BINDURA UNIVERSITY OF SCIENCE EDUCATION

DEPARTMENT OF ENVIRONMENTAL SCIENCES

THE INFLUENCE OF TOPOGRAPHIC VARIATION (POSITION, SLOPE GRADIENT, SLOPE ASPECT) ON THE "ABUNDANCE AND RICHNESS OF ANT, BEETLE AND OTHER INVERTEBRATES" ALONG AN AGE SEQUENCE OF ABANDONED GOLD TAILINGS DUMPS AND A NATURAL CONTROL SITE.

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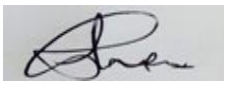
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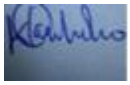
Declaration

I, ALBERT WAKATAMA (B252628A), declare this project is original work and has not been submitted for examination at any institution. All sources and references in this study were appropriately acknowledged.

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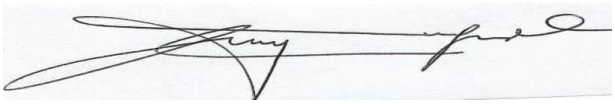
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Dedications

I dedicate this dissertation to my family, friends, and fellow students for their unwavering support, encouragement, and inspiration throughout my academic journey.

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Above all, I would like to thank God for granting me the patience, wisdom, strength, and determination to successfully complete this research project.

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Abstract

Abandoned gold tailings dumps are among the most ecologically degraded landscapes due to the loss of vegetation, altered soil properties, habitat fragmentation, and reduced biological diversity resulting from mining activities. Soil macroinvertebrates, particularly ants, beetles, and other ground-dwelling invertebrates, play fundamental roles in nutrient cycling, litter decomposition, soil formation, and ecosystem functioning, making them valuable bioindicators of ecological restoration. However, limited information exists on how topographic variation influences the abundance and richness of these organisms across abandoned gold tailings dumps in Zimbabwe. This study assessed the influence of topographic position, slope gradient, and slope aspect on the abundance and richness of ants, beetles, and other invertebrates along an age sequence of abandoned gold tailings dumps and a natural control site at Freda Rebecca Gold Mine, Bindura. A stratified field sampling design was employed using two abandoned gold tailings dumps (86 and 96 years old) and an adjacent natural control site. Surface-active invertebrates were sampled using pitfall traps, while beetles were collected from soil monoliths excavated at three depth intervals (0–10 cm, 10–20 cm, and 20–30 cm). Soil samples were collected to determine Soil Organic Carbon (SOC) and Bulk Density (BD). Data were analysed using the IBM Statistical Package for the Social Sciences (SPSS) version 27. Descriptive statistics, one-way Analysis of Variance (ANOVA), General Linear Models (GLM), Pearson's correlation analysis, and post hoc tests were used to evaluate differences and relationships among the study variables at a 5% level of significance. The study recorded substantial variation in cumulative abundance and richness among the sampling sites. The natural control site recorded the highest total abundance (661 individuals), while the 96-year-old tailings dump supported the greatest taxonomic richness (201 taxa), indicating considerable ecological recovery through natural succession. Conversely, the 86-year-old tailings dump exhibited extremely low abundance (29 individuals) and richness (21 taxa), reflecting poor habitat quality and limited biological recovery. Although the control site and the 96-year-old tailings dump generally recorded higher mean abundance and richness of ants, beetles, and other invertebrates than the 86-year-old tailings dump, the differences in mean values were not statistically significant ($P > 0.05$), suggesting high spatial variability among the sampling plots. Topographic variation influenced invertebrate distribution, with lower slope positions, moderate slope gradients, and favourable slope aspects generally supporting greater abundance and richness than exposed or unstable positions. Beetles were most abundant within the 10–20 cm soil layer, indicating

that intermediate soil depths provided more suitable microhabitat conditions than either the surface or deeper soil layers. Correlation analysis showed that Soil Organic Carbon exhibited stronger relationships with invertebrate abundance than Bulk Density, although several correlations were weak, indicating that soil biological recovery is influenced by multiple interacting environmental factors rather than by individual soil properties alone. The findings demonstrate that topographic variation contributes significantly to the spatial distribution of soil invertebrates on abandoned gold tailings dumps by influencing habitat quality, vegetation establishment, and soil development. Furthermore, ecological recovery following mining disturbance is determined not only by the age of the tailings dumps but also by the interaction among topography, soil properties, and habitat heterogeneity. The study concludes that ants, beetles, and other soil invertebrates are effective ecological indicators for monitoring rehabilitation success in post-mining environments. It is recommended that mine rehabilitation programmes incorporate topographic characteristics into restoration planning by prioritising erosion control, revegetation with indigenous plant species, enhancement of soil organic matter, and long-term biological monitoring using soil macroinvertebrates. Such strategies will enhance biodiversity conservation, accelerate ecosystem recovery, and promote the sustainable management of abandoned mine landscapes in Zimbabwe.

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List of Abbreviations and Acronyms

ANOVA	-	Analysis of Variance
SOC	-	Soil Organic Carbon
BD	-	Bulk Density
Fig	-	Figure
SPSS	-	Statistical Package for Social Sciences
SD	-	Standard Deviation
LSD	-	Least Squares Difference
HSD	-	Turkey's Honestly Significant Different
GLM	-	General Linear Models
FRGM	-	Freda Rebecca Gold Mine
CM	-	Centimeter
G/CM3	-	Grams Per Cubic Centimeter

CHAPTER 1: INTRODUCTION

1.1: BACKGROUND TO THE STUDY

The Freda Rebecca Gold Mine in Bindura provides an ideal setting for investigating the influence of topographic variation on biodiversity recovery because it contains abandoned gold tailings dumps representing different stages of ecological succession and exhibiting distinct topographic characteristics (Mtapuri & Ncube, 2023). The presence of tailings dumps of different ages, together with an adjacent natural control site, provides an opportunity to examine how ecological recovery progresses over time and how topographic position, slope gradient, and slope aspect influence the abundance and richness of ants, beetles, and other invertebrates (Prach & Walker, 2022). Such chronosequences are valuable ecological models because they enable researchers to assess long-term patterns of community development and ecosystem recovery following severe disturbance.

Topographic variation is widely recognised as an important determinant of biodiversity patterns because it influences environmental conditions that regulate species distribution and survival (Stein et al., 2023). Differences in slope position, slope gradient, and slope aspect affect soil moisture availability, temperature regimes, nutrient accumulation, vegetation establishment, and erosion processes. Upper slope positions are often characterised by greater exposure to solar radiation, lower moisture retention, and increased erosion, whereas lower slope positions tend to accumulate nutrients and organic matter transported from upslope areas (Wang et al., 2022). Similarly, slope aspect creates differences in microclimatic conditions by influencing the amount of solar radiation received, while slope gradient affects water movement, soil stability, and erosion potential (Liu et al., 2022).

These environmental variations create heterogeneous habitats that may favour different invertebrate communities and contribute to spatial variation in their abundance and richness. Ants, beetles, and other invertebrates are particularly suitable for assessing these patterns because they respond rapidly to environmental changes and perform critical ecosystem functions (García et al., 2022). They contribute to decomposition, nutrient cycling, soil aeration, seed dispersal, and the regulation of food-web interactions. Consequently, changes in their abundance and richness provide valuable insights into ecosystem condition and the effectiveness of rehabilitation efforts. Because invertebrate communities integrate the effects of multiple environmental factors over time, they are increasingly used as indicators of ecosystem recovery in disturbed landscapes (Katz et al., 2023).

This study is underpinned by the Habitat Heterogeneity Theory, which proposes that environmental variability creates diverse ecological niches capable of supporting different species assemblages, and the Ecological Succession Theory, which explains how biological communities change over time following disturbance (Stein et al., 2023; Prach & Walker, 2022). Together, these theories suggest that variation in topographic conditions across tailings dumps of different ages is likely to influence habitat quality and, consequently, affect the abundance and richness of invertebrate communities. As ecological succession progresses, improvements in habitat conditions may facilitate greater colonisation and diversification of invertebrate taxa, although these patterns may differ among topographic positions, slope gradients, and slope aspects (Munyati et al., 2022). Despite the growing interest in mine rehabilitation and biodiversity restoration worldwide, significant knowledge gaps remain regarding the role of topographic variation in shaping invertebrate communities on abandoned mine tailings. Globally, many studies have focused on vegetation recovery and soil physicochemical characteristics, whereas comparatively few have investigated how terrain-related factors influence the abundance and richness of terrestrial invertebrates (Nhamo et al., 2023).

Within the Southern African Development Community (SADC) region, and Zimbabwe in particular, research on mine rehabilitation has predominantly focused on vegetation establishment, soil quality, and heavy metal contamination, with limited attention given to the responses of ants, beetles, and other invertebrates to topographic gradients. Furthermore, little information is available on how these relationships vary across different stages of ecological recovery represented by tailings dumps of different ages and how the resulting invertebrate communities compare with those occurring in adjacent natural ecosystems (Zengeni et al., 2022; Nhamo et al., 2023).

1.2: STATEMENT OF THE PROBLEM

Abandoned gold tailings dumps represent highly disturbed ecosystems characterised by altered soil properties, reduced biodiversity, and impaired ecological functioning. Despite ongoing rehabilitation efforts at many mining sites in Zimbabwe, the recovery of biological communities remains uncertain due to a limited understanding of the environmental factors that influence biodiversity patterns on these degraded landscapes. Among these factors, topographic variation, including topographic position, slope gradient, and slope aspect, plays a significant role in determining microclimatic conditions, soil moisture availability, nutrient distribution, and erosion processes, all of which influence habitat suitability for soil- and surface-dwelling invertebrates. Ants, beetles, and other invertebrates are important components of terrestrial ecosystems because they contribute to nutrient cycling, organic matter decomposition, soil formation, and other essential ecosystem processes. Furthermore, they are widely recognised as sensitive bioindicators of environmental change and ecological restoration success. However, existing studies on mine rehabilitation in Zimbabwe have predominantly focused on vegetation establishment and physicochemical soil characteristics, with limited attention given to how topographic variation influences the abundance and richness of invertebrate communities across rehabilitating tailings dumps.

The influence of topographic position, slope gradient, and slope aspect on the abundance and richness of ants, beetles, and other invertebrates along an age sequence of abandoned gold tailings dumps remains poorly understood. In particular, there is insufficient information on how these topographic factors interact with different stages of ecological recovery represented by tailings dumps of varying ages and how the resulting invertebrate communities compare with those found at an adjacent natural control site. This knowledge gap limits the development of targeted rehabilitation strategies that promote biodiversity recovery and ecosystem resilience.

Consequently, the lack of site-specific information on the relationship between topographic variation and invertebrate community structure may result in ineffective rehabilitation practices, prolonged ecological degradation, and increased management costs. Therefore, there is a need to investigate the influence of topographic position, slope gradient, and slope aspect on the abundance and richness of ants, beetles, and other invertebrates along an age sequence of abandoned gold tailings dumps and a natural control site at Freda Rebecca Gold

Mine (FRGM), Bindura. The findings of this study are expected to generate evidence-based information to improve sustainable mine rehabilitation and biodiversity conservation.

1.3: JUSTIFICATION OF THE STUDY

This study is important because it will contribute to the growing body of knowledge in restoration ecology, biodiversity conservation, and mine rehabilitation by improving the understanding of how topographic variation influences invertebrate community structure on abandoned gold tailings dumps. Specifically, the study will provide empirical evidence on the influence of topographic position, slope gradient, and slope aspect on the abundance and richness of ants, beetles, and other invertebrates across an age sequence of abandoned gold tailings dumps and a natural control site. Such information is currently limited for Zimbabwean mining landscapes. Invertebrates play critical ecological roles in nutrient cycling, organic matter decomposition, soil formation, and ecosystem functioning while also serving as reliable bioindicators of ecological restoration success. Understanding how topographic conditions affect their distribution and diversity will enhance knowledge of the ecological processes that drive biological colonisation and recovery on degraded mine substrates. The findings will therefore contribute to ecological theory on species establishment and habitat suitability in disturbed environments undergoing natural or assisted rehabilitation. The study will also have practical significance for mine rehabilitation planning and management. By identifying topographic positions, slope gradients, and slope aspects that support higher invertebrate abundance and richness, mine managers and restoration practitioners will be able to prioritise these areas for conservation, rehabilitation interventions, and biodiversity enhancement initiatives. Such information can improve the spatial planning of restoration programmes by promoting rehabilitation strategies tailored to site-specific topographic conditions and stages of ecological recovery. Furthermore, comparing invertebrate communities across tailings dumps of different ages with those of a natural control site will provide valuable benchmarks for assessing rehabilitation progress and ecosystem recovery. The findings will support the use of ants, beetles, and other invertebrates as biological indicators for monitoring restoration success, thereby complementing conventional vegetation- and soil-based assessments. This integrated approach will provide a more comprehensive evaluation of ecosystem functioning and resilience in rehabilitating mine landscapes. The study is also relevant to environmental policy and sustainable mining practices in Zimbabwe. The information generated will assist

mining companies, environmental managers, and regulatory authorities, such as the Environmental Management Agency (EMA), in developing evidence-based mine closure and rehabilitation plans that promote biodiversity conservation and long-term ecosystem sustainability. Ultimately, the study will contribute to the improved management of abandoned gold tailings dumps and support efforts to restore ecological integrity in mining-affected landscapes.

1.4. DESCRIPTION OF THE STUDY AREA

The study was conducted at the Freda Rebecca Gold Mine in Bindura, focusing on an age sequence of abandoned gold tailings dumps and a natural control site. Specifically, the research was carried out at three distinct sites: the PP1 tailings dump, which has been abandoned for 86 years; the PP2 tailings dump, which has been abandoned for 96 years and an adjacent natural control site.

To investigate the influence of topographic heterogeneity, the study area was stratified into four primary topographic positions: the plateau, upper slope, mid-slope, and lower slope. Within these topographic positions, slope gradients of 11.3°, 14.0°, and 14.9°, as well as a flat surface with a 0° gradient, were examined. Furthermore, sampling was conducted across all eight cardinal and intercardinal slope aspects: North (N), North-east (NE), East (E), South-east (SE), South (S), South-west (SW), West (W), and North-west (NW), in addition to the flat surface.

Soil samples were collected from depths of 0–5 cm and 0–15 cm to determine key soil properties, namely Soil Organic Carbon (SOC) (%) and Bulk Density (BD) (g/cm^3), for correlation analysis with invertebrate abundance and richness. Soil monoliths were excavated at depth intervals of 0–10 cm, 10–20 cm, and 20–30 cm to assess the vertical distribution of beetles within the soil profile.

1.5: MAIN OBJECTIVE

To assess the abundance and richness of subsoil and surface-dwelling invertebrates across topographic variations along an age sequence of gold tailings dumps and a natural control site.

1.6: SPECIFIC OBJECTIVES

1. To determine the abundance and richness of ants, beetles, and other invertebrates across an age sequence of gold tailings dumps and a natural control site.
2. To determine the variation in the abundance and richness of ants, beetles, and other invertebrates across topographic positions, slope aspects, and slope gradients along an age sequence of gold tailings dumps and a natural control site.
3. To examine the variation in sub-soil beetle abundance and richness across monolith depth intervals along an age sequence of gold tailings dumps and a natural control site.
4. To correlate the abundance and richness of ants, beetles, and other invertebrates with soil properties (Bulk Density [g/cm³] and Soil Organic Carbon [%]).

1.7: RESEARCH QUESTIONS

i. How do the abundance and richness of ants, beetles, and other invertebrates vary across gold tailings dumps and a natural control site?

ii. How do the abundance and richness of ants, beetles, and other invertebrates vary with topographic position, slope aspect, and slope gradient across gold tailings dumps and a natural control site?

iii. How do subsoil beetle abundance and richness vary with monolith depth across gold tailings dumps and a natural control site?

iv. What is the relationship between the abundance and richness of ants, beetles, and other invertebrates and soil properties, namely Soil Organic Carbon (SOC) and Bulk Density (BD)?

CHAPTER 2: LITERATURE REVIEW

2.1: MINING, TAILINGS AND INVERTEBRATE BIOINDICATORS

Ants and other soil invertebrates are sensitive to mining disturbance and can monitor the effectiveness of rehabilitation on gold tailings dumps (Tuma et al., 2022). Research from the early 2010s indicates that ants are reliable bioindicators of restoration effectiveness on gold tailings dumps. According to Andersen et al., 2022; Yekwa et al., 2024, working in gold mining tailings deposits, demonstrated that ant communities varied significantly among recovered sites with varying ages and management regimes. This shows that ants (and consequently other macroinvertebrates) respond strongly to the harsh, oligotrophic, and frequently metalliferous conditions of tailings systems, which is directly related to the objective of evaluating how invertebrate distribution and diversity change across topographic gradients. Soil macrofauna (ants, beetles, termites, and earthworms) are frequently among the first groups to reestablish as vegetation and soil organic matter develop in post-mining landscapes; thus, their community composition can be used to track recovery trajectories relative to undisturbed reference ecosystems (Korboulewsky et al., 2023; Barros et al., 2022).

2.2: SOIL FAUNA, ECOSYSTEM ENGINEERING AND GRADIENTS IN UNDISTURBED ECOSYSTEMS

Parallel to mining research, publications in the 2010s explained how ants, termites, earthworms, and beetles function as "ecosystem engineers," altering microhabitats, soil structure, and the distribution of organic matter to affect their own distribution patterns (Angst et al., 2024; Lavelle et al., 2023). On highly structured substrates like mine tailings dumps, where topographic position regulates erosion, sediment deposition, and organic matter accumulation, these processes are particularly crucial. Global syntheses confirm that earthworms, ants, and termites drive important soil processes such as aggregation, water infiltration, and bioturbation (Jouquet et al., 2022; Blouin et al., 2023).

In the early to mid-2010s, research began linking the distribution of invertebrates in natural landscapes to environmental gradients analogous to topographic variance on tailings. According to Wang et al., 2022; Zhang et al., (2023) showed that soil macrofaunal assemblages varied significantly with distance from the sea along a coastal–inland gradient in China; individual density, richness, and diversity first increased and then decreased along the gradient. This gradient supports the hypothesis that invertebrate communities are not randomly structured along environmental gradients, with some groups acting as indicators of

more "extreme" conditions similar to the contrast between exposed upper slopes and more sheltered foot slopes on tailings dumps.

2.3: TOPOGRAPHIC AND ELEVATIONAL GRADIENTS IN SOIL INVERTEBRATES

Research conducted in the late 2010s and early 2020s specifically examining topographic or elevational gradients provides a closer analogy for this study. (Kongalsky et al., 2022) identified 265 species of soil macrofauna along a 1000 km latitudinal gradient in northwest Russia. They discovered that biomass patterns varied among feeding guilds, with herbivores and fungivores declining toward the north while detritivores and predators displayed less distinct trends. This highlights how distinct functional groups can react differently to the same gradient, which is important when comparing topographic positions of termites, ants, beetles, and earthworms on gold tailings versus natural sites (Potapov et al., 2023).

Studies on soil surface-dwelling Oribatida mites along altitudinal gradients in Changbai Mountain (China) revealed that alpha and beta diversity generally declined with increasing altitude, but density peaked at mid-high elevation where transitional vegetation created favorable microhabitats. Nonmetric multidimensional scaling (NMDS) analysis showed community organization altered dramatically throughout the gradient, with variance largely attributed to elevation and climate. Similarly, (Ferlian et al., 2022); (Meyer et al., 2023) provided evidence that combinations of elevation, aspect, and inclination form unique macrofaunal assemblages even at fine topographic scales in the European Alps. These patterns are directly comparable to the topographic variation (crest, midslope, toe slope) intended to be studied along gold tailings dumps.

2.4: GOLD MINING, TAILINGS AND INSECT BIODIVERSITY

Invertebrate reactions to gold mining offer vital background for contrasting gold tailings dumps with unaltered locations. Hattori et al., 2022; Alvarez-Berríos et al., (2023) connected field studies of insect families over a gradient of artisanal gold mining disturbance in the Guiana Shield with satellite images. Field plots with a larger percentage of mine cover had significantly lower insect family richness, and certain groups were particularly sensitive to mining disturbance, making them potential bioindicators. This demonstrates that gold mining land cover is linked to consistent decreases in taxonomic richness, supporting the study question about how invertebrates differ on gold tailings dumps compared to undisturbed sites.

Simultaneously, research on soilless revegetation of oligotrophic, heavy metal-contaminated gold tailings ponds showed that tailing fertility and microecological conditions can be significantly enhanced by producing vegetation without underlying soil. Li et al., 2023; Wang et al., (2022) found that soilless revegetation considerably raised nutrient content by around 50–170% and decreased heavy metal concentrations. Changes in microbial communities and functional genes were closely associated with these improvements. This background is crucial as it demonstrates how plant establishment on gold tailings quickly alters substrate fertility, creating the heterogeneous, resource-rich patches that normally support more varied invertebrate communities (Wang et al., 2024).

2.5: DEPTH GRADIENTS AND BEETLES

Beetles are the only invertebrate group in this study specifically targeted for depth variation analysis (Magura et al., 2022; Schneider et al., 2023). Recent research indicates that beetle population and community structure are highly depth-organized and substantially correlated with soil organic matter and land use (Buchholz et al., 2023; Görgen et al., 2023). A 2021 mesocosm study using X-ray tomography found that endogeic earthworms concentrated their burrowing in zones with higher organic matter content and stayed mostly near the soil surface in non-tilled soils, suggesting resource distribution influences depth distribution.

Dorji et al., 2022; Norbu et al., (2023) looked at earthworm density in Bhutan at different soil depths and land use categories. They discovered that earthworm density fell dramatically with increasing soil depth and was considerably higher in organically managed fields. Additionally, there was a favorable correlation between earthworm density and soil organic carbon in organic fields. These patterns demonstrate how depth gradients and soil organic matter jointly shape earthworm abundance, relating directly to the research question on how earthworms vary with depth and correlate with soil properties (Pelosi et al., 2023).

2.6: CORRELATING INVERTEBRATES WITH SOIL PROPERTIES

Recent conceptual and empirical research has reinforced the relationship between soil invertebrate communities, soil organic matter, and vegetation structure. Angst et al. (2024) proposed three main mechanisms (transformation, translocation, and microbial grazing) by which soil fauna influence organic matter formation, noting that various faunal strategies have distinct effects on nutrient cycling. This paradigm aids in interpreting connections

between invertebrates and soil organic carbon on tailings, as it emphasizes how earthworms, ants, and termites actively modify organic gradients through bioturbation.

Empirical correlations between soil organic carbon and earthworm abundance have been compiled globally. A meta-analysis by van Groenigen et al. (2023) showed that earthworm abundance and functional group diversity positively influence plant litter degradation and soil organic carbon levels across ecosystems. This confirms the hypothesis that earthworms on gold tailings will be more prevalent where organic carbon inputs are higher. Furthermore, earthworm activity is closely related to bulk density and soil compaction; experimental research shows earthworm burrowing enhances porosity, while high bulk density can restrict digging depth. These interactions are crucial to the final objective, as tailings dumps differ significantly from natural soils in bulk density.

Similarly, ants have been widely recognized as ecosystem engineers whose abundance, species richness, and nesting behaviour are strongly influenced by soil organic carbon, soil texture, moisture availability, and bulk density. Soil organic carbon enhances food availability through increased microbial biomass and detrital resources, thereby supporting both predatory and omnivorous ant species. Ant nesting activities, in turn, redistribute organic matter and mineral particles, improve soil aeration, and facilitate nutrient cycling, creating positive feedbacks between ant communities and soil quality. Studies conducted across disturbed landscapes have consistently demonstrated positive relationships between ant diversity and increasing soil organic carbon, while compacted soils with high bulk density reduce nest establishment and colony persistence because they restrict excavation and reduce soil pore spaces (Del Toro et al., 2023; Wills et al., 2024).

Beetles, particularly ground beetles (Carabidae), scarab beetles (Scarabaeidae), and rove beetles (Staphylinidae), are also closely associated with soil physicochemical properties. Ground beetles respond rapidly to changes in soil organic matter because organic-rich soils support greater prey abundance and provide favourable microclimatic conditions. Dung beetles and litter-associated beetles contribute directly to decomposition processes by fragmenting organic residues, enhancing microbial decomposition, and facilitating nutrient incorporation into the soil. Recent studies have shown that increasing soil organic carbon significantly increases beetle abundance and functional diversity, whereas elevated bulk density reduces beetle movement, larval development, and habitat suitability by limiting soil porosity and oxygen diffusion (López et al., 2023; Phillips et al., 2024). Consequently, beetle

communities are increasingly used as ecological indicators of soil recovery and habitat quality in reclaimed mine sites.

Beyond ants and beetles, other soil macroinvertebrates, including termites, millipedes, centipedes, spiders, isopods, and springtails, exhibit strong associations with soil properties. These organisms play complementary ecological roles in decomposition, nutrient mineralization, predation, and soil aggregation. Soil organic carbon provides both food resources and favourable habitat conditions for detritivores such as millipedes and isopods, while predators such as spiders and centipedes benefit indirectly from increased prey availability in soils with higher biological activity. Conversely, elevated bulk density often limits habitat complexity, reduces pore connectivity, and restricts organism mobility, leading to lower species richness and abundance. Several recent restoration studies have reported significant positive correlations between macroinvertebrate diversity and soil organic carbon, alongside negative correlations with soil bulk density, indicating that improving soil structure promotes the re-establishment of diverse soil faunal communities (Liu et al., 2023; Bardgett & van der Putten, 2024).

In post-mining environments, the relationships between soil properties and invertebrate communities are particularly important because mine tailings are typically characterised by low organic matter, poor aggregation, high compaction, and limited biological activity. As ecological succession progresses, vegetation establishment increases litter deposition, root biomass, and microbial activity, gradually enhancing soil organic carbon while reducing bulk density through root penetration and faunal bioturbation. These improvements create increasingly favourable conditions for colonisation by ants, beetles, earthworms, and other soil invertebrates. Consequently, strong positive correlations between invertebrate abundance and soil organic carbon, together with negative correlations with bulk density, are commonly interpreted as indicators of successful ecosystem recovery and restoration on rehabilitated mine tailings (Angst et al., 2024; Phillips et al., 2024).

Overall, examining the relationships between soil organic carbon, bulk density, and the abundance and richness of ants, beetles, and other soil invertebrates provides valuable insight into ecological restoration processes on gold tailings. These soil biological indicators not only reflect improvements in soil quality but also reveal the extent to which ecosystem functions, including decomposition, nutrient cycling, soil formation, and habitat development, are being re-established during succession.

2.7: ANTS, BEETLES AND SUBSTRATE FERTILITY

Ants and termites have garnered special attention as bioindicators of mining disturbance and modifiers of substrate fertility. Tuma et al. (2022) investigated how termites and mound-building ants modify soil chemical properties throughout a gradient of tropical habitat alteration (Tuma et al., 2022). They discovered that ant and termite mounds significantly altered soil nutrients, creating localized "fertility hotspots" that differ systematically from the surrounding matrix. On gold tailings, where vegetation varies across topographic gradients, these mounds may shape small-scale patterns of invertebrate diversity (Ashton et al., 2023).

Historical and modern data compiled in "The smallest miner of the animal kingdom" emphasize that ants have long been employed in gold prospecting and as biomarkers to track rehabilitation in abandoned mines (Hoffmann et al., 2022). Ant diversity has been used to assess rehabilitation performance among various restoration regimes, supporting the goal of employing ants as markers of the relationship between substrate fertility and topographic variation. Although beetles are rarely purposefully used in mine rehabilitation, research on post-mining landscapes in South Africa has demonstrated that beetle activity can improve soil health parameters by improving dung burial and nutrient incorporation. This implies that ground beetles on gold tailings are likely to react strongly to both topography and local substrate fertility, aligning with previous research showing certain beetle taxa can act as indicator taxa along environmental gradients (Schirmel et al., 2024).

CHAPTER 3: MATERIALS AND METHODS

3.1: STUDY AREA DESCRIPTION

The present study was done on 2 abandoned (86years and 96years) gold tailings dumps located in Bindura (Fig 3.1). Bindura is approximately 89km north-east of Harare. The two gold tailings dumps are 600m South of Freda Rebecca Gold Mine (Fig 3.1). Bindura is in agro-ecological region lla and it has an average temperature of 28^0C and annual precipitation of around 800mm (Zim Meteorological Services, 2020). The study area lies at an altitude of 1070m, latitude $17^0$17’54.18S and longitude $31^0$18’44.89E (Masvodza et., 2013)

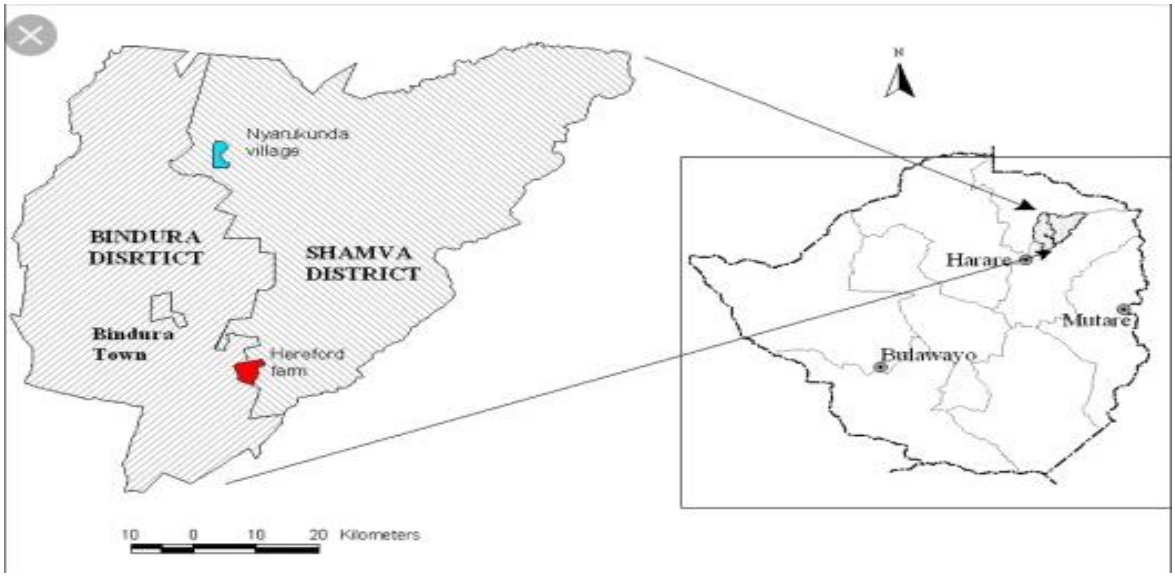


Figure 3. 1: Study area map

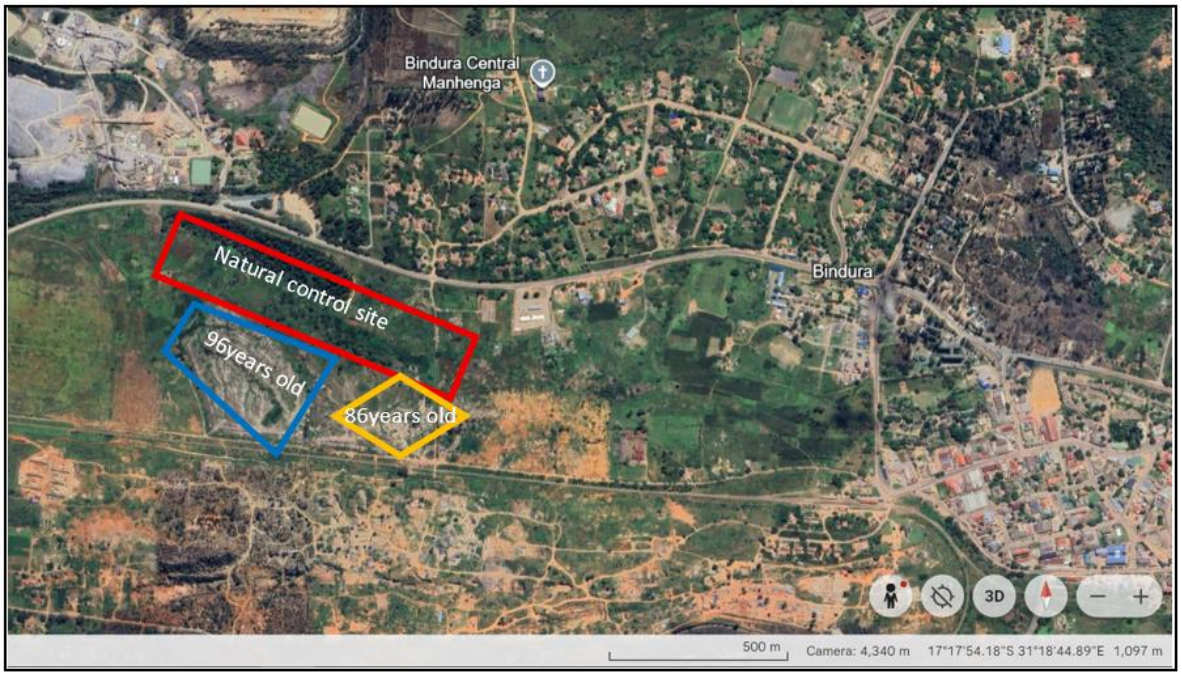


Figure 3. 2: Location map of the study area

3.2 GEOLOGY AND SOIL

The geology is generally a greenstone formation that is composed of gabbro and komatiitic rocks joint with volcanic tuffs and stripy iron formations (Masvodza et al., 2013). The soils in the area are largely kaolinitic. The area is partly covered by fersialitic group of soils that are deep reddish to brown (Nyamapfene 1991).

3.3: RESEARCH DESIGN

The study area was stratified into two abandoned gold tailings dumps, aged 86 and 96 years, and a natural control site. The sample plots were further stratified according to plateau (flat top), slope aspect (Flat, N, NE, E, SE, S, SW, W, and NW), and slope gradient. The slope gradients comprised a 2 m rise over a 10 m horizontal run, a 3 m rise over a 12 m horizontal run, and a 4 m rise over a 15 m horizontal run for each tailings dump and the control site.

Sampling transects were established diagonally across each tailings dump and the natural control site. One transect was established diagonally across the plateau and extended down the slope aspect at each tailings dump and the control site. Sampling points were positioned at 20 m intervals along each transect, with five quadrats established at each sampling point, as described by Nyenda et al. (2020) (Figure 1). One quadrat was positioned at the centre of each sampling point, while the remaining four quadrats were established 2 m from the centre in the four principal cardinal directions (north, south, east, and west). A pitfall trap was installed at the centre of each quadrat. Purposive sampling was used to select the monolith sampling points. The study focused on naturally revegetated gold tailings dumps and an adjacent natural control site for comparison.

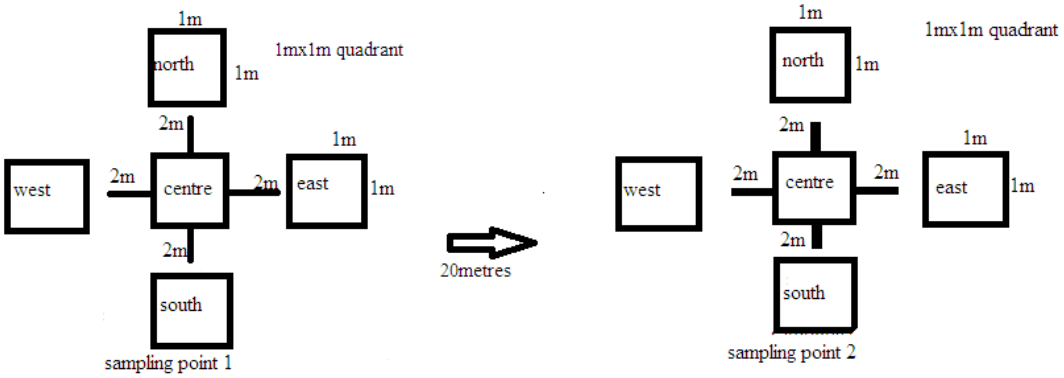


Figure 3. 3: Diagram of five quadrants per sampling point

3.4: TRAPPING OF ANTS AND BEETLES

Ants, beetles, and other ground-dwelling invertebrates were sampled using the pitfall trap method described by Bertoia et al. (2023). The first sampling point was established at one corner of each tailings dump. Pitfall traps were installed at the centre of each 1 m × 1 m quadrat, following the procedure described by Nyenda et al. (2020). Sampling was conducted in January and March 2026.

The pitfall traps consisted of plastic containers buried flush with the soil surface and partially covered with small twigs to minimise rainwater entry and reduce disturbance while allowing invertebrates to enter the traps. Each trap measured 10 cm in diameter and 15 cm in depth, dimensions suitable for capturing a wide range of ground-dwelling arthropods. Each trap was filled to approximately half its volume with a solution of water and a small amount of detergent to break the surface tension and immobilize the specimens. The traps remained in the field for 48 hours, after which the captured specimens were collected. Sampling was conducted twice during the study period to maximize the likelihood of capturing the diversity of invertebrate species present. The same sampling procedure was repeated along the transects of all tailings dumps and at the natural control site to obtain replicate samples.

The collected specimens were carefully removed from the pitfall traps using fine-tipped forceps, sorted, and identified to the lowest possible taxonomic level. Their abundance and species richness were subsequently determined. All collected arthropods were preserved in 70% ethanol for subsequent identification and storage, following the recommended entomological preservation procedures described by Brito et al. (2022)



Figure 3. 4: Pitfall trap set to collect surface invertebrates

3.5: COLLECTION OF BEETLES

Soil monoliths were excavated along diagonal transects across the tailings dumps to assess the vertical distribution of beetles. A spade, shovel, measuring tape, large plastic sheet, labelled sample containers, permanent marker, and field notebook were used during sampling.

At each sampling point, the surface litter within a 25 cm × 25 cm quadrat was carefully removed without disturbing the underlying soil. A soil monolith measuring 25 cm × 25 cm × 30 cm was then excavated by cutting a few centimetres beyond the perimeter of the quadrat with a spade and digging a trench around the soil block to facilitate its removal. The intact soil block was carefully lifted onto a clean plastic sheet and gently broken apart by hand.

The excavated soil was manually sorted and divided into three depth intervals (0–10 cm, 10–20 cm, and 20–30 cm) following the standardised Tropical Soil Biology and Fertility (TSBF) monolith method, which remains the internationally accepted approach for sampling soil macrofauna and has been widely adopted in recent ecological studies (Bottinelli et al., 2023; Mathieu et al., 2024). Each soil layer was thoroughly examined for the presence of beetles and other visible soil macroinvertebrates. All specimens recovered from each depth interval were collected using fine-tipped forceps, counted, and preserved in 70% ethanol for subsequent identification in the laboratory, following the procedures described by Bottinelli et al. (2023) and Phillips et al. (2022).



Figure 3. 5: A monolith of size (0-10cm; 10-20cm; 20-30cm depth)

3.6: SOIL PROPERTIES SAMPLING

Soil samples were collected randomly along the diagonal transect of each tailings dump at depths of 0–5 cm and 0–15 cm using an 8 cm diameter bucket soil auger. The collected samples were placed in labelled sample bags and transported to the Kutsaga Research Board Soil Laboratory, Harare, between 12 and 19 February 2026 for laboratory analysis. In the laboratory, the samples were air-dried at room temperature and sieved through a 2 mm mesh before analysis. Soil Organic Carbon (SOC) (%) and Bulk Density (BD) (g/cm^3) were determined using the analytical procedures described by Tandon (2009). Bulk density is an important indicator of soil compaction and soil structural condition, whereas Soil Organic Carbon (SOC) reflects soil quality and nutrient availability (FAO, 2023). High bulk density generally indicates greater soil compaction, which reduces pore space, restricts water infiltration and aeration, and limits root penetration, as well as the movement and establishment of soil fauna (Hicks Pries et al., 2023). Conversely, increased Soil Organic Carbon improves soil aggregation, reduces bulk density, and enhances habitat suitability for soil organisms. Recent studies have shown that reclaimed mine tailings may experience gradual reductions in soil compaction and corresponding increases in Soil Organic Carbon as vegetation becomes established and organic matter accumulates over time (Villas-Boas et al., 2025). However, bulk density values exceeding approximately 1.4 g/cm^3 in fine-textured soils may still restrict root development and reduce biological activity, thereby influencing the abundance and diversity of soil invertebrates.

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Figure 3. 6: Soil samples collected at depths of (0-5cm and 0-15cm) and ready for analysis.

3.7 DATA ANALYSIS

Data were entered, cleaned, and analysed using IBM Statistical Package for the Social Sciences (SPSS) version 27. Prior to analysis, total abundance, species richness, and diversity indices, including the Shannon–Wiener Diversity Index (H'), Simpson's Diversity Index (D), and Pielou's Evenness Index (J), were calculated for ants, beetles, and other invertebrate groups. Descriptive statistics (means, standard deviations, ranges, and standard errors) were generated to summarise the distribution of invertebrate abundance and richness across the gold tailings dumps and the control site. Where assumptions of normality and homogeneity were met, one-way Analysis of Variance (ANOVA) and General Linear Models (GLM) were used to test for significant differences among tailings dumps age classes and the control site. The Post hoc Least Squares Difference (LSD) at 5% significance level was performed for multiple comparisons using Tukey's Honestly Significant Difference (HSD) test.

To determine the influence of topographic position, slope aspect, and slope gradient on invertebrate abundance and richness across the age sequence of gold tailings dumps and the control site, factorial General Linear Models (GLM) were performed, tailings dumps age, topographic position, slope gradient and slope aspect treated as fixed factors. For soil-dwelling invertebrates, variation in abundance and richness across monolith depth layers and site types was analysed using Linear Mixed Models (LMMs), with depth and site type specified as fixed effects and monolith identity included as a random effect to account for repeated measurements within monoliths.

Relationships between invertebrate community metrics (abundance and richness) and soil properties, namely Soil Organic Carbon % (SOC) and Bulk Density % (BD), were examined using Pearson's correlation analysis. Where necessary, Spearman's rank correlation was used for non-normally distributed data. Partial correlation analyses were further conducted to assess relationships between invertebrate variables and soil properties while controlling for site type and other environmental factors. Statistical significance for all analyses was determined at $\alpha = 0.05$. All results from the SPSS were presented as bar graphs.

CHAPTER 4: RESULTS

4.1 TOTAL ABUNDANCE AND TOTAL RICHNESS ACROSS AN AGE SEQUENCE OF GOLD TAILING DUMPS AND A CONTROL SITE.

Figure 4.1 presents the cumulative abundance (a) and cumulative richness (b) of ants, beetles, and other soil invertebrates recorded across the control site and gold tailing dumps of different ages (96 years and 86 years).

Figure 4.1(a) shows clear variation in the total abundance of soil invertebrates among the three sampling sites. The control site recorded the highest cumulative abundance, with 661 individuals, followed closely by the 96-year-old tailings dump, which supported 556 individuals. In contrast, the 86-year-old tailings dump had a markedly lower abundance, with only 29 individuals recorded during the sampling period. The results indicate that the older, more established 96-year-old tailings dump supported a relatively large invertebrate population comparable to that of the control site, whereas the 86-year-old tailings dump supported substantially fewer individuals. This pattern suggests considerable differences in the overall number of invertebrates occurring across the age sequence of the gold tailings and the control site.

Figure 4.1(b) illustrates differences in the cumulative taxonomic richness of soil invertebrates among the sampling sites. The 96-year-old tailings dump exhibited the greatest richness, with 201 taxa recorded, exceeding the 161 taxa observed at the control site. Conversely, the 86-year-old tailings dump recorded the lowest richness, with only 21 taxa. These results demonstrate that the 96-year-old tailings dump supported the most diverse assemblage of ants, beetles, and other invertebrates, while the 86-year-old tailings dump contained a comparatively depauperate community. Overall, both abundance and richness were substantially reduced at the 86-year-old tailings dump relative to the control site and the 96-year-old tailings dump

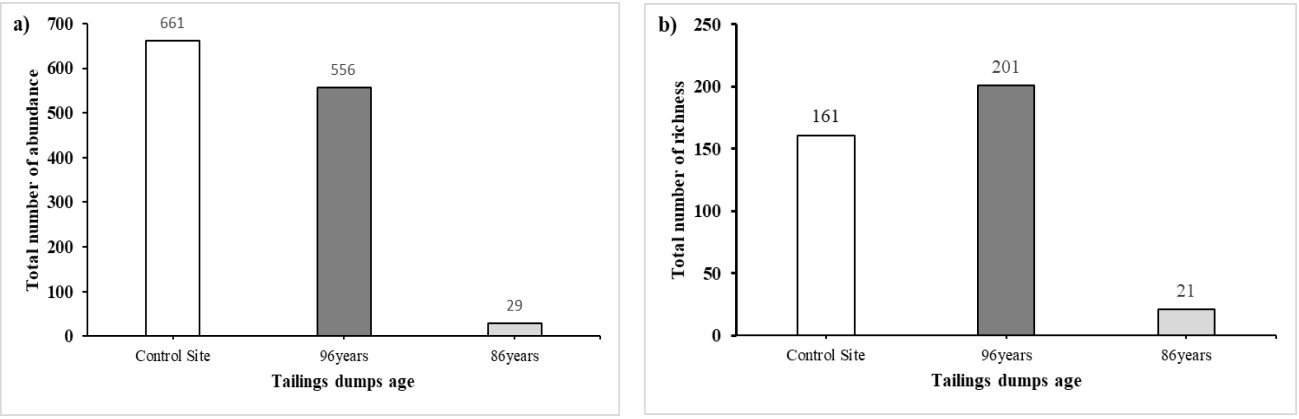


Figure 4. 1: Total abundance (a) and total richness (b) across an age sequence of gold tailing dumps and a control site.

4.2 MEAN TOTAL ABUNDANCE OF ANT, BEETLE AND OTHER INVERTEBRATE ACROSS AN AGE SEQUENCE OF GOLD TAILING DUMPS AND A CONTROL SITE

Figure 4.2(a) shows the mean abundance of ants across the three sampling sites. The control site recorded the highest mean ant abundance (3.37 ± SD), followed by the 96-year-old tailings dump (2.77 ± SD), whereas the 86-year-old tailings dump exhibited the lowest mean abundance (0.15 ± SD). Although the control site and the 96-year-old tailings dump supported relatively greater numbers of ants than the 86-year-old tailings dump, all three sites were assigned the same significance grouping ("a"), indicating that the observed differences in mean ant abundance were not statistically significant ($P > 0.05$). The wide error bars further suggest considerable variability in ant abundance among the sampling plots within each site.

Figure 4.2(b) illustrates the mean abundance of beetles across the age sequence of the gold tailing dumps and the control site. The 96-year-old tailings dump recorded the highest mean beetle abundance (0.67 ± SD), followed by the control site (0.55 ± SD), while the 86-year-old tailings dump had the lowest mean abundance (0.45 ± SD). Despite these numerical differences, all treatments shared the same statistical grouping ("a"), demonstrating that mean beetle abundance did not differ significantly among the three sites ($P > 0.05$). The overlapping error bars indicate substantial within-site variation, suggesting that beetle abundance was highly variable across sampling plots.

Figure 4.2 (c) shows the mean abundance of other soil invertebrates among the sampling sites. The control site recorded the highest mean abundance (3.11 ± SD), followed by the 96-year-old tailings dump (2.48 ± SD), whereas the 86-year-old tailings dump recorded the

lowest mean abundance (0.85 ± SD). Although the control site and the 96-year-old tailings dump generally supported higher numbers of other invertebrates than the 86-year-old tailings dump, the identical significance letter ("a") across all treatments indicates that these differences were not statistically significant ($P > 0.05$). The relatively large error bars associated with each site further demonstrate considerable variability in the distribution of other invertebrates among the replicate sampling plots.

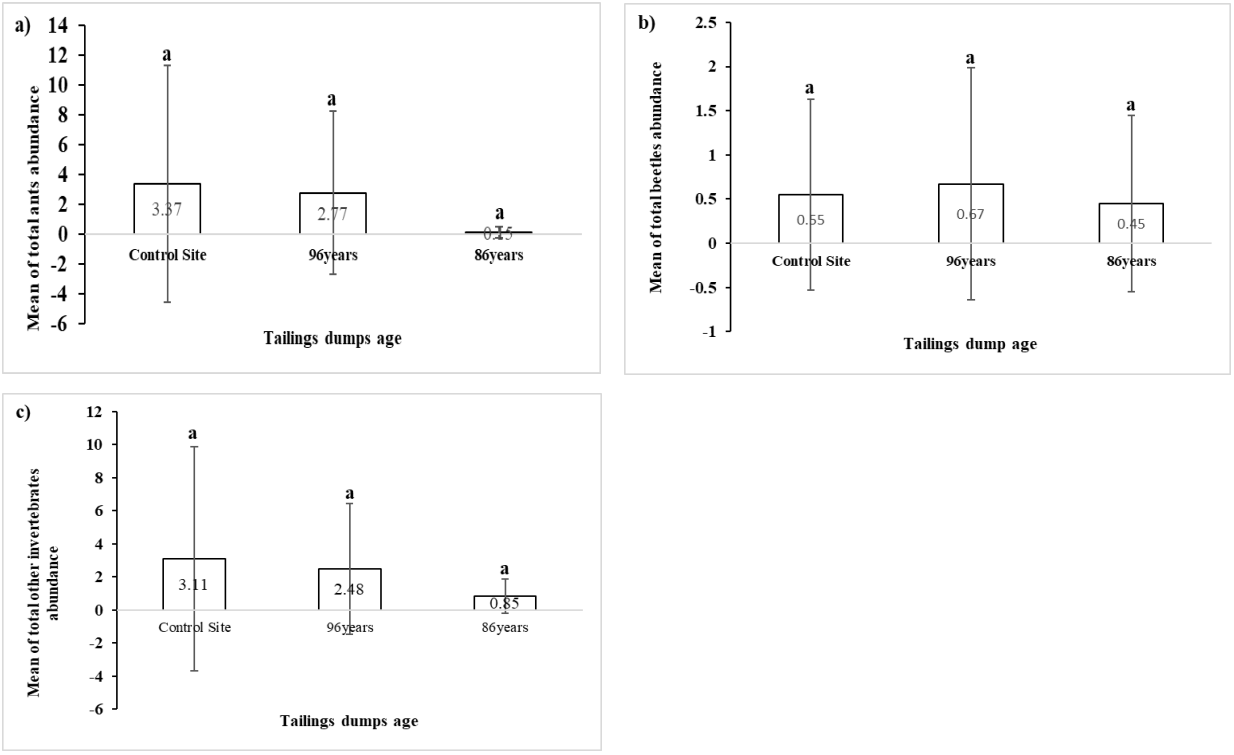


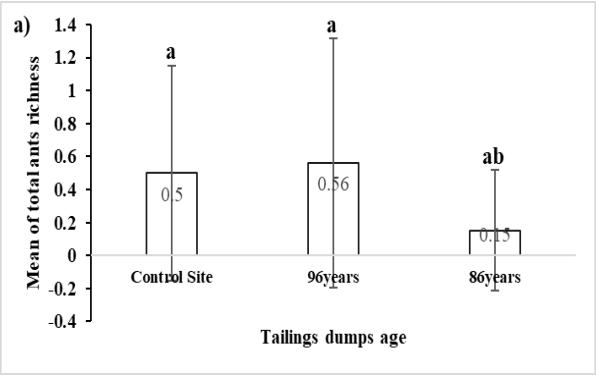
Figure 4. 2: Mean ant abundance (a) beetle abundance (b) other invertebrate abundance (c) across an age sequence of gold tailing dumps and a control site.

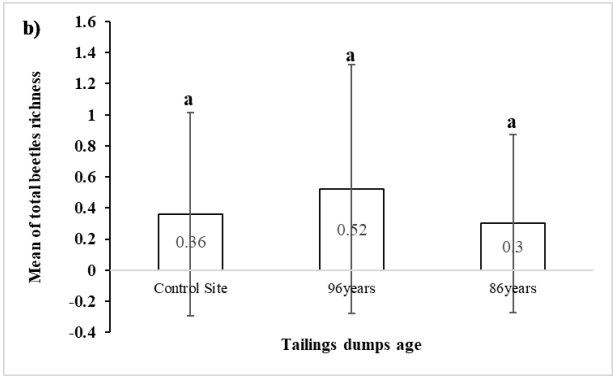
4.3 MEAN TOTAL RICHNESS OF ANT, BEETLE, AND OTHER INVERTEBRATE ACROSS AN AGE SEQUENCE OF GOLD TAILING DUMPS AND A CONTROL SITE

Figure 4.3(a) illustrates the mean ant richness across the three sampling sites. The 96-year-old tailings dump recorded the highest mean ant richness (0.56 ± SD), followed closely by the control site (0.50 ± SD), whereas the 86-year-old tailings dump had the lowest mean richness (0.15 ± SD). The control site and the 96-year-old tailings dump were assigned the same significance grouping ("a"), while the 86-year-old tailings dump was assigned the intermediate grouping ("ab"). This indicates that the 86-year-old tailings dump did not differ

significantly from either of the other two sites, and no statistically significant differences in mean ant richness were detected among the sampling sites ($P > 0.05$). The relatively large error bars further demonstrate substantial variation in ant richness among the replicate sampling plots. Figure 4.3(b) shows the mean beetle richness across the control site and the two gold tailings dumps. The 96-year-old tailings dump exhibited the highest mean beetle richness (0.52 ± SD), followed by the control site (0.36 ± SD) and the 86-year-old tailings dump (0.30 ± SD). Although the 96-year-old tailings dump recorded a numerically higher mean richness than the other two sites, all treatments shared the same significance letter ("a"), indicating that the differences in mean beetle richness were not statistically significant ($P > 0.05$). The overlapping error bars also suggest considerable within-site variability in beetle richness across the sampling plots.

Figure 4.3(c) presents the mean richness of other soil invertebrates. The 96-year-old tailings dump supported the highest mean richness (1.05 ± SD), followed by the control site (0.85 ± SD), while the 86-year-old tailings dump recorded the lowest mean richness (0.60 ± SD). Despite the numerical decline from the 96-year-old tailings dump to the 86-year-old tailings dump, all three sites were assigned the same significance grouping ("a"), demonstrating that the observed differences in mean richness of other invertebrates were not statistically significant ($P > 0.05$). The wide error bars indicate considerable variability among sampling plots within each site.





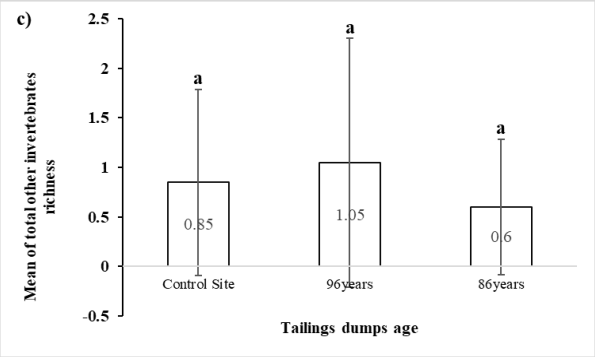


Figure 4. 3: Mean ant richness (a) beetle richness (b) other invertebrate richness (c) across an age sequence of gold tailing dumps and a control site.

4.4 MEAN TOTAL ABUNDANCE AND RICHNESS BY TOPOGRAPHIC POSITION (SURFACE, UPPER-SLOPE, MID-SLOPE, LOWER- SLOPE) ACROSS AN AGE SEQUENCE OF GOLD TAILING DUMPS AND A CONTROL SITE

Figure 4.4(a) illustrates the distribution of mean invertebrate abundance across topographic positions. At the control site, the lower slope recorded the highest mean abundance (10.00 individuals), followed by the surface (7.82 individuals) and the upper slope (7.61 individuals), while the mid slope supported the lowest abundance (1.50 individuals). On the 96-year-old tailings dump, the lower slope again recorded the highest mean abundance (9.50 individuals), followed by the surface (6.66 individuals) and the upper slope (5.22 individuals), whereas the mid slope exhibited the lowest abundance (1.50 individuals). In contrast, the 86-year-old tailings dump supported substantially lower invertebrate abundance across all topographic positions. No individuals were recorded at the lower and mid slopes, while only 1.45 individuals were observed at the surface, and no individuals were recorded at the bottom slope. Overall, the lower slope consistently supported the greatest mean abundance at both the control site and the 96-year-old tailings dump, whereas the 86-year-old tailings dump exhibited very low abundance across all sampled positions.

Figure 4.4(b) shows the variation in mean invertebrate richness across the same topographic positions. At the control site, the lower slope recorded the highest mean richness (2.45 taxa), followed by the surface (1.79 taxa) and the upper slope (1.28 taxa), while the mid slope had the lowest richness (1.17 taxa). A similar trend was observed on the 96-year-old tailings dump, where the surface supported the highest richness (2.89 taxa), followed by the lower slope (2.30 taxa) and the upper slope (1.22 taxa), whereas the mid slope recorded the lowest richness (1.28 taxa). In contrast, the 86-year-old tailings dump exhibited markedly reduced richness, with no taxa recorded at the lower, mid, and bottom slopes, while only the surface supported a mean richness of 1.05 taxa. These findings indicate that the control site and the

96-year-old tailings dump generally maintained greater taxonomic richness across topographic positions than the 86-year-old tailings dump.

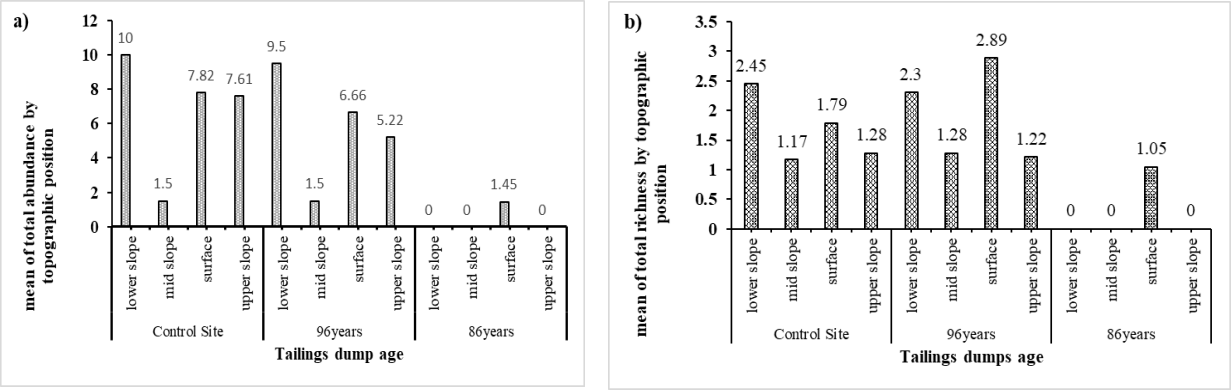


Figure 4. 4: Mean abundance (a) mean richness (b) by topographic position across an age sequence of gold tailing dumps and a control site.

4.5 MEAN TOTAL ABUNDANCE AND RICHNESS BY SLOPE ASPECT (E, N, NE, NW, S, SE, SW, W, FLAT) ACROSS AN AGE SEQUENCE OF GOLD TAILING DUMPS AND A CONTROL SITE

Figure 4.5(a) illustrates the variation in mean invertebrate abundance among slope aspects across the study sites. At the control site, the West-facing slope recorded the highest mean abundance (14.50 individuals), followed by the North-facing slope (10.40 individuals) and the Flat position (7.82 individuals). Intermediate abundances were observed on the South-East (5.50), South (4.67), North-East (5.90), North-West (3.50) and South-West (3.33) aspects, while the East-facing slope recorded the lowest abundance (2.00 individuals). On the 96-year-old tailings dump, the highest mean abundance occurred on the West-facing slope (10.17 individuals), followed by the North-facing slope (8.90 individuals) and the Flat position (6.66 individuals). Moderate abundances were recorded on the North-East (5.70), South-West (4.33), South (3.50), North-West (3.33) and South-East (3.50) aspects, whereas the East-facing slope (1.33 individuals) and South-West exhibited comparatively lower values. In contrast, the 86-year-old tailings dump recorded extremely low abundance across all slope aspects. Only the Flat position supported a mean abundance of 1.45 individuals, while all remaining slope aspects recorded no individuals. These results indicate that west-facing and north-facing slopes generally supported greater mean abundance than the other slope aspects, whereas the 86-year-old tailings dump exhibited minimal invertebrate occurrence regardless of slope orientation.

Figure 4.5(b) shows the variation in mean invertebrate richness across the different slope aspects. At the control site, the highest mean richness was recorded on the North-facing slope (2.30 taxa), followed by the North-East (2.00 taxa) and Flat position (1.79 taxa). Richness values on the East (1.17), North-West (1.83), South (1.33), South-East (1.17), South-West (1.00) and West (1.83) aspects were comparatively lower but remained relatively similar. On the 96-year-old tailings dump, the Flat position exhibited the highest mean richness (2.89 taxa), followed by the North-East (2.20 taxa) and North-facing slope (2.00 taxa). Moderate richness values were recorded on the North-West (1.83), East (1.00), South (1.33), South-East (1.00), South-West (1.00) and West (2.00) aspects. Conversely, the 86-year-old tailings dump displayed very low richness, with only the Flat position (1.05 taxa) supporting invertebrate taxa, while all other slope aspects recorded no taxa.

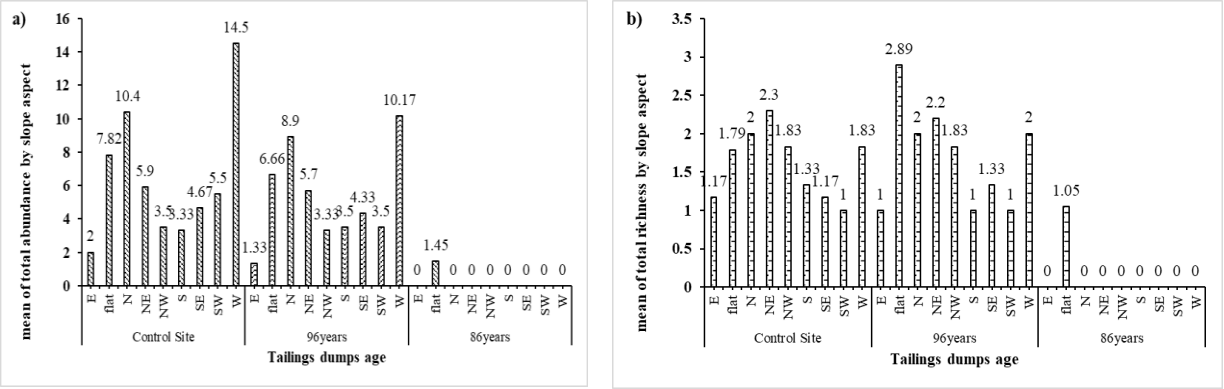


Figure 4. 5: Mean abundance (a) mean richness (b) by slope aspect across an age sequence of gold tailing dumps and a control site.

4.6 MEAN TOTAL ABUNDANCE AND RICHNESS BY SLOPE GRADIENT (0^0, 11^0, 14^0, 14.9^0) ACROSS AN AGE SEQUENCE OF GOLD TAILING DUMPS AND A CONTROL SITE

Figure 4.6(a) illustrates the variation in mean invertebrate abundance across slope gradients. At the control site, the highest mean abundance was recorded at the 14.9° slope gradient (10.00 individuals), followed by the 0° gradient (7.82 individuals) and the 11° gradient (7.61 individuals), whereas the 14° gradient supported the lowest mean abundance (1.50 individuals). A similar pattern was observed on the 96-year-old tailings dump, where the 14.9° gradient also recorded the highest mean abundance (9.10 individuals), followed by the 0° gradient (6.66 individuals) and the 11° gradient (5.22 individuals). The 14° gradient exhibited the lowest abundance (1.50 individuals). In contrast, the 86-year-old tailings dump recorded extremely low abundance across all slope gradients. Only the 0° gradient supported

a mean abundance of 1.45 individuals, while no individuals were recorded at the 11°, 14°, and 14.9° gradients. These results indicate that steeper slope gradients (14.9°) at the control site and the 96-year-old tailings dump generally supported higher mean abundance than the gentler gradients, whereas the 86-year-old tailings dump maintained very low abundance irrespective of slope gradient.

Figure 4.6(b) shows the variation in mean invertebrate richness across the four slope gradients. At the control site, the 14.9° gradient supported the highest mean richness (2.45 taxa), followed by the 0° gradient (1.79 taxa), while the 11° and 14° gradients recorded mean richness values of 1.28 and 1.17 taxa, respectively. On the 96-year-old tailings dump, the 0° gradient exhibited the highest mean richness (2.89 taxa), followed by the 14.9° gradient (2.30 taxa), whereas the 11° and 14° gradients recorded lower richness values of 1.22 and 1.28 taxa, respectively. Conversely, the 86-year-old tailings dump displayed substantially reduced richness, with only the 0° gradient supporting a mean richness of 1.05 taxa, while no taxa were recorded at the 11°, 14°, and 14.9° gradients.

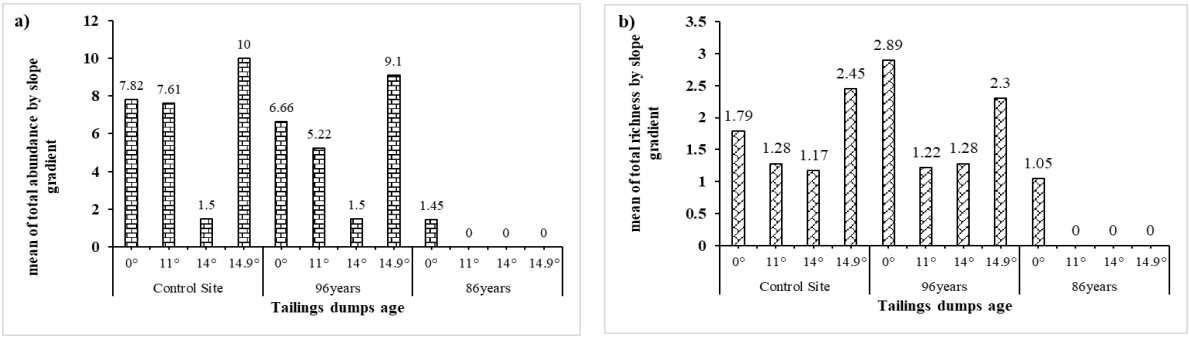


Figure 4. 6: Mean abundance (a) mean richness (b) by slope gradient across an age sequence of gold tailing dumps and a control site.

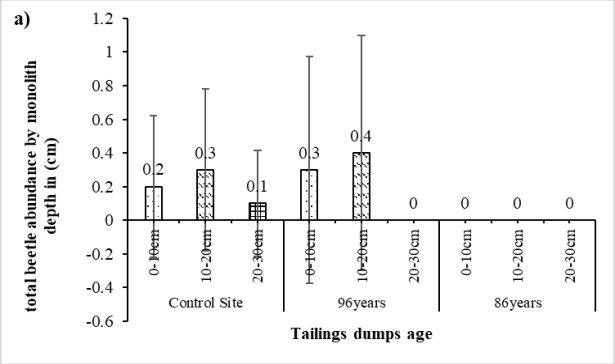
4.7 MEAN TOTAL BEETLE ABUNDANCE AND RICHNESS BY MONOLITH DEPTH (CM).

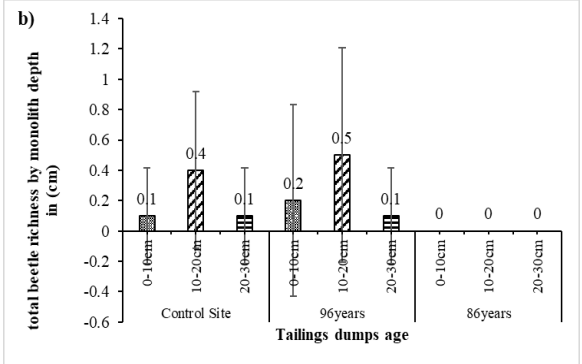
Figure 4.7(a) illustrates the distribution of mean beetle abundance across the three monolith depths. At the control site, the 10–20 cm depth recorded the highest mean beetle abundance (0.30 individuals), followed by the 0–10 cm depth (0.20 individuals), while the 20–30 cm depth supported the lowest abundance (0.10 individuals). A similar pattern was observed on the 96-year-old tailings dump, where the 10–20 cm depth exhibited the highest mean abundance (0.40 individuals), followed by the 0–10 cm depth (0.30 individuals), whereas the 20–30 cm depth recorded no beetles. In contrast, the 86-year-old tailings dump recorded no beetles at any of the sampled depths, indicating the complete absence of beetle individuals

throughout the soil profile. Overall, beetle abundance was greatest within the intermediate soil layer (10–20 cm) at both the control site and the 96-year-old tailings dump and declined with increasing depth.

Figure 4.7(b) shows the variation in mean beetle richness across the three monolith depths. At the control site, the 10–20 cm depth supported the highest mean richness (0.40 taxa), while the 0–10 cm and 20–30 cm depths each recorded a mean richness of 0.10 taxa. Similarly, the 96-year-old tailings dump exhibited the highest richness at the 10–20 cm depth (0.50 taxa), followed by the 0–10 cm depth (0.20 taxa), whereas the 20–30 cm depth recorded a lower richness of 0.10 taxa. The 86-year-old tailings dump recorded no beetle taxa at any of the sampled depths, indicating an absence of beetle richness throughout the monolith profile. These results demonstrate that beetle richness was concentrated within the upper and intermediate soil layers, particularly at the 10–20 cm depth.

Figure 4.7(c) compares the combined mean beetle abundance and richness across monolith depths for the three study sites. At the control site, both abundance and richness peaked at the 10–20 cm depth, with mean abundance (0.30 individuals) and mean richness (0.40 taxa) exceeding those recorded at the 0–10 cm and 20–30 cm depths. Likewise, the 96-year-old tailings dump exhibited the highest combined values at the 10–20 cm depth, recording 0.40 individuals for abundance and 0.50 taxa for richness. At the 20–30 cm depth, beetle abundance was absent, although a small level of richness (0.10 taxa) was still observed. Conversely, the 86-year-old tailings dump recorded no beetle abundance or richness at any of the sampled depths, confirming the absence of beetle communities throughout the soil profile.





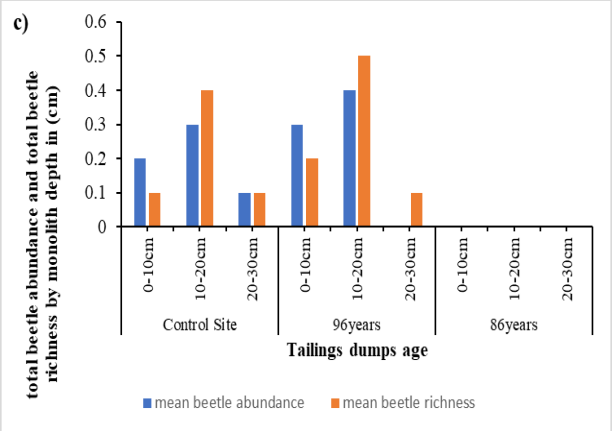


Figure 4. 7: Mean subsoil-beetle abundance (a) beetle richness (b) and combined mean total beetle abundance and richness (c) by monolith depth (cm) across an age sequence.

4.8 CORRELATION OF BULK DENSITY (g/cm³) WITH TOTAL ABUNDANCE AND RICHNESS.

The relationship between total abundance and bulk density is illustrated in Figure (a). Overall, the scatter plot indicates a very weak positive association between total abundance and soil bulk density, as shown by the slightly upward-sloping regression line ($y = -2.17 \times 10^2 + 1.69 \times 10^2 x$). However, the coefficient of determination ($R^2 = 0.032$) demonstrates that bulk density accounted for only 3.2% of the observed variation in total abundance, indicating that the relationship was negligible. Across the bulk density range of 1.41–1.46 g/cm³, total abundance exhibited considerable variability. At a bulk density of 1.41 g/cm³, abundance ranged from approximately 6 to 37 individuals, while values at 1.42 g/cm³ varied between 23 and 35 individuals. At 1.44 g/cm³, abundance ranged from about 12 to 24 individuals, whereas the widest variation occurred at 1.46 g/cm³, where abundance ranged from approximately 10 to 75 individuals. The exceptionally high abundance recorded at 1.46 g/cm³ contrasted with other observations at the same bulk density, indicating substantial variability among sampling sites. These results suggest that total abundance did not consistently increase or decrease with increasing bulk density and that other environmental factors are likely to have exerted a greater influence on invertebrate abundance than soil compaction alone.

Figure (b) presents the relationship between total richness and soil bulk density. In contrast to abundance, the regression line shows a negative trend ($y = 31.39 - 19.95x$), indicating that species richness tended to decline as bulk density increased. Nevertheless, the relationship remained relatively weak, with an R^2 value of 0.221, indicating that approximately 22.1% of the variation in total richness was explained by bulk density. Species richness was highest at a bulk density of 1.42 g/cm³, where values reached 4 taxa, while richness at 1.41 g/cm³

ranged from 2 to 3 taxa. At 1.44 g/cm³, richness was consistently around 3 taxa, whereas at the highest bulk density (1.46 g/cm³), richness declined to values between 1 and 3 taxa. Although the downward trend suggests that increasing soil compaction may be associated with reduced taxonomic richness, the observed variability across sampling points indicates that bulk density alone was not a strong predictor of species richness.

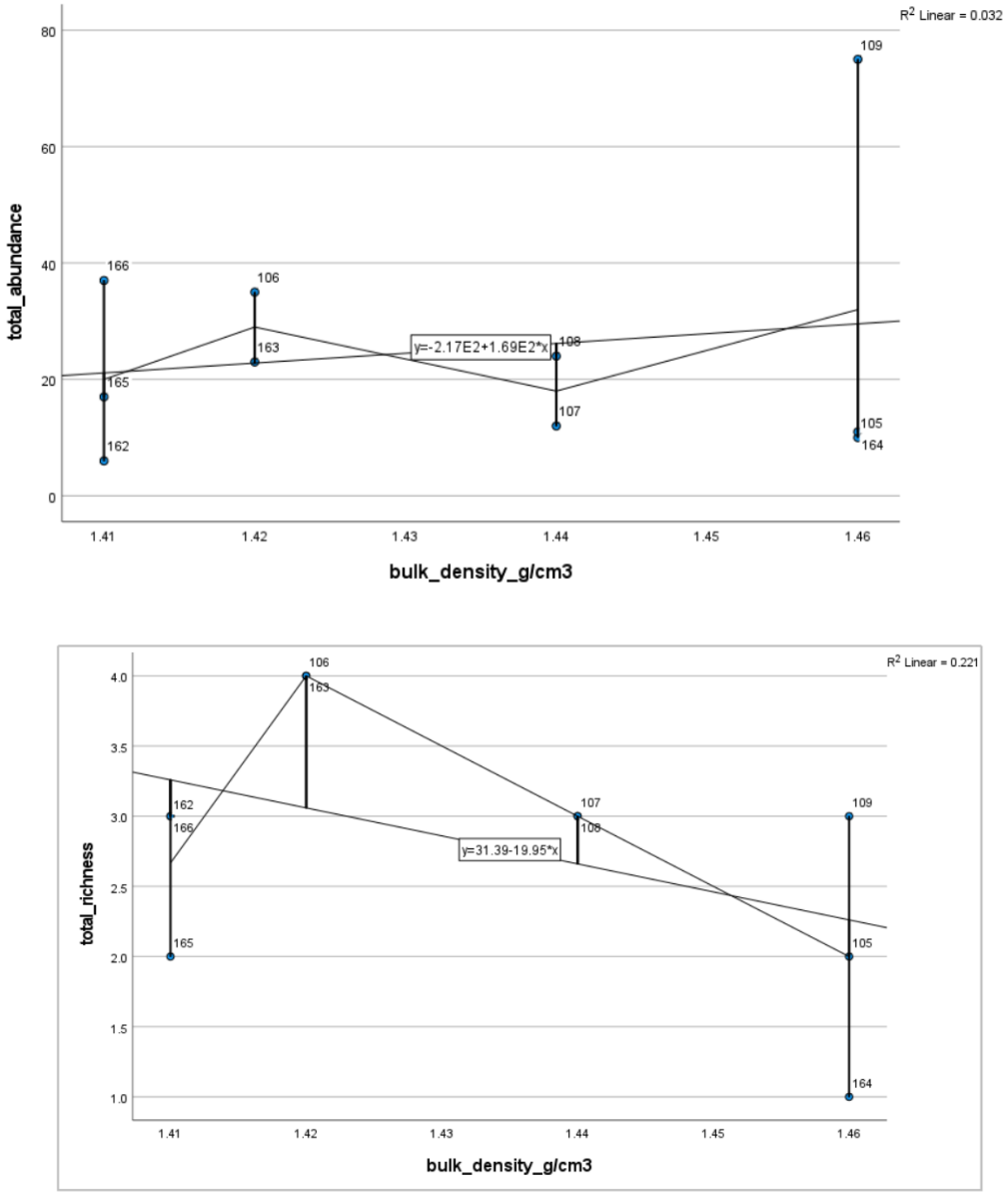


Figure 4. 8: Correlation of bulk density (g/cm³) vs total abundance (a) and richness (b).

4.9 CORRELATION OF SOIL ORGANIC CARBON (%) WITH TOTAL ABUNDANCE AND RICHNESS.

The relationship between total abundance and Soil Organic Carbon (SOC) (%) is presented in Figure 9(a). The scatter plot indicates a moderate negative linear relationship between the two variables, with a coefficient of determination of $R^2 = 0.499$. The fitted regression equation ($y = 146 - 465.2x$) shows that total abundance tended to decline as soil organic carbon increased. Approximately 49.9% of the variation in total abundance was explained by changes in SOC, while the remaining variation was attributable to other environmental factors not included in the model.

The observed data demonstrate considerable variability across the sampled sites. The highest abundance (75 individuals; Site 109) occurred at a relatively low SOC value of approximately 0.21%, whereas lower abundances were generally associated with higher SOC values. For example, abundance declined to approximately 11 individuals at an SOC value of 0.29% (Site 164) and remained similarly low at 0.32% (Site 105). Intermediate SOC values (0.24–0.27%) showed substantial fluctuations in abundance, ranging from approximately 6 to 35 individuals, indicating that although abundance generally decreased with increasing SOC, local site conditions also influenced beetle abundance.

Figure 9(b) illustrates the relationship between total richness and Soil Organic Carbon (%). The regression analysis revealed a weak negative relationship between richness and SOC, with a coefficient of determination of $R^2 = 0.145$. The regression equation ($y = 5.74 - 11.28x$) indicates a slight decrease in richness with increasing soil organic carbon. However, SOC accounted for only 14.5% of the observed variation in total richness, suggesting that soil organic carbon had a relatively limited influence on the number of taxa recorded across the study sites. The distribution of richness values showed substantial variation throughout the SOC gradient. The highest richness values (4 taxa) occurred at intermediate SOC levels of approximately 0.25% and 0.27% (Sites 163 and 106), while the lowest richness (1 taxon) was recorded at an SOC value of approximately 0.29% (Site 164). Richness values of 2–3 taxa were observed across most other SOC levels, with no consistent pattern of increase or decrease. Although the fitted regression line slopes downward, the wide scatter of observations around the trend line indicates that richness varied considerably among sites with similar SOC values. Overall, the results suggest that soil organic carbon exhibited only a weak association with total richness, implying that additional environmental factors likely

played a more important role in determining taxonomic richness across the gold tailings dumps and the control site.

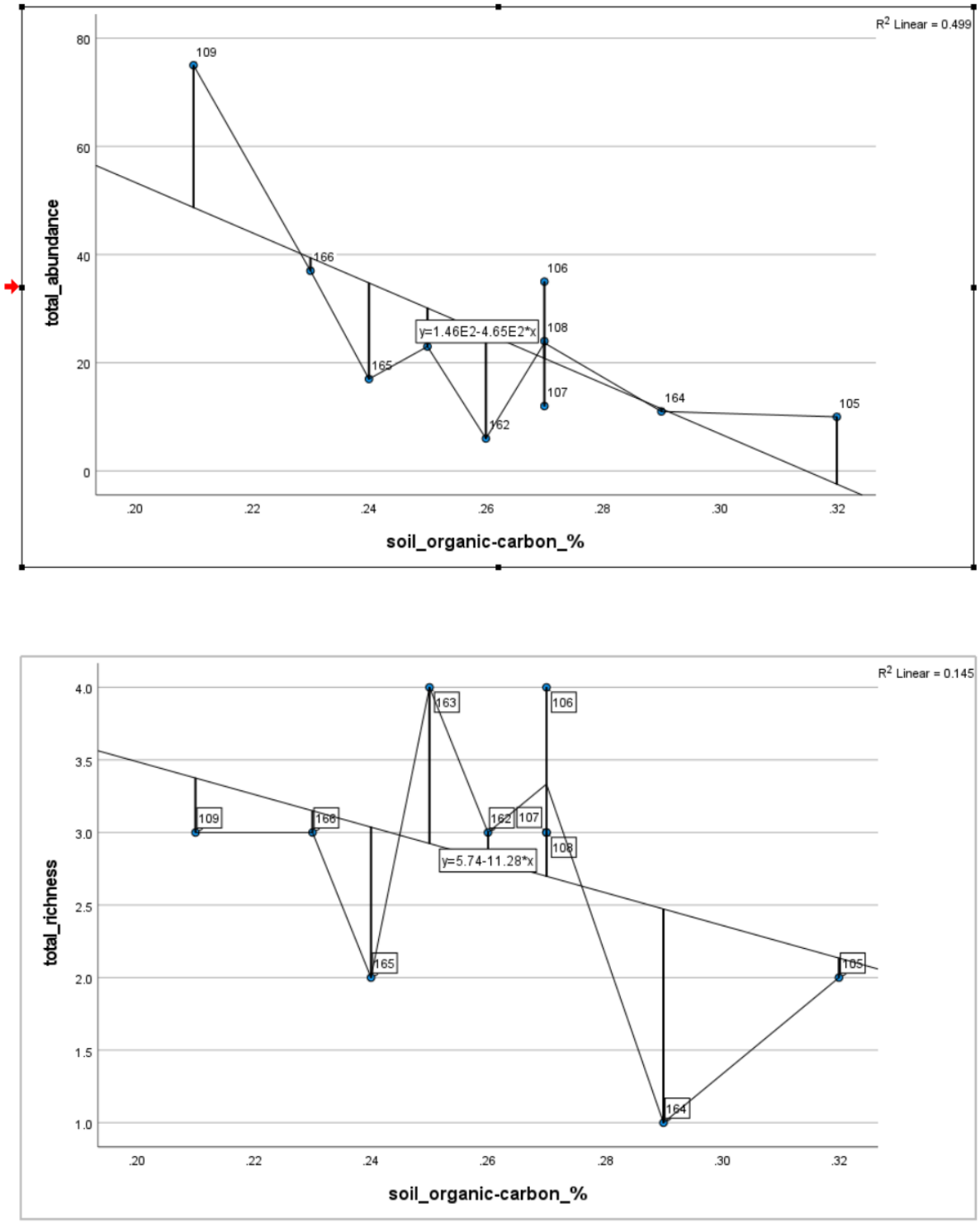


Figure 4. 9: Correlation of soil organic carbon (%) vs total abundance (a) and richness (b).

Table 4. 1: Pearson correlation showing relationships between soil properties (soc and bulk density) with invertebrate metrics (abundance, richness and shannon index)

The results show that soil organic carbon (SOC) exhibited stronger relationships with invertebrate communities than bulk density. Total abundance was significantly and negatively correlated with soil organic carbon (r = –0.712, *P* = 0.021), indicating that variations in soil organic carbon were closely associated with changes in overall invertebrate abundance. Similarly, ant abundance showed a moderately strong negative relationship with soil organic carbon (r = –0.624), while other invertebrate abundance also displayed a significant negative correlation (r = –0.643, *P* = 0.045). In contrast, beetle abundance showed only a weak positive relationship with soil organic carbon (r = 0.047), which was not statistically significant. These findings suggest that soil organic carbon influenced the abundance of some invertebrate groups more strongly than others, with ants and other invertebrates responding more consistently than beetles.

Regarding species richness, soil organic carbon generally exhibited weak to moderate negative correlations with richness variables. Total richness was negatively correlated with soil organic carbon (r = –0.290), while ant richness (r = –0.391), beetle richness (r = 0.047) and other invertebrate richness (r = –0.021) showed weak and statistically non-significant relationships. These results indicate that although soil organic carbon was associated with abundance, it had comparatively little influence on the number of taxa recorded across the sampling sites.

Bulk density showed comparatively weaker associations with both abundance and richness. The correlation between bulk density and total abundance was weak and positive (r = 0.184), whereas bulk density was weakly negatively correlated with total richness (r = –0.381). Similar weak relationships were observed for individual taxonomic groups, with ant abundance (r = –0.161), beetle abundance (r = –0.208), ant richness (r = 0.138), beetle richness (r = –0.206) and other invertebrate richness (r = –0.415). None of these relationships were statistically significant, indicating that bulk density had a limited direct influence on the abundance and richness of soil invertebrates within the sampled sites.

The correlation matrix also revealed strong positive relationships among the biological variables themselves. Total abundance was strongly and positively correlated with ant abundance (r = 0.824, P < 0.001), other invertebrate abundance (r = 0.741, P < 0.001) and total richness (r = 0.451, P < 0.001). Likewise, total richness showed significant positive correlations with ant richness (r = 0.548, P < 0.001), beetle richness (r = 0.437, *P*

< 0.001) and other invertebrate richness (r = 0.781, P < 0.001). These positive relationships indicate that sampling sites with higher numbers of individuals also tended to support a greater diversity of taxa, reflecting a close association between abundance and species richness across the gold tailings dumps and control site.

Finally, the Shannon diversity index was positively correlated with most richness variables, including total richness (r = 0.656, P < 0.001), beetle richness (r = 0.445, P < 0.001) and other invertebrate richness (r = 0.445, P < 0.001), demonstrating that sites with greater taxonomic richness also exhibited higher community diversity. Overall, the correlation analysis suggests that soil organic carbon had a stronger association with invertebrate community structure than bulk density, while abundance, richness and diversity remained strongly interrelated across the sampled habitats

Correlations

		ant_abundance	beetle_abundance	other_invertebrates_abundance	total_abundance	ant_richness	beetle_richness	other_invertebrates_richness	total_richness	bulk_density_g/cm3	soil_organic_carbon_%	Shannon_Index
ant_abundance	Pearson Correlation	1	.013	.249**	.824**	.511**	.063	.004	.238**	-.161	-.624	.154*
	Sig. (2-tailed)		.856	<.001	<.001	<.001	.370	.958	<.001	.656	.054	.026
	N	208	208	208	208	208	208	208	208	10	10	208
beetle_abundance	Pearson Correlation	.013	1	.121	.199**	.181**	.880**	.314**	.653**	-.208	.047	.435**
	Sig. (2-tailed)	.856		.083	.004	.009	<.001	<.001	<.001	.565	.898	<.001
	N	208	208	208	208	208	208	208	208	10	10	208
other_invertebrates_abundance	Pearson Correlation	.249**	.121	1	.741**	.232**	.047	.401**	.373**	.369	-.643*	.198**
	Sig. (2-tailed)	<.001	.083		<.001	<.001	.501	<.001	<.001	.294	.045	.004
	N	208	208	208	208	208	208	208	208	10	10	208
total_abundance	Pearson Correlation	.824**	.199**	.741**	1	.501**	.178*	.264**	.451**	.184	-.712*	.269**
	Sig. (2-tailed)	<.001	.004	<.001		<.001	.010	<.001	<.001	.611	.021	<.001
	N	208	208	208	208	208	208	208	208	10	10	208
ant_richness	Pearson Correlation	.511**	.181**	.232**	.501**	1	.165*	.107	.549**	.138	-.281	.428**
	Sig. (2-tailed)	<.001	.009	<.001	<.001		.017	.125	<.001	.703	.432	<.001
	N	208	208	208	208	208	208	208	208	10	10	208
beetle_richness	Pearson Correlation	.063	.880**	.047	.178*	.165*	1	.219**	.637**	-.208	.047	.449**
	Sig. (2-tailed)	.370	<.001	.501	.010	.017		.001	<.001	.565	.898	<.001
	N	208	208	208	208	208	208	208	208	10	10	208
other_invertebrates_richness	Pearson Correlation	.004	.314**	.401**	.264**	.107	.219**	1	.781**	-.415	-.021	.449**
	Sig. (2-tailed)	.958	<.001	<.001	<.001	.125	.001		<.001	.233	.954	<.001
	N	208	208	208	208	208	208	208	208	10	10	208
total_richness	Pearson Correlation	.238**	.653**	.373**	.451**	.549**	.637**	.781**	1	-.381	-.290	.656**
	Sig. (2-tailed)	<.001	<.001	<.001	<.001	<.001	<.001	<.001		.277	.416	<.001
	N	208	208	208	208	208	208	208	208	10	10	208
bulk_density_g/cm3	Pearson Correlation	-.161	-.208	.369	.184	.138	-.208	-.415	-.381	1	.389	-.008
	Sig. (2-tailed)	.656	.565	.294	.611	.703	.565	.233	.277		.267	.983
	N	10	10	10	10	10	10	10	10	10	10	10
soil_organic_carbon_%	Pearson Correlation	-.624	.047	-.643*	-.712*	-.281	.047	-.021	-.290	.389	1	.679*
	Sig. (2-tailed)	.054	.898	.045	.021	.432	.898	.954	.416	.267		.031
	N	10	10	10	10	10	10	10	10	10	10	10
Shannon_Index	Pearson Correlation	.154*	.435**	.198**	.269**	.428**	.449**	.449**	.656**	-.008	.679*	1
	Sig. (2-tailed)	.026	<.001	.004	<.001	<.001	<.001	<.001	<.001	.983	.031	
	N	208	208	208	208	208	208	208	208	10	10	208

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

CHAPTER 5: DISCUSSION

5.1 INFLUENCE OF GOLD TAILINGS DUMPS AGE AND A NATURAL CONTROL SITE ON TOTAL ABUNDANCE AND TOTAL RICHNESS.

The results showed that the control site had the highest total abundance, with 661 individuals, followed by the 96-year-old tailings dump with 556 individuals, while the 86-year-old tailings dump had only 29 individuals. This suggests that soil invertebrate recovery on gold tailings is not controlled by age alone, but by the degree of habitat development, vegetation cover, soil stability, litter accumulation and microhabitat availability. The high abundance at the control site is expected because undisturbed soils usually provide more stable moisture, organic residues, root systems and shelter for ants, beetles and other invertebrates. The relatively high abundance on the 96-year-old dump indicates that long-term natural succession may have allowed partial recovery of soil structure and vegetation, creating conditions suitable for recolonization. This agrees with Tibbett et al. (2024), who emphasized that post-mining ecosystem reconstruction must begin with soil development because biological recovery depends strongly on below-ground habitat quality.

Total richness was highest on the 96-year-old tailings dump, with 201 taxa, followed by the control site with 161 taxa, while the 86-year-old dump recorded only 21 taxa. The higher richness on the 96-year-old dump may be explained by habitat heterogeneity created during succession, where patches of vegetation, litter, exposed tailings and variable slope positions create different microhabitats. This can allow both disturbance-tolerant and late-colonizing taxa to coexist. The result supports the intermediate disturbance concept, where moderately disturbed or recovering habitats may sometimes support high diversity because they contain a mixture of pioneer and more stable-habitat species. However, the very low richness on the 86-year-old dump shows that some tailings remain biologically poor despite their age, possibly because of poor vegetation establishment, low organic matter, compaction, erosion, toxic residues or limited moisture retention. Cacciuttolo et al. (2022) similarly reported that mine tailings often remain environmentally problematic because they can contaminate soil, water and air, while also creating poor conditions for ecological recovery.

5.2 INFLUENCE OF GOLD TAILINGS DUMPS AGE AND A NATURAL CONTROL SITE ON MEAN ABUNDANCE OF ANT, BEETLE AND OTHER INVERTEBRATES.

Mean ant abundance was highest at the control site, followed by the 96-year-old dump and lowest at the 86-year-old dump. Although the differences were not statistically significant,

the ecological trend is meaningful because ants are highly sensitive to food availability, nesting space, soil temperature and vegetation structure. The higher ant abundance in the control and 96-year-old sites suggests that these habitats provided better nesting conditions and foraging resources. Ants often respond positively to litter, roots, seeds and small arthropod prey, all of which are likely to be limited in poorly developed tailings. The lack of statistical significance may be due to high spatial variability among plots, meaning some plots contained many individuals while others contained few or none.

Beetle abundance was highest on the 96-year-old tailings dump, followed by the control site and then the 86-year-old dump. This suggests that beetles may have benefited from habitat heterogeneity on the older tailings dump. Beetles include predators, decomposers and herbivores, so their presence depends on prey availability, organic residues, vegetation and soil cover. The absence of strong statistical differences indicates that beetle distribution was patchy. This is common in recovering mine landscapes because beetles often colonise suitable microsites rather than spreading evenly across the whole site.

Other invertebrates were most abundant at the control site and 96-year-old dump, but much lower on the 86-year-old dump. This pattern shows that general soil habitat quality was better in the control and older tailings dump. Soil fauna influence litter breakdown, nutrient cycling, aggregation and organic matter formation, and Angst et al. (2024) explained that soil fauna contribute to soil organic matter through transformation, translocation and microbial grazing processes. Therefore, the low abundance of other invertebrates on the 86-year-old dump suggests weak biological functioning and limited soil recovery.

5.3 INFLUENCE OF GOLD TAILINGS DUMPS AGE AND A NATURAL CONTROL SITE ON MEAN RICHNESS OF ANT, BEETLE AND OTHER INVERTEBRATES.

Mean richness of ants, beetles and other invertebrates was generally highest on the 96-year-old dump and lowest on the 86-year-old dump. This indicates that the 96-year-old site supported a wider range of ecological niches than the younger or less-developed tailings dump. The high richness on the 96-year-old dump may be linked to greater vegetation complexity, improved litter input and better microclimatic conditions. In contrast, the 86-year-old dump likely had fewer suitable niches due to limited organic resources, exposed surfaces, compaction or poor moisture retention.

The non-significant differences in mean richness suggest that taxonomic richness varied strongly among plots. This does not mean that the observed ecological pattern is unimportant; rather, it shows that recovery was uneven across the landscape. In mine tailings, some

microsites may accumulate litter and support vegetation, while nearby areas remain bare and biologically poor. Mou et al. (2025) also reported that revegetation is important for improving reclaimed mine soil quality, which supports the interpretation that biological richness depends on local habitat improvement rather than age alone.

5.4 INFLUENCE OF TOPOGRAPHIC VARIATION ON MEAN ABUNDANCE AND RICHNESS ALONG AN AGE SEQUENCE OF ABANDONED GOLD TAILINGS DUMPS AND A NATURAL CONTROL SITE

Topographic position influenced invertebrate abundance and richness. The lower slope recorded the highest abundance at both the control site and the 96-year-old dump, while the 86-year-old dump recorded very low values across most positions. Lower slopes often receive runoff, eroded fine particles, seeds, litter and organic residues from upper positions. These materials improve moisture, food availability and shelter, making lower slopes more favourable for soil invertebrates. The surface and upper slope also supported invertebrates, but the mid-slope was generally poorer, possibly because of erosion, unstable substrate and reduced accumulation of organic matter.

Richness followed a similar pattern, with the control and 96-year-old sites supporting more taxa than the 86-year-old dump. The high richness on the surface of the 96-year-old dump may reflect improved colonisation where vegetation and litter are more accessible. This shows that rehabilitation planning should not treat tailings dumps as uniform landscapes. Instead, each topographic position should be managed according to its limitations. Lower slopes may recover faster, while mid-slopes may require erosion control, organic amendments and vegetation stabilization

5.5 INFLUENCE OF SLOPE ASPECT ON MEAN ABUNDANCE AND RICHNESS ALONG AN AGE SEQUENCE OF ABANDONED GOLD TAILINGS DUMPS AND A NATURAL CONTROL SITE

Slope aspect affected abundance and richness, with west-facing and north-facing slopes generally supporting higher abundance, especially at the control site and 96-year-old dump. This may be due to differences in sunlight, temperature, moisture and vegetation growth. In the Southern Hemisphere, slope orientation can influence heat exposure and soil moisture retention, which affects soil invertebrate survival. Slopes that retain more moisture and support better vegetation are likely to provide more favourable habitats.

The 86-year-old dump showed almost no invertebrates across slope aspects except the flat position. This suggests that aspect alone could not support recovery where the general soil environment remained poor. Flat areas may retain more water, litter and fine particles than steep or exposed slopes, explaining why they supported the few invertebrates recorded on the 86-year-old dump. These results are consistent with recent work on mine restoration showing that slope conditions strongly affect revegetation success because steep and exposed surfaces are more vulnerable to erosion and poor plant establishment (Liu et al., 2022; Tibbett et al., 2024).

5.6 INFLUENCE OF SLOPE GRADIENT ON MEAN ABUNDANCE AND RICHNESS ALONG AN AGE SEQUENCE OF ABANDONED GOLD TAILINGS DUMPS AND A NATURAL CONTROL SITE

The 14.9° gradient supported the highest mean abundance at the control site and 96-year-old dump, while the 0° gradient supported the highest richness on the 96-year-old dump. This suggests that gentle to moderate slope conditions can create favourable ecological niches when vegetation and soil cover are present. The higher abundance at 14.9° may be due to organic matter and moisture movement downslope, creating resource-rich microsites. However, very exposed or unstable slopes can reduce colonisation if erosion removes litter and fine soil particles.

The 86-year-old dump supported invertebrates only at the 0° gradient, showing that flat areas were more favourable under poor tailings conditions. This result has practical importance for restoration. Flat or gently sloping areas may act as initial recovery zones, while steeper areas require physical stabilization, mulching, contouring and vegetation cover. Without such interventions, slope erosion can delay soil development and reduce invertebrate recolonization.

5.7 INFLUENCE OF MONOLITH DEPTH ON BEETLE ABUNDANCE AND RICHNESS ACROSS AN AGE SEQUENCE

Beetle abundance and richness were highest at the 10–20 cm depth in the control site and 96-year-old dump, while the 86-year-old dump recorded no beetles at any depth. The concentration of beetles at 10–20 cm may be due to more stable moisture and temperature conditions compared with the surface, while still having enough organic inputs and root material compared with deeper soil. The surface layer may be more exposed to heat, dryness

and disturbance, while the 20–30 cm layer may have less oxygen, fewer roots and lower food availability.

The absence of beetles in the 86-year-old dump indicates poor subsoil habitat quality. Beetles require suitable pore spaces, prey or organic matter, and protection from extreme conditions. If the tailings profile is compacted, dry, chemically poor or low in organic matter, beetles may fail to colonise deeper layers. This supports the view that successful tailings rehabilitation should improve both surface and subsurface conditions, not only visible vegetation cover.

5.8 INFLUENCE OF SOIL ORGANIC CARBON AND BULK DENSITY ON INVERTEBRATE ABUNDANCE AND RICHNESS

Bulk density showed a weak positive relationship with total abundance but a weak negative relationship with total richness. The weak positive relationship with abundance indicates that abundance did not respond consistently to compaction. This may be because some highly abundant groups, especially ants, can tolerate moderately compacted soils if food and nesting opportunities are available. However, the negative trend with richness suggests that increasing compaction may reduce the number of taxa by excluding sensitive organisms that need pore spaces, oxygen and loose soil for movement.

The Pearson correlation table confirmed that bulk density had weak and non-significant relationships with most biological variables, including total abundance, total richness, ant abundance, beetle abundance and other invertebrate richness. This suggests that bulk density alone was not the main driver of invertebrate patterns in this study. Instead, its effect likely interacted with vegetation, moisture, organic carbon, slope position and tailings chemistry. This agrees with mine restoration studies showing that soil biological recovery is controlled by multiple interacting physical, chemical and biological factors rather than by one soil property alone.

5.9 CORRELATIONS

Soil organic carbon showed a moderate negative relationship with total abundance and a weak negative relationship with total richness. The Pearson correlation table also showed that total abundance was significantly and negatively correlated with SOC, while ant abundance and other invertebrate abundance also declined as SOC increased. This result appears to contradict the common expectation that higher SOC supports more soil organisms. However,

several practical explanations are possible. First, SOC values may have been higher in microsites where organic matter accumulated but where other limiting factors, such as poor aeration, low pH, toxic metals or moisture stress, reduced invertebrate abundance. Second, the SOC range was generally low, so small changes in SOC may not have represented true habitat quality. Third, high abundance at low SOC may have been caused by disturbance-tolerant taxa, especially ants, which can dominate poor or open habitats.

The weak relationship between SOC and richness suggests that organic carbon alone did not determine the number of taxa. Richness depends on a broader set of conditions, including vegetation structure, litter diversity, soil moisture, microhabitat complexity and absence of toxic stress. Angst et al. (2024) argued that soil fauna and organic matter influence each other through several pathways, meaning that SOC should be interpreted as part of a wider soil biological system rather than as a single predictor. Therefore, the negative SOC relationship in this study should not be interpreted as evidence that organic matter is harmful, but rather as evidence that SOC alone was not enough to explain invertebrate recovery on gold tailings.

CHAPTER 6: CONCLUSSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

This study showed that soil invertebrate abundance and richness varied strongly across the control site and gold tailings dumps. The control site supported the highest total abundance, while the 96-year-old tailings dump supported the highest total richness. This indicates that long-term natural recovery can support diverse invertebrate communities, but recovery is uneven and depends on habitat quality rather than age alone. The 86-year-old dump had very low abundance and richness, showing that some tailings remain biologically degraded even after many decades.

Topographic position, slope aspect and slope gradient influenced invertebrate distribution by controlling moisture, organic matter accumulation, erosion and microhabitat conditions. Lower slopes, flat areas and some moderate gradients generally supported better invertebrate communities, while exposed or unstable positions had fewer organisms. Beetles were mainly concentrated at the 10–20 cm depth, suggesting that intermediate soil layers provided more stable conditions than the surface or deeper soil.

The correlation results showed that SOC had stronger associations with invertebrate abundance than bulk density, although the relationship was negative. Bulk density had weak and mostly non-significant relationships with abundance and richness. Overall, the findings show that invertebrate recovery on gold tailings is controlled by combined effects of soil condition, vegetation development, topography, slope stability and microhabitat quality.

6.2 RECOMMENDATIONS

Rehabilitation of gold tailings dumps should prioritise improvement of soil habitat quality through revegetation, organic amendments, mulching and erosion control. Particular attention should be given to poorly recovered areas such as the 86-year-old dump, where low abundance and richness indicate weak ecological functioning. Native plant species should be established to increase litter input, root development and habitat complexity for ants, beetles and other invertebrates.

Future restoration should treat tailings dumps according to topographic position. Mid-slopes and exposed slopes should be stabilized using contouring, grass strips, mulch, stone lines or other erosion-control methods. Flat and lower-slope areas should be protected as recovery zones because they can act as sources for invertebrate recolonization. Monitoring should

include both soil chemical properties and biological indicators, because soil fauna provide useful evidence of ecosystem recovery.

For future generations, rehabilitation should aim not only to reduce pollution but also to rebuild functioning ecosystems. Restored tailings landscapes can improve biodiversity, reduce dust and erosion, increase carbon storage, protect water quality and create safer land for surrounding communities. Future studies should include soil pH, heavy metals, vegetation cover, litter depth, moisture and seasonal sampling to better explain the drivers of invertebrate recovery.

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