INFLUENCE OF TOPSOIL-TILL COVER DEPTH AND AMENDMENTS ON ECOSYSTEM RECLAMATION OF A CLOSED TAILINGS STORAGE FACILITY

by

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ABSTRACT

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The mining industry plays a pivotal role in British Columbia's economic development. Yet, its presence often intersects with the province's ecologically fragile grassland ecosystems, highlighting the importance of reclamation practices to return the disturbed grassland to a sustainable ecosystem. This study explores strategies to enhance reclamation efforts by conducting a field experiment in a reclaimed tailings storage facility (TSF) and a companion greenhouse experiment to investigate the effects of different topsoil and subsoil cover depths (i.e. 10 cm topsoil, 20 cm subsoil and 15 cm topsoil and 15 cm subsoil), and amendments including zeolite, leonardite, and compost in different ratios on soil and plant community properties. Furthermore, the effects of tilling a closed and reclaimed TSF after ~20 years post-reclamation on soil and plant community properties were examined. The results of this study revealed that covering tailings with 15 cm topsoil and 15 cm subsoil resulted in an increase in above-ground biomass and demonstrated the potential of zeolite and compost as sustainable tools for tailings storage facility reclamation. The study also examined the influence of tillage on reclaimed sites, which resulted in a lower carbon-to-nitrogen ratio and a negative impact on alpha diversity in comparison to the reclamation practices on bare tailings. The findings of this research provide valuable insights into the use of different amendments and topsoil-subsoil cover depths for a sustainable reclamation of tailings storage facilities in the semiarid interior of BC.

Keywords: Tailings storage facilities, mine reclamation, soil amendments, soil cover depths, semiarid grassland, zeolite, leonardite

DEDICATION

I would like to dedicate this thesis to my beloved husband, Pouya, who has been an unwavering listener and supporter throughout my academic journey. Also, to my wonderful parents, whose support has been a source of strength despite the miles that separate us in different countries.

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CHAPTER 1 – INTRODUCTION

The extraction of minerals and resources has played a pivotal role in human development, powering industries and economies worldwide (Worlanyo & Jiangfeng, 2021). However, the environmental repercussions of these activities have become increasingly evident, prompting the need for responsible reclamation practices to restore ecosystems impacted by natural resource extractions, such as mining operations (Polster, 2013). Tailings storage facilities (TSFs), where waste materials from mining processes are stored, require management and monitoring due to their potential to cause environmental pollution if not adequately reclaimed (Cacciotti, 2023). Therefore, efforts are underway by scientists to devise effective strategies that mitigate the ecological footprint of mining, facilitate the recovery of disturbed landscapes, and embody the ideals of environmental stewardship and sustainable development.

Mining Industry as a Valuable Factor in The Canadian Economy

The mining industry is beneficial to human society, but there is environmental risk associated with mining (Yousefian et al., 2023). In terms of benefits, the mining industry is responsible for extracting and processing a wide variety of resources that are essential to produce energy resources, such as coal and natural gas and metals such as copper, gold, and iron (Young et al., 2022). These resources are used in a wide range of products and industries, including construction, transportation, and manufacturing.

In the Canadian economy, the mining industry contributed $105 billion to the nation’s Gross Domestic Product (GDP) and was responsible for roughly 5 percent of Canada’s total GDP in 2019 (Statistics Canada, 2022). Canada is a global leader in the mining industry and produces 60 minerals and metals at almost 200 mines and 6,500 sand, gravel and stone quarries (Department of Natural Resources, 2022). Canada’s mineral production was valued to be $43.8 billion in 2020, and even after the initial COVID-19 shock to the world’s and Canada’s economy, mining production increased by 15.5 percent in September 2021 over the same month in the previous year (Statistics Canada, 2022). According to the British Columbia Ministry of Energy, Mines and Low

Carbon Innovation, after the pandemic shock, which resulted in a demand decrease for mineral commodities (except for gold), the prices have surged in the past two years, which positively impacted the industry. Mostly because of that, in 2021 alone, mineral exploration in B.C. saw C$660 million spent, with more than half of it in advanced explorations by mining companies with existing mines, and more than half of the exploration spending was for gold (54%), followed by base metals (29%) and coal (11%) (British Columbia Ministry of Energy, Mines and Low Carbon Innovation, 2021). The expenditure of funds will ultimately transition into an estimated production value of C$7.3 billion from mining output in B.C. Furthermore, in 2021, the Minister of Energy, Mines and Low Carbon Innovation stated that production from B.C. mines was forecasted to be C$12.6 billion, which would be an all-time high. Based on the 2022 preliminary values B.C. mines produced even more than that estimated value, at C$13.4 billion production (British Columbia Ministry of Energy, Mines and Low Carbon Innovation, 2022).

In Canada, mining occurred long before the arrival of Europeans, when Indigenous people utilized diverse minerals to craft tools, weapons, art, and artifact items (Manitowabi, 2018). Evidence of a long mining history by Indigenous people includes copper trading around Lake Superior approximately 6000 years ago and silver mining in the Cobalt area around 200 years before Western colonization (Manitowabi, 2018). In the mid-1800s, the coal mines on Vancouver Island and the placer gold camps in the Cariboo region made British Columbia one of the world's major mining regions (Barazzuol et al., 2003). British Columbia is a significant producer and exporter of copper, gold, silver, lead, zinc, molybdenum, coal and industrial minerals (Ministry of Energy, Mines and Low Carbon Innovation, 2020). In general, mining accounts for B.C.'s second most valuable export, with metallurgical coal and copper being the most important. The rich history of mining in B.C. indicates its contribution to sustaining the Canadian economy.

Environmental Aspects of the Mining Industry

Mining is a crucial factor in the economy, employment, infrastructure and society, but there is environmental risk in the extraction of natural resources (Yousefian et al., 2023). In general, there are two stages when mining activities can have a negative impact on the environment. First, mineral resources are underground and cannot be accessed without removing the soils and vegetation that cover them. Second, due to excavation, many mine tailings and waste materials are stored at the mine's site (Bradshaw, 1997). According to estimates, over 10 billion tons of mining tailings are generated each year (Adiansyah et al., 2015), and tailings management facilities are frequently built to hold the tailings (Shrestha & Lal, 2006). According to Errington (2001), for every kilogram of copper produced in British Columbia, 200 kg of waste rock is excavated and stored in waste dumps, as well another 200 kg of tailings may be excavated and stored in tailings storage facilities. These mining activities can change the land ecology and negatively affect the environment, through the loss of native vegetation, reduction in biodiversity and the introduction of invasive species that ultimately decrease the terrestrial ecosystem’s quality (Shrestha & Lal, 2006; Orlando, 2021). Furthermore, the environmental impact of the mining industry on lands, especially grasslands in B.C., can negatively influence ecosystem services, as grasslands produce the forage for livestock, control the rate of erosion, provide habitat for wildlife, and influence hydrology, water filtration, nutrient cycling, and pollination (Costanza et al., 1997; Wilson, 2009). Furthermore, it can lead to issues such as acid mine drainage, land subsidence, heightened vulnerability to natural disasters, and adverse effects on animals and human health (Fashola et al., 2016).

Mine Tailings and Efforts Toward Mitigating the Environmental Footprint

In recent decades significant policies and actions have been made to minimize the environmental footprint of mining operations. Examples of the many positive policies are the Canadian Environmental Protection Act, including the Chemicals Management Plan and Interprovincial Movement of Hazardous Waste Regulations, the Fisheries Act, including the Metal Mining Effluent Regulations, Navigable Waters Protection Act/Navigation Protection Act, Species at Risk Act, Migratory Birds Convention Act, and Transportation of Dangerous Goods Act (British Columbia Mine Information, 2023).

The mining industry in British Columbia and its communities, including associations, companies, and regulatory bodies, are all committed to protecting the environment before, during, and after mining activities. To achieve this goal, guidelines for land reclamation have been developed and revised many times by the Ministry of Energy within the Government of British Columbia in the form of The Mines Act and the Health, Safety and Reclamation Code for Mines in British Columbia (the Code) (Government of British Columbia, Ministry of Energy, last revision in 2021). According to the BC Ministry of Energy, Mining and Low Carbon Innovation (2021), each mine is required to prepare a reclamation and closure plan, including activities conducted during a mine's lifespan to mitigate mining impacts, ensure stable landforms, restore ecosystems, manage water quality, and remediate contamination. Furthermore, the closure of tailing storage facilities needs to achieve the approved end land and water use objectives in British Columbia (Health, Safety and Reclamation Code for Mines in British Columbia, 2021).

Land reclamation involves the return of mining sites and tailings pond surfaces to their natural or usable state after mine closure or the decommissioning of tailings facilities. To effectively mitigate the environmental impact of mine tailings, one effective reclamation approach post-mine closure is the use of subsoil and topsoil cover on the tailings. This reclamation strategy encompasses three primary techniques: physical, chemical, and vegetation covers, all of which play a crucial role in significantly decreasing downhill drainage, water infiltration, and the transportation of hazardous metals (Xie & Zyl, 2020; Wang et al., 2017).

Rebuilding Ecosystems Through Land Reclamation

The recovery of essential ecosystem services and biogeochemical functions within a newly established ecosystem can be termed reclamation, and the preliminary purpose of reclamation is vegetation cover establishment, enhancement of soil and water conditions for stability, and improvement of ecosystem services (Asiedu, 2013). On the other hand, the transformation and repurposing of the landscape, termed rehabilitation, can also represent effective strategies to address the lasting impacts of surface mining activities (Bradshaw, 1996; Ofosu & Sarpong, 2023).

There is a significant difference between ecological restoration and land reclamation. Ecological restoration is the practice of restoring degraded land to its pre-disturbance state with an emphasis on restoring the composition and structure of the ecosystem and is considered a long-term objective. Land reclamation serves as a short-term objective and is the process of revegetating the disturbed land and seeks to restore environmental quality and improve land management capability, to develop a functional ecosystem that delivers important ecological services while structurally, it can be different from the pre-disturbance ecosystem (Bradshaw, 1987; Favas et al., 2018). If we add diversity, species composition and ecosystem function to land reclamation, we have ecological restoration (Bradshaw, 1987).

Topsoil, Subsoil, and Their Role in Land Reclamation

Soil is a valuable resource for reclamation, but its worth is often underestimated. Topsoil or A-horizon refers to the upper or outer layer of soil and is usually the top 25 cm, has the highest density of organic matter and microorganisms, has experienced eluviation and is rich with minerals and organic particles as well as water and air (Power et al., 1981). Most of the biological activities of the planet occur in topsoil, and almost all plant roots find their needed nutrients in topsoil (Fischer, 2023). Subsoil or B-horizon is the layer of soil under the topsoil, where minerals leached from the topsoil layer can be stored, typically with a lower percentage of organic matter (Sanaullah et al., 2011). In the mining industries, surface soil horizons are frequently removed and stockpiled at the mine sites, which leads to significant alterations in nitrogen (N) transformations and movements, ultimately resulting in considerable losses (Sheoran et al., 2010; Fischer et al., 2022). During the first years of stockpiling, the highest loss of organic carbon, nitrogen, potassium, and phosphorus and the microbial community in soil dumps occurs (typically 30 percent after one year, and in many cases, 50 percent after three years of stockpiling) (Ghose, 2001). Also, the organic matter in the soil is rapidly reduced when topsoil is lost or removed (Fischer et al., 2022). Although surface horizons can be restored by importing topsoil, this is a costly and inefficient method, so it is desirable for the industry to undertake land reclamation that is as inexpensive and effective as possible (Larney & Angers, 2012; Darmody et al., 2009). Salvaged topsoil holds immense value for the reclamation of mining sites, and a prevalent approach involves relocating topsoil from excavated regions to the areas undergoing reclamation, but this soil often cannot be used immediately and needs to be stored in stockpiles (Valliere et al., 2021).

Amendments and Their Role in Land Reclamation

The addition of suitable amendments to the adequately placed cover depth (topsoil and subsoil) may be an effective way to promote plant growth and vegetation development. Reclamation and ecosystem development can occur through natural processes over time, however this process is slow (Christensen, 2014). Reclamation initiatives often incorporate strategies to expedite the process of natural succession, thereby achieving the desired endpoint more rapidly (Palmer et al., 2016). One of the reclamation efforts in mining is to cover tailings with the topsoil and subsoil materials that were removed and stockpiled during the building of TSFs to promote vegetation and ecosystem development. Soil materials, especially topsoil, provide favorable physical, chemical, and microbiological properties that are vital for successful plant establishment (Strohmayer, 1999; Hargis & Redente, 1984; Rivera et al., 2014; Merino-Martín et al., 2017). However, the series of actions involved in topsoil deterioration, ranging from stripping to relocation and storage, holds the potential to impact the soil's physio-chemical characteristics, subsequently diminishing its capacity to facilitate ecosystem reclamation effectively (Mummey et al., 2002b). Furthermore, topsoil availability is often limited at mine sites, therefore, determining its cover depth along with subsoil is crucial (Merino-Martín et al., 2017).

Organic amendments can provide the soil with the necessary organic material and carbon source for re-activating the nutrient cycle, which is the positive interaction between soil and plants where plants use the nutrients stored in the soil and distribute them on the surface as organic matter (Bradshaw, 1997; Heiskanen et al., 2022; Asemaninejad et al., 2021). Therefore, designing a balance of the appropriate cover depth amount and the suitable types of amendments can implement a successful way for reclamation in mining sites. In addition, as mine tailings consist of various toxic metals, it can be beneficial to add an amendment capable of ameliorating contaminated soils by immobilizing heavy metals (Palansooriya et al., 2020).

Zeolites are crystalline aluminum–silicate (Al-Si) minerals with porous properties and high specific surface areas, present in natural volcanic rocks and can be produced from various silicon (Si) and aluminum (Al) compounds. This mineral is acknowledged for its effective water retention capability, which stands out as a valuable option for improving moisture levels in arid regions (Jakkula & Wani, 2018). Moreover, it is known for its strong adsorption capacity and catalytic applications based on their unique physical structure (Jakkula & Wani, 2018; Lin et al., 1998). In addition, zeolites can act as a sponge to release a source of nutrients upon being recharged with ammonium nitrogen, potassium, or iron (Kithome et al., 1998). A study by Glab et al. (2021) demonstrated that the use of zeolite in contaminated soil significantly increased root biomass. Many studies have shown that applying zeolite results in reduced heavy metal uptake, especially copper, by plants and decreases concentration of available metals in the soil (Belviso, 2020; Cadar et al., 2022; Zorpas et al., 2000). Furthermore, due to the porous nature of zeolites, they can have a low bulk density. So, their addition to mine soils with coarse texture can result in lower bulk density and an increase of water holding capacity to assist with vegetation establishment (Misaelides, 2011; Kesraoui-Ouki, 1993; Hazrati et al., 2022).

In addition to zeolite, leonardite has lately gained popularity as a soil amendment and humic acid source for improving soil and plant yields. Leonardite is an oxidized form of lignite, displaying a brown and coal-like appearance which formed through a billion-year-long breakdown process. It has a limited water solubility and does not often include significant levels of nitrogen (N), phosphorus (P), or potassium (K). Its strong ion exchange capacity has been shown to be helpful in eliminating heavy metals like lead (Pb), zinc (Zn), nickel (Ni), copper (Cu), and silver (Ag) from contaminated groundwater (Wandruszka, 2000). Most importantly, as leonardite is a source of humic acid, it decreases water evaporation from soils, which is essential in arid areas with sandy soils that retain little to no water (Piccolo et al., 1996). Therefore, the high concentration of humic acid makes leonardite an ideal amendment in arid and semi-arid areas (Piccolo et al., 1997; Iakimenko, 2005). Furthermore, physiologically active humic substances have been found to exhibit the most significant impact when plants are exposed to unfavorable environmental conditions, including inadequate or excessive moisture levels, low temperatures, and the presence of heavy metals. This suggests that the presence of active humic acid in leonardite not only enhances plant resistance to specific environmental factors but also contributes to overall plant resistance (Iakimenko, 2005).

Compost amendment consisting of wood waste, urea, some beneficial microbes, also has the potential to promote plant growth and soil fertility in disturbed lands (Percival et al., 2023). The high diversity of the compost microorganisms can result in a reinforcement of the overall microbial activity both by high physiological redundancy and an abundance of metabolic potential in various microorganisms (Kastner & Miltner, 2016). Furthermore, compost has high organic matter content, and when organic matter is added to soil, it causes a significant change in microbial activity and improve cation exchange capacity (Scharenbroch & Watson, 2014). This enhancement contributes to an increased water retention capacity in the soil, facilitating both the retention and release of water and nutrients (Krull et al., 2004). The presence of wood chips also can provide the compost with great benefits such as the augmentation of soil moisture, mitigation of temperature variations, suppression of weed proliferation, and control of soil-borne diseases (Percival et al., 2023).

Importance of Native Species and Grasslands in Mine Reclamation

Recent studies point out the role of native plants in natural ecological succession and reclaiming the land to the pre-mining ecosystem (Godefroid et al., 2011). However, due to heavy disturbance, lack of soil, high procurement costs, difficult propagation, and poor growth of native plants in disturbed sites, mining sites are often reclaimed using non-native plants. These plants, described as agronomics, are economical, easy to establish, fast-growing, and are often grown in monocultures (Dormaar et al., 1995; Swab et al., 2017). Introduce and grow native species in the disturbed sites is challenging, especially once agronomics are established as they can out-compete native species (Hagen et al., 2014). Nevertheless, the establishment of native plant communities is becoming an increasing target for mine closure plans because Indigenous peoples, as the primary beneficiaries and stakeholders of the land prior to mining activities, tend to have more land-use objectives associated with native plants than with the non-natives (Collins, 2015). When successfully accomplished, high native plant diversity can translate into a high level of ecosystem services and ecological succession (Bradshaw, 1987).

Native grasslands in British Columbia play a vital role as a pivotal yet endangered ecosystem, offering priceless ecosystem services to local communities. These grasslands contribute significantly to biodiversity, carbon sequestration, and water filtration, underscoring their ecological importance (Boval & Dixon, 2012). Recognizing their value, it becomes imperative to address the challenges posed by the degradation of these grasslands, particularly during mining activities. The sensitivity of grasslands, particularly in semiarid conditions prevalent in the southern interior of British Columbia, adds an additional layer of complexity to the reclamation process. The arid climate can make it challenging for vegetation to re-establish and thrive, prolonging the recovery period and potentially requiring many years to achieve successful restoration (Wetland Stewardship Partnership, 2010).

THESIS RESEARCH OBJECTIVES

This study examines whether two various subsoil and topsoil cover depths combined with different types of amendments (namely zeolite, leonardite, and compost) can enhance the soil fertility, plant growth and ultimately the return of grasslands at the Historic Afton TSFs near Kamloops, B.C. Therefore, a comprehensive study, including a greenhouse and a field experiment, was conducted to achieve the above-mentioned purposes. The objectives of the greenhouse study (Chapter 2) are twofold: 1) to examine how zeolite, leonardite, and their combined application in varying ratios affect soil fertility and the growth of bluebunch wheatgrass, and 2) evaluate the impact of incorporating compost alongside these amendments on plant growth and the enhancement of soil properties. The objectives of the field study (Chapter 3) encompass three primary aspects: 1) exploring the impact of incorporating zeolite, leonardite, and compost as soil amendments on plant productivity, biodiversity, and soil properties, 2) investigating how two different topsoil and subsoil cover depths influence the reclamation succession, and 3) assessing the effects of the above-mentioned treatments on both bare tailings and a reclaimed TSF that underwent tillage. It is hoped that the results of this thesis will contribute to the information on sustainable TSFs management and reclamation practices in semiarid environments and provide insights into influence of the amendments and the topsoil-till cover depths on plant growth and soil properties for environmental scientists and practitioners.

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CHAPTER 2 – APPLICATION OF ZEOLITE, LEONARDITE, AND COMPOST AS A TOOL FOR MINE RECLAMATION: A GREENHOUSE STUDY

INTRODUCTION

Mineral resource consumption is constantly increasing, resulting in more mining excavation to extract the desired minerals and more mine waste deposits on lands (Plante et al., 2023). Mine waste, non-marketable rock, is gathered and stored on mine sites. Tailings are one type of mine waste material produced during the processing of minerals, which are obtained from a mine source and separated from the ore through a mill, washery, or concentrator (Lottermoser, 2010). These materials usually contain heavy metals and are required to be deposited in safe tailing storage facilities (TSFs) (Cacciotti, 2023). The process of building TSFs involves the removal of topsoil, subsoil and materials from lands that can take up several square kilometers and reach tens of meters in depth (Schoenberger, 2016).

Relying on natural processes for the ecological restoration of TSFs filled with mine tailings may take several hundred years (Bradshaw, 1987). On the other hand, studies have shown a risk of mine tailings on the environment and health (Cacciotti, 2023). In recent decades, significant policies and actions have been devised to minimize the environmental footprint of mining operations by improving reclamation practices. Land reclamation aims to build and enrich the soil and encourage the establishment of plant and animal communities. This is a challenge because mine tailings have an inferior soil structure due to the lack of nutrients and organic matter, and high levels of heavy metals (Gardner et al., 2010; Hayes et al., 2009).

To reduce the environmental impact of mine tailings and promote vegetation and ecosystem development, placing topsoil and subsoil covers on top of the tailings has become a common and direct way of reclamation following mine closure. The topsoil and subsoil that were removed prior to the construction of TSFs can be reapplied and levelled to provide a planting medium (Zhu et al., 1999). However, the disturbed topsoil and subsoil may not be as nutrient-rich as they were prior to removal (Fischer et al., 2022). The act of disturbing the surface layer of soil through stripping, long-term stockpiling, and reinstatement can induce notable transformations and movements of nitrogen (N), ultimately leading to substantial nutrient loss and significant soil quality degradation over time (Strohmayer, 1999; Sehorn et al., 2010; Fischer et al., 2022). Incorporating appropriate amendments to the soil can improve the structure of the microbial community and enrich soil with organic material and carbon sources to re-activate the nutrient cycle (Bradshaw, 1997; Asemaninejad et al., 2021).

Although there are different types of amendments that can assist with the reclamation of contaminated sites, the use of natural zeolites has gained attention due to their low cost, widespread availability in the world and unique physicochemical properties (Manu et al., 2022). Natural zeolites are crystalline aluminosilicates that originated from volcanic rocks and are known for their ion-exchange properties, and ability to enhance plant growth, improve soil properties, reduce drought effects and nutrient leachate, mitigate soil contaminations, and increase water retention capacity of the soil (Misaelides, 2011; Kesraoui-Ouki et al., 1994). Another amendment with potential use for mine reclamation is leonardite. Leonardite is a naturally occurring type of oxidized lignite, rich in humic and fulvic acids (Ozdoba et al., 2001). Research findings indicate that the presence of humic substances can lead to favorable outcomes in plant growth. This is attributed to their ability to indirectly influence soil properties, thereby enhancing the absorption of nutrients, promoting soil aggregation, improving aeration, and increasing permeability (Chen et al., 2004, Piccolo et al., 1996).

Based on the individual properties of zeolite and leonardite, a combination of these amendments can provide significant benefits in soil remediation and reclamation. The addition of carbon-rich materials like leonardite has proven effective in stimulating microbial activity, while zeolite can increase soil sorption capacity and increase the number of microorganisms in soil because of porous properties and by acting as habitat for microorganisms (Szerement et al., 2023). Furthermore, as the porosity of zeolite absorbs nutrients and the high humic substance content in leonardite can improve soil, a mix of these amendments can have the potential to reclaim degraded soil. More specifically, the findings of a study on agricultural soil demonstrated that the slow-release fertilizer derived from leonardite and zeolite exhibited lower nutrient release rates compared to a commercially available fertilizer (Chawakitchareon et al., 2014). The controlled release of nutrients from zeolite and leonardite can ensure a more sustained and prolonged supply of essential elements to plants, promoting steady and balanced growth.

Another beneficial amendment to improve the soil properties of contaminated sites is compost containing beneficial microbes and bacteria. Compost amendments stand out due to their ability to improve soil health and foster pollutant degradation. By introducing active microorganisms, compost can enhance the soil's microbial activity and nutrient content, stimulating the natural degradation of hazardous compounds (Kastner & Miltner, 2016). Additionally, the organic matter in compost can act as a sorbent, reducing the bioavailability of contaminants and preventing their migration (Kastner & Miltner, 2016). Research has proven that even small amounts of compost added to the soil can have a significant impact on the level of organic matter present, especially in the initial growing season (Heiskanen et al., 2022).

The return of mine-disturbed lands to an end land use of grassland is important because grasslands, specifically in B.C., are a highly endangered ecosystem due to human activities, livestock and invasive plants (British Columbia Ministry of Sustainable Resource Management & Ministry of Water, Land and Air Protection, 2004). As grasslands provide numerous benefits to communities, including erosion protection, providing habitat for wildlife (especially species at risk), carbon sequestration and contributing to climate stability, their loss can negatively impact human health and associated ecosystem services (Wetland Stewardship Partnership, 2010).

One of the dominant species in southern B.C. grasslands is bluebunch wheatgrass *(Pseudoroegneria spicata)*. Bluebunch wheatgrass is a perennial drought tolerant native grass in semi-arid regions of B.C. (Wikeem & Wikeem, 2004; Tisdale, 1947). Many studies showed a notable decline in prevalence of bluebunch wheatgrass due to frequent disruption and the widespread growth of invasive species in the region since the beginning of 20th century which highlights the importance of bluebunch wheatgrass conservation (Miller et al., 1994).

Despite the potential benefits of the mentioned amendments (zeolite, leonardite and compost), there is a lack of comprehensive research on their combined application in the context of mine reclamation and their specific impacts on bluebunch wheatgrass growth. Moreover, the influence of compost on the effectiveness of zeolite and leonardite amendments and its role in enhancing soil fertility remains underexplored. Addressing this knowledge gap is crucial for developing effective and sustainable strategies to reclaim TSFs, degraded mine soils and mitigate the environmental impact of mining operations.

Considering the current environmental challenges and the need for sustainable mine reclamation practices, this chapter aims to summarize the results of a greenhouse study that was designed to 1) investigate the influence of zeolite, leonardite, and their combination in two different ratios on bluebunch wheatgrass *(Pseudoroegneria spicata)* growth and soil properties, and 2) examine the effect of compost amendment in conjunction with the treatments described in objective 1 to assess their combined potential for improving plant growth and soil fertility at the Historic Afton Tailings Storage Facility (HATSF). Understanding the interactions between these amendments and their impact on plant growth and soil properties will contribute to the development of innovative and environmentally friendly approaches for the reclamation of the HATSF and similar mine sites.

MATERIALS & METHODS

Mine Tailings and Amendments

New Afton mine is a Canadian gold and copper mine, located approximately 350 km northeast of Vancouver and 10 km west of the City of Kamloops, in the south-central interior of British Columbia (50° 39’ N, 120° 32’ W; elevation 700 m) (Figure 2.1). Samples of bulk tailings were obtained from the Historic Afton Tailings Storage Facility, and topsoil and subsoil samples were collected from stockpiles at New Afton mine. The historic Afton tailings exhibit a coarse texture accompanied by a medium bulk density. The tailings were characterized by a moderately alkaline pH and low amounts of organic matter, total carbon, and total nitrogen. Topsoil and subsoil from the Afton stockpile also had a coarse soil texture, a moderately alkaline pH and low organic matter (Table 2.1).

The compost used in this study was made of wood wastes, urea and a blend of composting microbes, including some fungi and bacteria that were more adept at metabolizing hydrocarbons. Leonardite was sourced from the Red Lake deposit, located approximately 40 kilometres northwest of Kamloops, and zeolite from Bromley Creek Mine, approximately 7.5 kilometres southwest of Princeton in British Columbia, Canada.

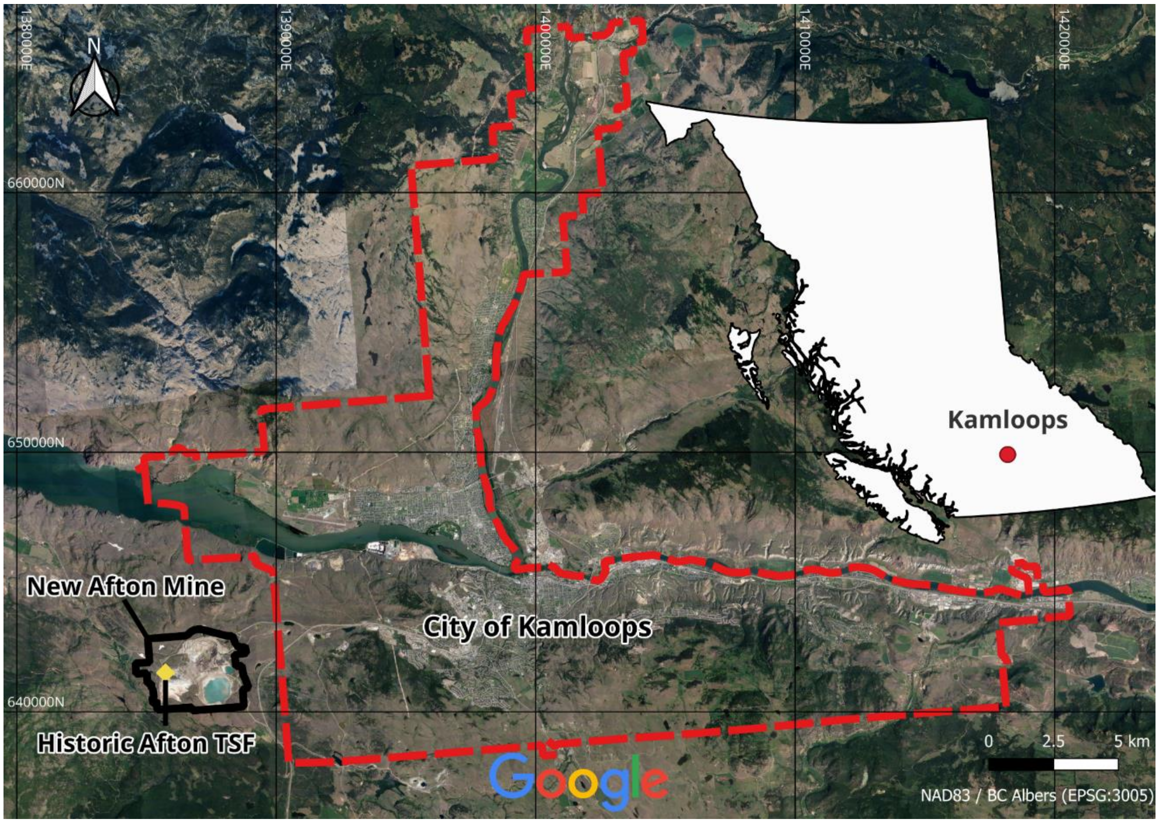

Figure 2.1. Location of the historic Afton tailings storage facility (HATSF) and New Afton mine, from which the material used in this study was obtained. New Afton mine is 10 km west of the center point of the city of Kamloops, British Columbia. Inset shows the location of Kamloops within the province.

Table 2.1. Chemical and physical parameters of the mine tailings, subsoil and topsoil used in this study. Abbreviations: OM, organic matter; TC, total carbon; TKN, total Kjeldahl nitrogen, dS/m, deciSiemens per meter; EC, electrical conductivity; BD, bulk density; SA, sieve analysis; ST, soil texture. Parentheses denote the units of measurement, except for pH where (1:2) refers to the soil-to-water ratio of the sample used for measurements.

Substrate/ Materials	**pH (1:2)**	**OM (%)**	**TC (%)**	**TKN (%)**	**EC (dS/m)**	**BD (kg/m^3)**	**SA- 75 microns (%)**	**ST**
Tailings	8.38	1.7	0.93	<0.01	3.33	1340	76	Coarse
Subsoil	7.98	0.6	1.04	0.0117	5.14	1460	73	Coarse
Topsoil	7.98	2.7	1.15	0.0317	3.51	1640	88	Coarse

Greenhouse Experimental Design

The greenhouse experiment was carried out at the Thompson Rivers University Research Greenhouse located in Kamloops, British Columbia, from December 2021 to March 2022. Pots with a diameter of 10.19 cm and a length of 60 cm, connected to water collection drainages were first filled with 30 cm tailings, followed by 20 cm subsoil and 10 cm topsoil, respectively. Depending on the treatment, topsoil was mixed with zeolite (Z), leonardite (L) or their combination (ZL) at a high ratio of 0.0448 kg/m^2 or a low ratio of 0.0224 kg/m^2. Then, compost at a rate of 1:1 (compost:topsoil) was applied on top of the topsoil for half of the treatments. In total, there were 14 treatments combinations of Z, L and ZL in two ratios, with and without compost in addition to a control and a treatment solely amended by compost. The fourteen treatments were replicated six times for a total of 84 pots (Figure 2.2). Ten bluebunch wheatgrass *(Pseudoroegneria spicata)* seeds were planted per pot at approximately 0.5 cm depth, and the pots were randomly placed in the research greenhouse. After three weeks of germination, the seedlings were removed from each pot to leave one bluebunch wheatgrass in pots. During the experiment, the soil moisture was measured in each pot at a depth of 20cm using a soil moisture probe to ensure a soil moisture balance of 20% in each treatment that was maintained by watering every 2-3 days. Growth over 120 days was conducted under controlled conditions (natural and artificial light: day/night 18 h/6 h; temperature: day/night 25°C /22°C; humidity 40-70%) in the research greenhouse (Rayne & Forest, n.d.).

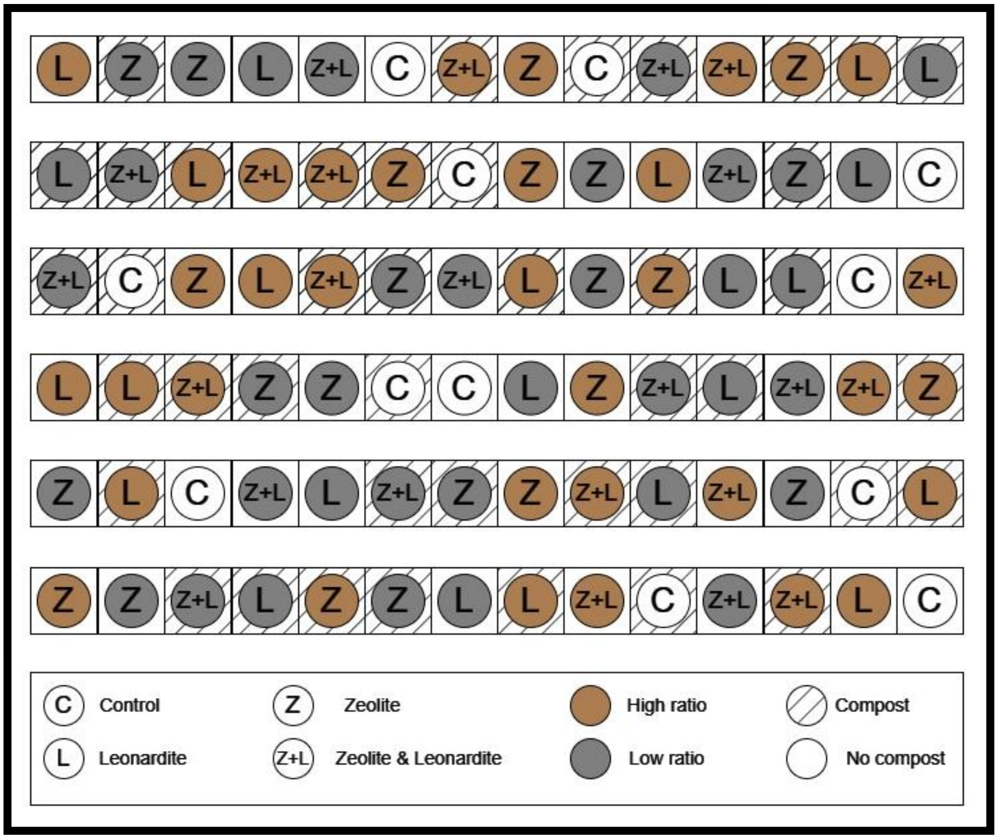

Figure 2.2. Study design: amendment composition with two different ratios.

Figure 2.3. Randomized complete block design implemented for the greenhouse growth trial. The arrangement highlights the controlled experimental setup at the TRU Research Greenhouse.

Soil, Biomass, and Sampling

At the end of the experiment, soil samples were extracted using a stainless-steel soil sampling probe with a core diameter of 2 cm. The top 0 – 10 cm, 10 – 20 cm and 20 – 30 cm were collected and stored in separate bags for further analyses. Soil samples from 10 – 20 cm were analyzed for total carbon (TC), and total nitrogen (TN), using a Thermo Scientific FlashSmart CHNS/CHNS elemental analyzer. Soil preparation for elemental analysis included passing soil through a 2 mm sieve and air drying within a Yamato™ drying oven (model DKN812) for 48 hours at 85°C to remove moisture. Next, approximately 10-15 mg of soil were weighed and placed in small tin capsules and loaded sequentially into the elemental analyzer sample wheel (Gavlak et al., 2005; ThermoScientific 2017). Soil organic matter content was also determined for all samples by loss on ignition at 550 °C for 4 hours (Singh et al., 2019).

Bluebunch wheatgrass shoots were clipped at the soil surface, and roots were retrieved from the amended soil and tailings substrate. Plant tissue samples were washed and dried at 65°C for 48 hours, then weighed on an analytical scale to determine root and shoot biomass.

Statistical Analysis

All statistical analyses and figures were produced using R version 4.2.3 (The R Foundation for Statistical Computing). To determine if any of the three factors (soil amendment, amendment ratios and compost condition) influenced reclamation success, the measured field parameters were analyzed using a three-factor analysis of variance (ANOVA), followed by Tukey's HSD post-hoc test ($P < 0.05$). Plant biomass data were checked for normality both visually and using the Shapiro-Wilks test. Homogeneity of variance was assessed using Levene's test, and when necessary, the data were transformed using a square root function (Levene, 1960; Shapiro & Wilk, 1965). Furthermore, an aligned rank transformation was applied to the soil data in order to properly run a three-way analysis of variance, as the soil data were not normal prior to analysis and data transformations were not effective in normalizing the data (Wobbrock et al., 2011).

RESULTS

Soil Total Carbon and Nitrogen

The analysis of total carbon revealed that both compost addition and amendments had significant effects on the total carbon content of the soil. Compost addition in all treatments exhibited a positive impact, resulting in a ~740% increase in total carbon content (Figure 2.4). Furthermore, a comparison between the Z, L and ZL treatments indicated that the Z treatment had the greatest increase of total carbon content in the soil. Similarly, the data for total nitrogen demonstrated that compost had a significant positive impact across all treatments. As observed with total carbon, the Z treatments exhibited significantly higher total nitrogen content in the soil compared to the L treatment.

The C/N ratio analysis highlighted the significant effect of compost, both when used independently and in combination with other amendments, on soil fertility. Both the L and Z treatments exhibited a more positive impact on the C/N ratio compared to the ZL treatments. Notably, the ratio of amendments did not show any significant differences in all the analyses (Figure 2.4).

These results demonstrate that compost addition had a consistently positive influence on soil carbon and nitrogen content, irrespective of the amendment types and ratios. The Z treatment proved to be effective in enhancing the soil's total carbon and nitrogen levels.

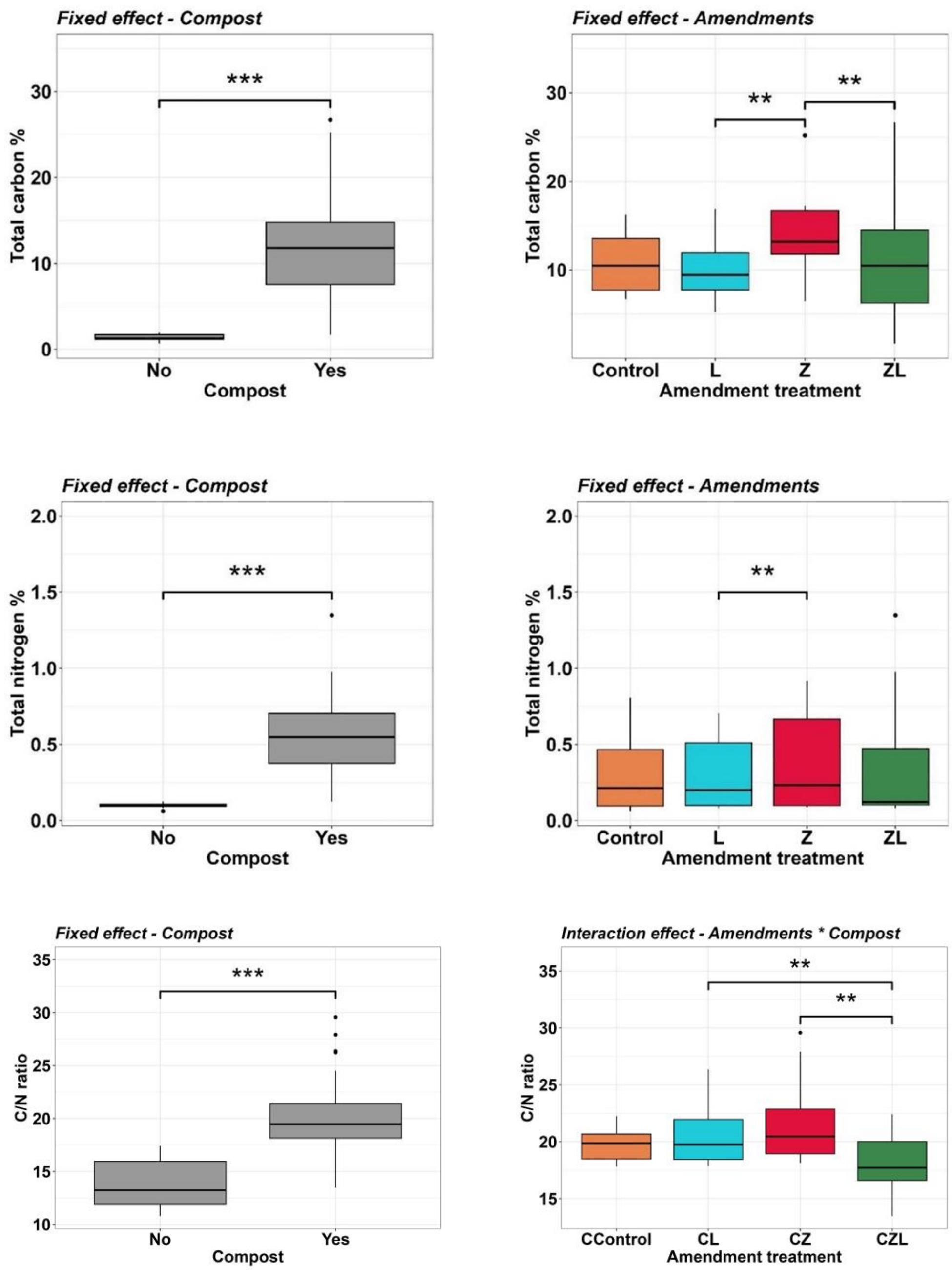

Figure 2.4. Total carbon, total nitrogen, and carbon to nitrogen (C/N) ratio were presented from top to bottom, respectively. C, compost; L, leonardite; Z, zeolite, ZL, mixed zeolite and leonardite. Pairwise comparisons were conducted within each group and were compared to the control and adjusted with BH corrections Significance levels were denoted as '**' for $p < 0.01$ and '***' for $p < 0.001$. Non-significant values were omitted from the plot. The main rectangular box represents the interquartile range, and the horizontal line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data. Total carbon and total nitrogen analyses did not show any significant influence of compost and amendment treatment interaction, while in the C/N ratio, the interaction demonstrated significant differences.

Soil Organic Matter

The results suggest that both compost application and amendment treatments significantly influenced soil organic matter content. The addition of compost to the soil resulted in an increase in soil organic matter compared to the control and other treatments (Figure 2.5). Moreover, the results showed that the Z treatment exhibited higher SOM content than the L treatment. Additionally, the different amendments ratios did not show any significant differences in soil organic matter content (Figure 2.5).

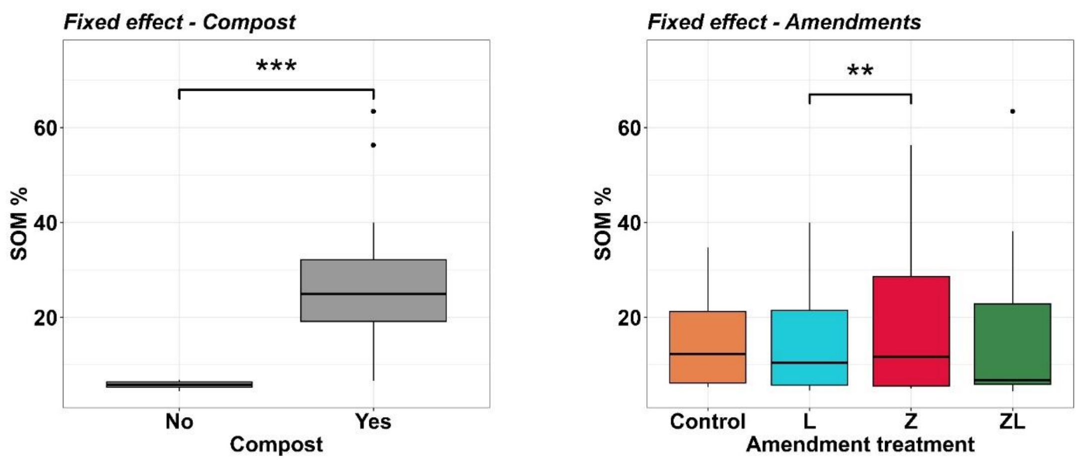

Figure 2.5. The soil organic matter percentage in compost amended treatment are presented on the left and amendment treatments effects are demonstrated on the right. Significance levels were denoted as '**' for $p < 0.01$ and '***' for $p < 0.001$. Non-significant values were omitted from the plot. The main rectangular box represents the interquartile range, and the horizontal line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data. No significant differences were seen in the interaction of amendment treatments and the presence/absence of compost.

Plant Productivity

The productivity of bluebunch wheatgrass was evaluated by measuring the shoot and root biomass in response to the different treatments. The results indicate that treatments using compost had a significant positive impact on the growth of bluebunch wheatgrass, resulting in significantly higher total biomass than other treatments at a 95% confidence level (Figure 2.6).

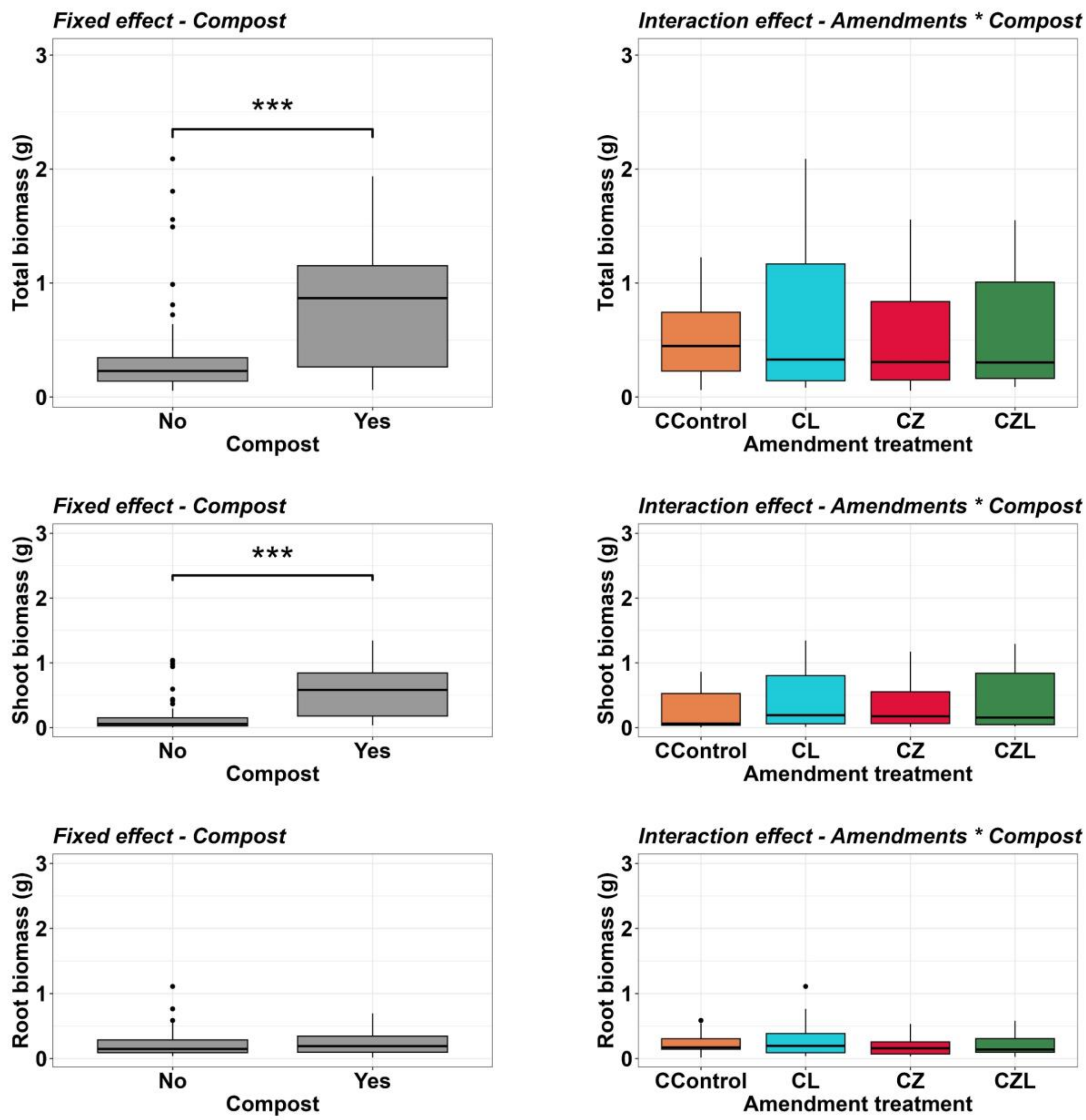

Figure 2.6. Sequential presentation of total biomass, shoot biomass, and root biomass from top to bottom. C, compost; L, leonardite; Z, zeolite, ZL, mixed zeolite and leonardite. Within each group, pairwise comparisons were performed and subjected to BH corrections. Significance levels were denoted as '**' for $p < 0.01$ and '***' for $p < 0.001$. Non-significant values were omitted from the plot. The main rectangular box represents the interquartile range, and the horizontal line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data. Notably, across all three analyses, the interaction between compost and amendments yielded no significant differences. However, it is noteworthy that the compost factor significantly influenced biomass production in the cases of total biomass and shoot biomass.

However, the use of Z, L, or their combinations (ZL) did not result in significant statistical differences in biomass production. Similarly, no significant differences were observed between the different ratios of the mentioned amendments. Interestingly, in the compost-amended treatments, the root-to-shoot biomass ratio was less than one. As shown in Figure 2.7, the root-to-shoot ratio of plants amended with compost was below the reference line, while treatments without compost addition were above the line. This suggests that compost played a crucial role in promoting the shoot growth. Figure 2.7 further supports this observation, as treatments with compost showed higher shoot biomass than root biomass, while treatments without compost resulted in higher root biomass than shoot biomass.

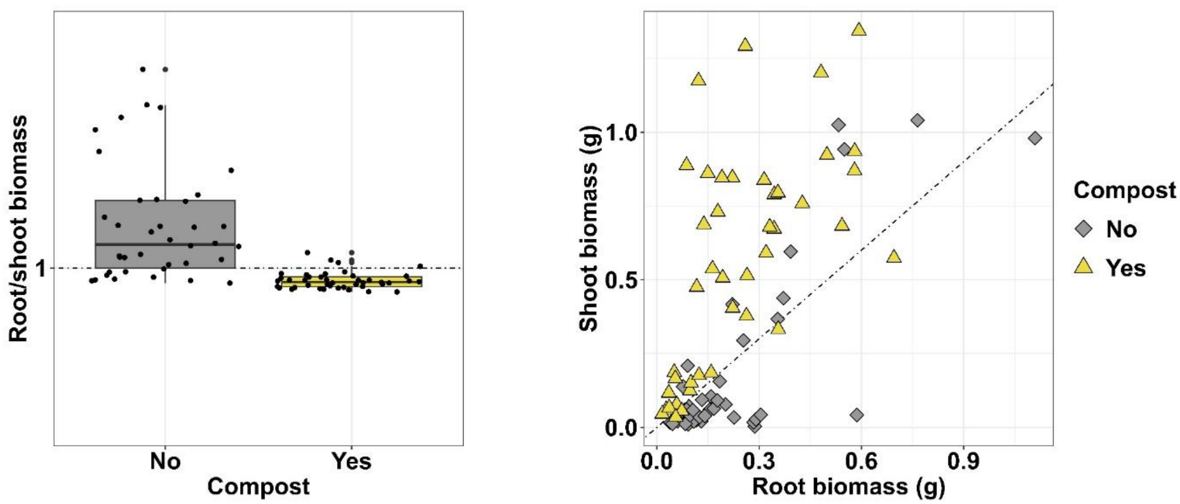

Figure 2.7. The left graph illustrates the root-to-shoot biomass ratio in treatments supplemented with or without compost. The main rectangular box represents the interquartile range, and the horizontal line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data. Values above the equilibrium line indicate a higher root-to-shoot ratio, whereas values below the line suggest a higher shoot-to-root ratio. The right graph showcases greater shoot production in compost-amended treatments (highlighted in yellow) and reduced production in treatments without compost (highlighted in grey).

These findings highlight the significant influence of compost on bluebunch wheatgrass productivity, particularly in enhancing above-ground biomass. The absence of significant differences among treatments using different ratios of amendments indicates that the type and proportion of amendments tested did not exert a notable influence on plant productivity.

DISCUSSION

Effects of Amendments on Soil Fertility

The carbon-to-nitrogen ratio analysis in this research resulted in a C/N ratio between 18:1 to 21:1 for treatments with compost, and a C/N ratio ranging from 13:1 to 14:1 for the ones without. Compost significantly impacted soil carbon and nitrogen content by increasing approximately nine times more carbon and six times more nitrogen compared to treatments without compost. Compost contains labile organic matter, wood chips, and beneficial fungi and bacteria that can improve the soil's organic matter. Furthermore, carbon and nitrogen available in compost must have leached from the surface into the soil profile during watering. These findings align with previous studies that have shown the addition of compost leads to improvements in carbon and nitrogen and, consequently, an increase in plant growth (Solís-Dominguez et al., 2012; Scharenbroch & Watson, 2014; Antonelli, 2018; Chalker-Scott, 2007; Scharenbroch, 2009). This research also found that treatments containing zeolite had significantly higher nitrogen than the L treatment and higher carbon than both L and ZL treatments. This can be because of zeolite's properties to absorb, store, and slowly release nutrients, mainly when recharged with nitrogen and carbon (Jarosz et al., 2022).

The primary organic components of soil are carbon (C) and nitrogen (N), both of which contribute to soil fertility (Swangjang, 2015). As a function of the C/N ratio, C and N status can have a significant impact on soil organic matter mineralization. In addition, C/N ratio can be used to predict the release of nutrients (Larney & Angers, 2012) and to establish whether carbon or nitrogen deficiencies are limiting soil microbial processes (Shrestha & Lal, 2007). As evidenced in a previous study, rapid mineralization occurs when a substrate's C/N ratio falls between 1 and 15, which means more nitrogen can be available for plants to absorb (Brust, 2019). In other words, a lower C/N ratio leads to a faster release of nitrogen because there is more nitrogen available in comparison to carbon in the soil (Watson et al., 2002; Brust, 2019). On the other hand, when the ratio is over 35, microbial immobilization occurs, which means that microorganisms in the soil consume nitrogen rather than releasing it for plant use and achieving a C/N ratio of 20-30 results in a balance between mineralization and immobilization (Brust, 2019). It is necessary for soil microorganisms to receive sufficient carbon and nitrogen from the soil in order to remain viable, and a C/N ratio of 24 has been found to facilitate their best performance (Brust, 2019). This ratio seems to balance mineralization and immobilization and has a significant impact on the nitrogen cycle and overall soil health. Therefore, the C/N ratio in treatments with compost maintained the balance and improved soil microbial process when comparing to C/N ratio in treatments without compost.

It is also important to consider ecosystem identity in the context of the C/N ratio in soil fertility. According to Mulder and Elser (2009), abandoned grassland had an average C/N ratio of 18.5. Swangjang (2015) also examined the C/N ratios in various ecosystems, including horticultural and agricultural ones, establishing a C/N ratio ranging from 10:1 to 18:1. Another study showed a C/N ratio between 13.4 to 14.2 in grasslands, and a ratio ranged from 13.3 to 15.7 in forest ecosystems (Cleveland & Liptzin, 2007). Therefore, the findings underscore the important role of compost in maintaining a favorable C/N ratio, potentially enhancing soil microbial processes. This is particularly relevant in the context of grassland end land use, aligning with findings from previous studies (Mulder & Elser, 2009).

Amendments and Soil Organic Matter Properties

The presence and structure of soil organic matter have a significant impact on various processes that occur within the terrestrial ecosystem. Soil organic matter acts as a reservoir and receiver of essential nutrients required for plant growth and plays a crucial role in maintaining soil structure, water retention, and preventing erosion (Batjes, 1996; Gregorich et al., 1993). In comparison to control treatments, compost-amended treatments showed a significantly higher soil organic matter content. The addition of compost resulted in a mean of 26.5% compared to a mean of 5.85% without compost. Based on the suggested ranking by Munshower (1994), the compost-amended treatment will be ranked as very high in soil organic matter (OM), while the ones without compost will be ranked as medium to high in terms of OM. The positive effect of compost-containing wood chips on soil organic matter improvement is consistent with previous studies (Antonelli, 2018). Leachate and decomposition products from compost increases the total carbon and nitrogen content, which likely reflect the increase of soil organic matter. Moreover, treatments amended with Z showed a higher soil organic matter content of 18.4%, significantly higher than L treatments with 14.9% soil organic matter content. The carbon and nitrogen results also showed that Z treatments had higher values in both parameters compared to L treatments.

Effect of Amendments on Plant Productivity

It has been observed that changes in plant productivity are often linked to variations in soil carbon levels. Aboveground productivity acts as a crucial source of soil carbon (Kunkel et al., 2011; Abraha et al., 2018). In this study, the significant biomass increase in compost-amended treatments can directly relate to nutrient improvement and microbial and fungi activities in the soil (Eisenhauer et al., 2012). However, the addition of other amendments did not show any significant improvement, which may be related to the limited time of the greenhouse trial (Coghill, 2021).

The research also found that plants grown with compost had a root-to-shoot ratio of less than 1, indicating an abundance of nutrients in the amended substrate, resulting in increased aboveground biomass production (Wilsey & Polley, 2006). However, according to Agren & Franklin (2003), a lack of nutrients can lead plants to allocate more resources to their root, and, consequently, increase root-to-shoot biomass in the growing medium. Therefore, the higher root-to-shoot ratios in treatments without compost observed in this study can be attributed to insufficient organic matter, and, more specifically, nitrogen. This nitrogen deficiency may have compelled the plants to prioritize root production over shoot production. Conversely, greater shoot biomass was produced in the treatments with compost, which is consistent with previous studies (Antonelli, 2018).

CONCLUSION

In conclusion, this research underscores the vital role of compost amendment in promoting plant growth and ameliorating soil fertility within the context of degraded mine topsoil and subsoil. The investigation provides valuable insights into the efficacy of distinct amendments, namely zeolite and leonardite, both individually and in synergy, with and without the addition of compost, as a tool for facilitating mine reclamation endeavours. The influence of these amendments on mine reclamation not only advances our current understanding but also illuminates their potential synergistic effects. These findings hold significant implications for sustainable land restoration efforts to make the mining sector more environmentally responsible. While the controlled greenhouse environment offers valuable insights, the translation of these outcomes into real-world scenarios necessitates conducting field experiments. Thus, further research is needed to validate the trends observed in the controlled setting, while also probing various zeolite amendment ratios under field conditions to find an optimal ratio.

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CHAPTER 3 – TOPSOIL-TILL COVER DEPTHS AND AMENDMENTS: INFLUENCE ON ECOSYSTEM RECLAMATION OF CLOSED TAILINGS STORAGE FACILITIES

INTRODUCTION

The mining and mineral industry plays a crucial role in the sustainable development of countries. However, large-scale mineral extraction can have noticeable and lasting impacts on natural landscapes. Mining operations can cause environmental changes and present potential chemical and physical hazards, including topsoil removal, loss of vegetation, soil erosion, surface disposal of waste material, failure of tailings containment structures, and gradual release of heavy metals into nearby water bodies (Beckett & Keeling, 2018; Hudson-Edwards et al., 2011).

In the context of mining projects, it is crucial to have a well-planned strategy to mitigate any adverse environmental impact. Reclamation plays a vital role in this mitigation process, as it aims to restore the land used for mining to a productive state and ensure that undesirable environmental consequences are minimized once the mining operation is complete (Straker et al., 2021). Mine reclamation was introduced with the primary objective of restoring mining sites by eliminating potential hazards, recycling harmful materials, and rehabilitating sites physically, chemically, and biologically (Hajkazemiha et al., 2021). The legal concept of reclamation planning in Canada was established in the late 1960s. Since then, the perception of mining and reclamation has undergone significant changes (Bowman & Baker, 1998). Traditionally, mines used to reclaim land at the end of the mining process by stabilizing the slopes and reseeding the affected area (Morris 1983; Bowman & Baker, 1998). However, in current mining practices, mine operators must create and regularly update a mine plan and reclamation program before mining and throughout all phases of the mine's life. This plan must be presented to regulators and other stakeholders for review (Straker et al., 2021). It is a crucial document that outlines reclamation objectives, progress, design, and research results and must be updated every five years, at a minimum, over the life of the mine. Furthermore, Festin et al. (2016) explained that reclamation encompasses the physical stabilization of terrain with the goal of returning the land to a proper state. However, unlike restoration, reclamation specifically targets a singular aspect of ecosystem services (Festin et al., 2016). The restoration of mining sites to their original natural habitat for the purpose of enhancing biodiversity and reinstating natural ecosystem services is increasingly becoming a standard practice (Lesica & Allendorf, 1999). The importance of reinstating biodiversity is widely recognized as the cornerstone of restoration success, given that diverse ecological communities are better able to withstand environmental disturbances (Ives & Cardinale, 2004). Therefore, the creation of diverse ecological communities that are capable of enduring environmental disruptions is crucial for achieving successful restoration outcomes (Antonelli, 2018).

British Columbia's grasslands, comprising both semi-arid expanses to the south and cooler regions in the north, are a relatively small fraction of the province's vast landscape (Grassland Conservation Council of BC, 2023). Yet, their ecological significance goes above their physical extent, serving as crucial habitats that foster a diverse range of rare and endangered plants and wildlife. These grasslands are important in biodiversity conservation, supporting the ecological composition of the province. British Columbia's semi-arid grasslands in the southern interior feature widely spaced desert shrubs, unique bunchgrasses, and sporadic cacti. However, the inherent fragility of these grasslands is exacerbated by their limited resilience to disturbances, primarily due to the arid climate in these ecosystems (British Columbia Ministry of Sustainable Resource Management & Ministry of Water, Land and Air Protection, 2004).

The increasing urbanization, industrialization, agriculture, over-grazing and the spread of invasive species are the main human-related threats that leave these grasslands vulnerable (Wetland Stewardship Partnership, 2010). In this context, it is imperative to consider the significance of reclamation, particularly when grasslands face destruction due to activities such as mining. The mining industry often intersects with grassland regions, posing a delicate challenge in balancing economic interests with ecological preservation. Grassland reclamation, a pivotal aspect of mitigating the environmental impact of mining, involves the restoration of affected lands to conditions as close as possible to their original state. This practice not only addresses the immediate ecological repercussions of mining but also strives to preserve the unique habitats and biodiversity that these grasslands sustain (Antonelli, 2018).

Furthermore, British Columbia's grasslands' importance in terms of climate change is becoming more evident. These ecosystems can act as pathways for species migration and adaptation in response to shifting climatic conditions (BC Ministry of Sustainable Resource Management & Ministry of Water, Land and Air Protection, 2004). Species that are situated in these areas can adjust to different conditions, which indicates how important grasslands are as safe places during uncertain climate times. Protecting and conserving these ecosystems can be an ecological imperative and a strategic approach to enhance climate resilience within the province (Wetland Stewardship Partnership, 2010).

Natural processes can restore disturbed grasslands, but the process is often slow (Andrade et al., 2015; Christensen, 2014). To accelerate the re-establishment of nutrient cycling and soil development, studies have suggested replacing topsoil and utilizing other organic amendments (Zhu et al., 1999; Asemaninejad et al., 2021). In the process of restoring surface-mined lands, the selection and application of an appropriate substrate for root establishment is a crucial aspect. This is because the soil acts as a fundamental basis for the development of a new ecosystem (Zipper et al., 2013). Restorative strategies include using topsoil and subsoil salvaged from mining activities to promote vegetation growth (Strohmayer, 1999; Hargis & Redente, 1984). Topsoil provides essential physical, chemical, and microbiological properties for plant establishment (Rivera et al., 2014; Merino-Martín et al., 2017). Due to stripping and long-term stockpiling, topsoil and subsoil are often nutrient-deficient, and their availability at mining sites can be limited, making the selection of a suitable amendment and topsoil-till cover depth crucial considerations (Fischer et al., 2022). According to Bowen et al. (2005), it is believed by researchers that altering the depth of the topsoil in reconstructed landscapes can potentially augment the diversity of the plant community as it imitates the natural edaphic diversity brought about by the deposition and erosion of soil.

Organic amendments, like zeolites, leonardite, and compost, can also play vital roles in mine reclamation and improving the disturbed soil. Zeolites can improve moisture levels, release nutrients, and reduce heavy metal uptake by plants (Jakkula & Wani, 2018; Głąb et al., 2021). Leonardite, rich in humic acid, enhances soil water retention and plant resistance to adverse conditions (Wandruszka, 2000; Iakimenko, 2005). Compost, with diverse microorganisms and high organic matter content, promotes microbial activity and soil health (Kastner & Miltner, 2016; Scharenbroch & Watson, 2014). These amendments can facilitate reclamation, mitigate environmental impacts, and aid ecosystem restoration in degraded areas. Additionally, tillage, which refers to mechanical modifications of soil profiles, has been shown to alleviate high subsoil strength, facilitating deeper rooting and increasing plant access to subsoil resources (Schneider et al., 2017). However, Garbout et al. (2013) note that topsoil structure is strongly influenced by tillage, which can have both positive and negative effects on soil health. Therefore, it is important to carefully consider the potential impacts of tillage on soil structure and function when making decisions about soil management practices in reclamation.

This chapter summarizes the results of a field experiment that examined the effects of different treatments on plants and soil characteristics on a reclaimed tailings storage facility (TSF) in the interior of BC. The objectives of this experiment are threefold: 1) investigate the effects of different topsoil and subsoil cover depths on plants and soil attributes, 2) determine if zeolite, leonardite and compost can enhance soil quality and plant community (richness, diversity, composition), and 3) examine the success of tilling the reclaimed tailing facility after almost 20 years in increasing soil and plant productivity. Here, the aim is to find a suitable treatment that positively influences the reclamation success of Historic Afton Tailings Storage Facility (HATSF) and mine sites with similar conditions.

MATERIALS & METHODS

Study Site

A research site was established at the Historic Afton Tailings Storage Facility (TSF), located approximately 15 km west of the City of Kamloops in the south-central interior of British Columbia (50° 39’ N, 120° 32’ W; elevation 700 m), in fall 2021. The TSF is situated in the Nicola variant of the extremely dry warm subzone of the Bunch Grass biogeoclimatic zone (BGxw1), known for its semi-arid climate with minimal annual precipitation, typically less than 350 mm. The summer months in this area are typically hot and dry (Meidinger & Pojar, 1991; Antonelli et al., 2021). In the 2021-2022 study year, the average daily temperature was 7°C, with a maximum temperature of 36.10°C, and mean precipitation was 241.81 mm at the New Gold New Afton Mine weather station (2023; Figure 3.1).

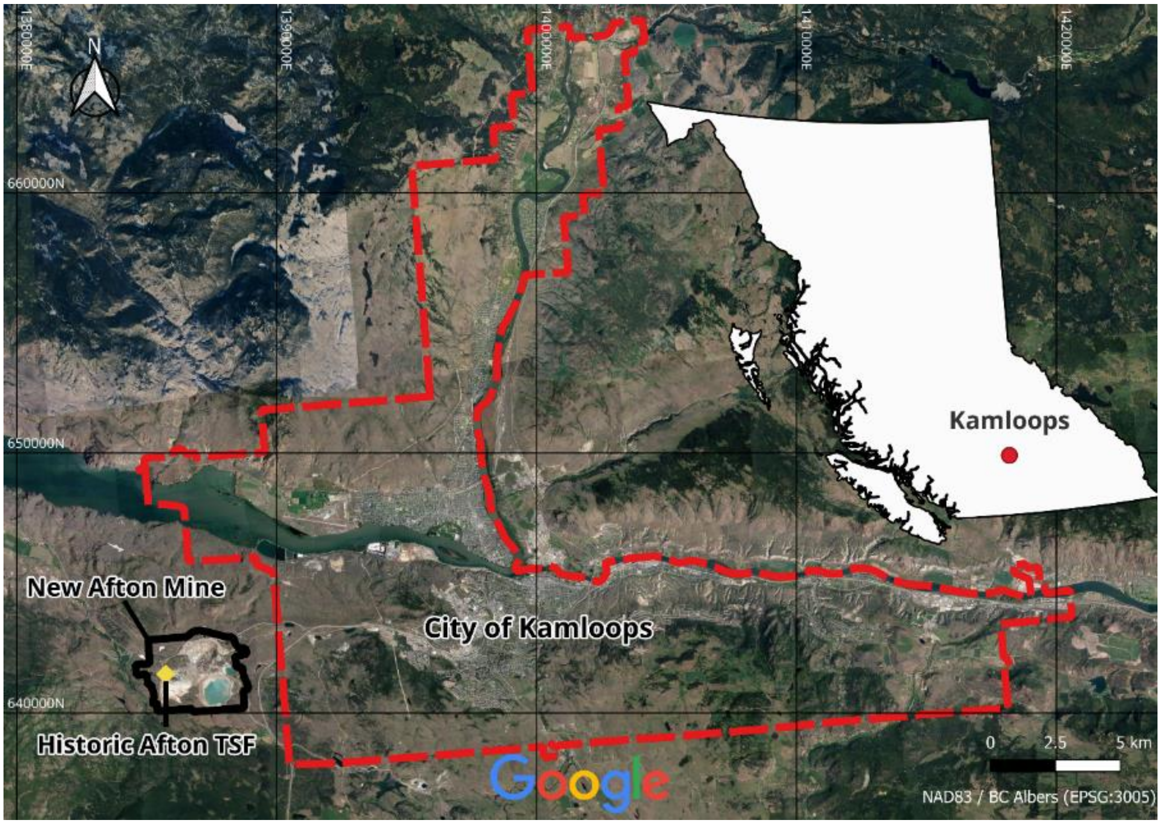

Figure 3.1. Location of the historic Afton tailings storage facility (HATSF) and New Afton mine, from which the material used in this study was obtained. New Afton mine is 10 km west of the center point of the city of Kamloops, British Columbia. Inset shows the location of Kamloops within the province.

Characteristics of Mine Tailings and Amendments

Between 1977 and 1997, mining operations were conducted in the Afton Pit, and the East and West Ajax Pits, from which finely textured tailings material was produced (Table 3.1). To prevent soil erosion and promote wildlife forage and domestic rangeland, reclamation activities were carried out on the approximately 75-hectare tailings storage facility between 1978 and 1992 (Akkerman & Martin, 2015). However, a recent study has revealed that the plant community in the area is sparse and predominantly consists of non-native agronomic grasses, as opposed to native plant species (Antonelli et al., 2021).

Table 3.1. Chemical and physical parameters of the mine tailings, subsoil and topsoil used in this study. Abbreviations: OM, organic matter; TC, total carbon; TKN, total Kjeldahl nitrogen, dS/m, deciSiemens per meter; EC, electrical conductivity; BD, bulk density; SA, sieve analysis; ST, soil texture. Parentheses denote the units of measurement, except for pH where (1:2) refers to the soil-to-water ratio of the sample used for measurements.

Substrate/ Materials	pH (1:2)	OM (%)	TC (%)	TKN (%)	EC (dS/m)	BD (kg/m^3)	SA- 75 microns (%)	ST
Tailings	8.38	1.7	0.93	<0.01	3.33	1340	76	Coarse
Subsoil	7.98	0.6	1.04	0.0117	5.14	1460	73	Coarse
Topsoil	7.98	2.7	1.15	0.0317	3.51	1640	88	Coarse

Experimental Design

The experimental site consisted of eighty plots, each measuring 3 by 3 meters. These plots were arranged in ten blocks, with a spacing of three meters between them. Half of the blocks were randomly selected to be tilled at approximately between 30 and 50 cm using a dozer with a 6-inch ripper on the back, whereas the other five blocks had their surface soil removed to reach the tailings surface. The blocks were then covered with two different topsoil-subsoil cover depths: one with 20 cm subsoil and 10 cm topsoil, and the other with 15 cm subsoil and 15 cm topsoil. In addition, four different amendment conditions were applied, including zeolite (Z), leonardite (L), compost (F), and control (C). The zeolite and leonardite were mixed with the topsoil at a rate of 0.0448 kg/m^2, while the compost was applied on top of the topsoil at a 1:1 (compost: topsoil) rate (Liu & Lal, 2012; Scharenbroch & Watson, 2014). For each treatment, a pre-selected seed mix comprising native and agronomic seeds, provided by New Gold Inc., was applied at a rate of 20 kg/ha in mid-November 2021 (Smirnov et al., 2021; Williams 2022; Table 3.2). Control plots were established using the subsoil and topsoil without any amendments. The study involved a total of sixteen treatments, which were replicated five times, resulting in eighty plots in total. (Table 3.3, Figure 3.2; Figure 3.3).

Table 3.2. List of plant species included in the operational seed mix**.**

No	Common Name	Scientific Name	% of Total by Weight	% by seed count	Type
1	Bluebunch Wheatgrass	*Pseudoroegneria spicata*	13	7	Native grass
2	Rocky Mountain Fescue	*Festuca saximontana*	5	13	Native grass
3	Sandberg Bluegrass	*Poa secunda*	2	7	Native grass
4	Idaho Fescue	*Festuca idahoensis*	5	8	Native grass
5	Crested Wheatgrass	*Agropyron cristatum*	15	11	Agronomic grass
6	Hard Fescue	*Festuca ovina*	10	23	Agronomic grass
7	Tall Wheatgrass	*Thinopyrum ponticum*	12	3	Agronomic grass
8	Tall Fescue	*Festuca arundinacea*	10	8	Agronomic grass
9	Slender Wheatgrass	*Elymus trachycaulus*	5	3	Native grass
10	Russian Wildrye	*Psathyrostachys juncea*	13	8	Agronomic grass
11	Spyder Alfalfa	*Medicago sativa*	10	9	Agronomic legume

Table 3.3. Experimental plot design for field study and amendments.

Tilled								Bare Tailings							
Topsoil depth: 10cm Subsoil depth: 20cm				Topsoil depth: 15cm Subsoil depth: 15cm				Topsoil depth: 10cm Subsoil depth: 20cm				Topsoil depth: 15cm Subsoil depth: 15cm			
Leonardite	Zeolite	Compost	Control	Leonardite	Zeolite	Compost	Control	Leonardite	Zeolite	Compost	Control	Leonardite	Zeolite	Compost	Control

Figure 3.2. Experimental design. As it is shown, there are six tilled and four bare tailings rows. The reason for the unbalanced design is mentioned in the "Research Limitations" section.

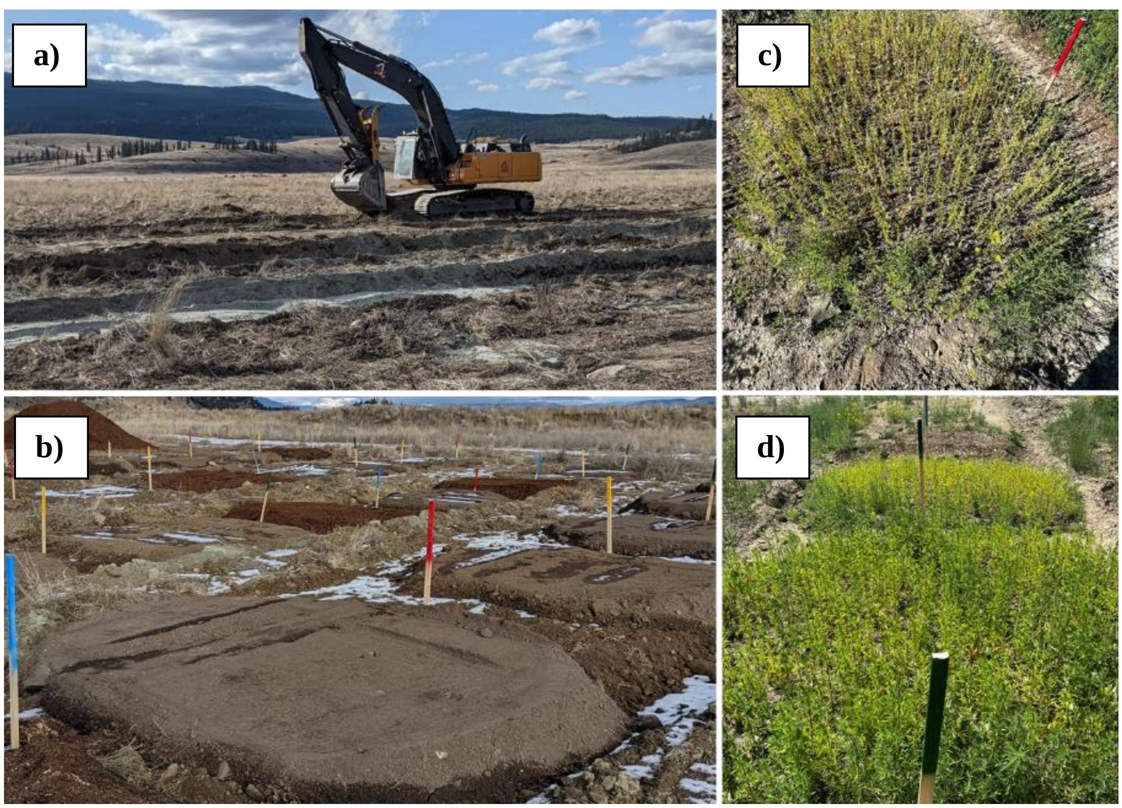

Figure 3.3. Field setup and plant growth in different treatments in the field study. **a)** soil cover removed to reach bare tailings in the reclaimed Historic Afton tailings storage facility. **b)** subsoil and topsoil, in two different depths were applied on bare tailings and tilled rows. **c)** Plant growth in a zeolite treatment plot. **d)** Plant growth in a control treatment plot.

Soil and Biomass Sampling

In mid-August 2022, three quadrats with an area of 50 cm by 50 cm were randomly sampled within each plot (Coulloudon et al., 1999). The purpose of this was to record the presence of different plant species, estimate their absolute percent canopy cover, and collect above-ground biomass and litter. The samples of above-ground biomass were dried at 65°C for 48 hours and were weighed on an analytical scale to evaluate plant production. Furthermore, the collected data were used to determine the Shannon-Wiener index, Simpson's diversity index, species richness and beta diversity (explained in the next section). In the below equations, p represents the proportion of individuals of one species divided by the total number of individuals, while s represents the number of species present (Colwell, 1988).

$$Shannon - Wiener\ Index\ (H) = -\sum_{i=1}^{s} p_i \ln p_i \qquad [1]$$

$$Simpson's\ Index\ (D) = 1 - \sum_{i=1}^{s} p_i^2 \qquad [2]$$

Soil samples were collected at a depth of 20 cm from the same location as the three quadrats per plot in mid-August 2022. One soil sample per plot was created by accumulating and mixing the collected samples. Each soil sample was analyzed for total carbon (TC) and total nitrogen (TN) using a Thermo Scientific FlashSmart CHNS/CHNS elemental analyzer. Before the analyses, the soil was passed through a 2mm sieve and air-dried in a Yamato™ drying oven (model DKN812) for 48 hours at 85°C to remove any moisture. Approximately 10-15 mg of soil was weighed and placed in small tin capsules, which were then loaded sequentially into the elemental analyzer sample wheel (Gavlak et al., 2005; ThermoScientific, 2017).

To measure soil moisture, the soil samples were weighed before and after drying for 48 hours at 85°C. Organic matter content was also determined for all air-dried samples (48 hours at 85°C) samples by loss on ignition at 550 °C for 4 hours after being ground (Singh et al., 2019). Soil samples from each treatment were analyzed for pH levels using a Fisherbrand™ accumet™ AB150 benchtop pH meter. The pH measurement was conducted in an aqueous medium with a water-to-soil ratio of 2:1 (Carter & Gregorich, 2007). The air-dried soil was mixed with deionized water for one minute, then centrifuged at 4000rpm for five minutes. Before conducting the analysis, the Fisherbrand™ accumet™ AB150 benchtop pH meter was calibrated with pH 4, 7, 10 solutions.

Statistical Analysis

All analyses and figures were produced using R version 4.2.3 from The R Foundation for Statistical Computing. The analyses included both fixed and interaction effects of the amendment treatments (i.e. zeolite, leonardite, compost, and control), cover depths (i.e. 10 cm topsoil;15cm subsoil and 15cm topsoil;15cm subsoil), and field condition (i.e. tilled, and bare tailings). To ensure normality, plant biomass data was checked visually as well as running the Shapiro-Wilks test then the data was transformed using a square root or a square function to pass the tests. The homogeneity of variance was assessed using Levene's test before using ANOVA. However, plant richness data was not normal and could not be transformed to fit a normal distribution. Therefore, an aligned rank transformation was used to handle the non-parametric data for the statistical tests (Wobbrock et al., 2011). Tukey's HSD test ($P < 0.05$) was used for grouping and ranking all treatments.

For beta diversity evaluation, zero values in species richness data were removed, and a Hellinger transformation (Hilbe, 2011) was applied to reduce rare species impact. The fixed effects of the amendment treatments (i.e. zeolite, leonardite, compost, and control), cover depths (i.e. 10 cm topsoil;15cm subsoil and 15cm topsoil;15cm subsoil), and field condition (i.e. tilled, and bare tailings) and their interactions were included in the beta diversity analysis. Beta diversity was quantified using the Bray-Curtis dissimilarity method (Bray & Curtis, 1957). Multivariate data were visualized using Principal Coordinate Analysis (PCoA), and the first two principal coordinates' percentage of variance was computed. The significance of differences in beta diversity was assessed using a Permutational Analysis of Variance (PERMANOVA; Anderson, 2001). Additionally, beta dispersion around centroids was investigated. Pairwise Wilcoxon rank-sum tests were used to explore differences, and p-values were adjusted using the Benjamini-Hochberg method (Benjamini & Hochberg, 1995) to control multiple comparisons.

The normality of soil sample data was checked using boxplots, residual plots, and the Shapiro-Wilks test (Shapiro & Wilk, 1965). The homogeneity of variance was assessed using Levene's test (Fox & Weisberg, 2019). A natural logarithm transformation was used when necessary. The influence of soil amendment, cover depth, condition and their interactions on the soil sample data was determined using a three-way analysis of variance (ANOVA;) followed by a Tukey-HSD post-hoc ($P < 0.05$) test. Notably, soil total carbon, carbon-to-nitrogen and organic matter data were not normal and could not be transformed to fit a normal distribution and pass the homogeneity of variance. Therefore, an aligned rank transformation was used to handle the non-parametric data for the statistical tests (Wobbrock et al., 2011).

RESULTS

Plant Productivity

Above-ground biomass results demonstrated that plots covered by 15 cm subsoil and 15 cm topsoil exhibited higher biomass, with a mean of 137.188 $\mathrm{g/0.25\,m^2}$, compared to plots with 20 cm subsoil and 10 cm topsoil cover depth, which had a mean of 103.81 $\mathrm{g/0.25\ m^2}$. In terms of amendments, the compost treatment yielded the lowest biomass (72.037 $\mathrm{g/0.25\,m^2}$), while the zeolite treatment produced the highest biomass (141.491 $\mathrm{g/0.25\,m^2}$), followed by the leonardite treatment (136.524 $\mathrm{g/0.25\,m^2}$) and the control (128.687 $\mathrm{g/0.25\,m^2}$) (Figure 3.4). Tilled plots did not yield any observable differences in comparison to the plots with bare tailings ground condition.

Species Richness

Regarding species richness, the zeolite and control treatments exhibited the highest mean number of species (5.05 and 5.03 per 0.25 $\mathrm{m^2}$, respectively), while the compost treatment displayed the lowest (2.1) (Figure 3.5). Statistical analysis detected significant differences among all amendment treatments except for zeolite and control. No significant differences were observed between tilled and bare tailings plots or different soil cover depths.

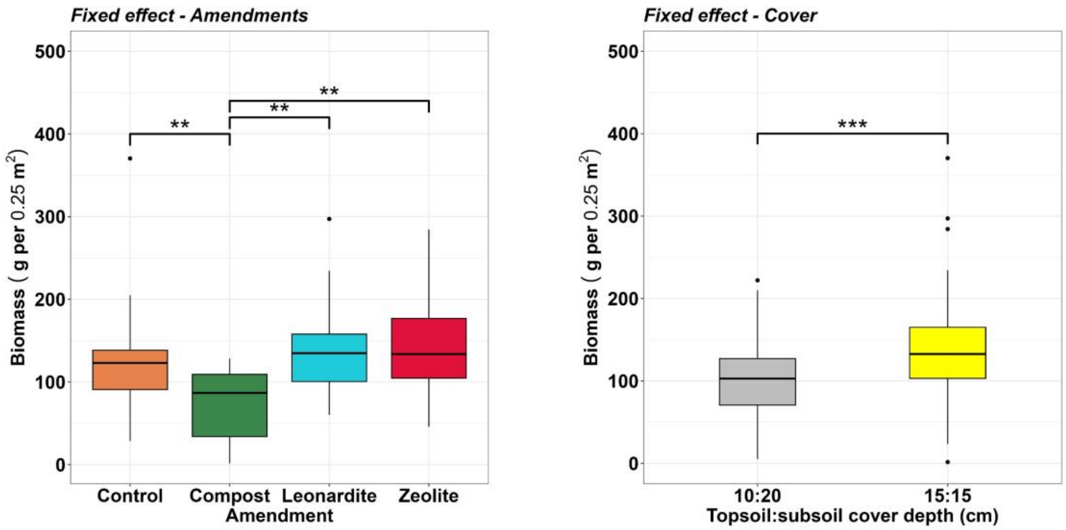

Figure 3.4. Above-ground biomass. Pairwise comparisons of above-ground biomass within each group were performed and subjected to Tukey corrections. Significance levels were denoted as '*' for $p < 0.05$, '**' for $p < 0.01$, '***' for $p < 0.001$ and '****' for $p < 0.0001$. Non-significant values were omitted from the plot. The main rectangular box represents the interquartile range (IQR), and the horizontal line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data.

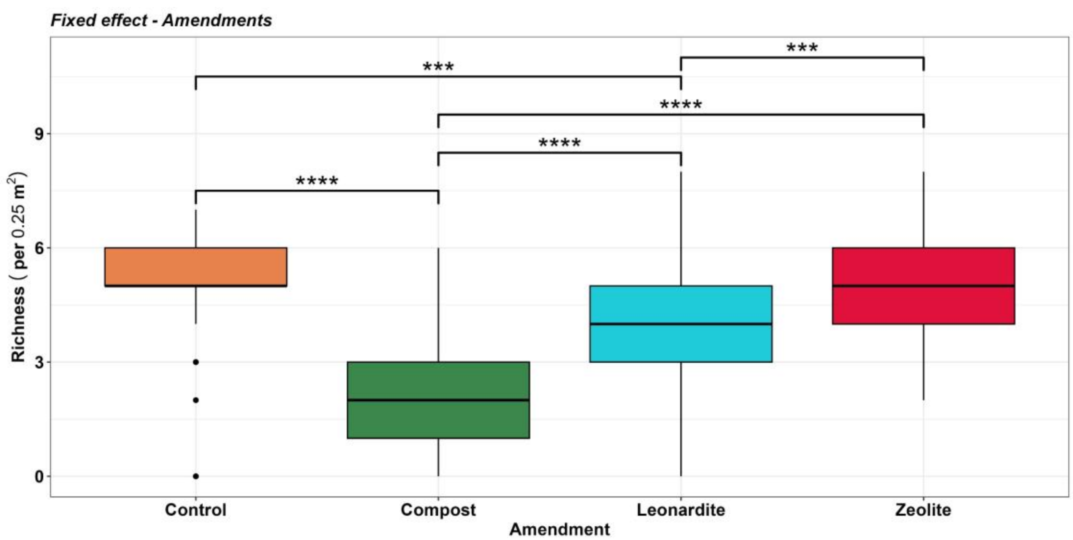

Figure 3.5. Species richness. Significance levels were denoted as '*' for $p < 0.05$, '**' for $p < 0.01$, '***' for $p < 0.001$ and '****' for $p < 0.0001$. Non-significant values were omitted from the plot. The main rectangular box represents the interquartile range (IQR), and the horizontal line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data.

Shannon and Simpson's Index

In terms of the Shannon-Wiener index (*H*), the condition of the plots (tilled, bare tailings), amendments, and amendments interaction with cover (the two topsoil-till depths) resulted in significant differences. The plots with bare tailings condition resulted in a higher Shannon index (1.13) than the ones with tilled condition (1.03), and in terms of amendments, the Shannon index of compost treatment (0.56) was significantly lower than zeolite (1.29), leonardite (1.22), and control (1.28) treatments. The interaction of amendments with cover depth resulted in significant differences, with zeolite treatments with 10 cm topsoil cover depth resulting in the highest Shannon index (1.42) and the interaction of compost treatment with 10 cm topsoil cover depth resulting in the lowest Shannon index (0.47) (Figures 3.6 and 3.7)

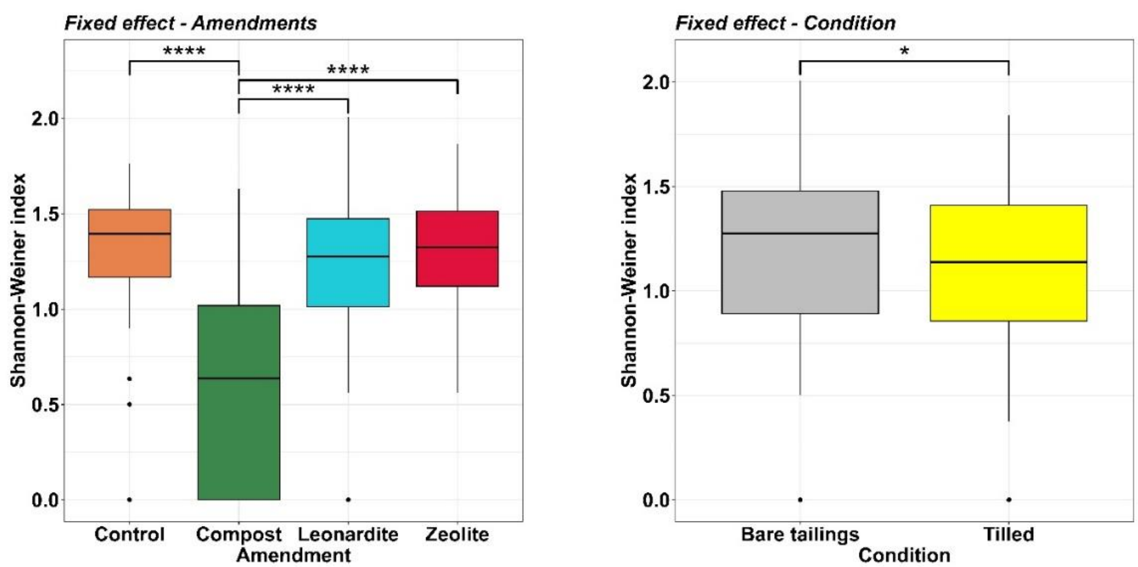

Figure 3.6. Shannon-Wiener index. Significance levels were denoted as ‘*’ for $p < 0.05$, ‘**’ for $p < 0.01$, ‘***’ for $p < 0.001$ and ‘****’ for $p < 0.0001$. Non-significant values were omitted from the plot. The main rectangular box represents the interquartile range (IQR), and the horizontal line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data.

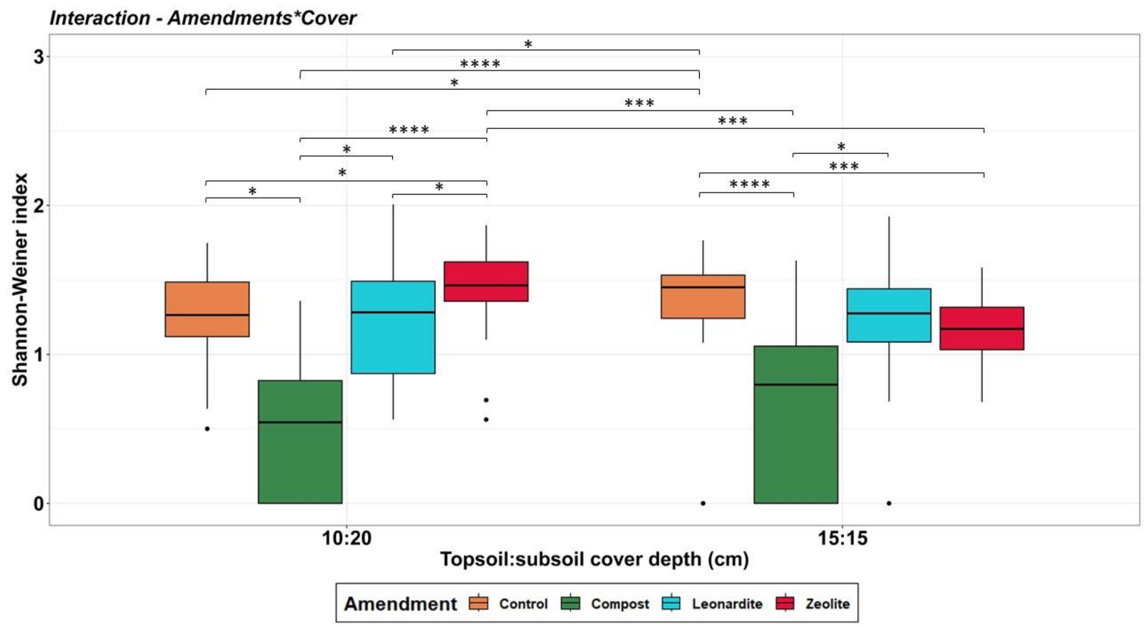

Figure 3.7. Shannon-Wiener index, indicating the interaction between amendments and cover depth. Significance levels were denoted as '*' for $p < 0.05$, '**' for $p < 0.01$, '***' for $p < 0.001$ and '****' for $p < 0.0001$. Non-significant values were omitted from the plot. The main rectangular box represents the interquartile range (IQR), and the horizontal line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data.

Simpson's index (1-*D*) statistical analysis revealed that field condition (bare tailings and tilled), amendments and amendments interaction with cover had a significant impact. The bare tailings condition resulted in a higher Simpson index (0.634) in comparison to the tilled condition (0.590; Figure 3.8). Moreover, control treatments resulted in the highest Simpson's index (0.698), while compost treatments resulted in the lowest (0.447) among the amendment treatments (Figure 3.8). The interaction of amendments with cover depth resulted in significant differences. Zeolite treatments with 10 cm topsoil cover depth resulted in the highest Simpson's index (0.744), and the interaction of compost treatment with 10 cm topsoil cover depth resulted in the lowest Simpson's index (0.420) (Figure 3.9).

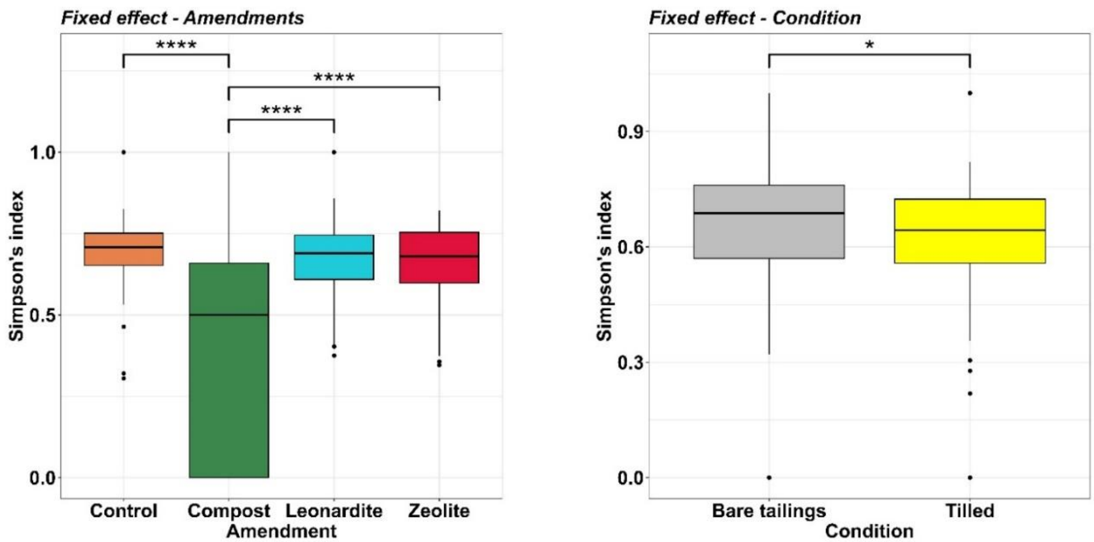

Figure 3.8. Simpson's index. Significance levels were denoted as '*' for $p < 0.05$, '**' for $p < 0.01$, '***' for $p < 0.001$ and '****' for $p < 0.0001$. Non-significant values were omitted from the plot. The main rectangular box represents the interquartile range (IQR), and the horizontal line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data

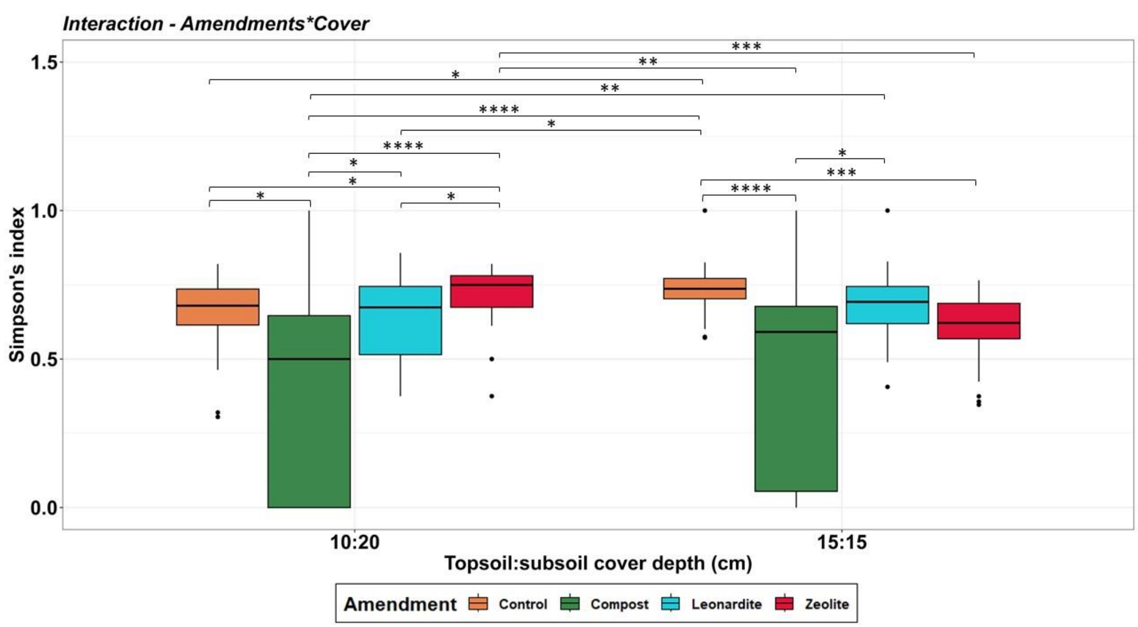

Figure 3.9. Simpson's index, indicating the interaction between amendments and cover depth. Significance levels were denoted as '*' for $p < 0.05$, '**' for $p < 0.01$, '***' for $p < 0.001$ and '****' for $p < 0.0001$. Non-significant values were omitted from the plot. The main rectangular box represents the interquartile range (IQR), and the horizontal line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data.

Beta Diversity and Functional Group Differences

To understand the differences between plant communities in each treatment, beta diversity was calculated. PCoA, a dimensional reduction statistical technic, was used in the beta diversity analysis to reduce all the dimensions of the data and represent that into two unique axes which explains most of the variation associated with the data (Goodrich et al., 2014). The two dimensions in this study represent over 50% of variations which compare to previous studies, is a reliable representation of the data (Michelsen et al., 2014; Figures 3.10 and 3.11). The findings indicate that the plant communities that developed under the compost treatment and under the leonardite treatment are quite different from each other, and from the zeolite and control treatments when grouped by amendments (Figures 3.10 and 3.12). The ellipses for each treatment were drawn at 95% confidence internal and the more distance the ellipses are from each other the more dissimilar the plant community in the treatments. Moreover, topsoil-subsoil cover depths also significantly affected beta diversity (Figures 3.11 and 3.12).

The distance from the centroid, which is a proxy for beta diversity, is an indicator of how similar or dissimilar plant communities are in each treatment (Perbiche-Neves et al., 2018). Centroids that are more distant from each other in multivariate space are more dissimilar from each other.

In Figures 3.13 and 3.14, an examination of the plant functional groups within each treatment revealed a conspicuous pattern. The compost treatment fostered the proliferation of grasses, whereas the control, zeolite, and leonardite treatments were conducive to the growth of forb species.

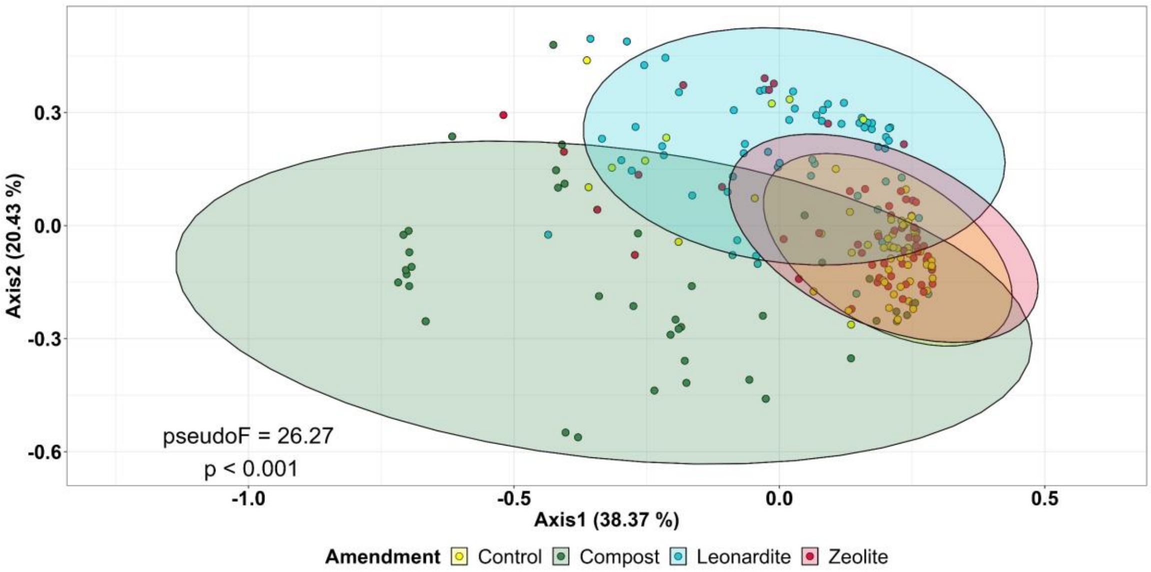

Figure 3.2. Influence of amendment treatment on beta diversity. Analysis of beta diversity indicates significant differences between treatment groups based on a pseudoF of 26.27, with Axis 2 explaining 20.43% of the variance and Axis 1 explaining 38.37% of the variance.

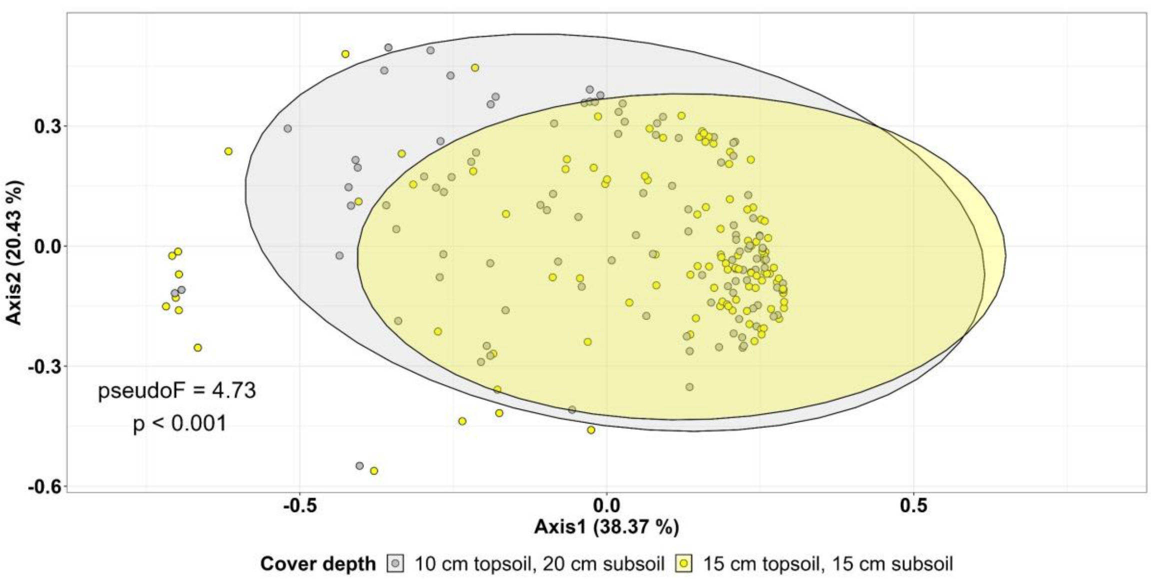

Figure 3.3. Influence of different cover depths on beta diversity. Analysis of beta diversity indicates significant differences between treatment groups based on a pseudoF of 4.73, with Axis 2 explaining 20.43% of the variance and Axis 1 explaining 38.37% of the variance.

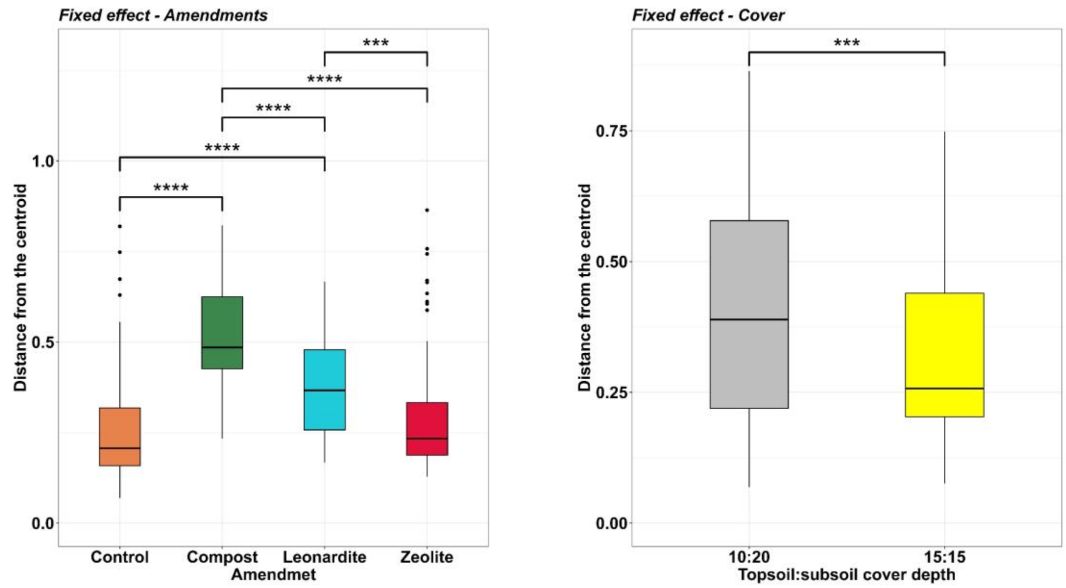

Figure 3.4. Distance from the centroid used as measure of beta diversity in each amendment treatment at left, and for different cover depths at right side of the figure. Significance levels were denoted as '*' for $p < 0.05$, '**' for $p < 0.01$, '***' for $p < 0.001$ and '****' for $p < 0.0001$. Non-significant values were omitted from the plot. The main rectangular box represents the interquartile range (IQR), and the horizontal line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data.

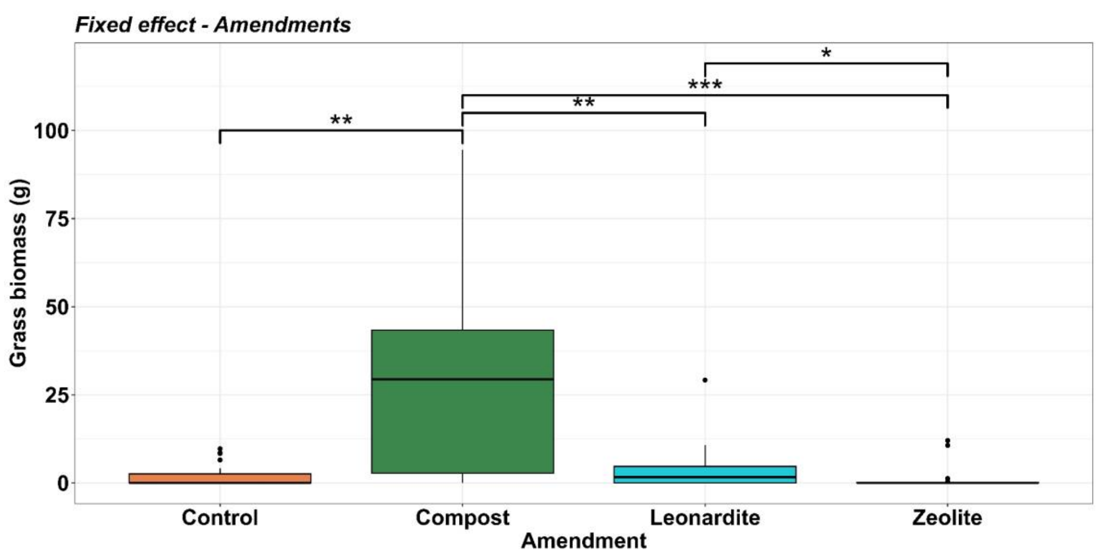

Figure 3.5. Grasses biomass from each amendment treatment. Significance levels were denoted as '*' for $p < 0.05$, '**' for $p < 0.01$, '***' for $p < 0.001$ and '****' for $p < 0.0001$. Non-significant values were omitted from the plot. The main rectangular box represents the interquartile range (IQR), and the horizontal line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data.

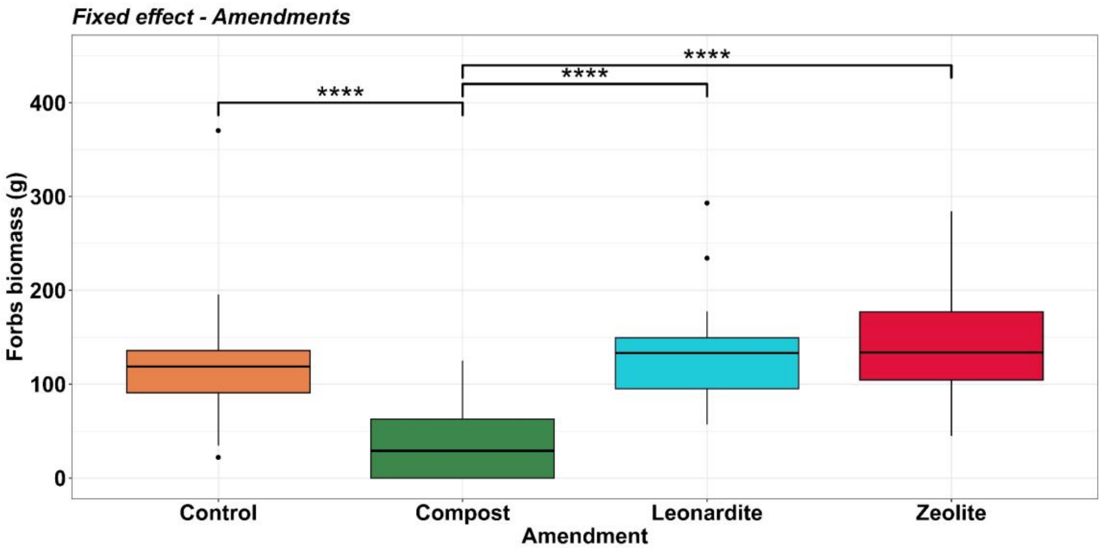

Figure 3.6. Forbs biomass from each amendment treatment. Significance levels were denoted as '*' for $p < 0.05$, '**' for $p < 0.01$, '***' for $p < 0.001$ and '****' for $p < 0.0001$. Non-significant values were omitted from the plot. The main rectangular box represents the interquartile range (IQR), and the horizontal line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data.

Soil Total Carbon and Nitrogen

The analysis of total carbon revealed that amendments had a significant effect on the total carbon content of the soil. Compost resulted in a significant positive impact on total carbon (Figure 3.15). Comparison between control and leonardite treatments indicated that leonardite has a negative impact on soil carbon. No differences were observed between zeolite and control. Furthermore, 15 cm topsoil with 15 cm subsoil cover depth resulted in higher total carbon content (mean total carbon of 2.51%) than 10 cm topsoil and 20 cm subsoil (2.25%.). In terms of total nitrogen, a similar amendment effect pattern to carbon was observed. Compost resulted in significantly higher nitrogen content than the other amendments, and leonardite resulted in the lowest nitrogen percentage (Figure 3.16). No significant differences were observed between zeolite and control treatments. Analysis of C/N ratio revealed that the soil carbon-to-nitrogen ratios of leonardite plots (25:1) were significantly greater than control and compost treatments (19.9:1, 18.5:1, respectively). Furthermore, the field condition also influenced the C/N ratio, as bare tailings plots resulted in a higher carbon-to-nitrogen ratio than the tilled ones (Figure 3.17).

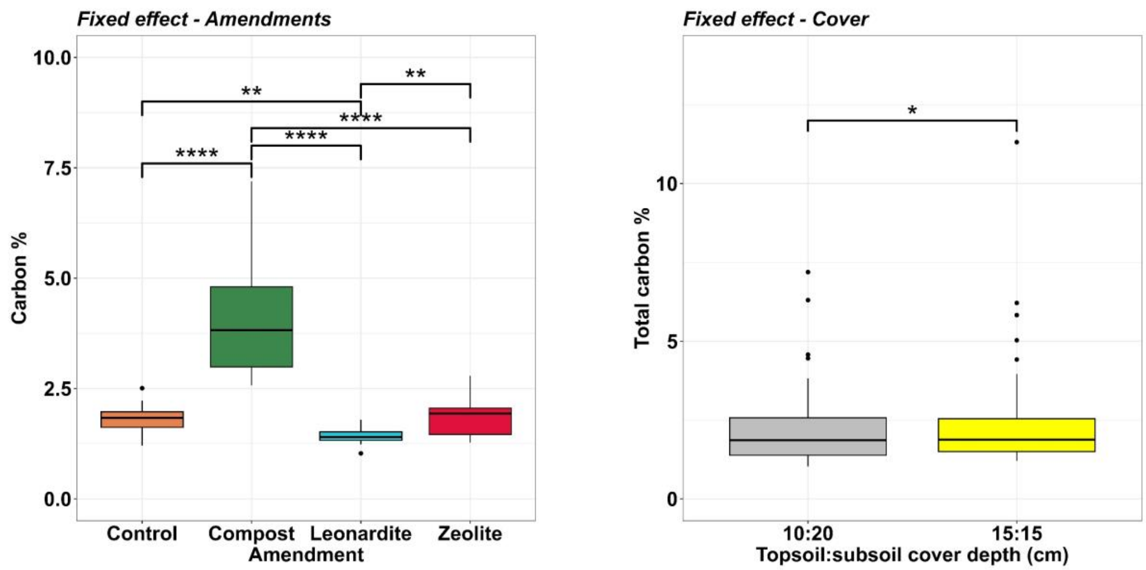

Figure 3.7. Total soil carbon content in each amendment treatment at left and different field condition at right side of the graph. Significance levels were denoted as ‘*’ for p < 0.05, ‘**’ for p < 0.01, ‘***’ for p < 0.001 and ‘****’ for p < 0.0001. Non-significant values were omitted from the plot. The main rectangular box represents the interquartile range (IQR), and the horizontal line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data.

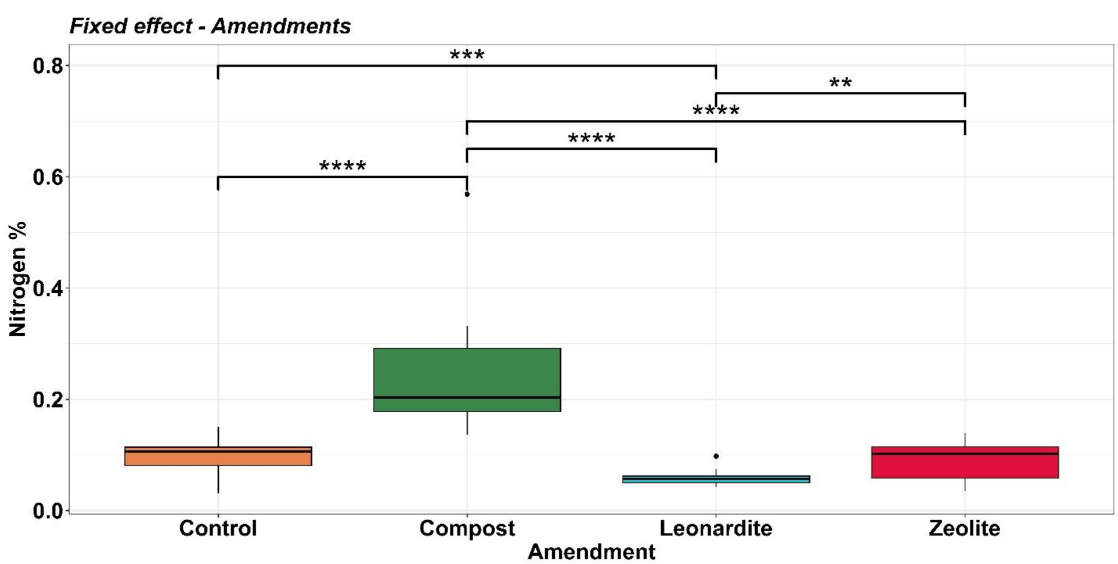

Figure 3.8. Total soil nitrogen content. Significance levels were denoted as ‘*’ for p < 0.05, ‘**’ for p < 0.01, ‘***’ for p < 0.001 and ‘****’ for p < 0.0001. Non-significant values were omitted from the plot. The main rectangular box represents the interquartile range (IQR), and the horizontal line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data.

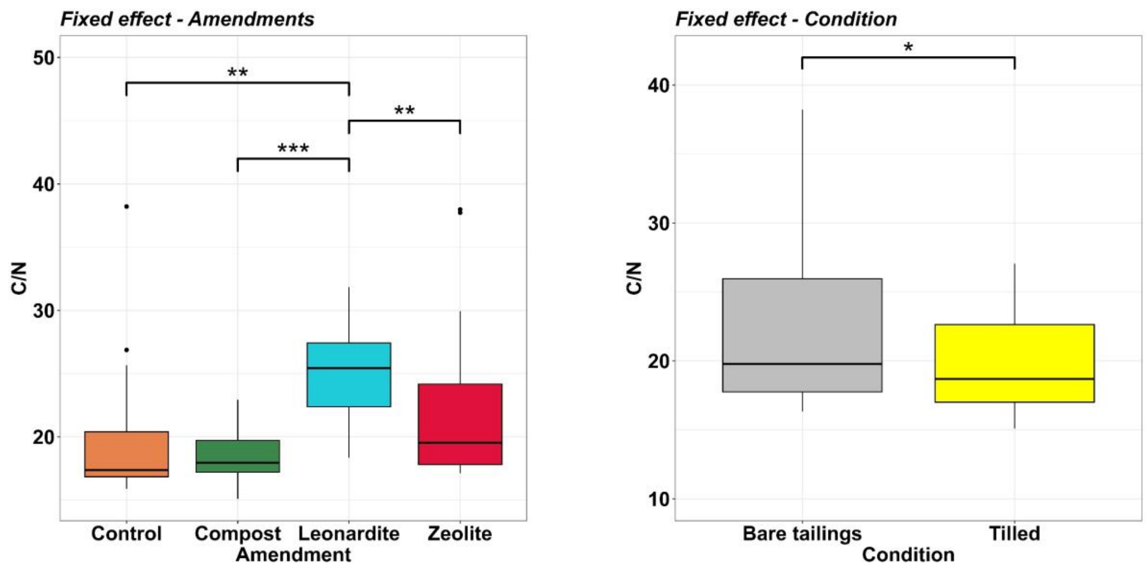

Figure 3.9. The total soil carbon to nitrogen ratio in each amendment treatment at left and different cover depths at right side of the graph. Significance levels were denoted as '*' for $p < 0.05$, '**' for $p < 0.01$, '***' for $p < 0.001$ and '****' for $p < 0.0001$. Non-significant values were omitted from the plot. The main rectangular box represents the interquartile range (IQR), and the horizontal line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data.

Soil Organic Matter

Soil organic matter analysis revealed a pattern similar to the total nitrogen analysis, with compost showing a significant positive impact, resulting in 8.41% OM and leonardite resulting in the lowest content (3.71%). No significant differences were observed between zeolite and control (4.88% and 5.24%, respectively) treatments (Figure 3.18). Furthermore, plot conditions (tilled or bare tailings) and their interaction with amendments had no significant impacts on soil organic matter.

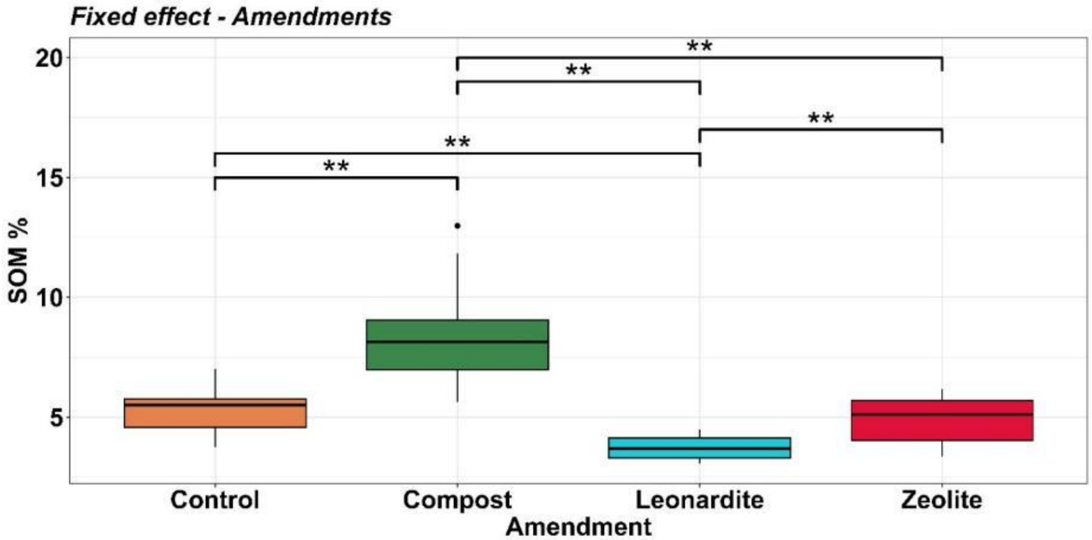

Figure 3.10. Soil organic matter (SOM) content. Significance levels were denoted as '*' for $p < 0.05$, '**' for $p < 0.01$, '***' for $p < 0.001$ and '****' for $p < 0.0001$. Non-significant values were omitted from the plot. The main rectangular box represents the interquartile range (IQR), and the horizontal line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data.

Soil pH

In terms of soil pH, compost treatments resulted in a mean pH of 7.33, which was statistically different from both zeolite and control treatments, each exhibiting an identical mean pH of 8.03 (Figure 3.19). Leonardite, with a mean pH of 7.67, also demonstrated statistical disparity from control, compost and zeolite treatments. Notably, the different cover depths, plot conditions (tilled or bare tailings) and their interaction with amendments had no significant impact on the soil pH.

Soil Moisture

Soil moisture analysis from the soil samples indicated that the compost treatment supported the highest soil moisture content (4.25%) in comparison to zeolite (2.59%), leonardite (2.39%) and control (2.62%) treatments (Figure 3.20). No significant influence was observed between zeolite, leonardite and control. Soil cover depths, plots conditions and their interaction with amendments did not result in significant differences.

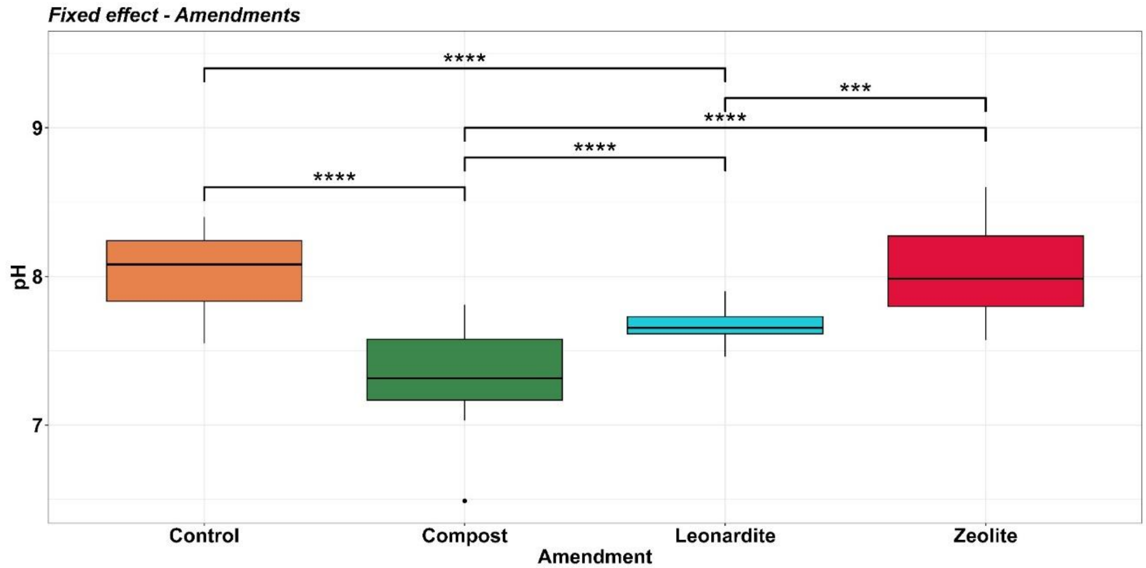

Figure 3.19. Soil pH. Significance levels were denoted as '*' for p < 0.05, '**' for p < 0.01, '***' for p < 0.001 and '****' for p < 0.0001. Non-significant values were omitted from the plot. The main rectangular box represents the interquartile range (IQR), and the horizontal line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data.

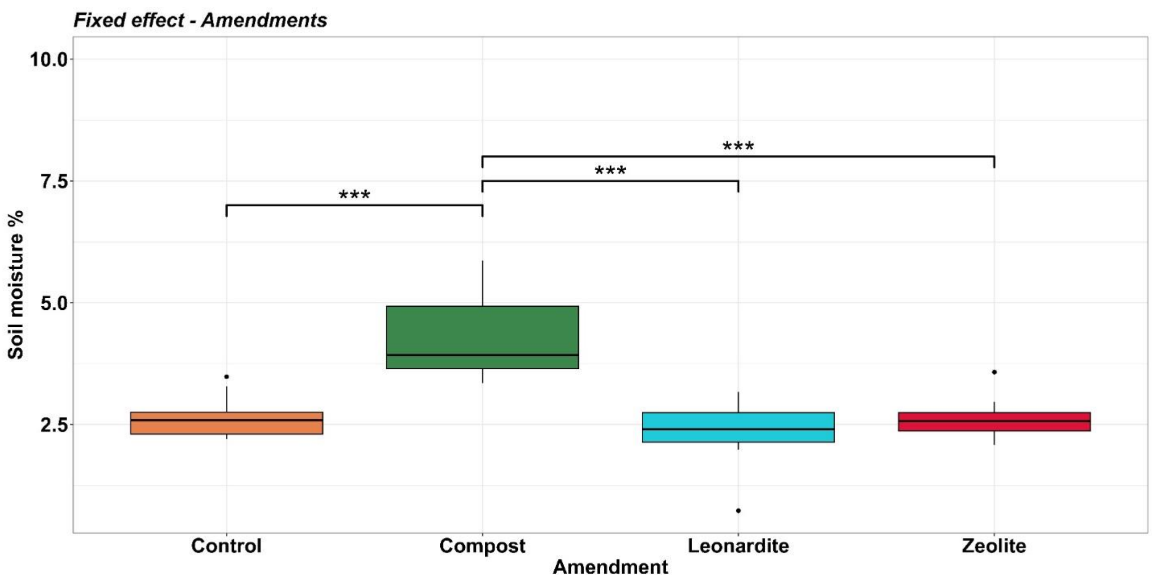

Figure 3.20. Soil moisture content. Significance levels were denoted as '*' for p < 0.05, '**' for p < 0.01, '***' for p < 0.001 and '****' for p < 0.0001. Non-significant values were omitted from the plot. The main rectangular box represents the interquartile range (IQR), and the horizontal line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data.

DISCUSSION

Plant Productivity and Species Richness

Previous studies have shown that topsoil depth is an important factor in determining reclamation success, as it influences water infiltration (Appendix A), water storage, plant productivity, and soil stabilization (Bowen et al., 2005). In this study, the greater topsoil depth resulted in higher biomass production. This result was expected based on soil organic matter content available in the topsoil and subsoil at this mine site. Soil organic matter plays a significant role in preserving soil structure, preventing soil erosion, and serving as a storage and receiver of vital nutrients required for plant growth (Batjes, 1996; Gregorich et al., 1993). The topsoil contained 2.7 % organic matter, which is 4.5 times higher than the organic matter content in the subsoil. Total carbon and nitrogen content that are components of soil organic matter are also higher in topsoil than subsoil (Table 3.1). Therefore, applying 15 cm topsoil and 15 cm subsoil on the site resulted in more biomass production in comparison to 10 cm topsoil and 20 cm subsoil.

The effect of amendments on plant growth indicated that compost treatments resulted in the lowest amount of biomass in comparison to other amendment treatments. However, according to the soil results, compost treatment was expected to result in high biomass production as it contained significantly higher organic matter, total carbon, and nitrogen content in comparison to other amendment treatments. One of the factors that can explain this contrast is the application of compost as a mulch and its thickness while other amendments were mixed into the topsoil. A 10 cm layer of compost on top of topsoil could result in lower soil bulk density, enabling plants to root in and strengthen their roots to the mulch and soil. From visual observation of the site, there were grasses with short roots that had fallen over in the compost treatment, seemingly unable to gain structural support from the roots. Also, around the edge of compost treatments, there was greater plant growth, while inside the plots, there were barely any grasses (Figure 3.21). These findings are aligned with previous studies that indicated mulch depth is vital for the establishment and survival of plants; deeper mulches showed a positive influence for better control of some plant populations like weeds, so this approach towards plant establishment may not be effective (Iqbal et al., 2020). Other studies showed that organic mulch promotes easier plant pulling due to softer soil, increased moisture, larger pores, greater aggregation, and shallower rooting (Greenly & Rakow,1995; Pakdel et al., 2011).

Figure 3.11. Compost treatment plots at the research site in August 2022

Plant Community Diversity and Composition

Plant species richness is an essential measure of biodiversity that strongly impacts how ecosystems are structured. A diverse range of plant species in an area can signify greater ecological diversity, and this diversity supports the overall stability of ecosystems (Tilman et al., 2014; Cardinale et al., 2012; Soliveres et al., 2016). However, the significance of factors influencing diversity patterns varies considerably across different studies. Anthropogenic and abiotic factors were found significant in different studies, but in the case of grasslands, abiotic factors such as high habitat heterogeneity, soil parameters, elevation, and climate have been found to be more influential in terms of diversity (Dembicz et al., 2021).

In this study, species richness was highest in zeolite and control plots, significantly different from leonardite and compost plots. Previous studies showed that the addition of zeolite to soil can increase seed germination (Prisa, 2019). Additionally, studies have shown that soils moderately rich in nutrients can support a diverse range of plant species, while nutrient-poor soils may limit the number of species that can grow (Tilman et al., 2012; Grime, 1977). In this study, zeolite and control treatments contained significantly higher carbon, nitrogen and soil organic matter content than leonardite. Therefore, these treatments resulted in a more favourable environment for the germination of different species than leonardite plots. Furthermore, the number of species was lowest in treatment with compost, which, based on the compost influence on plant productivity and plant establishment that was mentioned above, this result was expected. It is worth mentioning that based on previous studies, the diversity of species begins to improve soon after the restoration activities have taken place, which is a positive outcome (Lindborg & Eriksson, 2004). However, despite this initial increase in species richness, some species that are considered rare or have a short lifespan may not yet have returned to the restored ecosystem. These species may require more time or specific conditions to establish themselves and become part of the ecosystem again. So, while previous studies showed there is a positive trend over time in terms of species richness, the restoration process may not have fully reintroduced all the rare or short-lived species into the ecosystem at the time of assessment (Lindborg & Eriksson, 2004).

While species richness results are important, they do not account for the relative abundance of each species or their roles within the ecosystem. Shannon-Wiener and Simpson's indices, on the other hand, consider both species richness and evenness, providing a more complete picture of community structure (Magurran, 2004). The two indices in this research showed the same results as species richness in regard to the use of amendments (amendments as a fixed effect); in addition, they demonstrated significant influences of the field conditions (bare tailings, tilled), and the interaction of amendments with cover depths. The negative impact of tillage on both indices could be related to the fact that tillage impacts soil chemical, biological and physical properties, such as pore-size distribution and total porosity, soil structure, and soil carbon sequestration capacity (Feiziene et al., 2018; Pelosi et al., 2017; Ali et al., 2019). These impacts can alter nutritional conditions and affect plants diversity and composition (Janusauskaite & Kadziene, 2022).

The interaction between amendments and cover revealed that in both diversity indices, the most significant interactions were between compost in different soil depths with other amendments. However, it is interesting that only in the interaction of zeolite with 10 cm topsoil indices were significantly higher than zeolite 15 cm topsoil. One of the reasons could be the plant productivity relationship with plant alpha diversity. A study by Fraser et al. (2015) showed the hump-backed relationship between richness and dry biomass, with maximum richness found at intermediate levels of plant biomass.

Therefore, it is possible that as the amount of plant biomass was greater in 15 cm topsoil, this amount may have exceeded the biomass that expressed the maximum potential species richness, therefore results in lower diversity. Zeolite in 10 cm topsoil may result in plant biomass achieving the maximum potential for species richness, resulting in highest diversity indices.

To understand and quantify the variation in species composition or community structure among different treatments, beta diversity (inter-plot compositional dissimilarity) was measured. Significant differences existed between different amendments. Compost treatments were quite distinct from the rest of the amendment treatments, and the community within compost was more dissimilar to other treatment communities according to distance from centroid results. This can be related to the soil nutrients and water content in the treatments. Previous studies showed that plant communities with limited nitrogen have different species than those limited by other nutrients despite no productivity differences (Palpurina et al., 2019; Koerselman & Meuleman, 1996; Verhoeven et al., 1996). Furthermore, a study by Jiang et al. (2021) revealed that the water content in soil is the primary environmental factor that affects the distribution of plants. In both cases (soil nutrient and water content), compost treatments were different from the rest of the treatments. Similarly, the differences between plant communities in zeolite and leonardite treatments can be related to the significant differences between these treatments regarding soil nitrogen. Apart from the influence of amendments, the topsoil-subsoil cover depths significantly affected beta diversity, which could be because of more nutrient availability and higher SOM in 15 cm topsoil and 15 cm subsoil than the 10cm topsoil, 20 cm subsoil (Jiang et al., 2021).

A functional group assessment revealed that compost treatments were more favorable for grasses, while zeolite, leonardite and control plots supported more forbs. These differences between amendment treatments were expected based on the beta diversity results. The reason compost resulted in more grass biomass can be explained by the higher total nitrogen content than the rest of the amendments. A study by You et al. (2017) revealed that an increase in nitrogen resulted in a 79% increase in the above-ground biomass of grass species and had no influence on the biomass increase of forbs.

Soil Carbon and Nitrogen

Compost treatment resulted in significantly higher total carbon and total nitrogen content in comparison to other amendments and control plots. The soil total carbon content in compost treatment was more than two times higher than the others, and the same pattern was observed for the total nitrogen. Previous studies also acknowledge the improvement of soil total carbon and nitrogen with the addition of compost (Solís-Dominguez et al., 2012; Scharenbroch & Watson, 2014; Chalker-Scott, 2007; Scharenbroch, 2009). Furthermore, the compost contained easily degradable organic matter, wood chips, and beneficial fungi and bacteria that could enhance the organic content of the soil. The results also showed significantly higher total carbon and nitrogen content of zeolite treatment when compared to leonardite. The ability of zeolite to take in, hold, and gradually release nutrients can explain the higher zeolite treatment's nitrogen level compared to leonardite (Jarosz et al., 2022). Furthermore, different combinations of topsoil-subsoil cover depths demonstrated a significant influence on the total carbon content. The plots covered by 15 cm of topsoil and 15 cm of subsoil resulted in higher total carbon content than the 10 cm to 20 cm topsoil-subsoil cover depth. This result was expected as the topsoil contained higher carbon content than subsoil; therefore, the addition of more topsoil instead of subsoil resulted in more carbon content (Table 3.1).

It is also important to measure the soil C/N ratio of the treatments to investigate if the carbon and nitrogen are in balance to promote plant growth and maintain microbial health (Shrestha & Lal, 2007). In terms of carbon-to-nitrogen ratio, the leonardite treatment showed the highest C/N ratio (25:1) and was significantly different from compost (18.5:1) and control (19.9:1) treatments. To better understand the influence of different ratios, the role of ecosystems in this context needs to be considered. A study on abandoned grassland revealed a C/N ratio of 18.5, while other studies on horticulture, agriculture and forest ecosystems resulted in a minimum of 10:1 and a maximum of 18:1 C/N ratios (Mulder & Elser, 2009; Swangjang, 2015; Cleveland & Liptzin, 2007).

Apart from the amendments, the field conditions exerted a substantial influence on the carbon-to-nitrogen ratio. Notably, plots situated on bare tailings exhibited a C/N ratio of 22.6:1, while those in tilled conditions recorded a ratio of 19.8:1. The variation observed in the tilled plots can be attributed to alterations in nutritional conditions and soil carbon sequestration capacity, which are influenced by tillage practices (Janusauskaite & Kadziene, 2022; Ali et al., 2019).

Soil Organic Matter

The significance of soil organic matter content, particularly in the context of reclamation, should not be underestimated. This metric serves as an essential nutrient reservoir for plants and facilitates the gradual release of nutrients as the organic material undergoes decomposition (Batjes, 1996; Gregorich et al., 1993). Soil organic matter content in this study showed the same pattern as total carbon and nitrogen data, with compost treatment resulting in the highest SOM content (8.41%) and leonardite treatment resulting in the lowest amount of soil organic matter (3.71%). As carbon and nitrogen can directly affect soil organic matter content these findings were expected. Based on other organic matter content, the compost and leonardite treatment plots were ranked as high and medium, respectively based on Munshower (1994).

Soil pH

The soil pH level plays a significant role in soil microbial community and water retention capacity, which are among the main factors for plant establishment (Brown et al., 2003; Pepper et al., 2012; Sheoran et al., 2010). In this study, mine tailings, topsoil and subsoil had pH levels of 8.38, 7.98 and 7.98, respectively, which are considered moderately alkaline based on Munshower's (1994) classification. Although, in general, a soil pH range from 6 to 7.5 in mine sites can be adequate for agronomic or horticultural end-land use (Sheoran et al., 2010), in arid climate environments, pH levels between 7 to 9 can be considered as normal and also beneficial in immobilization of heavy metal ions (Brady, 1990; Antonelli, 2018). The addition of organic amendments has been proven to be helpful in maintaining pH levels and providing a favorable environment for vegetation establishment (Brown et al., 2007; Drozdowski et al., 2012; Gardner et al., 2010; Shrestha et al., 2009; Antonelli, 2018). In the case of this study, compost and leonardite significantly reduced pH levels in comparison to the other treatments, resulting in a mean pH of 7.33 and 7.67, respectively. These findings revealed that the pH of compost treatment was within the natural range, leonardite treatment was slightly alkaline, and zeolite and control treatments with the same pH mean of 8.03 were moderately alkaline (Munshower, 1994). It is worth mentioning that each plant requires a specific soil pH level to successfully establish and grow, however, based on previous studies, a pH level between 6.5 and 7.5 can be beneficial for plant growth (Smith & Doran, 1996).

Soil Moisture

One of the important components in soil ecological functioning is water; the growth and survival of plants and other soil organisms is dependent on soil water as a medium for microbial activity, maintenance of cell turgor and vascular plant transpiration (Sack & Holbrook, 2006; Buckley, 2005; Fierer & Schimel, 2003). Furthermore, soil water can contain hundreds of dissolved organic and inorganic substances (Sumner, 2000). In this study, compost resulted in the highest soil moisture content, mainly because of the existence of wood chips in its texture and its application as mulch which can slow down the soil moisture loss through evaporation, thereby maintaining a more uniform moisture level in the soil (Donk et al., 2011; Tehranifar, 2011). Surprisingly, there were no significant differences between leonardite, zeolite and control treatments. One of the properties of leonardite and zeolite mentioned in the literature are leonhardite's ability to decrease water evaporation, and zeolite characteristics that help with water retention (Brandsma et al., 1999; Prisa, 2019). Although consistent with this research, a study by Shaykewich (2000) found that leonardite had no effect on soil water content, this finding might be related to the time of the sampling or the application rate of the amendments.

RESEARCH LIMITATIONS

To establish the field operationally, ensuring its practicality and feasibility for mine reclamation, we utilized excavators to prepare the soil. This process involved mixing amendments with topsoil and applying subsoil and topsoil to the designated plots. However, accidentally, one of the blocks that was planned to be tilled was excavated, resulting in 6 blocks of bare tailings condition and 4 blocks of tilled condition.

In addition, due to the limited time of a master's project, this study involved one year of data collection. More studies are needed to investigate the long-term effect of the treatments on soil and plant growth and overall reclamation success. Furthermore, it is important to note that each ecosystem has its unique characteristics and there are various factors including climate change, land-use, land cover changes, invasive species, and the type and degree of environmental degradation that can play a significant role in biodiversity changes and effectiveness of different reclamation treatments (Santos et al., 2021; Moreno-Mateos et al., 2020). Therefore, the results of this study are based on characteristics of the study site, however, it can provide insight for potential use of the mentioned treatment in alike ecosystem.

Lastly, soil moisture in this study were determined by one-time soil sampling in mid-August, therefore the soil moisture results cannot reflect the water infiltration and retention over the growing season.

CONCLUSION

The results of this study provide valuable insights into the use of different amendments and topsoil-subsoil cover depths for the reclamation of tailings storage facilities in the semiarid interior of BC. The addition of compost significantly increased soil total carbon, nitrogen, organic matter, and soil moisture, but it resulted in the lowest amount of above-ground biomass and species richness in comparison to other treatments, which can be due to its application as mulch. As the tailings were alkaline at the study site, the addition of compost and leonardite resulted in significant reductions in pH levels and fell within the neutral pH range and slightly alkaline category, respectively. Another significant difference between the various amendments was their effects on different functional groups, which indicated that the compost treatment supported grasses while in the other amendments, forb species were more dominant. In addition, the results indicated that covering tailings with 15 cm of topsoil and 15 cm of subsoil increases biomass production in comparison to 10 cm topsoil and 20 cm subsoil. Based on the findings of this study, tilling a reclaimed site may not be beneficial to plant diversity, as the comparison between the reclamation practices on tilled and bare tailings resulted in lower Shannon's and Simpson's indices.

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CHAPTER 4 – RESEARCH CONCLUSIONS, MANAGEMENT IMPLICATIONS AND FUTURE RESEARCH

RESEARCH CONCLUSION

Mining operations can result in environmental degradation and damage to soil, plant communities and the surrounding ecosystem. The mining operation involves removing soil from the surface to either get access to the desirable minerals or create tailings storage facilities to store waste materials and tailings. The human need for mineral extraction, economic development and industrialization is constantly increasing the demand for minerals. Increases in mineral extraction typically leads to more waste material and environmental damage to the ecosystem. To mitigate the downside of mineral exploration, mine reclamation is key. Through mine site reclamation, the mining industry can minimize the risk to human and animal health as well as improve ecosystem function. To reclaim tailings storage facilities (TSFs), the subsoil and topsoil that has been stockpiled during the construction can be reapplied to provide a medium for plant growth. However, determining a functional soil cover depth is important as the topsoil and subsoil amounts may be limited at mine sites, and additionally, the soil may not be as nutrient-rich as it was prior to-disturbance due to stripping and longtime stockpiling. Therefore, applying a suitable amendment that can activate soil microorganisms, improve soil water holding capacity and provide the soil with sufficient carbon, nitrogen and organic matter can encourage plant growth and establishment. Zeolite and leonardite are two by-products of mining which have recently gained attention for mining reclamation due to their ability to improve soil properties, boost plant growth, minimize nutrient leachate and drought effects, effectively mitigate soil contaminations, and substantially increase the soil's water retention capacity (Misaelides, 2011; Kesraoui-Ouki et al., 1994; Chen et al., 2004, Piccolo et al., 1996). Furthermore, the application of compost amendment made up of wood residuals and a blend of composting microbes can enhance the microbial activity in the soil. Previous studies have shown that the addition of compost to the soil can result in a significant improvement in the level of organic matter present (Heiskanen et al., 2022).

To examine the influence of the mentioned amendments individually and in their combination, and the effects of different topsoil-subsoil cover depths on reclamation success, a greenhouse and a field study were conducted.

The results of this study highlight the potential of zeolite and compost as sustainable tools for enhancing TSF reclamation. The compost treatments in the greenhouse study resulted in significant improvement in soil parameters, including total carbon, total nitrogen, and organic matter. The improvement in soil quality resulted in a significant increase in total biomass in the treatments supplemented with compost. Furthermore, the compost treatments supported shoot growth, while in the other treatments, more root growth occurred, which could be related to the adequate nutrients available in compost treatments that promoted relatively less root growth but greater shoot production (Wilsey & Polley, 2006). In addition, zeolite treatment alone resulted in higher organic matter content, and its combination with compost resulted in higher total carbon content and C/N ratio than found in untreated pots.

In the field experiment, the compost treatment resulted in the highest total carbon, nitrogen, soil organic matter, and soil moisture content. However, in terms of plant growth, the compost plots showed the lowest amount of above-ground biomass production. Furthermore, significant differences were observed in terms of plant functional groups and plant community diversity in different treatments. Moreover, the application of 15 cm subsoil and 15 cm topsoil resulted in higher biomass production than 20 cm subsoil and 10 cm topsoil. The field study also examined the influence of tillage on reclaimed sites, which resulted in a decrease in carbon-to-nitrogen ratio, and in Shannon and Simpson plant diversity indices in comparison to the reclamation practices on bare tailings.

The results related to soil analyses were similar in both field and greenhouse experiments; however, in terms of plant growth, opposite results were observed. Previous studies have investigated differences in plant growth between greenhouse and field experiments and have proven that significant differences can exist between greenhouse and field results, particularly in terms of biomass production. These studies emphasize that greenhouse experiments often tend to overestimate plant growth and may not accurately reflect real-world field conditions and complexities. Therefore, while greenhouse experiments play a crucial role in developing conceptual models, field experiments are essential for gaining a better understanding of plant growth dynamics within complex field communities (Forero et al., 2019; Heinze et al., 2016; Schittko et al., 2016).

Considerations for future research should focus on the influence of zeolite and leonardite in higher ratios and the mix of compost into topsoil instead of applying as mulch. Furthermore, testing the influence of combining compost and zeolite in the field experiment with more replicates could provide a more in-depth understanding of the effectiveness of these amendments. It is worth mentioning that long-term monitoring of the impact of the different treatments is essential; therefore, more follow-up research on the sites that have been reclaimed with specific treatments would be beneficial in a comprehensive understanding of treatments.

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APPENDIX A – TOPSOIL-TILL COVER DEPTH: INFLUENCE ON HYDRAULIC RATES FOR RECLAIMED TAILINGS FACILITIES

INTRODUCTION

Development of a reclamation plan to ensure the disturbed lands will be returned to a safe, sustainable, and acceptable end land use is essential and it is a requirement upon mining operations in British Columbia (Mining Act, 1996; the Code). Reclamation of Tailings Storage Facilities (TSFs) often involves the placement of subsoil and topsoil to provide a medium for plant growth; however, the limited supply of topsoil and till materials can create a barrier and highlights the importance of determining the appropriate depths of cover to support successful reclamation of TSFs (Bowen et al., 2005; Fischer et al., 2022). One aspect of successful reclamation is the return of vegetation and plant communities, which is heavily influenced by the infiltration of water through the topsoil-subsoil cover depth and moisture balance (Bowen et al., 2005). Therefore, it is vital to understand the movements of water within different cover depths and determine an efficient depth that can support water retention within the cover and promote vegetation growth. This study is designed to 1) determine if there is significant variation in water infiltration rate and moisture balance of three different cover depths and 2) examine the influence of the cover depths on plant growth.

MATERIALS & METHODS

In November 2020, a lysimeter trial was established at Historic Afton Tailings Storage Facilities (HATSFs), located approximately 10 km west of Kamloops, BC, owned and operated by New Gold Inc. The trial involved the use of open-topped cylindrical tanks, each having a height of 2.43 meters and dimensions measuring 1.24 meters. These tanks were filled with 2.10 meters of tailings and then covered by three different subsoil and topsoil cover depths (i.e. 10 cm topsoil and 20 cm subsoil, 15 cm topsoil and 15 cm subsoil, 5 cm topsoil and 25 cm subsoil; Table A.1).

Table A.1. Chemical and physical parameters of the mine tailings, subsoil and topsoil used in this study. Abbreviations: OM, organic matter; TC, total carbon; TKN, total Kjeldahl nitrogen, dS/m, deciSiemens per meter; EC, electrical conductivity; BD, bulk density; SA, sieve analysis; ST, soil texture. Parentheses denote the units of measurement, except for pH where (1:2) refers to the soil-to-water ratio of the sample used for measurements.

Substrate/ Materials	pH (1:2)	OM (%)	TC (%)	TKN (%)	EC (dS/m)	BD (kg/m^3)	SA-75 microns (%)	ST
Tailings	8.38	1.7	0.93	<0.01	3.33	1340	76	Coarse
Subsoil	7.98	0.6	1.04	0.0117	5.14	1460	73	Coarse
Topsoil	7.98	2.7	1.15	0.0317	3.51	1640	88	Coarse

Water content was measured in 60 cm, 30 cm and 0 cm into the tailings as well as on the surface of tailings and 15 cm above the tailings by installing HOBO data loggers in the mentioned depths (Figure A.1).

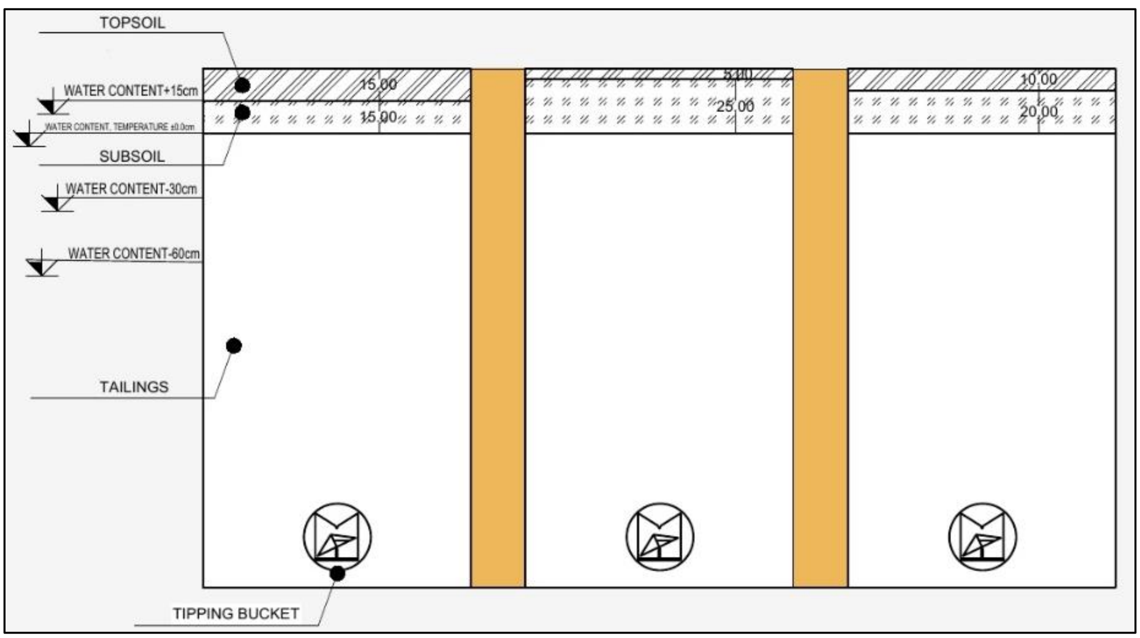

Figure A.1. Lysimeters design for different cover depths

Additionally, temperature was measured for each treatment at the surface of tailings using the data loggers. Each treatment was replicated three times and was handseeded with a mix of native and agronomic pre-selected seeds provided by New Gold New Afton Mine in late November (Table 3.2).

Under the natural condition, the water content and temperature data recording started in November 2020 and ended in March 2023. During this period, the data loggers were recording data every hour at the mentioned depths. At the end of August 2023, the presence of different plant species and their absolute percent cover were estimated for all the treatments in order to evaluate several parameters, including the Shannon-Wiener index, Simpson's diversity index, species richness and beta diversity.

COLLECTED DATA

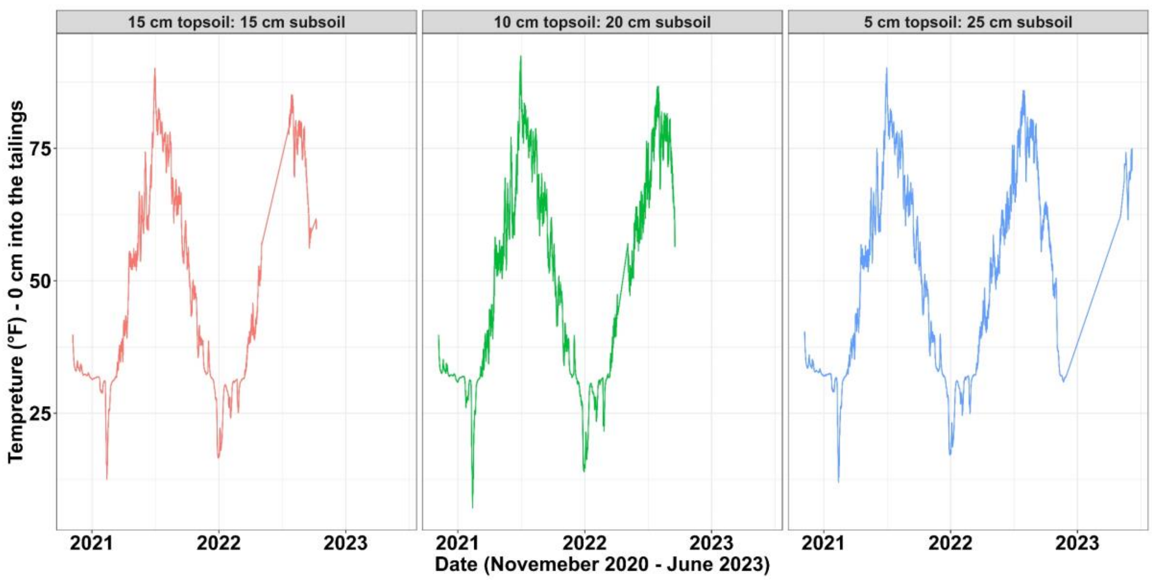

Figure A.2. Temperature data recorded on the tailings surface for the three topsoil and subsoil cover depths from November 2020 to June 2023 using data loggers.

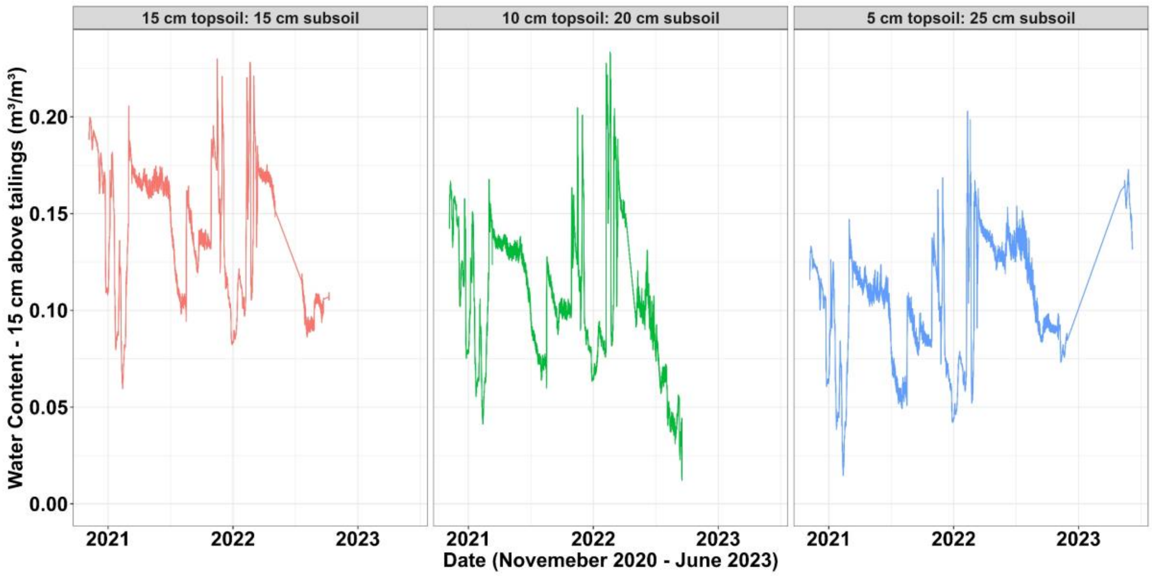

Figure A.3. Water content in 15 cm on top of the tailings measured in each treatment using data loggers from November 2020 to June 2023.

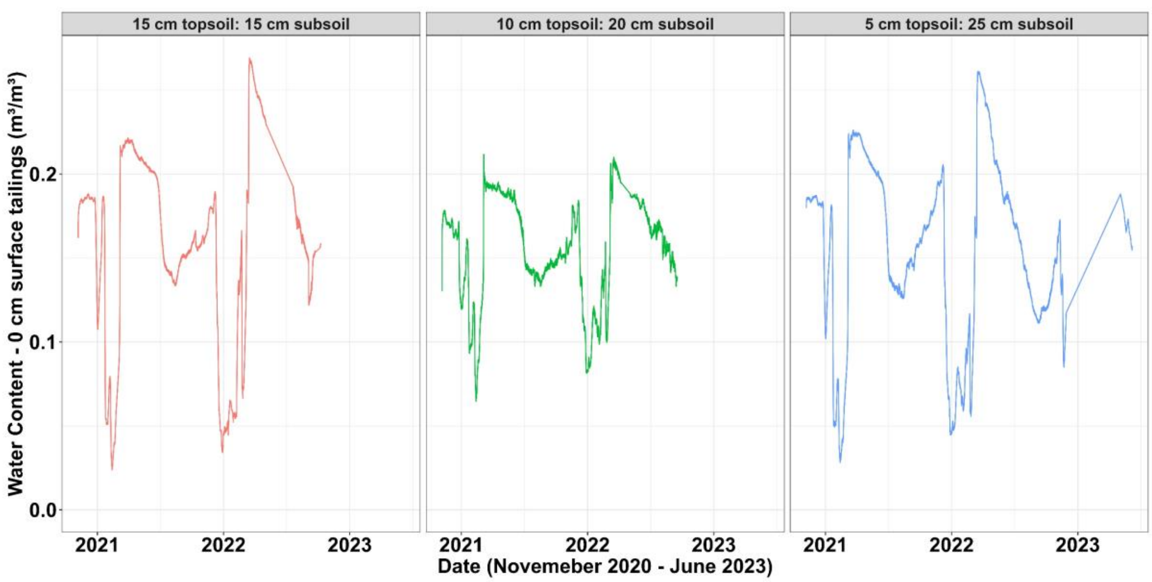

Figure A.4. Water content measure on surface of tailings (right below the 30 cm soil cover depth) using data loggers from November 2020 to June 2023

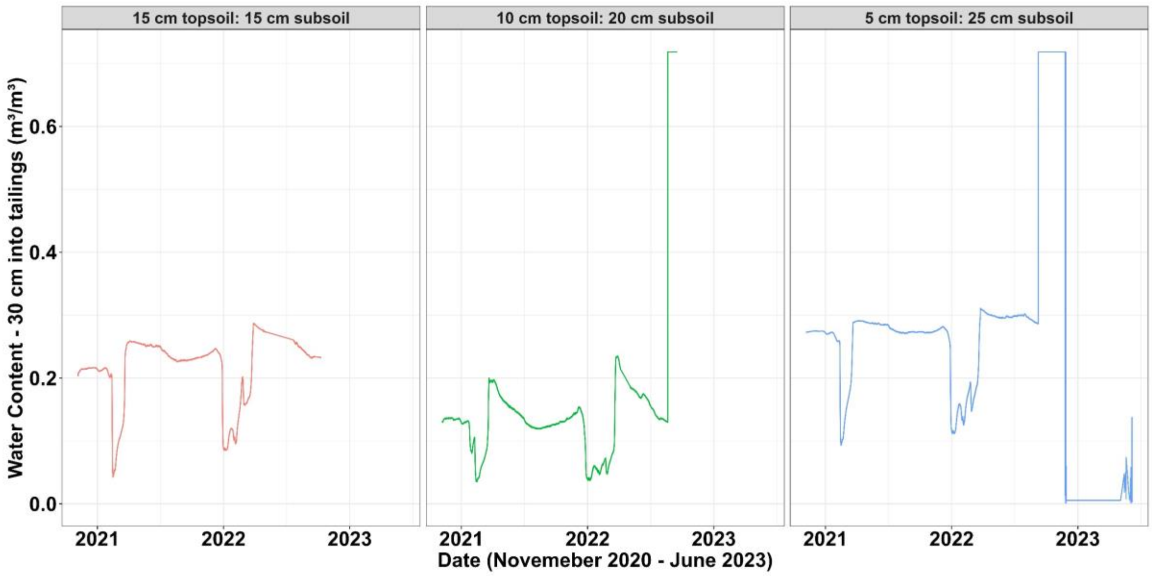

Figure A.5. Water content in 30 cm into the tailings measured by data loggers in the three treatments from November 2020 to June 2023.

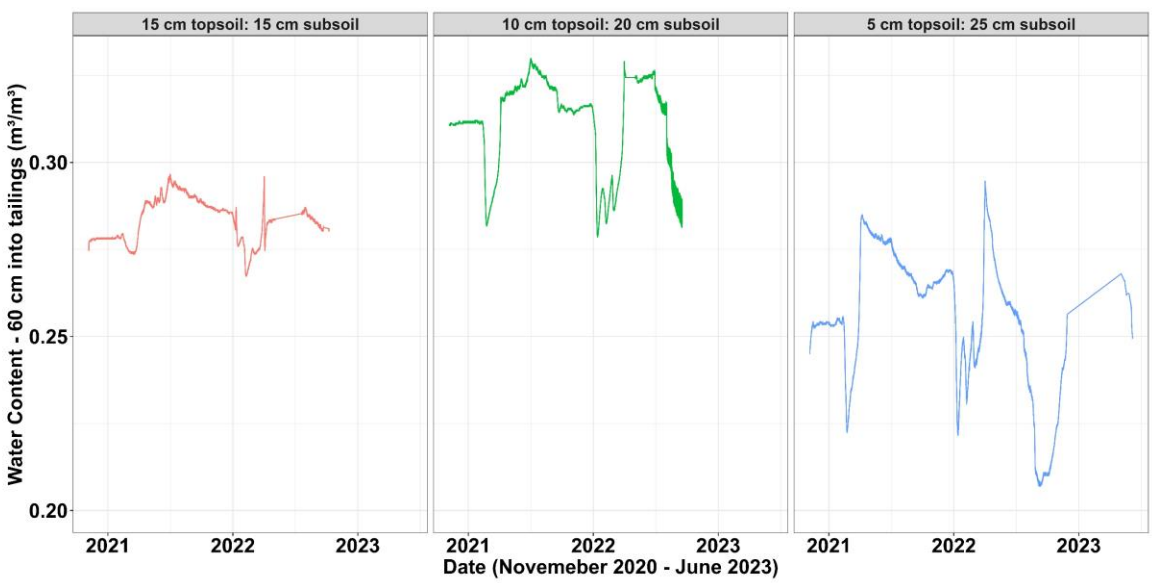

Figure A.6. Water content in 60 cm into the tailings, measured by data loggers from November 2020 to June 2023.

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APPENDIX B – PLANT COMMUNITY IN DIFFERENT TREATMENTS

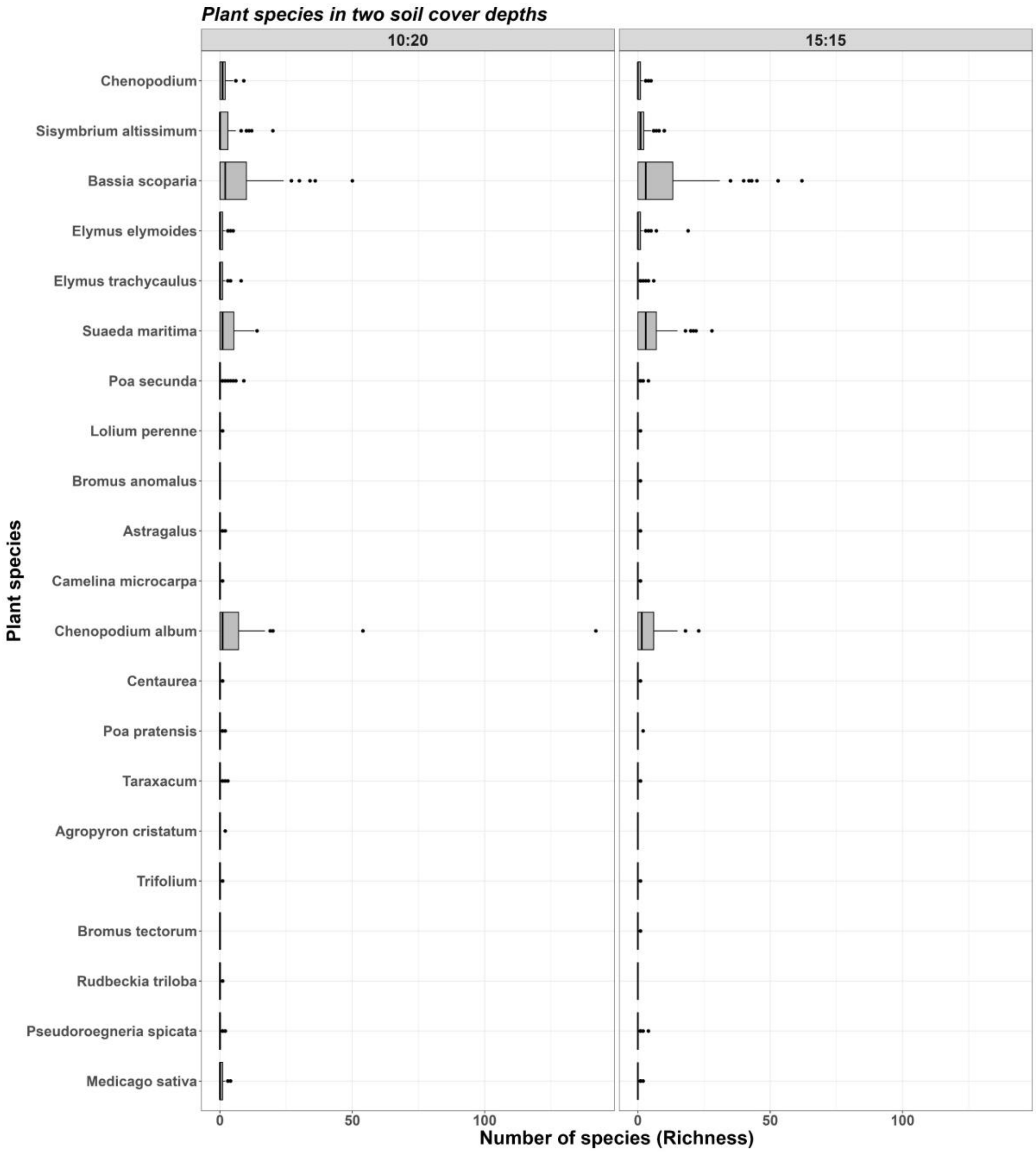

Figure B.1. number of different plant species presented in the two soil cover depths of 20 cm subsoil, 10 cm topsoil (left figure) and 15 cm subsoil, 15 cm topsoil (right figure).

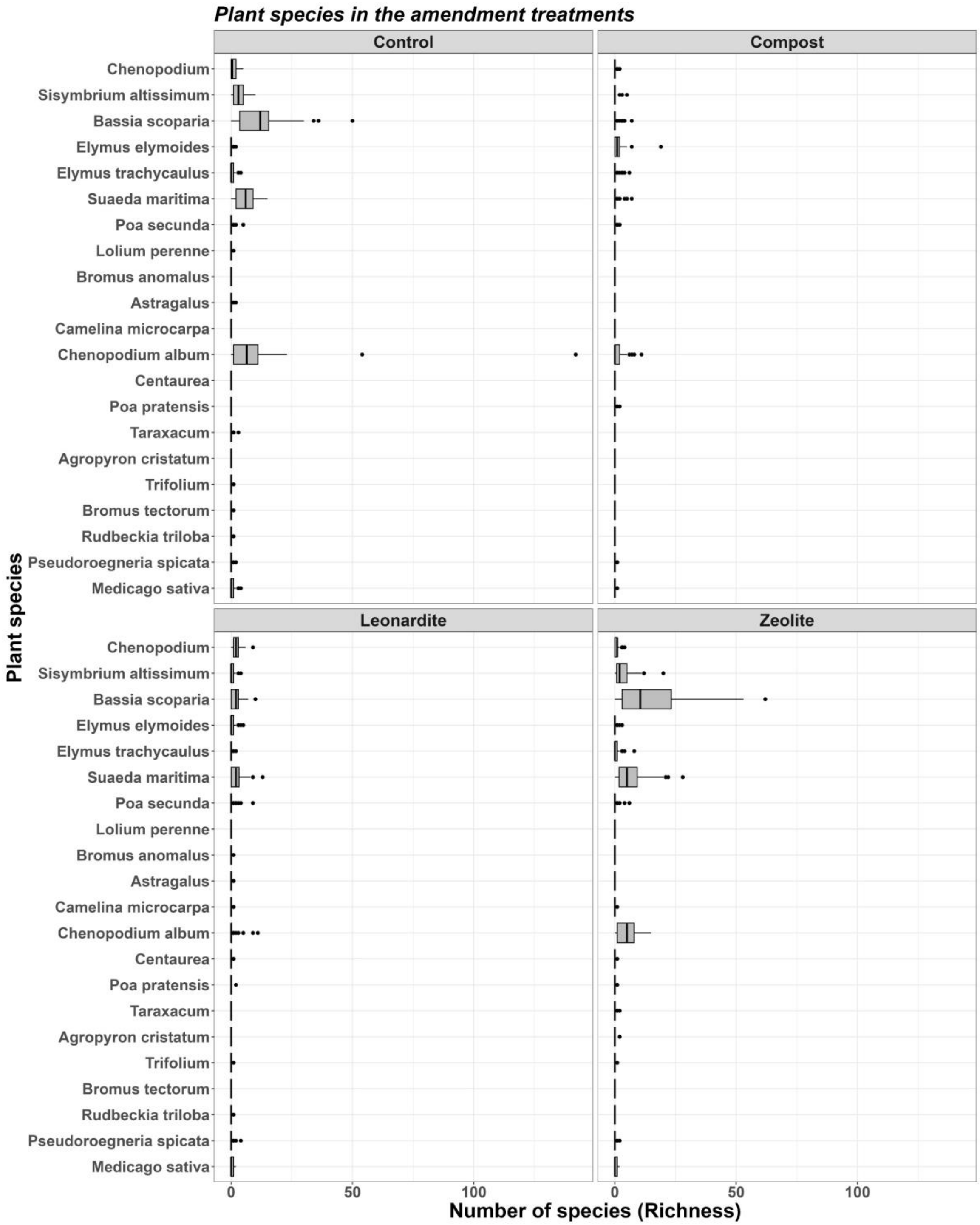

Figure B.2. Number of different plant species presented in the control, compost, leonardite and zeolite plots.