Received: 25 January 2021 | Revised: 27 July 2021 | Accepted: 8 September 2021

DOI: 10.1111/avsc.12612

RESEARCH ARTICLE

Applied Vegetation Science
IAVS

# Grassland reclamation of a copper mine tailings facility: Long-term effects of biosolids on plant community responses

Alyson Gagnon[1] | Laura W Ploughe[2] | Michelle P Harris[2] | Wendy C Gardner[2] | Thomas Pypker[2] | Lauchlan H Fraser[2]

[1]Département des science fondamentales, Université du Québec à Chicoutimi, Saguenay, QC, Canada

[2]Department of Natural Resource Science, Thompson Rivers University, Kamloops, BC, Canada

**Correspondence**
Alyson Gagnon, Département des Sciences fondamentales, Université du Québec à Chicoutimi, Saguenay, QC, Canada.
Email: alyson.gagnon1@uqac.ca

**Funding information**
The restoration and research projects were supported by the Natural Sciences and Engineering Research Council of Canada Industrial Research Chair in Ecosystem Reclamation [to LHF] and the Natural Sciences and Engineering Research Council of Canada Discovery and Engage grants [to TP], with support from Greater Vancouver Sewage and Drainage District, Teck Highland Valley Copper Mine, Geoscience BC, Arrow Transportation Systems, Real Estate Foundation of British Columbia, BC Cattlemen's Association, Thompson Rivers University, and Trans Mountain Corporation

**Co-ordinating Editor:** Norbert Hölzel

## Abstract

**Aim:** We explore long-term plant community responses 17 years after a one-time application of biosolids (0, 50, 100, 150, 200, 250 dry Mg/ha) to determine: (a) whether the land application of biosolids on mine tailings, seeded with an agronomic grass-legume mixture, affects long-term plant community responses; (b) how application rates and soil texture influenced plant community responses and community structure; and (c) whether native plant species have colonized and contributed to the reclaimed plant community.

**Location:** Two tailings deposits (sand and silt loam) generated by a copper–molybdenum (Cu–Mo) mine in southern British Columbia, Canada.

**Methods:** Plant communities were sampled by visual evaluation of cover percentage to the lowest taxonomic level possible. Vegetation surveys were completed on two mine tailings deposits within the storage facility that have different soil textures (sand and silt loam).

**Results:** Results showed that the interaction of biosolids applications and soil texture impacted multiple community plant responses, including increasing plant cover at both sites, and increasing richness, evenness and diversity at the sandy site. Biosolids application enhanced the performance of spontaneously established species (volunteer species) and non-native/naturalized grasses.

**Conclusion:** Our study demonstrated that biosolids application facilitates ecological succession by enhancing the establishment of non-native volunteer species over the long term, which increases vegetative cover on both deposits and promotes plant communities' diversity on sites with sandy soil texture.

KEYWORDS
biodiversity, biosolids, inorganic fertilizer, mine, organic amendment, plant communities, reclamation, tailings

## 1 | INTRODUCTION

Rehabilitation efforts are often required to initiate ecological succession on highly degraded ecosystems, such as mine tailings facilities, which are lands used to stock mining waste (Prach & Hobbs, 2008). The conditions on these sites limit vegetation establishment, as tailings lack organic matter and nutrients, have a low water-holding capacity, poor microbial diversity, and experience wind erosion (Gardner et al., 2010; Sheoran et al., 2010). Generally, the two main goals of restoration are: (a) to increase the natural integrity of a disturbed site; and (b) to improve ecosystem functions and services (e.g., carbon sequestration, hydrological controls, protection against erosion, biodiversity and wildlife habitats; Hobbs & Norton, 1996; Cusser & Goodell, 2013; Gastauer et al., 2017). Since bringing back mining sites to a state close to the historical ecosystem can be challenging, restoration efforts often lead to the creation of a novel ecosystem with different species, interactions, and functions than the original site (Hobbs et al., 2009). Novel ecosystems can be valuable natural assets, but there is an increasing desire to re-establish near-natural ecosystems to sustain biodiversity and improve resilience in a changing climate (Baethke et al., 2020; Salgueiro et al., 2020).

Traditional reclamation methods often involve the use of a chemical fertilizer, but this type of amendment has shown to have limited effects on enhancing soil properties for plant growth (Gardner et al., 2010). As an alternative, treated solid residue (sewage sludge) from municipal wastewater, known as biosolids, are used as a soil amendment to assist the establishment of a vegetative cover (CCME, 2012; Wallace et al., 2016; Avery et al., 2018). The use of biosolids provides a gradual source of plant-available nitrogen and phosphorus and improves the physical, chemical and biological properties of the soil, enhancing vegetation establishment (Cuevas et al., 2000; Martinez et al., 2003; Paschke et al., 2005; Walter et al., 2006; Gardner et al., 2010; Gardner et al., 2012; Ploughe et al., 2020; Harris et al., 2021). While traditional reclamation methods focus on the control of erosion, new methods generally aim to establish diverse, and preferably native plant communities.

Studies exploring the efficacy of biosolids in reclamation often focus on the early success of vegetation establishment. Many authors have demonstrated an increase in plant productivity and total cover percentage following biosolids application (Diaz et al., 1997; Brofas et al., 2000; Meyer et al., 2004; Moreno-Peñaranda et al., 2004; Madejón et al., 2006; Brown et al., 2009; Kowaljow et al., 2010; Gardner et al., 2012; Blumenthal et al., 2017; Antonelli et al., 2018). However, the effect that biosolids have on plant community responses, such as plant composition, richness, evenness, and diversity, is unclear, especially over the long term. An important management consideration is to determine the rate at which biosolids should be applied to establish diverse and sustainable plant communities over the long term. Specifically, some authors express concern that adding high levels of nutrients on degraded lands could increase competition between species, which could lead to a simplification of the community composition and an increase of exotic species success (DiTommaso & Aarssen, 1989; Carpenter et al., 1990; Moreno-Peñaranda et al., 2004; Cleland & Harpole, 2010; Yin et al., 2017). Heckman et al. (2016) showed that fertilization increased exotic plant cover but only in communities exposed to vertebrate herbivores in an old field in North Carolina.

Biosolids have been applied at variables rates ranging from 5 to 371 Mg/ha in mine restoration studies (e.g., Pierce et al., 1998; Pepper et al., 2013). Here, we assess the long-term effects following a one-time application of biosolids using various rates: 0, 50, 100, 150, 200, and 250 dry Mg/ha, or inorganic fertilizer on plant community responses, specifically total cover percentage, richness, evenness and diversity. Biosolids were applied 17 years and fertilizers 16 years prior to the vegetation samples taken in this study on two tailings deposits with different soil textures (silt loam and sand) located in the southern interior of British Columbia, Canada as described by Gardner et al. (2010). We were also interested in exploring how the amendment additions and soil texture impacted plant community structure, and the characteristics of plants that colonized the sites. At the time of reclamation, the goal was to establish a grassland type of ecosystem for agriculture and grazing use. The site was reclaimed with an agronomic seed mix with species that were palatable to cattle but had some level of resistance to create open grazing areas.

## 2 | METHODS

### 2.1 | Site description

This study was carried out on the tailings storage facility at the Teck-Highland Valley Copper (HVC) Cu–Mo mine located in southern interior of British Columbia, Canada (50°28′23.22″ N, 121°01′18.50″ W). The study area is part of the Thompson Plateau in an open-ended valley where predominant soils are cambisols and luvisols (FAO-UNESCO, 1975). The site receives 393.2 mm of precipitations annually and has a mean daily temperature of 4.4°C (Government of Canada, 2019). Warm, dry summers cause frequent water deficits and winters are cold. The study area is part of the Montane Spruce biogeoclimatic zone. The natural vegetation that characterizes this zone is subalpine fir (*Abies lasiocarpa*), douglas-fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus contorta*) and species such as pinegrass (*Calamagrostis rubescens*), lupine (*Lupinus arcticus*), and kinnikinnick (*Arctostaphylos uva-ursi*), etc.

Two storage facilities were used as part of this research: Trojan, a sandy tailings deposit, and Bethlehem, a silt loam deposit, approximately 1 km apart (Figure 1). Both sites have a soil pH of 8 and an elevation of 1,400 m. Natural vegetation was present surrounding the storage facilities (Figure 1).

### 2.2 | Experimental design and treatments

Gardner et al. (2010) established a randomized complete block experimental design where seven treatments were implemented: biosolids

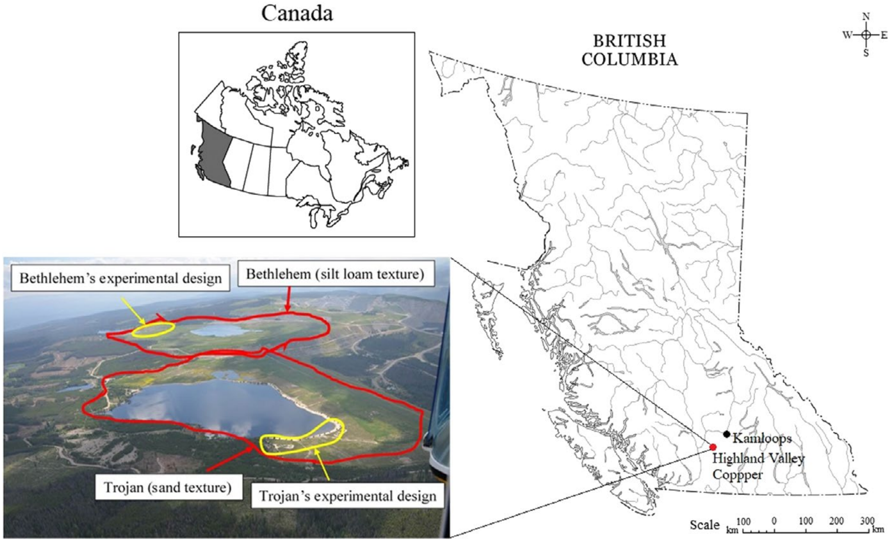

**FIGURE 1** Map of Bethlehem and Trojan's tailings storage facilities and their experimental design

at rates of 50, 100, 150, 200 and 250 dry Mg/ha (B50, B100, B150, B200 and B250), an inorganic fertilizer (F), and a control with no soil amendments (C). There were eight treatments replicates at each site. The biosolids were applied in 1998, and the fertilizer in 1999 at the time of seeding. No amendment was applied in the following years. Each plot measured 3 m × 7 m and was separated by a 1-m buffer. In 2015, the plots were reduced to 5 m × 2 m to reduce edge effects of vegetation encroachment and blown-in sediment noted on plot edges.

The biosolids used were a digested sewage sludge (class B biosolids — see Appendix S2) from Metro Vancouver. In British Columbia, Class B biosolids are stabilized sewage sludges recovered from a municipal wastewater treatment process, which have been treated to reduce pathogens and vector attraction to allow for their beneficial use. In June 1999, inorganic fertilizer treatments were manually broadcasted, but not incorporated, at a rate of 87 kg/ha ammonium nitrate (34.5–0–0; N–P–K fertilizer grades), 111 kg/ha triple superphosphate (0–45–0), 83 kg/ha potassium chloride (0–0–60) with a mineral mix containing 0.5 kg Zn/ha as zinc chloride (99.9%) and 21 kg/ha of granular boron (14%). Application rates were based on total nitrogen, phosphorus, potassium, zinc and boron concentrations found in B150 treatments the previous September. Concurrent to the fertilizer treatments, all treatments were seeded with an agronomic seed mix. The site was broadcast-seeded with an agronomic grass–legume mix at a rate of 36 kg/ha and lightly raked by hand. The seed mix consisted of 33.2% pubescent wheatgrass (*Agropyron trichophorum*), 7.5% orchard grass (*Dactylis glomerata*), 4.0% creeping red fescue (*Festuca rubra* subsp. *rubra*), 14.7% Russian wild ryegrass (*Elymus junceus*), 34.6% alfalfa (*Medicago sativa*), and 5.9% alsike clover (*Trifolium hybridum*); all non-native agronomics introduced to North America.

## 2.3 | Field sampling

Plant communities were sampled by visual evaluation of cover percentage to the lowest taxonomic level possible in August 2015, which was 17 years after biosolids were applied. A 0.2 m × 0.5 m quadrat was randomly set ten times in each experimental plot (2 sites × 7 treatments × 8 replicates × 10 quadrats by plot = a total of 1,120 quadrats). Plant cover data were evaluated by species and summed to get the total cover percentage by quadrat. Total cover could exceed 100% due to species overlap.

## 2.4 | Statistical analysis

Statistical analyses were completed using R-software, version 3.6.1 (R Core Team, 2018). Total cover percentage, species richness (*S*), Pielou's evenness (*J'*) and Shannon-Weaver diversity (*H'*) were calculated using the *vegan* package (Oksanen et al., 2019). ANOVAs (type 1) were conducted to test for differences in the plant communities (total cover percentage, *S*, *J'*, *H'*, functional groups, percentage of seeded and spontaneously established species [henceforth referred to as volunteer species], and percentage of native and non-native/naturalized species) according to the amendment applied and the soil texture of the site. Replicates were included as a random factor in the statistical models. Data for functional groups, native and non-native and seeded and volunteer species were square-root-transformed to meet model assumptions. Post-hoc tests (estimated marginal means; *emmeans* R package version 1.4.3.01) were conducted if effects were significant ($p < 0.05$). A permutational multivariate analysis of variance (PERMANOVA) based on a Bray–Curtis dissimilarity distances matrix was conducted to test for differences in community structures between treatments and was performed over square-root-transformed data (absolute abundances), and single occurrence taxa were removed as suggested in Clarke and Warwick (2001). Community structure was visualized via a non-metric multi-dimensional scaling (NDMS) graphic in PRIMER (Clarke & Gorley, 2015). Two SIMPER analyses were conducted in R to display the species that contributed the most to difference between sites and treatments.

## 3 | RESULTS

A total of 23 species were found on the two sites (Appendix S3). Among the six seeded species, three were observed (*Dactylis glomerata*, *Festuca rubra* subsp. *rubra*, and *Medicago sativa*). Twenty volunteer species were found; ten species were native, and the other ten were non-natives species.

### 3.1 | Biodiversity indexes

The interaction of the amendment applied and the two different soil textures between the tailings sites influenced total cover percentage, richness, and Shannon-Weaver diversity, while evenness was influenced only by amendment applications (Table 1).

On both deposits, total plant cover was significantly higher when biosolids were applied than on control plots (Figure 2a). Greater total plant cover was found on the silt loam deposit compared to the sandy site (Figure 2a). On the silt loam deposit, richness was the same on control and biosolids treatment plots, but decreased at the application rate of 200 Mg/ha (B200) (Figure 2c). On the sandy site, richness did not change between biosolids application rates, but was significantly higher on biosolids plots than on the control (Figure 2c). Evenness and diversity were not influenced by biosolids applications on the silt loam, while these indexes were significantly higher when biosolids were applied on the sandy site (Figure 2b,d). The one-time fertilizer application had no impact on all of the diversity indexes measured (total cover percentage, *S*, *J'* and *H'*) at both sites (Figure 2a–d).

### 3.2 | Performance of functional groups

The interaction of soil texture and amendment application also influenced functional group composition ($p < 0.001$). On the silt loam deposit, grasses performed better than forbs on all treatments plots, and their performance increased even more on biosolids plots (Figure 3). On the sandy deposit, the proportions of grasses and forbs were both low on control and fertilizer plots, and the performance of grasses was higher on biosolids plots (Figure 3).

### 3.3 | Performance of seeded and volunteer species

The interaction of soil texture and amendment applications influenced the cover of seeded and volunteer species ($p < 0.001$). On the silt loam site, seeded species performed better at a biosolids rate of 50 Mg/ha compared to the control, and volunteers performed better on biosolids plots of rates 100 Mg/ha and greater (Figure 4). At the sandy site, volunteers had a low cover percentage on the control plots, but performed significantly better when biosolids were applied (Figure 4). The inorganic fertilizer had no effect on percentage of seeded and volunteer species on either site compared to the control (Figure 4).

### 3.4 | Performance of native and non-native/naturalized species

The interaction of soil texture and amendment application influenced the abundance of native and non-native/naturalized species ($p < 0.001$). At both sites, non-native species performed better when biosolids were applied, while natives had a low abundance on all treatment plots (Figure 5). Both natives and non-natives had the same abundance on fertilizer and control plots (Figure 5).

### 3.5 | Performance of non-invasive and invasive species

Soil texture and treatments alone influenced the performance of non-invasives and invasives species ($p < 0.001$), while their interaction did

**TABLE 1** Summary of two-way ANOVAs testing the effect of amendment application (biosolids application [B50, B100, B150, B200, B250], an inorganic fertilizer [F] and a control [C]), and soil texture (sand and silt loam) on total cover percentage, richness (*S*), Pielou's evenness (*J'*) and Shannon–Weaver\ diversity (*H'*)

| Source | *df* | *F* ratio | *p*-Value | | *df* | *F* ratio | *p*-Value |
|---|---|---|---|---|---|---|---|
| *Total cover percentage* | | | | *Evenness (J')* | | | |
| Amend | 6 | 122.0 | <0.001*** | Amend | 6 | 0.0425 | 0.002** |
| Texture | 1 | 68.94 | <0.001*** | Texture | 1 | 3.8339 | 0.840 |
| Amend*texture | 6 | 2.219 | 0.049* | Amend*texture | 6 | 1.4010 | 0.224 |
| Total | 111[a] | | | Total | 111[a] | | |
| *Richness (S)* | | | | *Shannon-Weaver diversity (H')* | | | |
| Amend | 6 | 20.89 | <0.001*** | Amendment | 6 | 7.4074 | <0.001*** |
| Texture | 1 | 5.491 | <0.001*** | Texture | 1 | 0.1866 | 0.187 |
| Amend*texture | 6 | 5.651 | <0.001*** | Amend*texture | 6 | 4.8221 | <0.001*** |
| Total | 111[a] | | | Total | 111[a] | | |

***, ≤0.001; **, ≤0.01; *, 0.05.

[a] The total *df* equal 111 because results from one plot were missing.

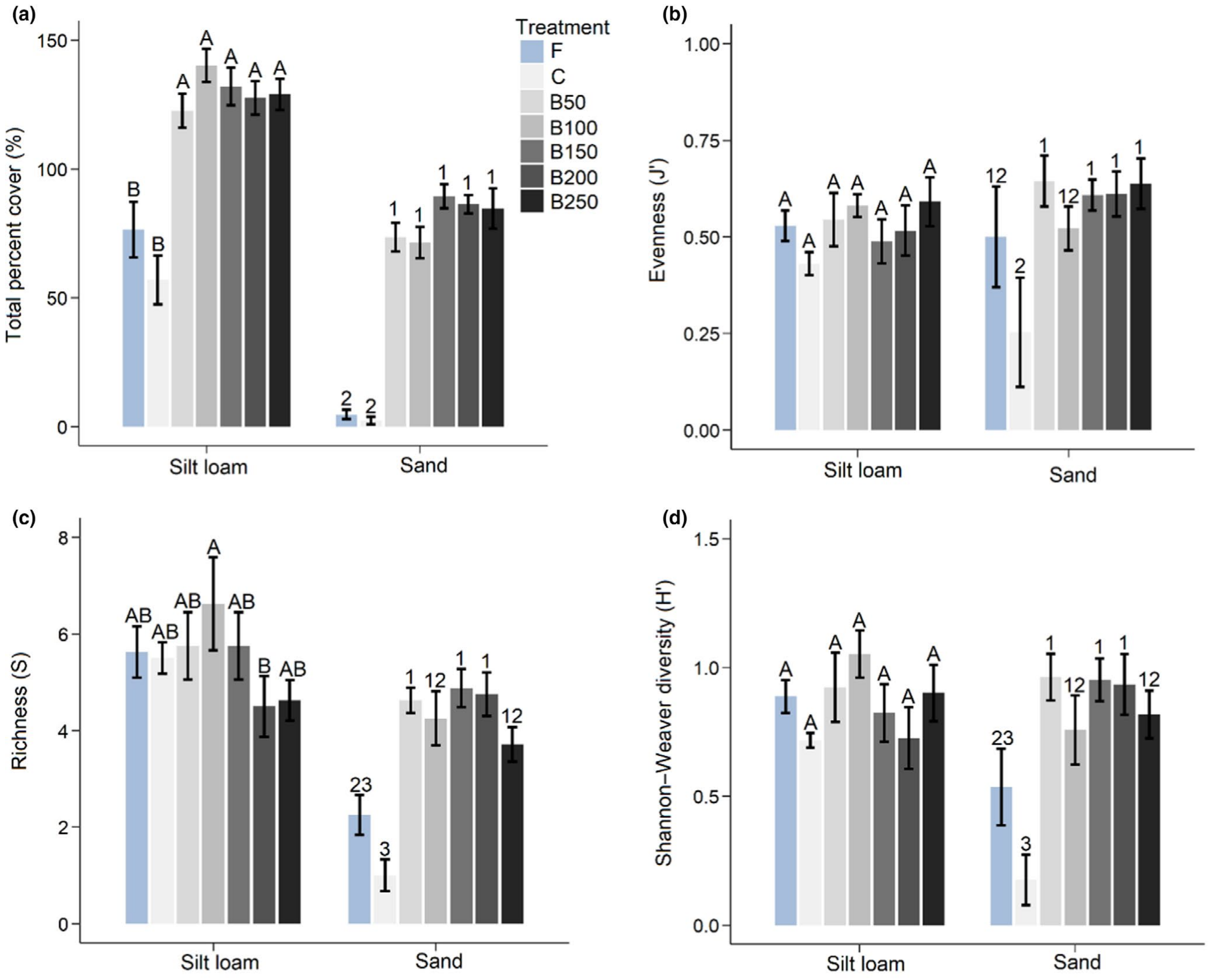

**FIGURE 2** Mean (a) total cover percentage (%), (b) Pielou's evenness (*J'*), (c) richness (*S*), and (d) Shannon-Weaver diversity (*H'*) according to the amendment applied (biosolids treatments at a rate of 50–250 Mg/ha [B50, B100, B150, B200, B250], inorganic fertilizer [F], and control [C]) and soil texture (sand and silt loam) (±*SE*; *n* = 8). Total cover percentage could exceed 100% due to species overlap. Letters and numbers indicate significant statistical differences between the amendment treatments

not have a significant influence ($p = 0.07$). Overall, all treatments at both sites were composed almost exclusively of non-invasive species.

### 3.6 | Plant community structure

The PERMANOVA revealed that species structure based on a Bray–Curtis distance matrix was influenced by the interaction of the soil texture and the amendment applied ($p = 0.001$, Table 2). This relationship is shown on a non-metric multi-dimensional scaling (NMDS) graphic (Figure 6), that illustrates that data are clustered into two distinct groups which shows that soil texture was an important driver of change for plant community development. According to the SIMPER analysis, the abundance of five species (*Festuca rubra*, *Thinopyrum intermedium*, *Psathyrostachys juncea*, *Chamaenerion angustifolium*, and *Poa pratensis*) explains 76.61% of the difference in diversity between sites. The species that influenced diversity between amendments plots were these same five species, and also *Achillea millefolium* and *Agropyron cristatum*. According to the vectors, *Thinopyrum intermedium*, *Psathyrostachys juncea* and *Agropyron cristatum* had a greater cover on biosolids plots (Figure 6). Also, the silt loam site was characterised by a high proportion of *Festuca rubra*, and the sandy site by a high proportion of *Psathyrostachys juncea* (Figure 3).

## 4 | DISCUSSION

### 4.1 | Influence of biosolids on cover percentage

Applying biosolids increased total cover percentage at both sites, which coincides with the results from prior studies exploring its

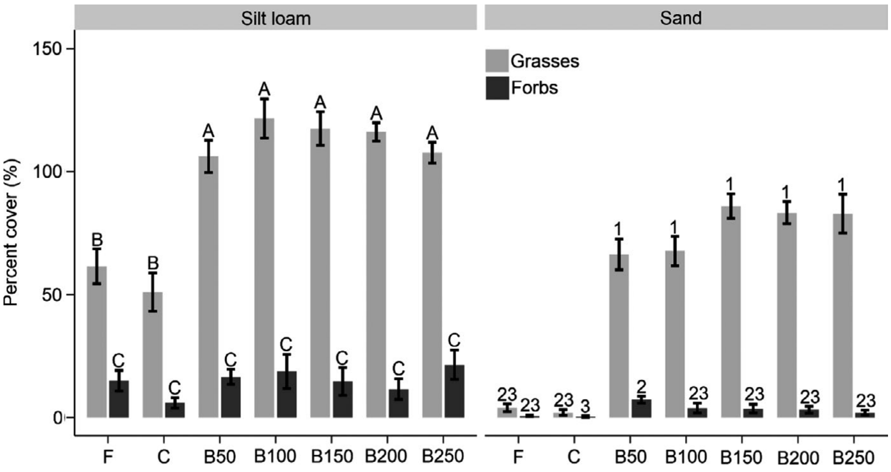

**FIGURE 3** Mean cover percentage (±*SE*; *n* = 8) of plant-functional groups (grass and forbs) according to the soil texture (between the two sites) and amendment application treatments. Total cover percentage could exceed 100% due to species overlap. Letters and numbers indicate significant statistical differences of functional groups between treatments plots

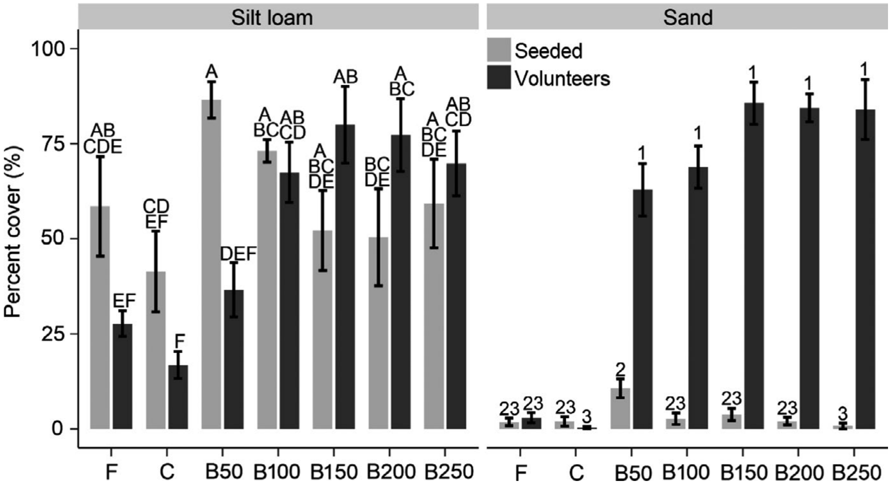

**FIGURE 4** Mean cover percentage (±*SE*; *n* = 8) of seeded and volunteer species according to the soil texture (between the two sites) and amendment application treatments. Total cover percentage could exceed 100% due to species overlap. Letters and numbers indicate significant statistical differences of plant groups (seeded and volunteer species) between treatments plots

use in reclamation (Brofas et al., 2000; Moreno-Peñaranda et al., 2004; Madejón et al., 2006; Brown et al., 2009; Gardner et al., 2012) and demonstrates this effect can persist for many years following one application. This positive response could be attributed to the improvement of physiochemical properties (e.g., bulk density and available nutrients) related to biosolids applications (Gardner et al., 2010; Antonelli et al., 2018). Gardner et al. (2010) reported that bulk density at year 1 (1999) and year 2 (2000) decreased when biosolids were applied, which may have created soil spaces and facilitated roots to penetrate the soil (Rigueiro-Rodríguez et al., 2000; Meyer et al., 2004). This suggests that plants in biosolids plots benefited from a better access to water and nutrients, which, in turn, positively influenced their growth (Boone, 1986; Arvidsson & Håkansson, 1991; Stirzaker et al., 1996). Also, Antonelli et al. (2018) and Harris et al. 2021 showed that concentrations of available P, available N and available K were greater on biosolids plots 13 years following the restoration. This indicates a greater access to these macronutrients for plants compared to control plots, which could have contributed to the increase in total cover percentage at this site (Sheoran et al., 2010).

## 4.2 | Influence of soil texture on cover percentage, richness, evenness and diversity

Our results showed that soil textures resulted in different plant community responses. For instance, total plant cover was higher on the silt loam than the sandy site which could be explained by the different conditions allowed for plants to grow at each site. According to the inverse-texture hypothesis, productivity is higher on finer soils than on coarser soils in semiarid regions (Noy-Meir, 1973; Sala et al., 1988; Epstein et al., 1997). Our results coincide with this theory as our sites are in a semi-arid region and we found higher cover percentage on the silt loam deposit (finer soil) than on the sand (coarser soil). This response could be attributed to the higher water-holding capacity of the silt loam soil, allowing for higher water and nutrient uptake for plant growth (Lane et al., 1998). This inherent capacity of fine soil's texture to hold water could also explain why richness, and evenness and diversity increased with the application of biosolids only at the sandy site. The limited vegetation cover on sand control plots (mean of 2.33% ± 1.50) indicated that the inherent condition of the coarser soil texture did not allow vegetation establishment unlike the silt loam deposit (56.94% ± 9.44) which is finer.

**FIGURE 5** Mean cover percentage (±*SE*; *n* = 8) of natives and non-natives/naturalized species according to the soil texture (between the two sites) and amendment application treatments. Total cover percentage could exceed 100% due to species overlap. Letters and numbers indicate significant statistical differences of plant groups (seeded and volunteer species) between treatments plots

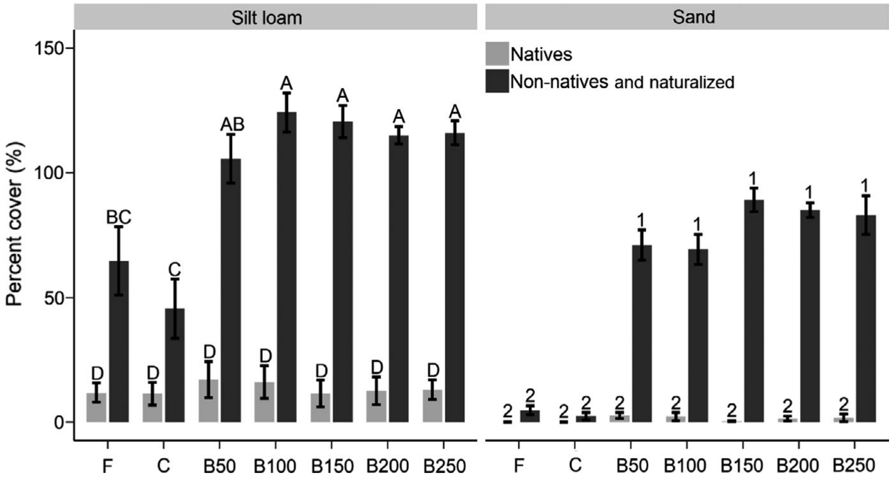

**TABLE 2** PERMANOVA's results testing the community structure according to the amendment applied (biosolids [B50, B100, B150, B200, B250] and inorganic fertilizer [*F*]) and soil texture (sand and silt loam)

| Source | *df* | *F* ratio | *p*-Value |
|---|---|---|---|
| Amendment | 6 | 67.9859 | 0.001*** |
| Texture | 1 | 9.6033 | 0.001*** |
| Amendment*texture | 6 | 5.0325 | 0.001*** |
| Residual | 93 | | |
| Total | 106 | | |

***, $p \le 0.001$; **, $p \le 0.01$; *, $p \le 0.05$.

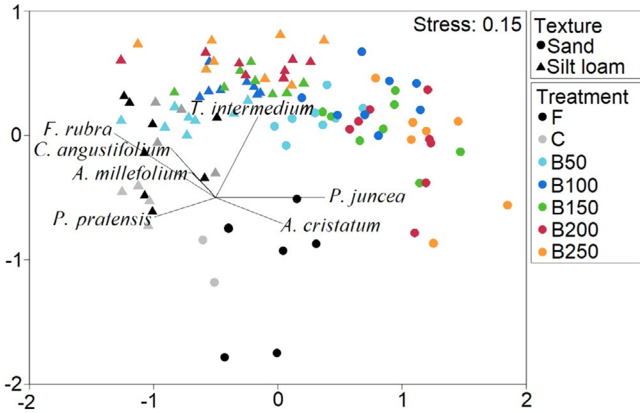

**FIGURE 6** Non-metric multi-dimensional scaling (NMDS) representation of plant community structure according to soil texture (between the two sites) and amendment application treatments. The species that contributed to the differences between textures and treatment according to SIMPER analysis were fitted to vectors along the direction of correlation. The length of the line reflects the strength of the correlation. *F. rubra* = *Festuca rubra*, *T. intermedium* = *Thinopyrum intermedium*, *P. juncea* = *Psathyrostachys juncea*, *C. angustifolium* = *Chamaenerion angustifolium*, *P. pratensis* = *Poa pratensis*, *A. millefolium* = *Achillea millefolium* and *A. cristatum* = *Agropyron cristatum*

### 4.3 | Influence of biosolids application rates on plant community responses (cover percentage, richness, evenness and diversity)

Our results demonstrated that plant community responses were not impacted by the level of biosolids applied. Diaz et al. (1997) also found no change in total plant cover at different biosolid application rates (13, 19.5 and 26 Mg/ha) in a semiarid Mediterranean site, which they attributed to the inhibitory effect of biosolids to increase electrical conductivity. High electrical conductivity indicates a high salt concentration, which can cause abiotic stress to plants and impact their growth (Yadav et al., 2011; Bai et al., 2017). The electrical conductivity of biosolids used in our study exceeded soil quality guidelines for agricultural land use (CCME, 2014), but Gardner et al. (2010) showed that salts leached in the years following their application. The lack of total cover percentage difference between biosolids rates is likely attributed to the greater availability of nutrients found in the biosolid-treated plots (Harris et al., 2021). This could be due to the slow nutrients release from biosolids attributed to the site's conditions allowing for a slow mineralization of the organic matter content (Ryals et al., 2015; Page-Dumroese et al., 2018). Changes in richness, evenness and diversity attributed to the application of amendments are generally explained by the increase in resource availability that allowed biomass increases of some species that exclude others from light access (DiTommaso & Aarssen, 1989; Carpenter et al., 1990; Cleland & Harpole, 2010; Yin et al., 2017). Given that the application rates tested did not influence plant community responses, this suggests that the rates applied result in the release of equivalent available nutrient quantities over the long term.

### 4.4 | Characteristics of plants that colonized the sites

Among the six species included in the seed mix, only three were observed on our sites and generally performed better on the silt loam deposit, especially *Festuca rubra* var. *rubra*. The fact that the plant community did not resemble the seed mix over the long term could be a result of the use of some species in combination with others or that some species were not best adapted to our sites (Sheoran et al., 2010; Borden & Black, 2011; Tarrasón et al., 2014). For example, *Thinopyrum intermedium* was reported to be best adapted to single-crop haying situations, and *Psathyrostachys junceus* is not to be considered the best choice for erosion control for either wind or water erosion objectives (USDA, n.d. a; USDA, n.d. b).

Our results showed that the predominant plants that established at both sites were volunteer species (non-seeded), mostly agronomic non-native/naturalized grasses. While nutrient addition often favours non-native/naturalized grasses at the expense of other species such as native forbs (Blumenthal et al., 2017), results showed that non-native/naturalized grasses were predominant on all treatments plots regardless if amendments were applied or not. This suggests that the conditions provided by tailings themselves favoured the establishment of non-native/naturalized grasses (Kuhman et al., 2010). The severe conditions provided by the nature of tailings and their exposition to erosion may have contributed to the colonization of these species, since they are better adapted to harsh conditions than slow-growing perennial species generally found in grasslands (Pysek & Richardson, 2007; Blumenthal et al., 2009, 2017; Leishman et al., 2010; Penuelas et al., 2010). Although applying biosolids and sowing enhanced the establishment of non-native/naturalized grasses, it did not appear to be an obstacle for native species. There were no differences in native species richness between all biosolids application levels at both sites (see Appendix S1). Native species did not spontaneously establish well when biosolids were not applied; specifically the mean richness for native species was low at the loamy sites, and the sandy site did not have any native species established. Considering that total cover percentage, and richness were low on control plots after 17 years, this suggests that spontaneous succession would not be an effective restoration method for our sites. As mentioned by Prach and Hobbs (2008), environmental site conditions have an important role to play in spontaneous succession and when conditions are too extreme technical measures are needed to restore degraded lands. However, the fact that non-native/naturalized grasses benefit more from nutrient addition show that this is still a challenge to overcome (Huang et al., 2018). Restoring with native seedlings may be an alternative and contribute to increase native species' success (Baethke et al., 2020).

Results also showed that the interaction of soil texture and amendment application rates had an impact on plant communities' structure. Although these two factors influenced performances of certain species, the fact that non-native/naturalized grasses were predominant showed that other factors might have influenced plant communities' compositions found. For instance, it is possible that seeding operations conducted annually close to our research area influenced the species found on our research plots, especially considering that non-native/naturalized grasses are often used to restore the tailings storage facility as they are well adapted to harsh conditions found on these sites. Lemke et al. (2013) showed that planting non-native species close to their site area was likely the major driver of the high diversity of non-native, invasive plants measured. Furthermore, Calinger et al. (2015) showed that the proximity to roads can promote non-native species' establishment as they provide corridors for the spread of species. This factor could have also influenced plant composition found at our sites as road embankments are usually reclaimed using non-native grasses (Kuhman et al., 2010). Overall, non-native/naturalized grasses showed to be well-adapted to establish and persist over the long term (17 years following the application of biosolids) on reclaimed tailings. The goals of establishing grasslands and providing ecosystem services such as erosion control and grazing areas for cattle were accomplished. As the species that established on our sites were different than those found in the reference natural ecosystem, the sites can be considered as novel ecosystems (Hobbs et al., 2009). In the future, the objective is to reclaim the rest of the tailings storage facility with a plan more focused for wildlife use.

## 5 | CONCLUSION

Our study found that applying biosolids at rates as low as 50 Mg/ha was enough to establish vegetative cover for 17 years following the initial application regardless of texture tailings deposits and this was not at the expense of diversity. The rate of application of biosolids (50–250 Mg/ha) yielded similar results in terms of all plant community responses. Sites that may be more challenging for vegetation to re-establish, such as sites with sandy soil texture, may benefit from the use of biosolids as this amendment has shown to increase richness, evenness and diversity. Overall, the use of biosolids to reclaim tailings storage facilities appears to provide the benefit of controlling erosion on the long term. However, further studies should be conducted to find strategies to improve the success of native species on reclaimed mining sites.

### ACKNOWLEDGEMENTS

We would like to thank Roz Kempe and Tania Gheseger from Metro-Vancouver for providing constructive feedback on our manuscript.

### CONFLICTS OF INTEREST

We are unaware of any conflicts of interest for this manuscript.

### AUTHOR CONTRIBUTIONS

WCG, MH and TP established the experimental design; MH and WCG made measurements on the field; AG and LP analyzed the data; AG wrote the manuscript; AG, LWP, MH, WCG, PT, and LHF contributed to reviewing and editing drafts and gave final approval for publication.

### DATA AVAILABILITY STATEMENT

All data and analysis scripts used in this study will be available on FigShare (DOI: 0.6084/m9.figshare.13636976).

## ORCID

*Alyson Gagnon* https://orcid.org/0000-0002-9815-6374
*Laura W Ploughe* https://orcid.org/0000-0002-8421-1299
*Lauchlan H Fraser* https://orcid.org/0000-0003-3998-5540

## REFERENCES

Antonelli, P.M., Fraser, L.H., Gardner, W.C., Broersma, K., Karakatsoulis, J. & Phillips, M.E. (2018) Long term carbon sequestration potential of biosolids-amended copper and molybdenum mine tailings following mine site reclamation. *Ecological Engineering*, 117, 38–49.

Arvidsson, J. & Håkansson, I. (1991) A model for estimating crop yield losses caused by soil compaction. *Soil and Tillage Research*, 20, 319–332.

Avery, E., Krzic, M., Wallace, B., Newman, R., Smukler, S. & Bradfield, G. (2018) One-time application of biosolids to ungrazed semiarid rangelands: 14 yr soil responses. *Canadian Journal of Soil Science*, 98, 696–708.

Baethke, K.A., Ploughe, L.W., Gardner, W.C. & Fraser, L.H. (2020) Native seedling colonization on stockpiled mine soils is constrained by site conditions and competition with exotic species. *Minerals*, 10, 1–15.

Bai, Y., Zang, C., Gu, M., Gu, C., Shao, H., Guan, Y. et al. (2017) Sewage sludge as an initial fertility driver for rapid improvement of mudflat salt-soils. *Science of the Total Environment*, 578, 47–55.

Blumenthal, D., Lecain, D. & Augustine, D. (2017) Composted manure application promotes long-term invasion of semi-arid rangeland by *Bromus tectorum*. *Ecosphere*, 8, e01960.

Blumenthal, D., Mitchell, C.E., Pysek, P. & Jarosik, V. (2009) Synergy between pathogen release and resource availability in plant invasion. *Proceedings of the National Academy of Sciences of the United States of America*, 106, 7899–7904.

Boone, F.R. (1986) Towards soil compaction limits for crop growth. *Netherlands Journal of Agricultural Science*, 34, 349–360.

Borden, R.K. & Black, R. (2011) Biosolids application and long-term noxious weed dominance in the western United States. *Restoration Ecology*, 19, 639–647.

Brofas, G., Michopoulos, P. & Alifragis, D. (2000) Sewage sludge as an amendment for calcareous bauxite mine spoils reclamation. *Journal of Environmental Quality*, 29, 811–816.

Brown, S., Svendsen, A. & Henry, C. (2009) Restoration of high zinc and lead tailings with municipal biosolids and lime: a field study. *Journal of Environmental Quality*, 38, 2189–2197.

Calinger, K., Calhoon, E., Chang, H.-C., Whitacre, J., Wenzel, J., Comita, L. et al. (2015) Historic mining and agriculture as indicators of occurrence and abundance of widespread invasive plant species. *PLoS One*, 10, e0128161.

Canadian Council of Ministers of the Environment (CCME). (2012) *Guidance document for the beneficial use of municipal biosolids, municipal sludge and treated septage*. Canadian Council of Ministers of the Environment, pp. 101. https://publications.gc.ca/collections/collection_2013/ccme/En108-4-56-2012-eng.pdf

Canadian Council of Ministers of the Environment (CCME). (2014) Canadian soil quality guidelines for the protection of environmental and human health. Summary tables. https://doi.org/10.1038/ncpcardio1302.3.4

Carpenter, A.T., Moore, J.C., Redente, E.F. & Stark, J.C. (1990) Plant community dynamics in a semi-arid ecosystem in relation to nutrient addition following a major disturbance. *Plant and Soil*, 126, 91–99.

Clarke, K. & Gorley, R. (2015) *PRIMER version 7: User manual/tutorial*. Devon, United Kingdom: PRIMER-E, 192.

Clarke, K.R. & Warwick, R.M. (2001) *Change in Marine Communities: An Approach to Statistical Analysis and Interpretation*, 2nd edition. Plymouth: PRIMER-E, Ltd.,. Plymouth Marine Laboratory.

Cleland, E.E. & Harpole, W.S. (2010) Nitrogen enrichment and plant communities. *Annals of the New York Academy of Sciences*, 1195, 46–61.

Cuevas, G., Blazquez, R., Martinez, F. & Walter, I. (2000) Composted MSW effects on soil properties and native vegetation in a degraded semiarid shrubland. *Compost Science & Utilization*, 8, 303–309.

Cusser, S. & Goodell, K. (2013) Diversity and distribution of floral resources influence the restoration of plant-pollinator networks on a reclaimed strip mine. *Restoration Ecology*, 21, 713–721.

Diaz, E., Roldan, A., Castillo, V. & Albaladejo, J. (1997) Plant colonization and biomass production in a xeric torriorthent amended with urban solid refuse. *Land Degradation & Development*, 8, 245–255.

DiTommaso, A. & Aarssen, L.W. (1989) Resource manipulations in natural vegetation: a review. *Vegetatio*, 84, 9–29.

Epstein, H., Lauenroth, W. & Burke, I. (1997) Effects of Temperature and Soil Texture on ANPP in the U.S. Great Plains. *Ecology*, 78, 2628–2631.

FAO-UNESCO. (1975) *FAO-UNESCO. Soil Map of the World, 1:5,000,000*. Vol I. Paris: FAO-UNESCO.

Gardner, W.C., Anne, N.M., Broersma, K., Chanasyk, D.S. & Jobson, A.M. (2012) Influence of biosolids and fertilizer amendments on element concentrations and revegetation of copper mine tailings. *Canadian Journal of Soil Science*, 92, 89–102.

Gardner, W., Broersma, K., Naeth, A., Chanasyk, D. & Jobson, A. (2010) Influence of biosolids and fertilizer amendments on physical, chemical and microbiological properties of copper mine tailings. *Canadian Journal of Soil Science*, 90, 571–583.

Gastauer, M., Silva, J.R., Junior, C.F.C., Ramos, S.J., Filho, P.W.M.S., Neto, A.E.F. et al. (2017) Mine land rehabilitation: Modern ecological approaches for more sustainable mining. *Journal of Cleaner Production*, 172, 1409–1422.

Government of Canada (2019) Canadian Climate Normals 1981-2010 Station Data. Available at: https://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?searchType=stnName&amp;txtStationName=Lornex&amp;searchMethod=contains&amp;txtCentralLatMin=0&amp;txtCentralLatSec=0&amp;txtCentralLongMin=0&amp;txtCentralLongSec=0&amp;stnID=998&amp;dispBack=1

Harris, M., Gardner, W.C. & Pypker, T. (2021). Influence of a one time biosolids application on elemental and nutrient concentrations on mine tailings. *Canadian Journal of Soil Science*. https://doi.org/10.1139/cjss-2020-0022

Heckman, R.W., Wright, J.P. & Mitchell, C.E. (2016) Joint effects of nutrient addition and enemy exclusion on exotic plant success. *Ecology*, 97, 3337–3345.

Hobbs, R.J., Higgs, E. & Harris, J.A. (2009) Novel ecosystems: implications for conservation and restoration. *Trends in Ecology and Evolution*, 24, 599–605.

Hobbs, R.J. & Norton, D.A. (1996) Towards a conceptual framework for restoration ecology. *Restoration Ecology*, 4, 93–110.

Huang, Q.Q., Fan, Z.W., Li, X.X., Wang, Y., Liu, Y. & Shen, Y.D. (2018) Effects of nutrient addition and clipping on biomass production of invasive and native annual Asteraceae plants. *European Weed Research Society*, 58, 318–326.

Kowaljow, E., Mazzarino, M., Satti, P. & Jiménez-Rodríguez, C. (2010) Organic and inorganic fertilizer effects on a degraded Patagonian rangeland. *Plant and Soil*, 332, 135–145.

Kuhman, T.R., Pearson, S.M. & Turner, M.G. (2010) Effects of land-use history and the contemporary landscape on non-native plant invasion at local and regional scales in the forest-dominated southern Appalachians. *Landscape Ecology*, 25, 1433–1445.

Lane, D.R., Coffin, D.P. & Lauenroth, W.K. (1998) Effects of soil texture and precipitation on above-ground net primary productivity and vegetation structure across the Central Grassland region of the United States. *Journal of Vegetation Science*, 9, 239–250.

Leishman, M.R., Thomson, V.P. & Cooke, J. (2010) Native and exotic invasive plants have fundamentally similar carbon capture strategies. *Journal of Ecology*, 98, 28–42.

Lemke, D., Schweitzer, C.J., Tazisong, I.A., Wang, Y. & Brown, J.A. (2013) Invasion of a mined landscape: what habitat characteristics are influencing the occurrence of invasive plants? *International Journal of Mining, Reclamation and Environment*, 27, 275–293.

Madejón, E., de Mora, A.P., Felipe, E., Burgos, P. & Cabrera, F. (2006) Soil amendments reduce trace element solubility in a contaminated soil and allow regrowth of natural vegetation. *Environmental Pollution*, 139, 40–52.

Martinez, F., Cuevas, G., Calvo, R. & Walter, I. (2003) Biowaste effects on soil and native plants in a semiarid ecosystem. *Journal of Environmental Quality*, 32, 472–479.

Meyer, V.F., Redente, E.F., Barbarick, K.A., Brobst, R.B., Paschke, M.W. & Miller, A.L. (2004) Plant and soil responses to biosolids application following forest fire. *Journal of Environmental Quality*, 33, 873–881.

Moreno-Peñaranda, R., Lloret, F. & Alcañiz, J.M. (2004) Effects of sewage sludge on plant community composition in restored limestone quarries. *Restoration Ecology*, 12, 290–296.

Noy-Meir, I. (1973) Desert ecosystems: environment and producers. *Annual Review of Ecology and Systematics*, 4, 23–51.

Oksanen, J., Blanchet, F.G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P., O'Hara, R.B., Simpson, G.L., Solymos, P.H., Stevens, M.H., Szoecs, E. & Wagner, H. (2019) Vegan: Community Ecology Package. Version 2.5-6. Available at: https://cran.r-project.org/web/packages/vegan/index.html

Page-Dumroese, D., Ott, M., Strawn, D. & Tirocke, J. (2018) Using organic amendments to restore soil physical and chemical properties of a mine site in Northeastern Oregon, USA. *Applied Engineering in Agriculture*, 34, 43–55.

Paschke, M., Topper, K., Brobst, R.B. & Redente, E. (2005) Long-term effects of biosolids on revegetation of disturbed sagebrush steppe in northwestern Colorado. *Restoration Ecology*, 13, 545–551.

Penuelas, J., Sardans, J., Llusia, J., Owen, S.M., Carnicer, J., Giambelluca, T.W. et al. (2010) Faster returns on 'leaf economics' and different biogeochemical niche in invasive compared with native plant species. *Global Change Biology*, 16, 2171–2185.

Pepper, I.L., Zerzghi, H.G., Bengson, S.A. & Glenn, E.P. (2013) Revegetation of copper mine tailings through land application of biosolids: long-term monitoring. *Arid Land Research and Management*, 27, 245–256.

Pierce, B.L., Redente, E.F., Barbarick, K.A., Brobst, R.B. & Hegeman, P. (1998) Plant biomass and elemental changes in shrubland forages following biosolids application. *Journal of Environmental Quality*, 27, 789–794.

Ploughe, L.W., Akin-Fajiye, M., Gagnon, A., Gardner, W.C. & Fraser, L.H. (2020) Revegetation of degraded ecosystems into grasslands using biosolids as an organic amendment: a meta-analysis. *Journal of Applied Vegetation Science*, 24. https://doi.org/10.1111/avsc.12558.

Prach, K., & Hobbs, R.H. (2008) Spontaneous succession versus technical reclamation in the restoration of disturbed sites. *Restoration Ecology*, 16, 363–366.

Pysek, P. & Richardson, D.M. (2007) Traits associated with invasiveness in alien plants: Where do we stand? In: Nentwig, W. (Ed.) *Biological invasion*. Berlin, Heidelberg, Germany: Springer-Verlag, pp. 97–126.

R Core Team (2018) *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria.

Rigueiro-Rodríguez, A., Mosquera-Losada, M.R. & Gatica-Trabanini, E. (2000) Pasture production and tree growth in a young pine plantation fertilized with inorganic fertilizers and milk sewage in northwestern Spain. *Agroforestry Systems*, 48, 245–256.

Ryals, R., Hartman, M.D., Parton, W.J., DeLonge, M.S. & Silver, W.L. (2015) Long-term climate change mitigation potential with organic matter management on grasslands. *Ecological Applications*, 25, 531–545.

Sala, O.E., Parton, W.J., Joyce, L.A. & Lauenroth, W.K. (1988) Primary production of the Central Grassland Region of the United States. *Ecology*, 69, 40–45.

Salgueiro, P.A., Prach, K., Branquinho, C. & Mira, A. (2020) Enhancing biodiversity and ecosystem services in quarry restoration – challenges, strategies and practice. *Restoration Ecology*, 28, 655–660.

Sheoran, V., Sheoran, A. & Poonia, P. (2010) Soil reclamation of abandoned mine land by revegetation: a review. *International Journal of Soil, Sediment and Water*, 3, 1–13.

Stirzaker, R., Passioura, J. & Wilms, Y. (1996) Soil structure and plant growth: Impact of bulk density and biopores. *Plant and Soil*, 185, 151–162.

Tarrasón, D., Ojeda, G., Ortiz, O. & Alcañiz, J.M. (2014) Can organic amendments be useful in transforming a Mediterranean Shrubland into a Dehesa? *Restoration Ecology*, 22, 486–494.

The U.S. Department of Agriculture (USDA), no date a. NRCS, Idaho State Office. Available at: https://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/idpmspg04843.pdf

The U.S. Department of Agriculture (USDA) no date b. NRCS, Idaho State Office. Available at: https://plants.usda.gov/plantguide/pdf/pg_psju3.pdf

Wallace, B.M., Krzic, M., Newman, R.F., Forge, T.A., Broersma, K. & Neilsen, G. (2016) Soil aggregate dynamics and plant community response after biosolids application in a semiarid grassland. *Journal of Environmental Quality*, 45, 1663–1671.

Walter, I., Martínez, F. & Cuevas, G. (2006) Plant and soil responses to the application of composted MSW in a degraded, semiarid shrubland in central Spain. *Compost Science & Utilization*, 14, 147–154.

Yadav, S., Irfan, M., Ahmad, A. & Hayat, S. (2011) Causes of salinity and plant manifestations to salt stress: a review. *Journal of Environmental Biology*, 32, 667–685.

Yin, X., Qi, W. & Du, G. (2017) Diversity effects under different nutrient addition and cutting frequency environments in experimental plant communities. *Ecological Research*, 32, 611–619.

## SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

**Appendix S1.** Richness (±SE; $n = 8$) of natives and non-natives/naturalized species according to the soil texture (between the two sites) and amendment application treatments.

**Appendix S2.** Quality criteria for class B biosolids.

**Appendix S3.** List of the species found at both sites (Bethlehem and Trojan).

**How to cite this article:** Gagnon, A., Ploughe, L.W., Harris, M.P., Gardner, W.C., Pypker, T. & Fraser, L.H. (2021) Grassland reclamation of a copper mine tailings facility: Long-term effects of biosolids on plant community responses. *Applied Vegetation Science*, 24, e12612. https://doi.org/10.1111/avsc.12612