Application of Zeolite, Leonardite and Compost as a Tool for Mine Reclamation: A Greenhouse Study Using Tailings from the Historical Afton Mine in South-Central British Columbia (Part of NTS 92I/09)

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Introduction

The global consumption of mineral resources is on the rise, with a key driver being the shift toward a low-carbon future (Church and Crawford, 2020). This transition is notably fueled by the demand for essential minerals such as copper, crucial for electricity transmission, and other precious metals required for batteries and electric vehicles (Gielen, 2021). This results in more mining excavation to extract the desired minerals, and production of mine waste materials (Plante et al., 2023). 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 may contain heavy metals and are required to be deposited in tailings storage facilities (TSFs; Cacciuttolo et al., 2023). The contemporary best practice in constructing TSFs emphasizes the preservation of soils, with the aim of facilitating their future reuse for reclamation purposes. In the TSF construction process, topsoil, subsoil and other materials are typically extracted from land that may extend over several square kilometres and reach tens of metres 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). Therefore, it is necessary to implement sustainable reclamation practices to facilitate the restoration of TSFs. Studies have shown that improperly managed (e.g., not effectively reclaimed) mine tailings pose an environmental and health risk (Cacciuttolo et al., 2023). In recent decades, significant policies have been put in place and actions have been taken to minimize the environmental footprint of mining operations by improving reclamation practices. Reclamation is crucial for mining companies and stakeholders aiming to create a functional and sustainable post-mining landscape (Hendrychová et al., 2020). A vital component of this process involves building and enriching the soil, as well as encouraging the establishment of plant and animal communities (Adesipo et al., 2021). However, reclamation of mine tailings is a challenge because of their inferior soil structure due to the lack of nutrients and organic matter (Gardner et al., 2010), and high levels of heavy metals (Hayes et al., 2009).

To reduce the environmental effect of mine tailings and promote vegetation growth 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-time stockpiling and reinstatement can induce notable transformations and movement of nitrogen (N), ultimately leading to substantial loss of nitrogen and significant degradation of the soil over time (Strohmayer, 1999; Sheoran et al., 2010; Fischer et al., 2022). Incorporating appropriate amendments to the soil can improve the structure of the microbial community; it can also provide the soil with the necessary organic material and carbon source for reactivating 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, and therefore soil can become suitable for the establishment of plants (Bradshaw, 1997; Asemaninejad et al., 2021).

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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 (Kesraoui-Ouki et al., 1994; Misaelides, 2011). 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 favourable 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 (Piccolo et al., 1996; Chen et al., 2004). Based on the individual properties of zeolite and leonardite, the combination of these amendments can provide benefits in soil remediation and reclamation. The addition of carbon-rich materials like leonardite has proven highly effective in stimulating microbial activity, whereas zeolite can increase soil sorption capacity and increase the number of micro-organisms in soil because it is porous and acts as an ideal habitat for micro-organisms (Szerement et al., 2023). Furthermore, as the porosity of zeolite absorbs nutrients and the high humic substance in leonardite can improve soil, the mix of these amendments can have the potential to ameliorate degraded soil. More specifically, the findings of a study on agricultural soil in 2014 demonstrated that a slow-release fertilizer derived from leonardite and zeolite exhibited lower nutrient-releasing rates compared to a commercially available fertilizer (Chawakitchareon et al., 2014).

Another beneficial amendment to improve the soil properties of contaminated sites is compost. Compost amendment can improve soil health and foster pollutant degradation. By introducing active micro-organisms, compost enhances the soil’s microbial activity and nutrient content, stimulating the natural degradation of hazardous compounds. Additionally, the organic matter in compost can act as a sorbent, reducing the bioavailability of contaminants and preventing their migration (Kästner and Miltner, 2016). Research has shown 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).

It is worth mentioning that the return of these disturbed lands to a sustainable and functional state similar to premining conditions is a regulatory and social licence requirement. In particular, the reclamation of grassland ecosystems that were disturbed during mining activities is of great importance. Grasslands, specifically in British Columbia (BC), are an endangered ecosystem due to human activities, livestock and invasive plants (Iverson, 2004). As grasslands provide numerous benefits to communities, including erosion protection, habitat for species at risk, carbon sequestration and climate stability, losing grasslands can negatively impact human health and the different communities that live in them (Wetland Stewardship Partnership, 2010). Bluebunch wheatgrass (*Pseudoroegneria spicata*), a perennial native grass, is one of the dominant species in BC grasslands, and its exceptional drought tolerance makes it a great species in semi-arid regions of BC (Tisdale, 1947; Wikeem and Wikeem, 2004).

Despite the potential benefits of these amendments, there is a lack of comprehensive research on their combined application in the context of mine reclamation and the specific impacts on bluebunch wheatgrass growth. Moreover, the influence of compost amendment on these treatments and its role in enhancing soil fertility remains underexplored. Addressing this knowledge gap is crucial for developing effective and sustainable strategies to reclaim TSFs and 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 paper summarizes the results of a greenhouse study that was designed to 1) investigate the influence of amendments such as zeolite, leonardite and their combination, in two different concentrations, on bluebunch wheatgrass (*Pseudoroegneria spicata*) growth and soil improvement; and 2) examine the effect of the addition of compost in conjunction with the aforementioned treatments on tailings from the historical Afton mine, to assess their combined potential for improving plant growth and soil fertility. Understanding how various amendments and their interactions impact plant growth and soil properties will contribute to the development of innovative and environmentally friendly approaches for the reclamation of the historical Afton tailings storage facility and similar sites.

Materials and Methods

Mine Tailings and Amendments

Samples of bulk tailings were obtained from the historical Afton tailings storage facility, and samples of topsoil and subsoil were collected from stockpiles at New Afton mine. 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 BC (latitude 50°39′N, longitude 120°32′W, elevation 700 m; Figure 1). The historical Afton tailings exhibit a coarse texture accompanied by a medium bulk density. The

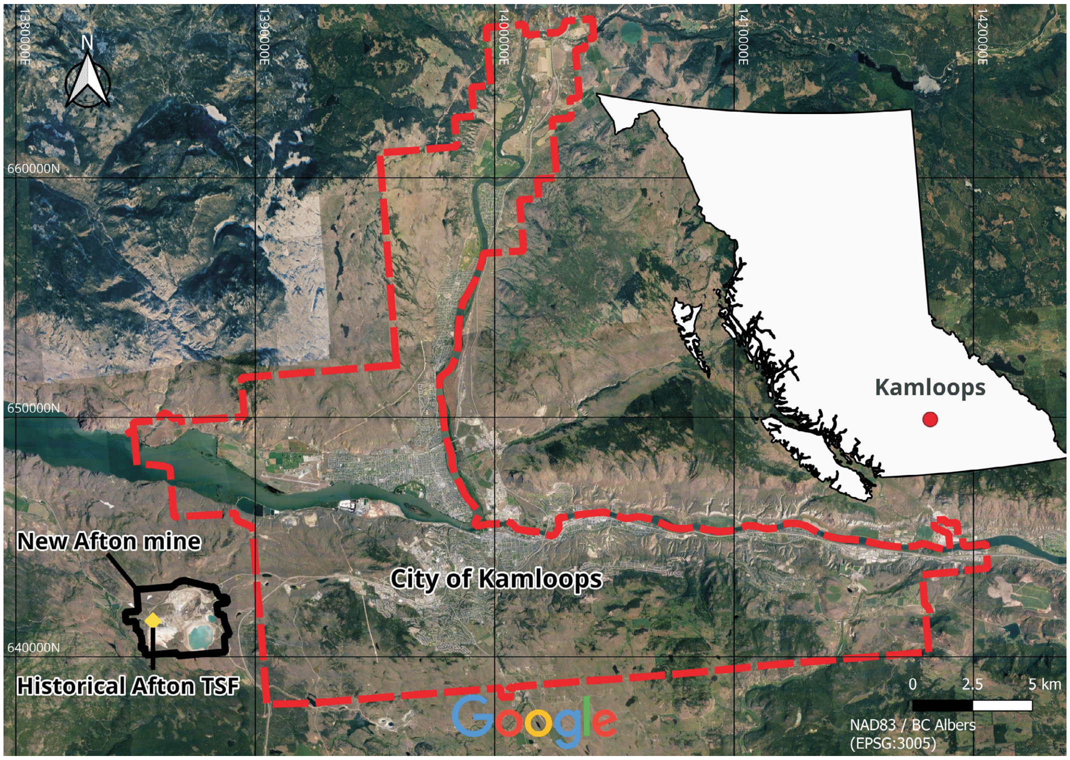

Figure 1. Location of the historical Afton tailings storage facility (TSF) and New Afton mine, from which the material used in this study was obtained. New Afton mine is 10 km west of the centre point of the city of Kamloops, British Columbia. Inset shows the location of Kamloops within the province.

tailings are characterized by a moderately alkaline pH and low amount of organic matter, total carbon and total nitrogen (Table 1; Munshower, 1994). Topsoil and subsoil from the New Afton stockpile also had a coarse soil texture, a moderately alkaline pH and low organic matter.

The compost used in this study was made of wood waste, with no soil present (class A compost), and contained a mix of urea and a blend of composting microbes and some fungi and bacteria that are more adept at absorbing hydrocarbons. Leonardite was sourced from the Red Lake deposit, located approximately 40 km northwest of Kamloops, and zeolite from the Bromley Creek mine, approximately 7.5 km southwest of the town of Princeton, also in the south-central interior of BC.

Design of the Greenhouse Experiment

The greenhouse experiment was carried out at the Thompson Rivers University Research Greenhouse, located in Kamloops, BC, 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 of tailings, followed by 20 cm of subsoil and 10 cm of topsoil (Figure 2a). Depending on the treatment, zeolite (Z), leonardite (L) or a combination of the two (ZL) were mixed into topsoil at a high (0.0448 kg/m^3) or low (0.0224 kg/m^3) ratio of amendments to topsoil. Then, compost at a ratio of 1:1 (compost:topsoil) was applied on top of the topsoil to half of the pots. In addition, there were two control pots, both filled with tailings covered by 20 cm of subsoil and 10 cm of topsoil, but one amended with compost and one without compost added. There were, therefore, in total, 12 combinations of Z, L and ZL with and without compost, in addition to the two control treatments. The 14 treatments were replicated six times for a total of 84 pots (Figure 2b).

Table 1. Chemical and physical parameters of the mine tailings, subsoil and topsoil used in this study. Abbreviations: dS/m, deciSiemens per metre; EC, electrical conductivity; OM, organic matter; TC, total carbon; TKN, total Kjeldahl nitrogen. The unit of measurement for pH refers to the soil-to-water ratio (1:2).

Substrate/ materials	pH (1:2)	OM (%)	TC (%)	TKN (%)	EC (dS/m)	Bulk density (kg/m^3)
Tailings	8.38	1.7	0.93	<0.01	3.33	1340
Subsoil	7.98	0.6	1.04	0.0117	5.14	1460
Topsoil	7.98	2.7	1.15	0.0317	3.51	1640

Ten bluebunch wheatgrass seeds (*Pseudoroegneria spicata*) were planted per pot at approximately 0.5 cm depth in the topsoil, and the pots were randomly placed (Figure 2b) in the research greenhouse. After three weeks of germination, nine of the planted bluebunch wheatgrass seedlings were removed from each pot, leaving one healthy-growing bluebunch wheatgrass seedling in each pot (Figure 3a, b).

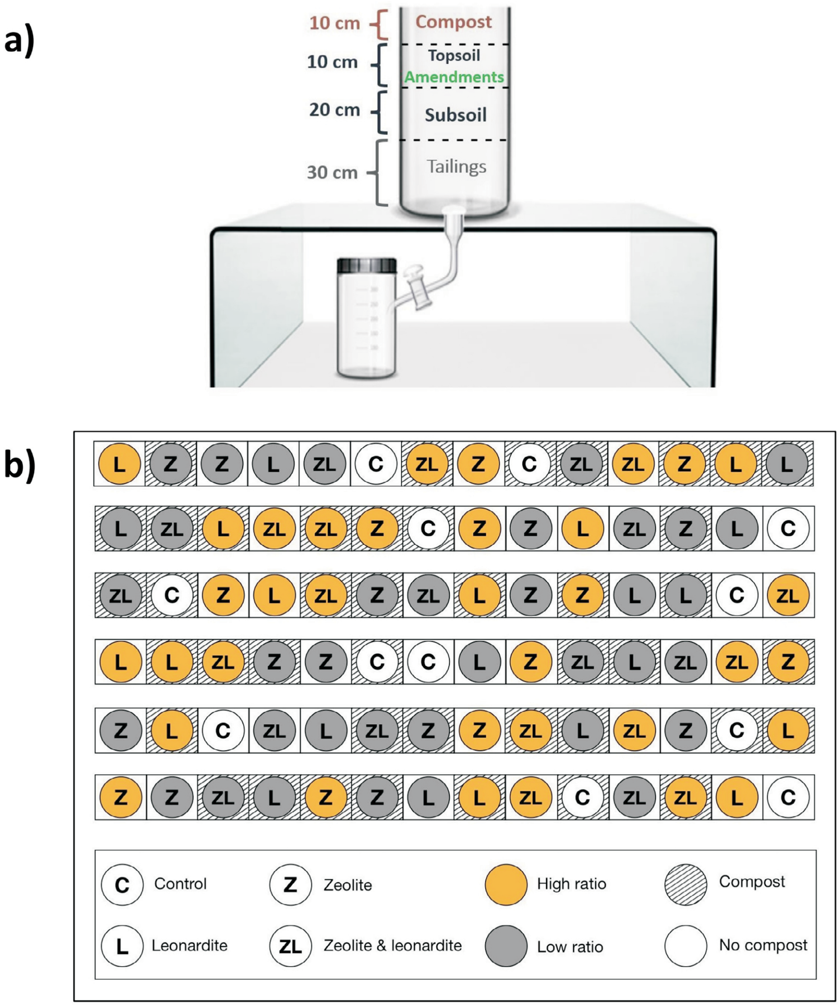

Figure 2. a) Example of a study pot. The pots were filled with 30 cm of tailings, 20 cm of subsoil and 10 cm of topsoil. Three different compositions of amendment were mixed into the topsoil (zeolite, leonardite, and a combination of zeolite and leonardite). Additionally, the effect of the presence or absence of compost was examined by placing 10 cm of compost on top of the topsoil in half of the pots. **b)** The design of the study: the variables are the three amendments (i.e., zeolite, leonardite, a combination of zeolite and leonardite) mixed into topsoil in a high ratio (0.0448 kg/m^3) or a low ratio (0.0224 kg/m^3) of amendments to topsoil, either with or without the addition of compost (i.e., Compost and No compost) on top of the topsoil. The control treatments are meant to examine the effect of the presence or absence of compost without the addition of the other amendments. The 14 treatments were replicated six times, for a total of 84 pots.

During the experiment, the soil moisture level was measured in each pot at a depth of 20 cm, using a Spectrum® Technologies, Inc. FieldScout TDR 300 soil moisture probe, to ensure a soil moisture balance of 20% in each pot. This moisture balance was maintained by watering every 2–3 days. Growth over the 120 days of the experiment was conducted under controlled conditions meant to replicate the climate of a semi-arid region in south-central BC. These conditions were: natural and artificial light—18 hours of daylight/6 hours of night; temperature—25° C during the day/22° C at night; humidity—40 to 70%; and are based on data recorded at the Kamloops climate station between 1990 and 2012 (Rayne and Forest, 2015).

Soil, Plant Biomass and Sampling

After the 120 day growth period of the experiment, samples of soil (topsoil and subsoil) were extracted from a depth of 10–20 cm from each of the 84 pots using a stainless-steel soil sampling probe with a core diameter of 2 cm. The soil samples were analyzed for total carbon (TC) and total nitrogen (TN) using a Thermo Scientific™ Flash*Smart*™ elemental analyzer. Soil preparation for elemental analysis included passing the 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 the sieved and dried soil were weighed, placed

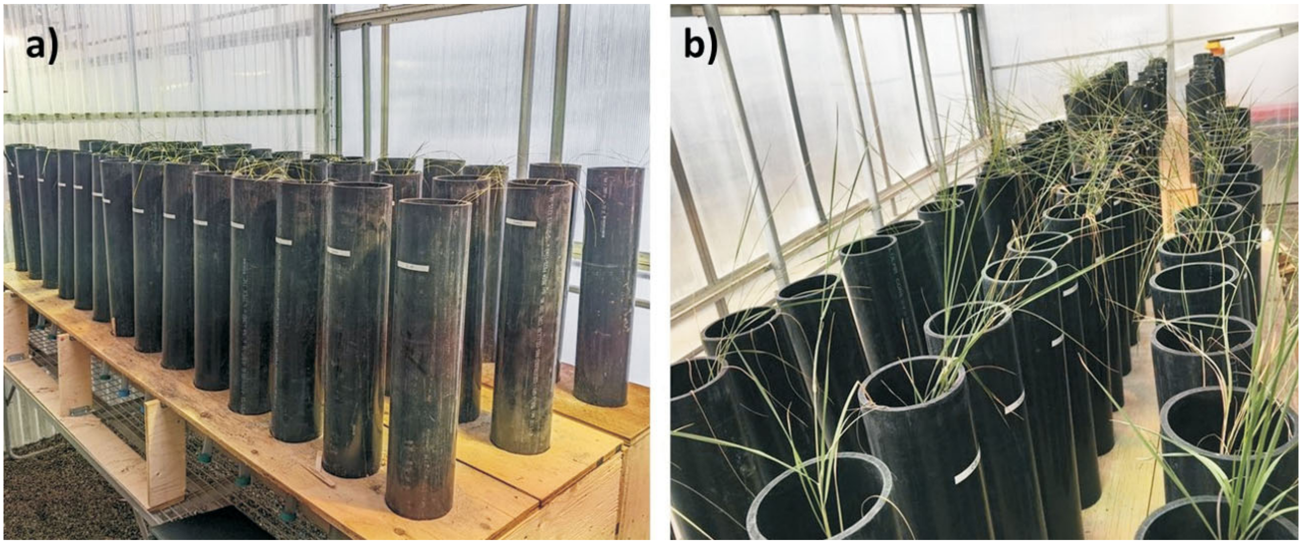

Figure 3. Photos of the experimental pots in the greenhouse: **a)** the arrangement shown demonstrates three replicates of the treatments; **b)** close-up of the experimental pots with only one healthy bluebunch wheatgrass seedling retained in each pot.

in small tin capsules and loaded sequentially into the elemental analyzer sample wheel (Gavlak et al., 2005; ThermoFisher Scientific, 2017). Soil organic matter (SOM) content was also determined for all samples by analyzing for loss-on-ignition at 550° C for 4 hours (Singh et al., 2019).

The bluebunch wheatgrass shoots were clipped at the soil surface, and the 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 (Bayliff, 2022).

Statistical Analysis

All statistical analyses and resultant figures were produced using R version 4.2.3 (The R Foundation for Statistical Computing). In all cases, the experimental treatments were grouped and ranked using Tukey's HSD (Honestly Significant Difference) test (*P* [probability] <0.05). Plant biomass data were checked for normality both visually and using the Shapiro-Wilk 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 and Wilk, 1965). Furthermore, an aligned rank transformation was applied to the soil data in order to properly run a two-way analysis of variances, as the soil data were not normal prior to analysis (Wobbrock et al., 2011).

Results

Soil Total Carbon and Nitrogen

The analysis of total carbon revealed that the addition of both compost and amendments had significant effects on the total carbon content of the soil (Figure 4a). Compost addition in all treatments exhibited a considerable positive impact, resulting in a substantial increase in total carbon content. Furthermore, a comparison between the Z, L and ZL treatments indicated that the Z treatment made a more significant contribution to the increase of total carbon content in the soil. Similarly, the data for total nitrogen demonstrated that the addition of compost had a significant positive impact across all treatments (Figure 4b). As observed with total carbon, the Z treatments exhibited significantly higher total nitrogen content in the soil compared to the L treatment (Figure 4a, b).

The results of analysis of the C/N ratio highlighted the significant effect of the addition of compost on soil fertility. Differences in C/N ratios were evident between the L and ZL treatments, and also between the Z and ZL treatments (Figure 4c). 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 to topsoil (i.e., high [0.0448 kg/m^3] or low [0.0224 kg/m^3]) did not appear to have any significant effect on the carbon or nitrogen content, or the C/N ratio in any of the analyses, therefore this variation in the treatments is not presented in the plots.

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

Soil Organic Matter

The results of analysis for soil organic matter (SOM) content suggest that both the addition of compost (Figure 5a) and the application of amendment treatments (Figure 5b)

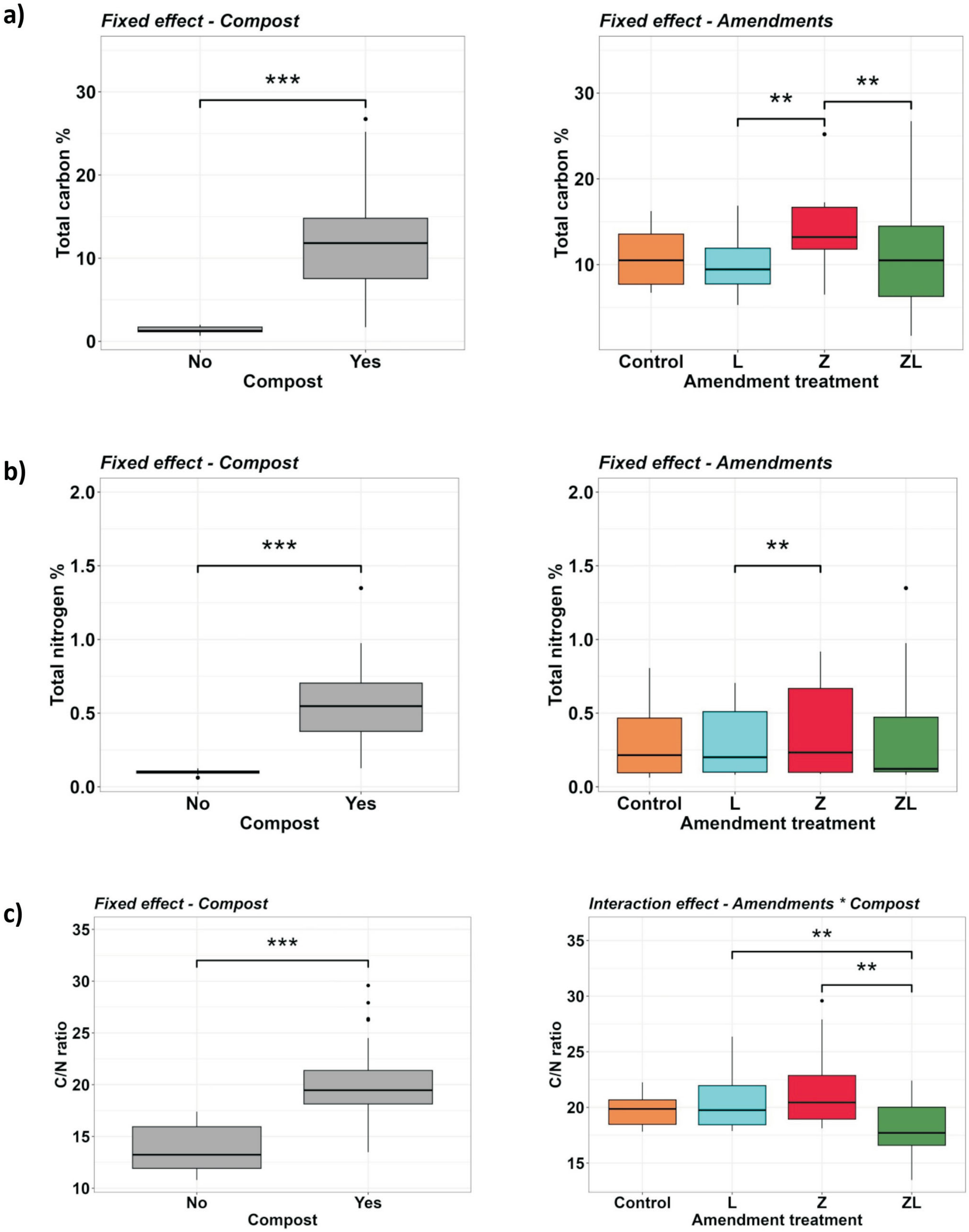

Figure 4. Results of analysis for **(a)** total carbon, **(b)** total nitrogen, and **(c)** the carbon to nitrogen (C/N) ratio. The graphs for total carbon and total nitrogen show a significant impact due to the addition of compost (represented as the "Fixed effect – Compost") and amendments (indicated as the "Fixed effect – Amendments"). The C/N ratio was significantly influenced by the addition of compost (represented as the "Fixed effect – Compost") and the interaction between compost and amendments (indicated as the "Interaction effect – Amendments * Compost"). In all the graphs, pairwise comparisons were conducted within each group that were then compared to the control pots and adjusted with Benjamini-Hochberg corrections. Significance levels were denoted as '**' for *P* (probability) <0.01 and '***' for *P* <0.001. Non-significant values were omitted from the plots. The main rectangular box represents the interquartile range, and the vertical line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data. In all the graphs No and Yes mean the absence and presence of compost, respectively. The two different ratios of amendments to topsoil did not significantly influence the total carbon, total nitrogen or C/N ratio; therefore, these results are not presented in the graphs. Abbreviations: L, leonardite; Z, zeolite; ZL, a combination of zeolite and leonardite.

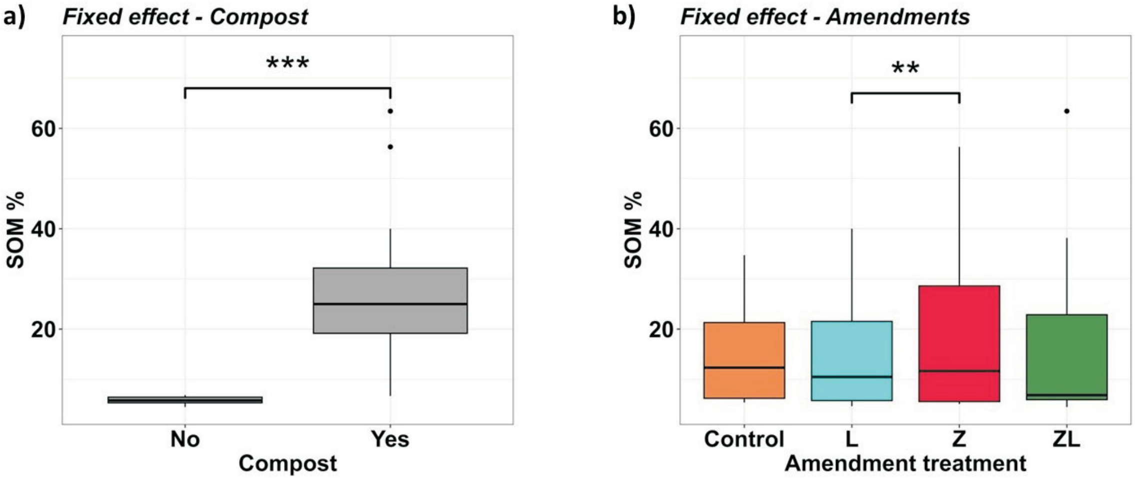

Figure 5. Effects of **(a)** addition of compost (shown as the "Fixed effect – Compost") and **(b)** amendments (represented as the "Fixed effect – Amendments") on the percentage of soil organic matter in the samples. In the graph in (a), No and Yes mean the absence and presence of compost, respectively. In all the graphs, significance levels were denoted as '**' for *P* (probability) <0.01 and '***' for *P* <0.001. Non-significant values were omitted from the plots. The main rectangular box represents the interquartile range, and the vertical line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data. The two different ratios of amendments to topsoil, and the interaction of amendments and compost did not significantly influence the percentage of soil organic matter; therefore, these results are not presented in the graphs. Abbreviations: L, leonardite; SOM, soil organic matter; Z, zeolite; ZL, a combination of zeolite and leonardite.

significantly influenced the SOM content. The addition of compost to the soil resulted in a substantial increase in SOM compared to the control and other treatments. Moreover, the results show that pots with the Z treatment exhibited higher SOM content than pots with the L treatment. As with the analyses for carbon and nitrogen, the different ratios of amendments to topsoil did not appear to have any significant effect on the SOM content.

Plant Productivity

The results of analysis of the biomass in the samples indicate that treatments using compost had a significant positive impact on the growth of bluebunch wheatgrass, resulting in a significantly higher total biomass content than the other treatments (Figure 6a–c), at a confidence level of 95%. However, the addition of Z, L or a combination of the two (ZL) did not result in significant statistical differences in biomass production. Similarly, no significant differences were observed between the different ratios of the amendments to topsoil.

Interestingly, in the compost-amended treatments, the root-to-shoot biomass ratio was less than one. As shown in Figure 7a, the root-to-shoot ratio of plants amended with compost was below the reference line (where the root-to-shoot ratio is one, meaning roots and shoots are present in equal proportions), whereas treatments without the addition of compost were above the reference line. This suggests that compost played a crucial role in promoting the root-to-shoot biomass ratio. Figure 7b further supports this observation, as treatments with compost added showed higher shoot biomass than root biomass, whereas treatments without compost resulted in higher root biomass than shoot biomass.

These findings highlight the significant influence of compost on bluebunch wheatgrass productivity, particularly in enhancing aboveground biomass. The absence of significant differences among treatments using different ratios of amendments to topsoil 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 carbon content by approximately nine times and nitrogen content by six times compared to treatments without compost. This is because the compost contains labile organic matter, i.e., wood chips, and beneficial fungi and bacteria that can improve the soil's organic matter. These findings align with previous studies that have shown the addition of compost leads to improvements in carbon and nitrogen levels and, consequently, an increase in plant growth (Chalker-Scott, 2007; Scharenbroch, 2009; Solís-Dominguez et al., 2012; Scharenbroch and Watson, 2014; Antonelli, 2018). The current research also found that treatments containing zeo-

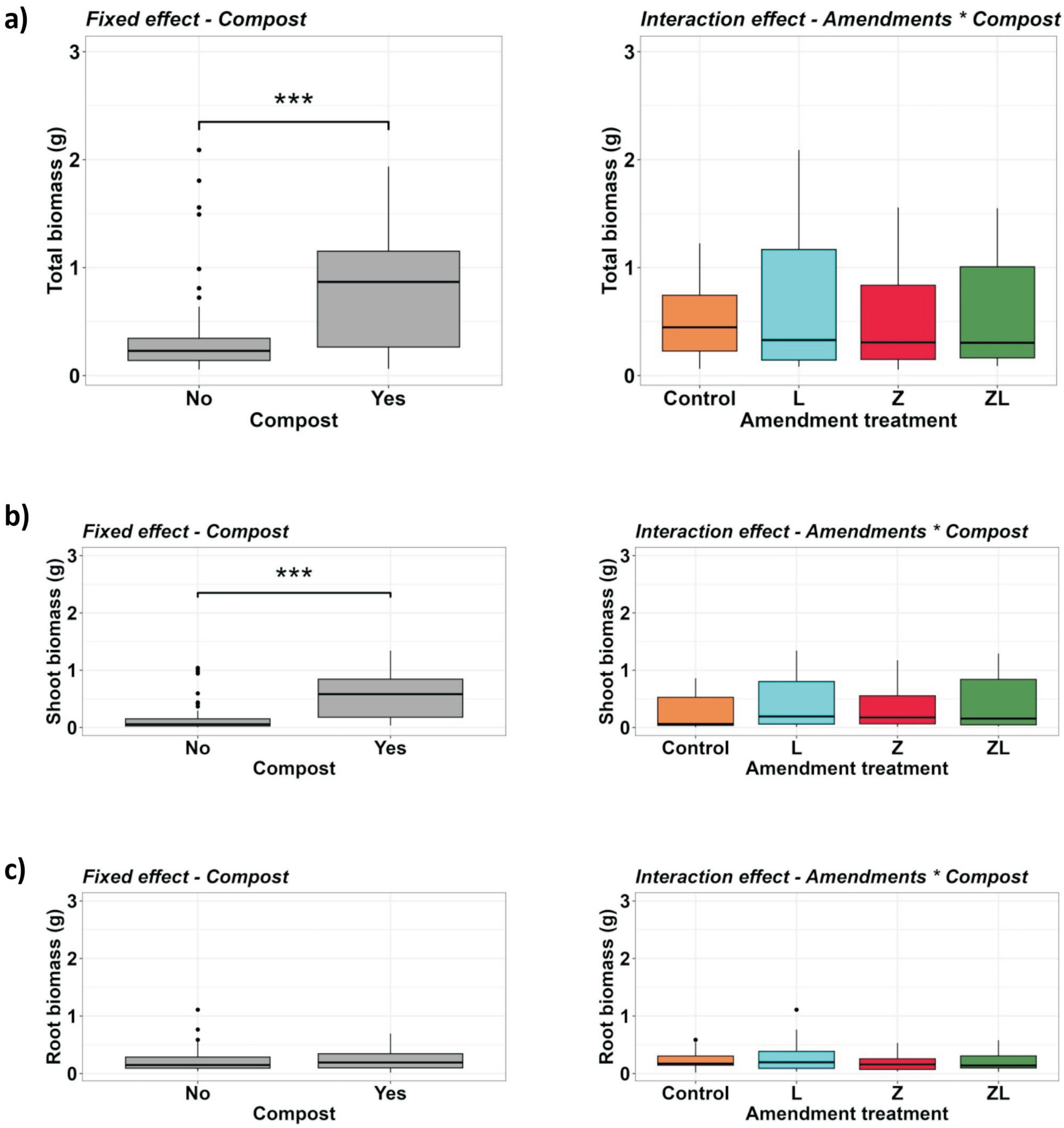

Figure 6. Effect of the addition of compost (shown as “Fixed effect – Compost”) and amendments plus compost (shown as “Interaction effect – Amendments * Compost”) on **(a)** total biomass, **(b)** shoot biomass, and **(c)** root biomass. The graphs show that the compost factor alone significantly influenced total biomass and shoot biomass; however, no significant effects of compost addition, amendments type or ratio to topsoil were observed in the root biomass, but the data are plotted in (c) to be consistent with the other two plots. Although the influence of the amendments was not significant for the shoot biomass, the data are plotted in (b) to be consistent with the total biomass plot. In all the graphs, pairwise comparisons were performed and subjected to Benjamini-Hochberg corrections. Significance levels were denoted as ‘**’ for *P* (probability)<0.01 and ‘***’ for *P* <0.001. Non-significant values were omitted from the plots. The main rectangular box represents the interquartile range, and the vertical line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data. In the graphs showing results of addition of compost, No and Yes mean the absence and presence and compost, respectively. The two different ratios of amendments to topsoil did not significantly influence the total biomass, shoot biomass or root biomass; therefore, these results are not presented in the graphs. Abbreviations: L, leonardite; Z, zeolite; ZL, a combination of zeolite and leonardite.

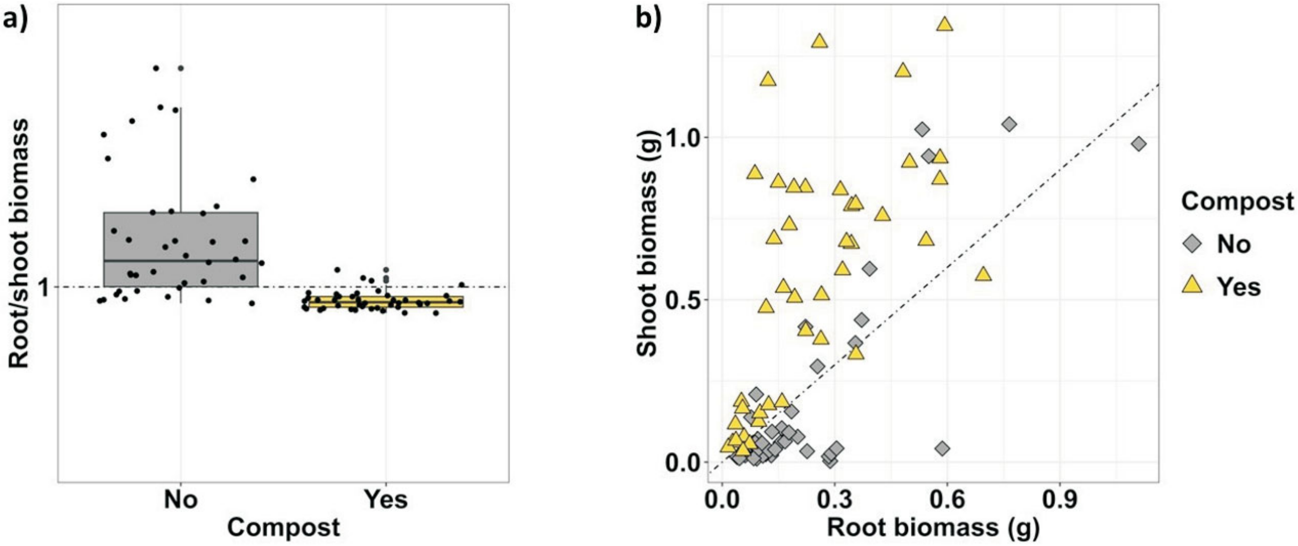

Figure 7. a) The root-to-shoot biomass ratio in treatments supplemented with compost (designated as "Yes") and those without compost (designated as "No"). The main rectangular box represents the interquartile range, and the vertical line inside the box indicates the median. The whisker lines provide a visual representation of the spread of the data. **b)** Root and shoot biomass relationship: the amount of root-to-shoot biomass was significantly influenced by the presence or absence of compost (shown as Yes and No, respectively). Values above the equilibrium line (reference line) indicate a higher root-to-shoot ratio, whereas values below the line suggest a lower root-to-shoot ratio. Graph (a) showcases a greater shoot production in compost-amended treatments (highlighted in yellow) and a reduced production in treatments without compost (highlighted in grey).

lite (Z) had significantly higher nitrogen levels than the leonardite (L) treatments, and higher carbon levels than both the L and ZL treatments. This may be because of zeolite's ability 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 SOM mineralization. In addition, the C/N ratio can be used to predict the release of nutrients (Larney and Angers, 2012) and to establish whether carbon or nitrogen deficiencies are limiting soil microbial processes (Shrestha et al., 2009). 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 micro-organisms in the soil consume nitrogen rather than releasing it for plant use. Achieving a C/N ratio of between 20 and 30 results in a balance between mineralization and immobilization (Brust, 2019). It is necessary for soil micro-organisms 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.

It is important to consider the role of ecosystems in the context of the C/N ratio in soil fertility. According to Mulder and Elser (2009), an 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 systems, 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 on grasslands, and a ratio ranging from 13.3 to 15.7 in a forest ecosystem (Cleveland and Liptzin, 2007).

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 (Gregorich et al., 1993; Batjes, 1996). In comparison to the control treatments in this study, compost-amended treatments showed a significantly higher SOM content. The addition of compost resulted in a mean SOM of 26.5%, whereas treatments without compost had a mean SOM of 5.85%. Based on the suggested ranking by Munshower (1994), the compost-amended treatments are ranked as very high, whereas the ones without compost are ranked as medium to high in terms of SOM. The positive effect of compost containing wood chips on SOM content is consistent with results demonstrated in previous studies (e.g., Antonelli, 2018). This is because compost increases the total carbon and nitrogen content, which can directly affect the increase of soil organic matter. Moreover, treatments amended with zeolite showed a higher mean SOM of 18.4%, significantly higher than treatments with leonardite (SOM of 14.9%). The carbon and nitrogen results also showed that treatments with zeolite had higher values in both parameters compared to treatments with leonardite.

Effect of Amendments on Plant Productivity

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

The results of this study also show 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 and Polley, 2006). However, according to Ågren and 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 observed in this study in treatments without compost (mean root-to-shoot ratio of 5.36 g/g) can be attributed to insufficient organic matter, and, more specifically, insufficient 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 (e.g., Antonelli, 2018).

It is worth mentioning that trace element analysis is underway to test the concentration of heavy metals in the leachate, soil and plant uptakes. These data will provide a comprehensive understanding of each treatment in reducing and eliminating trace elements.

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 fortified compost, as a tool for facilitating mine reclamation endeavours. The discerning exploration of these amendments not only advances our current understanding but also illuminates their potential synergistic effects. These findings provide insight to support the mining sector in more effective reclamation efforts on tailings storage facilities. It is imperative to acknowledge that 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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References

Abraha, M., Hamilton, S.K., Chen, J. and Robertson, G.P. (2018): Ecosystem carbon exchange on conversion of Conservation Reserve Program grasslands to annual and perennial cropping systems; Agricultural and Forest Meteorology, v. 253–254, p. 151–160, URL <https://doi.org/10.1016/j.agrformet.2018.02.016>.

Adesipo, A.A., Freese, D., Zerbe, S. and Wiegleb, G. (2021): An approach to thresholds for evaluating post-mining site reclamation; Sustainability, v. 13, no. 10, art. 5618, URL <https://doi.org/10.3390/su13105618>.

Ågren, G.I. and Franklin, O. (2003): Root:shoot ratios, optimization and nitrogen productivity; Annals of Botany, v. 92, p. 795–800, URL <https://doi.org/10.1093/aob/mcg203>.

Antonelli, P.M. (2018): Facilitating native plant recovery on copper mine tailings in the semiarid grasslands of southern interior British Columbia; M.Sc. thesis, Thompson Rivers University, 118 p., URL <https://www.tru.ca/__shared/assets/Paul_Antonelli_Thesis45148.pdf> [November 2023].

Asemaninejad, A., Langley, S., Mackinnon, T., Spiers, G., Beckett, P., Mykytczuk, N. and Basiliko, N. (2021): Blended municipal compost and biosolids materials for mine reclamation: long-term field studies to explore metal mobility, soil fertility and microbial communities; Science of The Total Environment, v. 760, art. 143393, URL <https://doi.org/10.1016/j.scitotenv.2020.143393>.

Batjes, N.H. (1996): Total carbon and nitrogen in the soils of the world; European Journal of Soil Science, v. 47, no. 2, p. 151–163, URL <https://doi.org/10.1111/j.1365-2389.1996.tb01386.x>.

Bayliff, S. (2022): Examining the effects of mowing, irrigation, and fertilization on plant productivity and soil carbon levels of perennial cropping systems; M.Sc. thesis, Thompson Rivers University, 110 p., URL <https://www.tru.ca/__shared/assets/Sarah_Bayliff_thesis55755.pdf> [November 2023].

Bradshaw, A.D. (1987): The reclamation of derelict land and the ecology of ecosystems; *in* Restoration Ecology: A Synthetic Approach to Ecological Research, W.R. Jordan, M.E. Gilpin and J.D. Aber (ed.), Cambridge University Press, Cambridge, United Kingdom, p. 53–74.

Bradshaw, A.D. (1997): Restoration of mined lands—using natural processes; Ecological Engineering, v. 8, no. 4, p. 255–269, URL <https://doi.org/10.1016/S0925-8574(97)00022-0>.

Brust, G.E. (2019): Management strategies for organic vegetable fertility; Chapter 9 *in* Safety and Practice for Organic Food, D. Biswas and S.A. Micaleff (ed.), Academic Press, London, England, p. 193–212, URL <https://doi.org/10.1016/B978-0-12-812060-6.00009-X>.

Cacciuttolo, C., Cano, D. and Custodio, M. (2023): Socio-environmental risks linked with mine tailings chemical composition: promoting responsible and safe mine tailings management considering copper and gold mining experiences from Chile and Peru; Toxics, v. 11, no. 5, art. 462, part of Special Issue “Migration and Transformation Law and Risk Assessment of Industrial and Mining Pollutants”, URL <https://doi.org/10.3390/toxics11050462>.

Chalker-Scott, L. (2007): Impact of mulches on landscape plants and the environment – a review; Journal of Environmental Horticulture, v. 25, p. 239–249, URL <https://doi.org/10.24266/0738-2898-25.4.239>.

Chawakitchareon, P., Poovuttikul, P. and Chantanurak, T. (2014): Slow-release fertilizer prepared from leonardite and zeolite; Advanced Materials Research, v. 931–932, p. 758–761, URL <https://doi.org/10.4028/www.scientific.net/amr.931-932.758>.

Chen, Y., Clapp, C. and Magen, H. (2004): Mechanisms of plant growth stimulation by humic substances: the role of organo-iron complexes; Soil Science and Plant Nutrition, v. 50, no. 7, p. 1089–1095, URL <https://doi.org/10.1080/00380768.2004.10408579>.

Church, C. and Crawford, A. (2020): Minerals and the metals for the energy transition: exploring the conflict implications for mineral-rich, fragile states; Chapter 12 *in* The Geopolitics of the Global Energy Transition, M. Hafner and S. Tagliapietra (ed.), v. 73 in the series “Lecture Notes in Energy”, Springer Nature, Switzerland, p. 279–304, URL <https://doi.org/10.1007/978-3-030-39066-2_12>.

Cleveland, C.C. and Liptzin, D.C. (2007): C:N:P stoichiometry in soil: is there a “Redfield ratio” for the microbial biomass?; Biogeochemistry, v. 85, p. 235–252, URL <https://doi.org/10.1007/s10533-007-9132-0>.

Coghill, M.G. (2021): Examining the soil legacy effects of spotted knapweed (*Centaurea stoebe*); M.Sc. thesis, Thompson Rivers University, 96 p., URL <https://www.tru.ca/__shared/assets/Matthew_Coghill_Thesis53561.pdf> [November 2023].

Eisenhauer, N., Scheu, S. and Jousset, A. (2012): Bacterial diversity stabilizes community productivity; PLOS ONE, v. 7, no. 3, art. e34517, URL <https://doi.org/10.1371/journal.pone.0034517>.

Fischer, A.M., Van Hamme, J.D., Gardner, W.C. and Fraser, L.H. (2022): Impacts from topsoil stockpile height on soil geochemical properties in two mining operations in British Columbia: implications for restoration practices; Mining, v. 2, no. 2, p. 315–329, URL <https://doi.org/10.3390/mining2020017>.

Gardner, W.C., Broersma, K., Naeth, A., Chanasyk, D. and Jobson, A. (2010): Influence of biosolids and fertilizer amendments on physical, chemical and microbiological properties of copper mine tailings; Canadian Journal of Soil Sciences, v. 90, p. 571–583, URL <https://doi.org/10.4141/cjss09067>.

Gavlak, R., Horneck, D. and Miller, R.O. (2005): Soil, Plant and Water Reference Methods for the Western Region, WREP-125 (3rd edition); Western Coordinating Committee on Nutrient Management, 207 p., URL <https://www.naptprogram.org/files/napt/western-states-method-manual-2005.pdf> [November 2023].

Gielen, D. (2021): Critical materials for the energy transition; International Renewable Energy Agency, Technical Paper 5/2021, Abu Dhabi, 42 p., URL <https://www.irena.org/-/media/Files/IRENA/Agency/Technical-Papers/IRENA_Critical_Materials_2021.pdf> [November 2023].

Gregorich, E.G., Reynolds, W.D., Culley, J.L.B., McGovern, M.A. and Curnoe, W.E. (1993): Changes in soil physical properties with depth in a conventionally tilled soil after no-tillage; Soil and Tillage Research, v. 26, no. 4, p. 289–299, URL <https://doi.org/10.1016/0167-1987(93)90002-7>.

Hayes, S.M., White, S.A., Thompson, T.L., Maier, R.M. and Chorover, J. (2009): Changes in lead and zinc lability during weathering-induced acidification of desert mine tailings: coupling chemical and micro-scale analyses; Applied Geochemistry, v. 24, p. 2234–2245, URL <https://doi.org/10.1016/j.apgeochem.2009.09.010>.

Heiskanen, J., Ruhanen, H. and Hagner, M. (2022): Effects of compost, biochar and ash mixed in till soil cover of mine tailings on plant growth and bioaccumulation of elements: a growing test in a greenhouse; Heliyon, v. 2, no. 8, art. e08838, URL <https://doi.org/10.1016/j.heliyon.2022.e08838>.

Hendrychová, M., Svobodova, K. and Kabrna, M. (2020): Mine reclamation planning and management: integrating natural habitats into post-mining land use; Resources Policy, v. 69, art. 101882, URL <https://doi.org/10.1016/j.resourpol.2020.101882>.

Iverson, K. (2004): Grasslands of the Southern Interior; BC Ministry of Sustainable Resource Management and BC Ministry of Water, Land and Air Protection, Ecosystems at Risk brochure, 6 p., URL <https://www2.gov.bc.ca/assets/gov/environment/plants-animals-and-ecosystems/species-ecosystems-at-risk/brochures/grasslands_southern_interior.pdf> [November 2023].

Jarosz, R., Szerement, J., Gondek, K. and Mierzwa-Hersztek, M. (2022): The use of zeolites as an addition to fertilisers–a review; CATENA, v. 213, art. 106125, URL <https://doi.org/10.1016/j.catena.2022.106125>.

Kästner, M. and Miltner, A. (2016): Application of compost for effective bioremediation of organic contaminants and pollutants in soil; Applied Microbiology and Biotechnology, v. 100, no. 8, p. 3433–3449, URL <https://doi.org/10.1007/s00253-016-7378-y>.

Kesraoui-Ouki, S., Cheeseman, C.R. and Perry, R. (1994): Natural zeolite utilisation in pollution control: a review of applications to metals' effluents; Journal of Chemical Technology and Biotechnology, v. 59, no. 2, p. 121–126, URL <https://doi.org/10.1002/jctb.280590202>.

Kunkel, M.L., Flores, A.N., Smith, T.J., McNamara, J.P. and Benner, S.G. (2011): A simplified approach for estimating soil carbon and nitrogen stocks in semi-arid complex terrain; Geoderma, v. 165, no. 1, p. 1–11, URL <https://doi.org/10.1016/j.geoderma.2011.06.011>.

Larney, F.J. and Angers, D.A. (2012): The role of organic amendments in soil reclamation: a review; Canadian Journal of Soil Science, v. 92, no. 1, p. 19–38, URL <https://doi.org/10.4141/cjss2010-064>.

Levene, H. (1960): Robust tests for equality of variances; *in* Contributions to Probability and Statistics, I. Olkin (ed.), Stanford University Press, Palo Alto, California, p. 278–292.

Lottermoser, B.G. (2010): Mine Wastes: Characterization, Treatment and Environmental Impacts (3rd edition); Springer, Berlin, Heidelberg, 404 p., URL <https://link.springer.com/book/10.1007/978-3-642-12419-8> [November 2023].

Manu, M., Wang, C., Li, D., Varjani, S. and Wong, J.W. (2022): Impact of zeolite amendment on composting of food waste digestate; Journal of Cleaner Production, v. 371, art. 133408, URL <https://doi.org/10.1016/j.jclepro.2022.133408>.

Misaelides, P. (2011): Application of natural zeolites in environmental remediation: a short review; Microporous and Mesoporous Materials, v. 144, no. 1–3, p. 15–18, URL <https://doi.org/10.1016/j.micromeso.2011.03.024>.

Mulder, C. and Elser, J.J. (2009): Soil acidity, ecological stoichiometry and allometric scaling in grassland food webs; Global Change Biology, v. 15, no. 11, p. 2730–2738, URL <https://doi.org/10.1111/j.1365-2486.2009.01899.x>.

Munshower, F.F. (1994): Practical Handbook of Disturbed Land Revegetation; Lewis Publishers, Boca Raton, Florida, 265 p.

Ozdoba, D.M., Blyth, J.C., Engler, R.F., Dinel, H. and Schnitzer, M. (2001): Leonardite and humified organic matter; *in* Humic Substances: Structures, Models and Functions, E.A. Ghabbour and G. Davies (ed.), Royal Society of Chemistry, Special Publication No. 273, p. 309–314.

Piccolo, A., Pietramellara, G. and Mbagwu, J. (1996): Effects of coal derived humic substances on water retention and structural stability of Mediterranean soils; Soil Use and Management, v. 12, no. 4, p. 209–213, URL <https://doi.org/10.1111/j.1475-2743.1996.tb00545.x>.

Plante, B., Pabst, T. and Wilson, D. (2023): Editorial for special issue "Environmental Geochemistry in the Mining Environment"; Minerals, v. 13, no. 1, art. 112, URL <https://doi.org/10.3390/min13010112>.

Rayne, S. and Forest, K. (2015): Declining relative humidity in the Thompson River Valley near Kamloops, British Columbia, Canada: 1990-2012; bioRxiv, preprint, URL <https://doi.org/10.1101/028894>.

Scharenbroch, B.C. (2009): A meta-analysis of studies published in *Arboriculture & Urban Forestry* relating to organic materials and impacts on soil, tree, and environmental properties; Arboriculture & Urban Forestry, v. 35, p. 221–231, URL <https://doi.org/10.48044/jauf.2009.036>.

Scharenbroch, B.C. and Watson, G.W. (2014): Wood chips and compost improve soil quality and increase growth of *Acer rubrum* and *Betula nigra* in compacted urban soil; Arboriculture & Urban Forestry, v. 40, no. 6, p. 319–331, URL <https://doi.org/10.48044/jauf.2014.030>.

Schoenberger, E. (2016): Environmentally sustainable mining: the case of tailings storage facilities; Resources Policy, v. 49, p. 119–128, URL <https://doi.org/10.1016/j.resourpol.2016.04.009>.

Shapiro, S.S. and Wilk, M.B. (1965): An analysis of variance test for normality (complete samples); Biometrika, v. 52, no. 3–4, p. 591–611, URL <https://doi.org/10.1093/biomet/52.3-4.591>.

Sheoran, V., Sheoran, A.S. and Poonia, P. (2010): Soil reclamation of abandoned mine land by revegetation: a review; International Journal of Soil, Sediment and Water, v. 3, no. 2, art. 13, URL <https://scholarworks.umass.edu/intljssw/vol3/iss2/13> [November 2023].

Shrestha, R.K., Lal, R. and Jacinthe, A. (2009): Enhancing carbon and nitrogen sequestration in reclaimed soils through organic amendments and chiseling; Soil Science Society of America Journal, v. 73, no. 3, p. 1004–1011, URL <https://doi.org/10.2136/sssaj2008.0216>.

Singh, J.P., Vaidya, B.P., Goodey, N.M. and Krumins, J.A. (2019): Soil microbial response to metal contamination in a vegetated and urban brownfield; Journal of Environmental Management, v. 244, p. 313–319, URL <https://doi.org/10.1016/j.jenvman.2019.04.111>.

Solís-Dominguez, F.A., White, S.A., Hutter, T.B., Amistadi, M.K., Root, R.A., Chorover, J. and Maier, R.M. (2012): Response of key soil parameters during compost-assisted phytostabilization in extremely acidic tailings: effect of plant species; Environmental Science and Technology, v. 46, no. 2, p. 1019–1027, URL <https://doi.org/10.1021/es202846n>.

Strohmayer, P. (1999): Soil stockpiling for reclamation and restoration activities after mining and construction; Restoration and Reclamation Review, v. 4, no. 7, 6 p., URL <https://conservancy.umn.edu/bitstream/handle/11299/59360/4.7.Strohmayer.pdf?sequence=1> [November 2023].

Swangjang, K. (2015): Soil carbon and nitrogen ratio in different land use; International Conference on Advances in Environment Research, v. 87, no. 7, p. 36–40, URL <https://www.researchgate.net/publication/335378514_Soil_Carbon_and_Nitrogen_Ratio_in_Different_Land_Use> [November 2023].

Szerement, J., Jurek, K., Mokrzycki, J., Jarosz, R., Oleszczuk, P. and Mierzwa-Hersztek, M. (2023): Zeolite composites from fly ashes mixed with leonardite as a useful addition to fertilizer for accelerating the PAHs degradation in soil; Soil and Tillage Research, v. 230, art. 105701, URL <https://doi.org/10.1016/j.still.2023.105701>.

ThermoFisher Scientific (2017): Flash*Smart*TM elemental analyzers; ThermoFisher Scientific, 94 p.

Tisdale, E.W. (1947): The grasslands of the Southern Interior of British Columbia; Ecology, v. 28, no. 4, p. 346–382, URL <https://doi.org/10.2307/1931227>.

Watson, C.A., Atkinson, D., Gosling, P., Jackson, L.R. and Rayns, F.W. (2002): Managing soil fertility in organic farming systems; Soil Use and Management, v. 18, p. 239–247, URL <https://doi.org/10.1111/j.1475-2743.2002.tb00265.x>.

Wetland Stewardship Partnership (2010): Grasslands in British Columbia: A Primer for Local Governments; Wetland Stewardship Partnership, 16 p., URL <https://bcwetlandsca.files.wordpress.com/2016/11/grasslands-primer_wsp_2010.pdf> [November 2023].

Wikeem, B. and Wikeem, S. (2004): The Grasslands of British Columbia; Grasslands Conservation Council of British Columbia, 497 p., URL <https://bcgrasslands.org/wp-content/uploads/2017/06/gcc_e-book_grasslands-of-bc.pdf> [November 2023].

Wilsey, B.J. and Polley, H.W. (2006): Aboveground productivity and root-shoot allocation differ between native and introduced grass species; Oecologia, v. 150, no. 2, p. 300–309, URL <https://doi.org/10.1007/s00442-006-0515-z>.

Wobbrock, J.O., Findlater, L., Gergle, D. and Higgins, J.J. (2011): The aligned rank transform for nonparametric factorial analyses using only anova procedures; *in* CHI '11: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, May 7–12, 2011, Vancouver BC, Association for Computing Machinery, p. 143–146, URL <https://doi.org/10.1145/1978942.1978963>.

Zhu, D., Schwab, A.P. and Banks, M.K. (1999): Heavy metal leaching from mine tailings as affected by plants; Journal of Environmental Quality, v. 28, no. 6, p. 1727–1732, URL <https://doi.org/10.2134/jeq1999.00472425002800060006x>.