structural attributes while it is towards references, takes a significantly shorter period when the tailings are rehabilitated rather than left for spontaneous revegetation. Contrary to the general thinking that view reclamation by nutrient application and planting a few indigenous species would accelerate a compositional restoration trajectory (Fig 1.4), evidence from the study suggests divergence. Figure 9.1 illustrates revegetation trajectories and their determinants as suggested by evidence from this study.

The results have therefore brought forth evidence to support new thinking that: (1) contrary to the usual framework (Fig 1.4) where reclamation is thought to promote a trajectory towards restoration of plant communities, this in fact is likely to promote divergence, (2) leaving mine tailings to spontaneous

revegetation during ecosystem development again in contrary to the usual framework (Fig 1.4), may in fact, gradually attain restoration of pristine composition in terms of composition and structure rather than divergence to novel ecosystems (Fig 9.1). The implications of the results to theory and restoration praxis are explained in section 9.3.



**Figure 9.1:** Conceptual diagram showing the trajectory of ecosystem components in relation to reference conditions and their determinants (diagram developed purely based on study findings). The plant mechanisms dominating the succession stage are also shown. Length of arrows depict rate of development towards references (longer= faster; shorter = slower).

### 9.3 Implication of study findings for the broader theoretical context and restoration praxis

Overall, in relation to existing theories the results were three-pronged: (1) some fit into existing divergent theories, (2) some fit into the existing novel concept, and, (3) some generated new hypothesis that can be used to expand the existing theories. For instance, the findings that vegetation structural attributes converged towards reference conditions for both unrehabilitated (Chapter 6) and rehabilitated tailings (Chapter 8), support the traditional vegetation convergence theory. However, the contrasting trajectories for floristic composition for unrehabilitated and rehabilitated mine tailings largely dispel the existence of single end-points either novel or restoration of pristine conditions. This finding, rather expands the theories by proposing that revegetation does not follow a single trajectory, rather multiple trajectories which are mainly influenced by the type of reclamation (Fig 9.1). The finding that climatic differences had low to moderate effect on vegetation structural and compositional attributes on both unrehabilitated and rehabilitated mine tailings do not fit into existing theories such as Clements (1916) as shown in the framework figure 1.4. The study therefore generated a new hypothesis: “climatic gradients do not affect vegetation development on anthropogenic sites in the same manner they do on natural substrate but rather larger climatic thresholds exist to influence vegetation compositional differences on anthropogenic sites”. The findings on the correlation of BCs with vegetation and substrate properties (Figure 9.1) helped generate a new insights in expanding existing theories, that trajectories of ecosystem development on anthropogenic sites must be defined in consideration of both BCs and vegetation and their interrelationships, rather than traditional use of vascular plants alone. Another key point to expansion of the theories is on the existence of thresholds for facilitation and inhibition relationships between BCs and vegetation. Another area of expansion of existing theories is on the need to consider specific plant growth forms, life cycle and their interactions with biotic and abiotic factors when making generalizations about trajectories of ecosystem development and their determinants.

To restoration praxis, the differential trajectories therefore give an insight that restoration practitioners must carefully consider potential variation of trajectories of different vegetation attributes and ecosystem components in defining their rehabilitation plans. First the spontaneous convergence of plant communities to reference conditions on unrehabilitated tailings (Chapter 6; Figure 9.1) and divergence of communities following rehabilitation (Chapter 8, Figure 9.1) gave a new insight on the importance of considering the natural potential of the substrate in influencing vegetation recovery. While traditionally reclamation by planting a few indigenous trees and nutrient application is generally thought to accelerate restoration evidence from the present study is to the contrary. Rehabilitation can therefore focus on how natural processes can be optimized to speed restoration. Such efforts must also therefore consider substrate age and characteristics rather than taking a generic approach.

The spatial and temporal changes in BCs and their correlation with substrate and vegetation attributes underline the potential of these biota in rehabilitation of unique anthropogenic sites like mine tailings. Results of physicochemical properties of substrate underneath the crust (Chapter 4) gave insight on ecological engineering capabilities of such biota in early ecosystem development on mine wastes. This might be a key insight into cheaper natural ameliorants in an area usually dominated by use of expensive chemical ameliorants. Evidence provided suggests that BCs must be considered in the development of ecosystem development theories that are often based on vascular plant species composition.

Unlike the traditional theories citing heavy metals as the key determinants of vegetation composition at mine sites, the study findings in Chapter 6 and 8 bring an insight into the importance of pH, compaction and traditionally N dynamics in shaping vegetation development on mine tailings (Fig 9.1). The observed little effect of local topography on plant species composition against theory provides lessons for criteria for selection of adaptable candidate rehabilitation species. The higher similarity of plant communities on gold and nickel tailings in different climatic regions (Chapter 7 and 8) despite reclamation type shows the importance of considering substrate characteristics when developing theories on climatic influences and when planning rehabilitation. Unlike in many natural ecosystems where climatic differences of 100 mm in rainfall are sufficient to drive vegetation compositional and structural differences (Duruibe *et al.*, 2007), this may be different on mine tailings. The differential responses of different growth forms and life cycles highlight the importance of considering taxa and species traits in reclamation of mine tailings in different contexts.

#### **9.4 Evaluation of the theoretical and methodological approach**

The approach used was informed by ecosystem development conceptual frameworks that stress substrate and environmental factors and biotic to biotic and abiotic to biotic interactions as key determinants of trajectories of vegetation community development. This often yields a basic successional trajectory that moves bare land to sparse covers and dense cover over time and movement of bare-cryptograms- herbaceous –woody stands all coinciding with changes in substrate properties. The use of adjacent references partly checked the hypotheses of convergence to reference conditions since the reference is expected to be the source of the propagules and to test the possible formation of novel ecosystems. The use of dumps of different ages to a greater extent helped in determining the direction and indirectly rate of change in measured vegetation and substrate attributes including their temporal correlations and comparisons with reference sites. The use of chronosequences widely known as time substitution for space concept (Picket, 1989) enabled the assessments over a longer period up to 110 years which is often difficult to do using permanent plots whose monitoring was not feasible for the study time-frame. The chronosequences have been considered very useful in assessing trajectories of vegetation and soils in a number of studies (Walker *et al.*, 2010). Replication of the age factor at other

gold sites along a climatic gradient helped in widening the investigation of the influence of the age factor on vegetation structural attributes. This to a greater extent catered for the potential effects of lack of replication of each dump at the main sites which was unavoidable due to the disposal patterns for mine tailings, where dumping is done sequentially in a single dump per period of time up to 20 years before going to another. The laying of sampling points systematically across dump faces and positions as opposed to strictly simple random sampling ensured the capture of more detail from expected spatial heterogeneity. Further, the vertical stratification of sampling from dump top to the base also in a way created a suite of mini-chronosequences at each site making sure that replication demands are guaranteed where between four and six dumps were used at the main sites. This to a greater extent catered for the possible risk of potential pseudo replication.

The simultaneous assessment on tailings sites adjacent to each other in same climatic zones and of varying geologies had several advantages to the generalizability of the outcomes of this research: (1) conducting the research on two clear sets of chronosequences in the same region provided a platform for increased external validity of the results especially where consistent results were obtained, this further managing the effects of potential pseudo replication, (2) conducting the assessments on two chronosequences of different substrates allowed the investigation of substrate type as a potential determinant of trajectories of vegetation development in addition to the substrate age-the principal factor topical in the investigation. Use of both gold and nickel tailings also help provide more generic answers to mine tailings restoration or rehabilitation that are widely applicable, rather than internalised to either of the two only. The approach used therefore was useful in that while it answered substrate specific trajectories, it indirectly would inherently also cater for overlap trajectories important for general application in mine restoration at large. Further, the use of two contrasting chronosequences, unrehabilitated and rehabilitated tailings allowed simultaneous testing of both contexts and the evaluation of existing theories on revegetation trajectories where there is no human intervention and conversely. Results obtained again will in addition to providing invaluable insights in an internal context, will increase the generalizability of the results in tailings restoration at large.

The replication of references, adjacent and one further away as was done ensured the potential feedback effects of the tailings to its surroundings were catered for. The assumption was that mine tailings are influenced by the adjacent reference site yet the tailings through wind and water erosion and other dispersal means can also influence the adjacent vegetation matrix. Use of a further away replicate reference site in similar conditions closed this potential gap. The combined assessment of larger scale and micro-scale effects of reclamation on vegetation structural and compositional attributes facilitated the definition of the specific and general effects of planted species on subsequent natural succession. The stratification of tailings into potential nutrient hot spots and non-hotspots e.g. canopies of planted trees versus off- canopy patches on nickel tailings and BC versus non-BC patches on gold tailings enabled the



assessment of the ecological engineering capability of planted leguminous species and biological crusts on tailings and their role in ecosystem genesis on anthropogenic substrates. This could not have been possible if a general design that only acknowledged the age factor was employed.

The combined investigation of the impact of climatic gradients on vegetation of mine tailings, both rehabilitated and unrehabilitated and gold and nickel substrates has a marked benefit of yielding results that are widely applicable in varying geographical zones characterized by varying or ever-changing climatic conditions. Indirectly this approach ensures generalization and application of results to other geographic areas which may have varying climatic conditions where climate differences can be used as a proxy to geographic differences. The use of several vegetation layers starting with micro flora such as lichens, mosses, algae and cyanobacteria to macro flora such as forbs, grasses and woody trees and their classification into functional classes, life forms or growth forms allowed in-depth examination of trends for each component which is often overridden where a general approach is used. The tracking of pioneer species over time allowed the identification of mechanisms driving succession such as facilitation and competitive exclusion while also testing models of succession such as floristic relay model and the initial floristic composition model. Further the simultaneous analysis of vegetation structural, compositional and diversity attributes was critical to increase specificity where otherwise richness and cover are used.

A mixed approach in data analysis combining general analysis of variance, ordination and correlation analysis allows for accounting for observed patterns while also screening significant effects of predictors. Ordination also gives a spatial perspective of the vegetation communities and the proportion explained by explanatory variables including those not explained by measured variables.

Overall, some other competing approaches such as state transition models and use of permanent plots could have been used, in particular the use of permanent plots. This would have allowed detection of short interval changes or trajectories. This was however difficult to adopt for longer periods due to time and practicality. Although chronosequences may miss this short term dimension and also assumes similar starting points, they are still suitable to cover longer periods (Walker *et al.*, 2010). To cater for assumptions of chronosequences about initial starting points, the study used dumps derived from areas of similar geologies and those under similar management including protection from human disturbances. An effort to test the effect of mineral processing technologies was done (Chapter 3). Use of a few geochemical parameters as a proxy for pedogenesis may lead to overstatement of soil trajectories as pedogenesis is a complex process. However, the few parameters used are known determinants of plant growth in natural ecosystems.



## 9.5 Future direction for research

While the study has generated the afore-mentioned contributions, future research should focus on:

- Continued monitoring of changes on the study sites.
- Testing the theories using different tailing substrates in order to refine existing theories and test the proposed hypothesis.
- Use of permanent plots to capture short term changes to complement chronosequences. Despite the use of different tailings of different ages to ascertain direction of change in measured attributes, the research did not focus on determining specific rates of change which can be explored using permanent plots and more frequent measurements.
- Exploring causality relationships among substrate, BCs and vegetation variables measured since the present study used correlations to make inferences. Complementary causal experiments can be done in future using tailings substrate and various treatments.
- Investigating the trajectories of vegetation development along with other ecosystem components e.g. below ground biomass and ecological engineers such as earth worms, ants and beetles including effects of climatic gradients to all ecosystem components.

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## Supplementary materials

**Table S3.2:** Depth variation of physical properties on gold tailings (Only the 92 year-year old dump and Ref- 2Km are used for illustration. Superscripts for mean separation: Small letters (across depth - columns) and capital letter (across sites-rows).

	site	0-5cm	5-15cm	15-25cm	30-50cm	1m
pH	92	5.1±0.41 <sup>aA</sup>	5.7±0.40 <sup>aA</sup>	6.4±0.35 <sup>aA</sup>	5.85±0.41 <sup>aA</sup>	6.210±0.31 <sup>aA</sup>
	Ref-2km	5.4±0.41 <sup>aA</sup>	5.36±41 <sup>aA</sup>	5.2±0.46 <sup>aB</sup>	4.87±0.53 <sup>aA</sup>	4.967±0.53 <sup>aB</sup>
Total N	92	0.05±0.02 <sup>aA</sup>	0.03±0.02 <sup>acA</sup>	0.03±0.02 <sup>bcA</sup>	0.03±0.02 <sup>bcA</sup>	0.01±0.01 <sup>aA</sup>
	Ref-2km	0.12±0.02 <sup>aA</sup>	0.06±0.02 <sup>aB</sup>	0.05±0.02 <sup>aB</sup>	0.18±0.03 <sup>aA</sup>	0.03±0.03 <sup>aB</sup>
P	92	48.5±8.40 <sup>aA</sup>	25.5±8.40 <sup>bA</sup>	47.0±14.80 <sup>aA</sup>	46.00±11.88 <sup>aA</sup>	45.2±9.76 <sup>aA</sup>
	Ref-2km	7.3±6.9 <sup>aB</sup>	2.7±2.86 <sup>aA</sup>	3.11±2.86 <sup>aA</sup>	2.00±8.38 <sup>aB</sup>	1.00±8.40 <sup>bB</sup>
Clay	92	5.8±2.25 <sup>aA</sup>	4.4±2.14 <sup>aA</sup>	4.5±2.49 <sup>aA</sup>	4.08±2.19 <sup>aA</sup>	4.08±2.12 <sup>aA</sup>
	Ref-2km	3.80±2.23 <sup>aA</sup>	7.0±2.23 <sup>aA</sup>	7.3±2.87 <sup>aB</sup>	5.00±2.87 <sup>aA</sup>	6.67±2.87 <sup>aA</sup>
Silt	92	26.4±5.7 <sup>aA</sup>	29.78±5.39 <sup>aA</sup>	26.50±6.27 <sup>aA</sup>	26.83±5.53 <sup>aA</sup>	26.00±4.24 <sup>aA</sup>
	Ref-2km	21.2±5.65 <sup>aA</sup>	17.6±5.61 <sup>aA</sup>	12.7±7.24 <sup>aB</sup>	16.0±7.24 <sup>aA</sup>	15.66±7.24 <sup>aA</sup>
Sand	92	70.3±5.92 <sup>aA</sup>	67.0±5.64 <sup>aA</sup>	69.0±6.56 <sup>aA</sup>	69.9±5.78 <sup>aA</sup>	69.92±5.78 <sup>aA</sup>
	Ref-2km	75.4±5.86 <sup>aA</sup>	75.6±5.86 <sup>aA</sup>	80.3±7.57 <sup>aA</sup>	79.3±7.57 <sup>aA</sup>	77.67±7.57 <sup>aA</sup>
Mn	92	7.19±2.62 <sup>aA</sup>	5.42±2.50 <sup>b</sup>	0.55±2.90 <sup>bA</sup>	4.2±2.56 <sup>bA</sup>	5.267±2.56 <sup>bA</sup>
	Ref-2km	8.20±2.60 <sup>aA</sup>	11.4±2.60	4.4±3.35 <sup>aB</sup>	6.5s±3.36 <sup>aA</sup>	11.13±3.352 <sup>aB</sup>
Fe	92	0.6±0.13 <sup>aA</sup>	0.87±0.13 <sup>aA</sup>	0.5±0.15 <sup>aA</sup>	0.58±0.13 <sup>aA</sup>	0.58±0.13 <sup>aA</sup>
	Ref-2km	0.4±0.13 <sup>aA</sup>	0.44±0.13 <sup>aA</sup>	0.7±0.20 <sup>aA</sup>	0.6±0.17 <sup>aA</sup>	0.53±0.12 <sup>aA</sup>
OM	92	0.27±0.04 <sup>aA</sup>	0.27±0.04 <sup>aA</sup>	0.06±0.05 <sup>bA</sup>	0.20±0.04 <sup>aA</sup>	0.20±0.04 <sup>aA</sup>
	Ref-2km	0.22±0.04 <sup>aA</sup>	0.23±0.04 <sup>aA</sup>	0.2±0.06 <sup>aB</sup>	0.2±0.06 <sup>aA</sup>	0.147±0.06 <sup>aA</sup>
EC	92	3.42±0.27 <sup>aA</sup>	3.3±0.27 <sup>bA</sup>	3.5±0.11 <sup>abA</sup>	3.3±0.12 <sup>abA</sup>	3.313±0.12 <sup>abA</sup>
	Ref-2km	3.46±0.28 <sup>aA</sup>	3.3±0.35 <sup>aA</sup>	3.5±0.14 <sup>aA</sup>	3.3±0.16 <sup>aA</sup>	3.3±0.16 <sup>aA</sup>

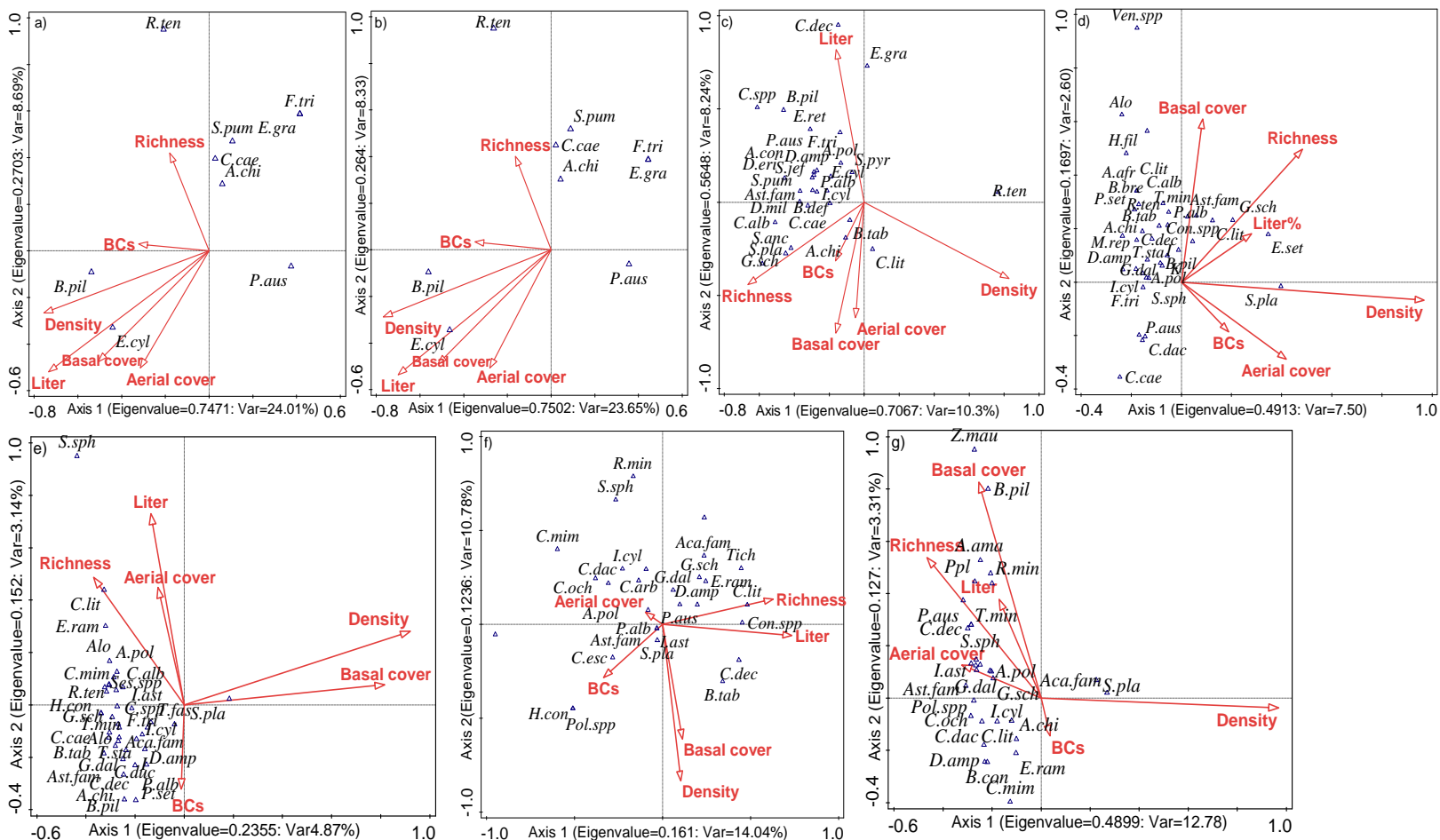
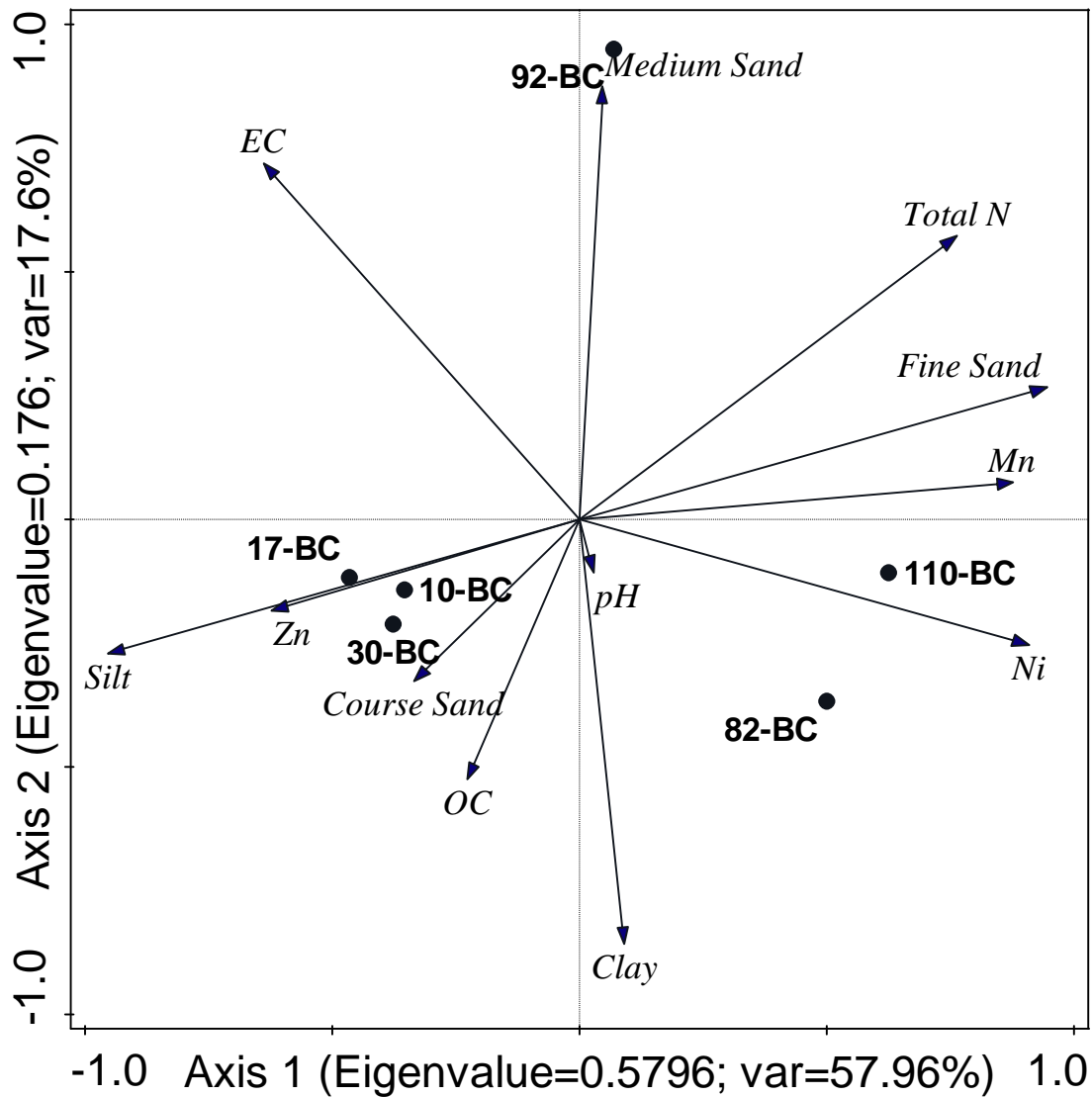


Figure S5.1: Correlation of BCs and vegetation structural and compositional attributes (a) 10 (b) 17 (c) 30 (d) 82 (e) 92, (f) 110, (g) Ref



**Figure S5.2:** Correlation of BC sites only and tailings physicochemical properties. Numer represents tailings age.

**Table S5.1:** Spearman correlation (r) between BC cover and vegetation attributes. P values in bold indicate significant difference at \*\* p<0.01 and \*p <0.05. BCs = Biocrust, AC= aerial cover; BC = basal cover.

	BCs vs. AC		BCs vs. BC		BCs vs. richness		BCs vs. density	
	R	p	r	P	r	P	r	P
10 years	0.314	0.091	0.428	<b>0.018*</b>	0.007	0.971	0.007	0.971
17 years	0.289	0.121	0.390	<b>0.033*</b>	0.001	0.994	0.001	0.994
30 years	0.194	0.116	0.340	<b>0.005**</b>	0.249	<b>0.042*</b>	0.249	<b>0.042*</b>
82 years	0.192	<b>0.001*</b>	0.031	0.590	0.039	0.494	0.039	0.494
92 years	0.083	0.231	0.156	<b>0.023*</b>	0.2	<b>0.001**</b>	0.2	<b>0.001**</b>
110 years	-0.341	<b>0.049*</b>	0.164	0.355	-0.073	0.681	-0.073	0.681
R-200m	-0.203	<b>0.045*</b>	-0.199	<b>0.049*</b>	-0.240	<b>0.038*</b>	-0.240	<b>0.038*</b>
R-2km	0.081	0.836	-0.059	0.881	0.005	0.990	0.005	0.990

**Table S6.1:** Occurrence of different plant growth forms on a chronosequence of gold tailings dumps. (Species richness/ m<sup>2</sup>). Values are Mean ±Standard deviation (SD).

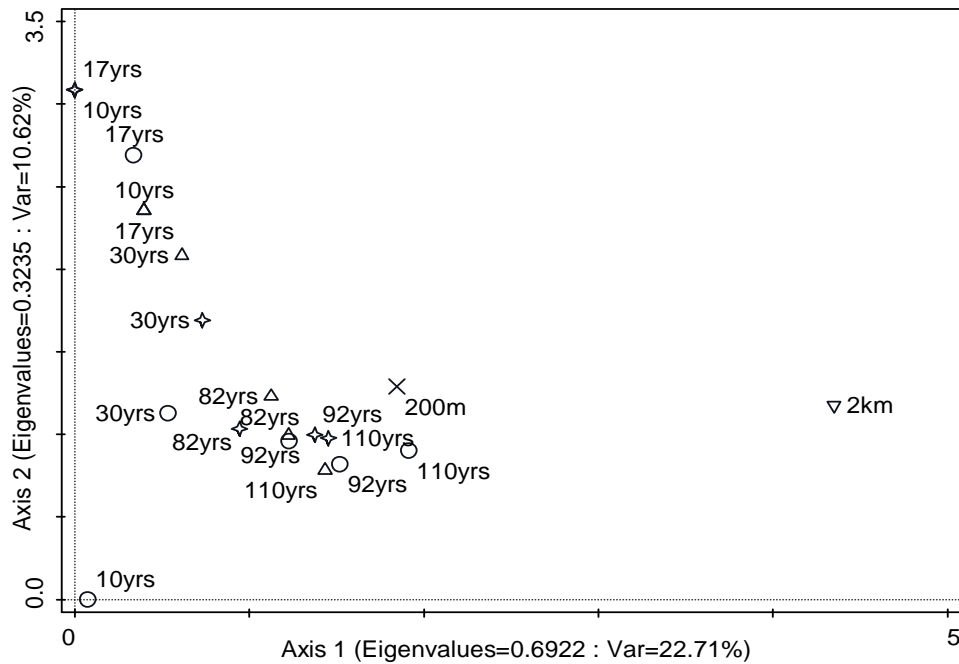
Site	Forb Mean±SD	Fern Mean±SD	Grass Mean±SD	Sedge Mean±SD	Woody Mean±SD
10yrs	0.16±0.03	0.01±0.01	0.89±0.05	0.1±0.02	0.12±0.02
17yrs	0.23±0.04	0±0.02±0.00	1.08±0.05	0±0	0.17±0.03
30yrs	1.71±0.10	0.04±0.02	2.29±0.12	0.03±0.02	0.6±0.06
82yrs	3.56±0.21	0.37±0.05	3.85±0.13	0±0	0.37±0.06
92yrs	4.16±0.23	0.24±0.05	3.8±0.17	0.12±0.04	0.39±0.08
110yrs	2.88±0.27	0.03±0.03	3.91±0.17	0.85±0.09	0.61±0.11
Ref-200m	4.14±0.27	0.03±0.02	3.42±0.13	0.47±0.05	0.42±0.07
Ref-2km	11.29±0.99	0.14±0.14	6.71±0.61	1.71±0.29	4.29±0.71
<b>Position</b>					
Plateau	1.3±0.12	0.05±0.02	1.9±0.13	0.2±0.03	0.2±0.04
Slope	1.6±0.09	0.1±0.01	2.1±0.07	0.1±0.01	0.3±0.02
Ref-200m	4.1±0.27	0.03±0.02	3.4±0.13	0.5±0.05	0.4±0.07
Ref-2km	11.3±0.99	0.14±0.14	6.7±0.61	1.7±0.29	4.3±0.71

**Table S6.2:** Changes in abundances (Mean  $\pm$ SD) of plants on of different growth forms on a chronosequence of gold tailings.

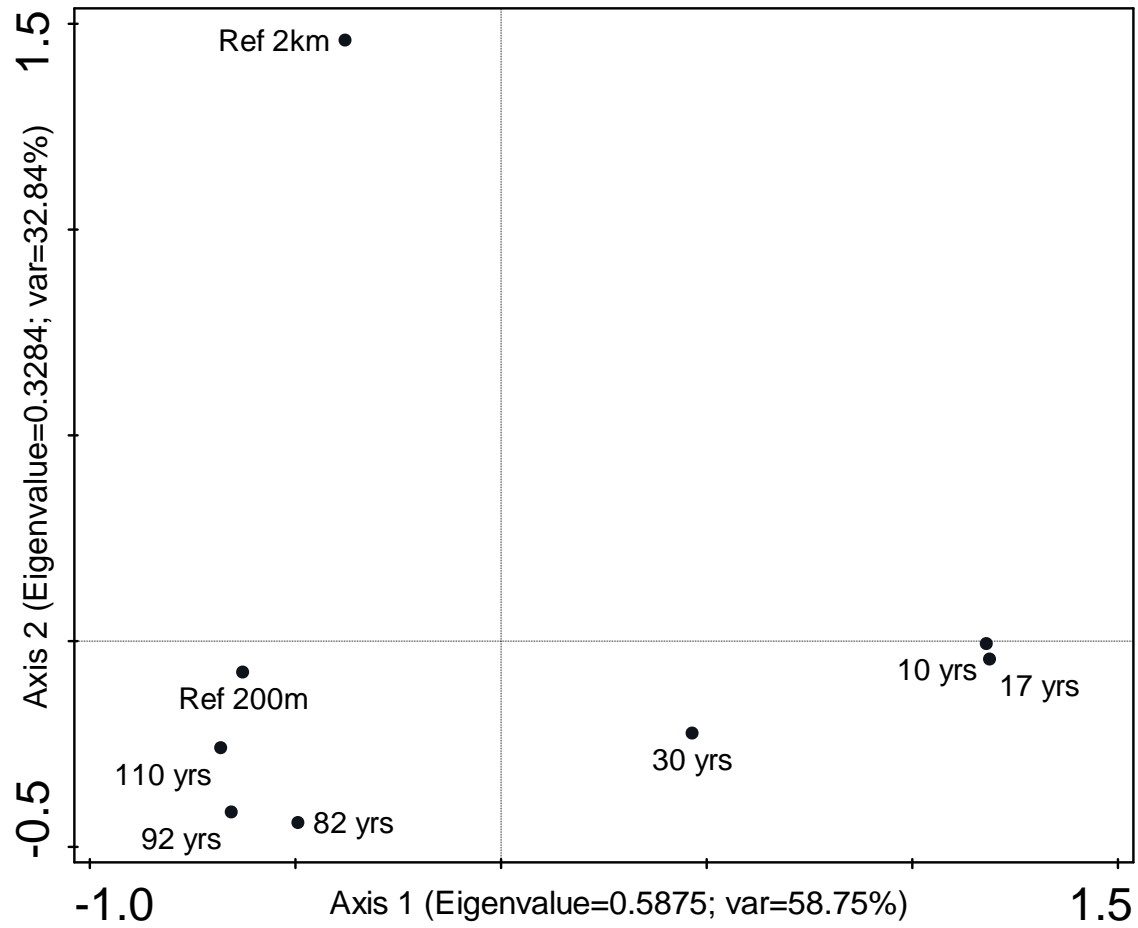
Site	Forb No./m <sup>2</sup>	Fern No./m <sup>2</sup>	Grass No./m <sup>2</sup>	Sedge No./m <sup>2</sup>	Woody Seedlings No./m <sup>2</sup>	Trees/shrubs Density(No./Ha)
10yrs	1.7 $\pm$ 0.8	0.01 $\pm$ 0.01	25.2 $\pm$ 2.0	14.5 $\pm$ 6.9	0.1 $\pm$ 0.0	0
17yrs	11.9 $\pm$ 5.8	0 $\pm$ 0	29.5 $\pm$ 2.2	0 $\pm$ 0	0.2 $\pm$ 0.0	1.9
30yrs	62.0 $\pm$ 13.5	0.7 $\pm$ 0.4	42.4 $\pm$ 6.5	0.6 $\pm$ 0.4	0.6 $\pm$ 0.0	7.4
82yrs	27.5 $\pm$ 5.6	1.2 $\pm$ 0.2	237.9 $\pm$ 20.2	0 $\pm$ 0	0.4 $\pm$ 0.0	120.9
92yrs	103.5 $\pm$ 18.8	2.4 $\pm$ 1.3	523.1 $\pm$ 93.4	3.9 $\pm$ 1.8	0.4 $\pm$ 0.0	139.7
110yrs	115.5 $\pm$ 52.8	0.03 $\pm$ 0.0	1485.4 $\pm$ 16	21.2 $\pm$ 4.4	0.6 $\pm$ 0.1	200.5
Ref-200 m	131.6 $\pm$ 29.4	0.07 $\pm$ 0.0	561.7 $\pm$ 78.8	21 $\pm$ 3.7	0.4 $\pm$ 0.1	554.2
Ref-2 km	254.6 $\pm$ 55.5	0.14 $\pm$ 0.1	323 $\pm$ 89.0	65.4 $\pm$ 40.2	4.3 $\pm$ 0.7	907.5

Position	Forb No./m <sup>2</sup>	Fern No./m <sup>2</sup>	Grass No./m <sup>2</sup>	Sedge No./m <sup>2</sup>	Woody Seedlings No./m <sup>2</sup>	Trees/shrubs Density(No./Ha)
Plateau	42.5 $\pm$ 10.9	0.5 $\pm$ 0.2	288.3 $\pm$ 51.8	16.4 $\pm$ 7.4	16.7 $\pm$ 7.8	45.1
Slope	31.0 $\pm$ 4.5	0.6 $\pm$ 0.2	140.8 $\pm$ 14.5	1.7 $\pm$ 0.4	4.3 $\pm$ 0.7	84.3
Ref-200m	131.6 $\pm$ 29.4	0.2 $\pm$ 0.1	561.7 $\pm$ 78.8	21.0 $\pm$ 3.6	1.1 $\pm$ 0.3	552.2
Ref-2 km	254.6 $\pm$ 55.6	0.2 $\pm$ 0.1	323.0 $\pm$ 89.0	65.4 $\pm$ 40.2	9.1 $\pm$ 1.4	907.5



**Figure S6.1:** DCA monoplot showing sites separation based on herbaceous and woody seedlings plant community composition.



**Figure S6.2:** NMDS Plot of plant communities using combined herbaceous and woody vegetation data on a chronosequence of gold tailings.

**Table S7.1:** Plant species richness on gold tailings dams situated down a rainfall gradient in Zimbabwe

<b>Sites</b>	<b>Region</b>	<b>Richness</b>	<b>Forbs</b>	<b>Gramminoids</b>	<b>Woody</b>
Vumbachikwe	300-450	24	9	6	9
West Nicolson	300-450	22	7	9	5
Sabi	450-600	39	17	16	6
How mine	450-600	29	17	8	4
Chakari	600-800	75	26	22	27
Connemara	600-800	40	10	15	15
Kwekwe	600-800	42	8	13	21
Shurugwi	600-800	37	15	12	10
FRGM	800-1000	67	26	32	9
Phoenix Prince	800-1000	85	37	30	18
Ran	800-1000	87	38	31	15
Shamva	800-1000	88	38	36	14
Mazowe	800-1000	75	33	30	12
Acturus	800-1000	60	26	26	8

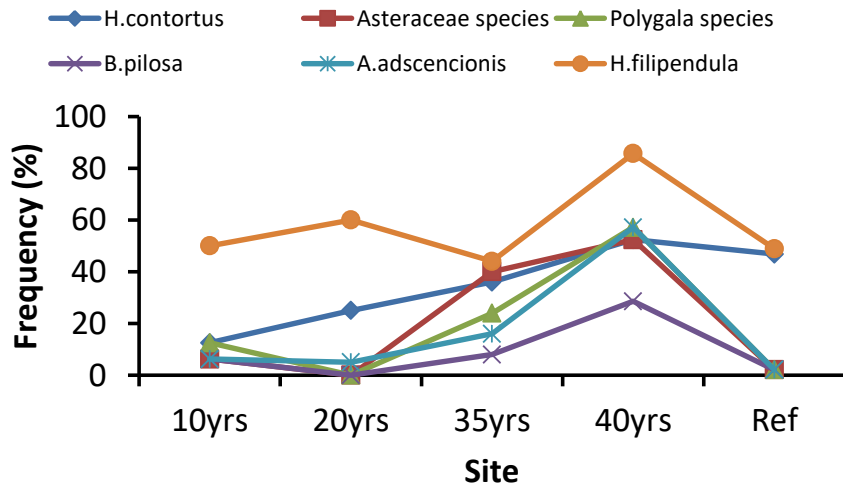
**Table S7.2:** Frequency of occurrence of species of different life cycles at different mines situated along a climatic gradient sampled sites

<b>Site</b>	<b>Rainfall (mm)</b>	<b>Annuals %</b>	<b>Biennials %</b>	<b>Perennials %</b>	<b>A/B %</b>
FRGM	800-1000	6.3	0	87.5	6.3
Phoenix	800-1000	4.3	0	91.34	4.4
Ran	800-1000	6.5	0	87.1	6.5
Shamva	800-1000	5.6	0	88.9	5.6
Mazowe	800-1000	6.7	0	90.0	3.3
Acturus	800-1000	7.7	0	88.5	3.8
Chakari	600-800	0	0	100.0	0
Shurugwi	600-800	0	0	100.0	0
Connemara	600-800	14.3	0	85.7	0
Kwekwe	600-800	0	0	100.0	0
Sabi	450-600	12.5	0	87.5	0
How Mine	450-600	12.5	0	87.5	0
Vumbachikwe	<450	11.1	0	88.9	0
West Nicolson	<450	7.7	0	92.3	0

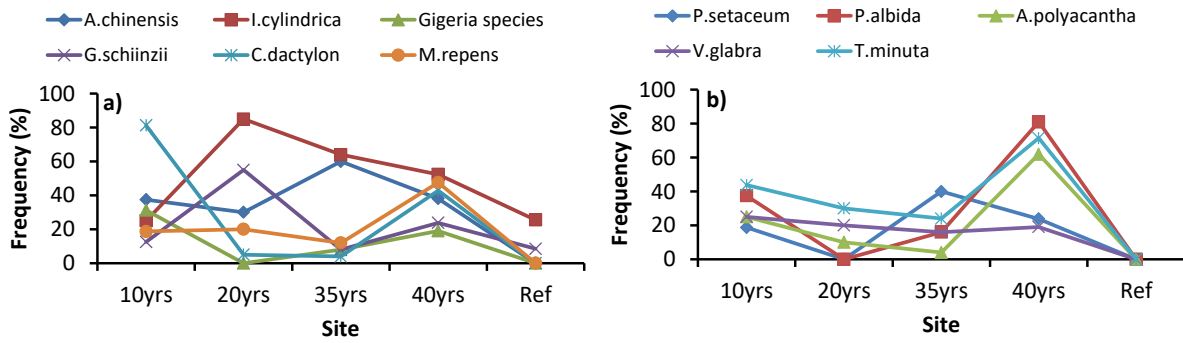
**Table S7.3:** Full names of plant species occurring on gold tailings dumps in Zimbabwe. (The list entails species abbreviated in ordination diagrams).

<i>Flaveria trinervia</i> (F.tri),	<i>Imperata cylindrica</i> (I. Cyl),	<i>Bidens pilosa</i> (B.pil),	<i>Schizachyrium jeffreysii</i> ( S.jey),
<i>Penisetum setaceum</i> (P.set),	, <i>Andropogon chinensis</i> (A.chi),	<i>Blumea brevipes</i> (B. bre),	<i>Hyparhenia filipendula</i> (H. fil),
<i>Venonia glabra</i> (V.gla),	<i>Diheteropogon amplexens</i> (D. amp),	<i>Tagetes minuta</i> (T. min),	<i>Hyparhenia rufa</i> (H. ruf),
<i>Polygala albida</i> (P. alb);	<i>Setaria sphacelata</i> (S. sph),	<i>Conyza albida</i> (C. alb)	<i>Cynodon dactylon</i> (C. dac),
<i>Ricinus communis</i> (R.com),	<i>Schizachyrium platyphyllum</i> (S. pla),	<i>Solanum species</i> ( <i>Solanum</i> spp),	<i>Melinis repens</i> (M. rep),
<i>Eragrostis aspera</i> (E.asp),	<i>Sporobolus pyramidalis</i> (S. pyr),	<i>Pogonathria squarrosa</i> (P.squ),	<i>Heteropogon contortus</i> (H.con),
<i>Aristida adscensionis</i> (A.ads)	<i>Aristida congesta</i> (A. con),	<i>Bulbostylis contexta</i> (B. con);	<i>Cyperus esculentis</i> (C. esc),
<i>Phragmites australis</i> (P. Aust)	<i>Acacia polyacantha</i> (A. pol),	<i>Acacia karoo</i> (A.kar),	, <i>Terminalia Sericea</i> (T.ser),
<i>Vachelia nilotica</i> (V.nil),	, <i>Sesbania sesban</i> (S. ses);	<i>Tecoma stans</i> (T.sta),	<i>Rhus tenuinervis</i> (R.ter),
<i>Dichrostachys cineria</i> (D. cin),	<i>Piliostigma thoningii</i> (P. tho)	<i>Lonchorcarpus capassa</i> (L. cap),	<i>Asparagus africanus</i> (A.afr),
<i>Albizia amara</i> (A. ama)	<i>Ficus sycomorus</i> (F.syc)	<i>Azanza garkeana</i> (A. gar),	<i>Acacia nigrescens</i> (A.nig),
<i>Ziziphus mauritania</i> (Z. mau),	<i>Ziziphus mucronata</i> (Z. muc),	<i>Combretum apiculatum</i> (C. api),	<i>Dalbergia melanoxylon</i> (D. mel),
<i>Afzelia quanzensis</i> (A.qua),	<i>Burkea</i> spp ( <i>Burkea</i> spp),	, <i>Eurphobia indica</i> (E. ind),	<i>Sida alba</i> (S. alb),
<i>Cobichornia decumbens</i> (C.dec),	, <i>Chamarseae hirta</i> (C. hirta),	<i>Waltheria indica</i> (W. ind),	<i>Jasticia</i> spp (J. spp),
<i>Datura stramonium</i> (D.str),	<i>Hibiscus meeusei</i> (H. meu),	<i>Amaranthus hybridus</i> (A. hyb)	, <i>Eragrostis rigidior</i> (E.rig),
<i>Panicum maximum</i> (P. max),	<i>Aristida rhinocloa</i> (A rhi),	<i>Venonia adoensis</i> ( V. ado),	<i>Perotis patens</i> (P.pat),
<i>Eragrostis racemosa</i> (E. rac),	<i>Tephrosia fasigiutum</i> (T. Fau),	<i>Setaria pumila</i> (S. pum),	<i>Aristida junciformis</i> (A. jun),
<i>Aristida Scabivulvis</i> (A. sca),	<i>Digitaria eriantha</i> (D. eri)		





Species increasing



Fluctuating species

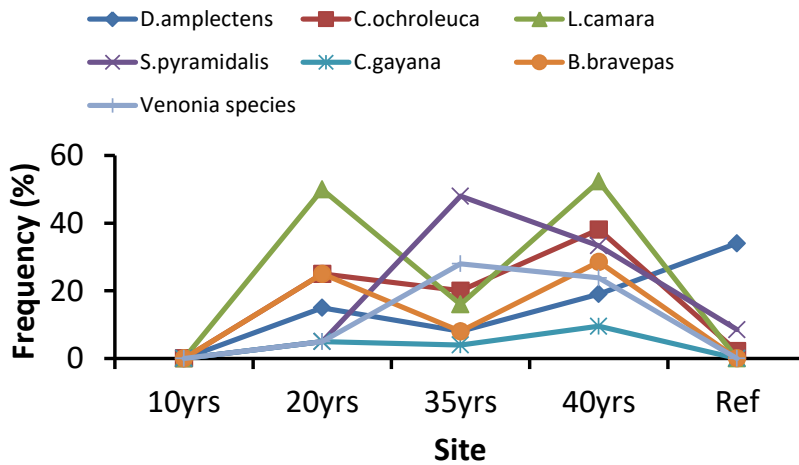


Figure S8.1: Frequencies of individual species along an age sequence of nickel mine tailings

**Plates**



Dump top (17 years –Gold tailings)



Top patches - 82 year-old-dump





**Top (92-year old-dump)  
Ref-200m**



**Slope (92 -year old dump) + Adjacent**



**Biocrusts extracted from 92 year-Gold dump**



**Dump top – (35 year reclaimed Ni)**

### List of publications

1. Nyenda, T., Jacobs, S. M., Gwenzi, W., & Muvengwi, J. (2019). Biological crusts enhance fertility and texture of gold mine tailings. *Ecological Engineering*, 135, 54-60.
2. Nyenda, T., Gwenzi, W., Piyo, T. T., & Jacobs, S. M. (2019). Occurrence of biological crusts and their relationship with vegetation on a chronosequence of abandoned gold mine tailings. *Ecological Engineering*, 139, 105559.