Can graminoids used for mine tailings revegetation improve substrate structure?
Can graminoids used for mine tailings revegetation improve substrate structure?

Marie Guittonny-Larchevêque,*a Yasmine Meddeb,a Dominique Barrettea

a Research Institute on Mines and Environment – Université du Québec en Abitibi-Témiscamingue, 445 Bd de l’Université, Rouyn-Noranda (QC) J9X 5E4 Canada

*Corresponding author:
marie.guittonny-larcheveque@uqat.ca
Tel. 001-819-732-8809 ext. 8226
Fax. 001-819-732-8805
Abstract

Seeding of agronomic graminoid species that are tolerant to the compacted and low aeration conditions associated with mine tailings allow for rapid cover of mine waste, which, in turn, controls erosion. These graminoids have the potential to be used as primer-species on mine tailings to improve the rooting of other plant species compared to other plants types which may not tolerate soil compaction and low aeration. Yet tailings colonization by graminoid roots could alleviate ecological filters such as low air-filled porosity and elevated bulk density. The effect of above- and below-ground development of hay graminoid species on macroporosity and density of gold mine tailings was studied under controlled conditions as well as in situ. All graminoids improved tailings macroporosity after only two months of growth under greenhouse conditions, but had no effect on tailings density. Perennial *B. inermis* was most efficient in improving tailings macroporosity with greater root diameter, biomass, and volume. Annual *A. sativa* also produced high root biomass and length which improved tailings’ macroporosity. However, under field conditions, graminoids had a low cover and no effect on macroporosity, which highlights that their growth should be improved to use them as primer-plants.

**Keywords:** abiotic filters, agronomic hay species, bulk density, macroporosity, mine wastes, root morphology
Introduction

Human activities that move great quantities of earth and rocks, such as mining, quarrying, and road and dam construction, create new substrates that need to be stabilized and revegetated. These new substrates, particularly the storage areas of mine wastes, can show clear abiotic and biotic limitations to plant primary succession. Among mine wastes, metalliferous mine tailings consist of finely crushed ore (70% to 80% of particles range from 2 µm to 80 µm, Aubertin et al. 2002) that remains after valuable metals have been removed. Mine wastes are transported from the mine plant (usually pumped) as aqueous slurries and deposited into tailings storage facilities that generally cover large surface areas that are prone to erosion. Mine tailings are prone to several concomitant stresses: lack of water, nutrients, and air; extreme temperatures; wind exposure; and salinity due to chemical addition during the ore processing (Huang et al. 2011; Parraga-Aguado et al. 2013). Moreover, they lack organic matter and soil organisms (Tordoff et al. 2000) that are essential to releasing nutrients and building adequate physical structure. Finally, due to weathering of freshly exposed minerals, mine tailings may have extreme pH values, and contain potentially phytotoxic levels of salts and heavy metals. In particular, sulfide minerals, such as pyrite, react with water and oxygen to produce sulfuric acid (Kleinmann et al. 1981), which increases some trace metal mobility towards plants’ available fraction. In contrast, low-sulfide tailings may be less toxic to plant roots (Bagatto and Shorthouse 1999).

In fine-grained tailings, main ecological filters (Keddy 1992) for tree growth may be the low air-filled porosity and elevated density, which impede root development. In revegetated tailings, some studies showed tree root development to be restricted to cover soils over the tailings (Borgegard and Rydin 1989; Larchevêque et al. 2013) or amended tailings (Guittonny-Larchevêque et al. 2016). In low-sulfide tailings, the use of organic amendments to facilitate plant establishment
has been studied extensively (Boyer et al. 2009; Emerson et al., 2009; Lunt and Hedger 2003; Whitbread-Abrutat 1997). Amendments improve mine tailings’ structure and associated water and air circulation, as well as their nutrient content (Larchevêque et al. 2013; Guittonny-Larchevêque et al. 2016). Direct seeding of stress-tolerant herbaceous species with fertilizers can also be used for the revegetation of tailings. Agronomic herbaceous species are well adapted to revegetate tailings because they are tolerant to the compacted and low aeration conditions that are associated with mine tailings (Emerson et al. 2009). However, herbaceous plants must also grow quickly in order to rapidly cover mine tailings and limit wind and water erosion. Graminoids in particular have a high productivity (Louarn et al. 2012) that qualifies them to be used as pioneer plants to rapidly cover and protect the tailings from erosion (Burger and Zipper 2002; Ranjan et al. 2015).

Like amendments added to tailings, agronomic graminoids established on tailings could help to alleviate ecological filters associated with the tailings structure that impedes the root growth of other plants. Annual graminoids, such as small-grained cereals, are often used in tailings in Quebec as cover crops and are considered nurse plants that increase the establishment success of other plants, such as forbs, included in seeding mixes. But the mechanisms through which their nursing effect occurs are not well known. Annual graminoids could improve microclimatic conditions or resource availability associated with the tailings (Padilla and Pugnaire 2006), but they could also alleviate structural limitations. For example, their extensive root systems, composed of numerous fine roots, appear to be particularly effective at promoting the formation of stable aggregates (Oades 1984; Tisdall 1991).

The beneficial changes in the substrate structure due to herbaceous species and their facilitating effect on the rooting of other species have been studied primarily in agricultural settings (Wang et al. 1986; Angers and Caron 1998; Dexter 1991). The primer-plants concept was defined
by Yunusa and Newton (2003) as “cropping systems where short-phases of appropriate plant species are grown to condition the soil for subsequent crops of high economic value,” but studies on this matter remain scarce. In a plant succession context on tailings, graminoid roots (dead or alive) could create continuous biopores and promote aggregate formation, which could improve the macroporosity, aeration, and water circulation of tailings (Grevers and De Jonc 1990; Angers and Caron 1998), thus encouraging the development of other species’ roots (Dexter 1991). Root diameter in particular directly influences macropore formation and soil hydraulic conductivity (Bodner et al. 2014). Moreover, root length and biomass are generally correlated to soil aggregation (Angers and Caron 1998). Since the roots of perennial graminoids may reach a larger diameter than those of annual graminoids, their positive effect on macroporosity could be greater (Bodner et al. 2014). The effect of above- and below-ground development of several graminoid species on macroporosity (or air-filled porosity) and density was studied after direct seeding of gold mine tailings, and compared under controlled conditions and in the field. Metalliferous mine tailings were classified as a silt loam (USDA soil taxonomy), and contained low concentrations of sulfides and trace metals. Their macroporosity and density values before seeding could limit tree root development (Larchevêque et al. 2013). The following hypotheses were formulated: 1) Graminoid root development increases the macroporosity and decreases the density of tailings; 2) The macroporosity of tailings increases with root diameter and/or biomass; 3) The effects of roots on macroporosity are lower in the field due to lower plant biomass (greater stress exposure).

Material and methods

Site description
The Canadian Malartic gold mine (property of the Canadian Malartic Partnership, Malartic, northwestern Quebec, Canada, 48°13’N, 78°12’W) is a large open-pit mine that began production in 2011. It is located in the northern Clay Belt region of Quebec and Ontario. The typical forest vegetation that surrounds the mine includes jack pine (*Pinus banksiana* Lamb.), black spruce (*Picea mariana* Mill. Britton), trembling aspen (*Populus tremuloides* Michx.), paper birch (*Betula papyrifera* Marsh.), tamarack or eastern larch (*Larix laricina* Du Roi K. Koch), and balsam fir (*Abies balsamea* L. Mill.). In this boreal region, the growing season typically begins in mid-May and ends in early October, with a mean temperature during the three warmest months (June, July, and August) of around 18°C–19°C. The average annual temperature is 1°C, and the average number of frost-free days is 80. Mean annual precipitation is around 900 mm (Environment Canada 2004).

**Mine tailings**

The Canadian Malartic ore is mineralized greywacke. The tailings have low sulfide content (around 1% S) and contain calcite, which can neutralize acidity. They consist of finely milled wastes from the gold extraction process (cyanide leaching) with 86% particles < 80 µm and a uniformity coefficient *C*<sub>U</sub> = *D*<sub>60</sub>/*D*<sub>10</sub> of 12.7. (*D*<sub>10</sub>: 0.002 mm and *D*<sub>60</sub>: 0.025 mm, *D*<sub>10</sub> and *D*<sub>60</sub> being the size of the sieve through which 10% and 60% of the material passes, respectively). They were deposited in the storage facility as thickened tailings (around 60% solids by mass). Among milling wastes, thickened tailings (Robinsky et al. 1991) represent an emerging technology for surface deposition. Their basic properties are similar to those of conventional deposited tailings (slurried) (Bussière 2007), but the uniform grain-size distribution generated in the facility (Al and Blowes 1999) confers more homogeneous hydraulic conductivities (average saturated hydraulic conductivity *K*<sub>sat</sub> = 5 × 10<sup>-8</sup> m s<sup>-1</sup>, Woysner and St-Arnaud 1994) in tailings storage areas. The tailings were treated by cyanide detoxification (SO<sub>2</sub>/H<sub>2</sub>O<sub>2</sub> technology), which left free CN<sup>-</sup> concentrations lower than 20 mg
kg\(^{-1}\). As expected, the tailings deposited in the facility had low macroporosity (2.6%) and high density (1.5 g.cm\(^{-3}\)), which were respectively below and above the thresholds reported to impede root growth (Archer and Smith 1972; Schuurman 1965). Tailings were air-dried before pot filling and rewatering in the greenhouse, which increased their macroporosity to around 7%; however, macroporosity remained below the 10% threshold that impedes root growth, as indicated by another study using the same tailings (Larchevêque et al. 2013). Chemical characteristics of the tailings are summarized in Table 1. Trace metal concentrations are below Quebec’s regulatory thresholds for residential lands (Government of Quebec 2014).

Seeded graminoids

The selected graminoid species were among the herbaceous species used in agriculture for hay field seeding and mine revegetation in northwestern Quebec. They had differing root system morphology. They were used for two experiments on Canadian Malartic tailings: a greenhouse experiment (L. perenne, A. sativa, B. inermis, P. arundinacea, and F. rubra) and a field experiment (H. vulgare, L. perenne, A. gigantea, and P. arundinacea). Lolium perenne L. has a dense and fibrous root system that can extend deep into the soil (De Baets et al. 2011). Avena sativa L. and Hordeum vulgare L. also have a fibrous root system, but with roots that extend superficially (De Baets et al. 2011). Festuca rubra is rhizomatous and has a fibrous and superficial root system (Green and Renault 2008; Nelson Brown et al. 2010). Bromus inermis Leyss., Agrostis gigantea Roth, and Phalaris arundinacea L. have a fibrous and rhizomatous root system that extends deep into the soil. B. inermis roots can penetrate soils to 2 m deep or more (Sahramaa and Jauhiainen 2003). All tested species were perennials except A. sativa and H. vulgare. Seeds of each species were obtained from Coop Val-Nord (Amos, QC).
Experimental designs

Greenhouse experiment

Frozen tailings (deposited less than six months before the experiment) were collected with a mechanical shovel at the surface (0 m to 1 m) of the tailings facility in February 2014 and transported to the greenhouse for the pot experiment. In mid-March 2014, 100 plastic pots (3.6 L) were filled with 2.6 kg (2 L) of air-dried tailings. All pots were fertilized with 1 g of granular, starter mineral fertilizer (9% nitrogen (N), 28% phosphoric acid (P), 9% potash (K), (Coop Agricole, Amos, QC), which was mixed with the tailings before seeding according to the recommended concentrations for the revegetation of mine wastes (Burger and Zipper 2002). The plants were continually fertilized to provide them with the best possible conditions of growth on a harsh substrate like tailings. A complete and randomized block design was used: 100 pots = 10 blocks (replicates) x 5 graminoid species (L. perenne, A. sativa, B. inermis, P. arundinacea, F. rubra) x 2 pots. In each of the 20 pots by species, 5 seeds were planted at 3 cm intervals, according to recommended seeding rates in mine revegetation studies (Burger and Zipper 2002). Seeds were buried at depths of 0 cm to 2 cm, depending on the species, to promote germination. Additional pots filled with commercial PRO-MIX® (Premier Horticulture Ltd., Dorval, QC) peat were also seeded with the five graminoid species (4 repetitions x 5 species). This standard substrate, meant to have an optimized effect on plant development, was used to determine ideal germination rates and root development of plants and acted as a positive control. Pots were watered daily with water containing 0.3 g.L⁻¹ of liquid fertilizer (30% N, 10% phosphoric acid, 10% potash, Nutrite tree and shrub fertilizer with micronutrients, St-Michel, QC). Plants were grown for two months, from March 13 to May 23, 2014, under natural daylight conditions supplemented by high pressure sodium lamps under 16-h photoperiod at 25°C and under ambient humidity.
Field experiment

The experimental area consisted of one hectare of moraine close to the waste rock berms containing the tailings facility. In May 2013, tailings deposited less than six months before in the facility were excavated and transported to cover the experimental area. Around 50 cm to 1 m of tailings were spread evenly and were contained by moraine walls. A complete randomized block design was used: 6 plots (each 20 m x 15 m = 300 m²) = 3 blocks (replicates) x 2 treatments (seeded versus non-seeded tailings). Plots were separated by at least 5 meters from each other. For seeded tailings, 10% by mass *H. vulgare*, 40% *L. perenne*, 40% *A. gigantea*, and 10% *P. arundinacea* (100 kg/ha) were applied manually along with 8-32-16 fertilizer (8% N, 32% P, and 16% K, di- and mono-ammonium phosphates and potassium chloride) (750 kg/ha) as well as commercial mycorrhizal inoculum MYKE® (Premier Tech Biotechnologie, Rivière-du-Loup, QC) as recommended by the manufacturer. Graminoids’ cover and associated macroporosity as well as the density of tailings were measured during the third growing season after seeding (summer 2015). Additional tailings samples were simultaneously taken in the tailings facility for structure measurements. Those tailings had been deposited in the facility less than six months before.

Plant and substrate measurements

Tailings characterization

Three samples (0 cm – 10 cm) of the tailings used in the field experiment were collected in each of the three non-seeded plots in June 2013 to characterize the tailings. Nutrient and trace metal analyses were conducted on sieved (2 mm mesh), finely ground, oven-dried samples (50°C) (Lakehead University Centre for Analytical Services, Thunder Bay, ON). Total N was analyzed by the Dumas combustion method (LECO CNS 2000, Mississauga, ON) and organic carbon (C) was analyzed using the thermogravimetric method (LECO-TGA, Mississauga, ON). Organic matter
concentrations were calculated as $1.72 \times$ organic carbon (C) (Allison 1965). Following HNO$_3$-HCl digestion, sample concentrations of total P, K, Ca, Mg, Na, Al, As, B, Ba, Be, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, Pb, S, Se, Sr, and Tl were determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES, Vista PRO, Varian Canada, Mississauga, ON). Available P was determined in a sodium bicarbonate solution using spectrophotometry (Olsen et al. 1954). The pH was determined in a saturated paste extract and electrical conductivity in a 1:2 water solution.

In the greenhouse experiment, after cutting of aboveground parts, undisturbed 100 cm$^3$ soil samples were taken at a depth of 0 cm to 10 cm with a double cylinder soil sampler at the centre of each pot (50 cores). In the field experiment, 20 undisturbed 100 cm$^3$ soil samples were randomly taken on July 8, 2015 at 0 cm to 10 cm depth with a double cylinder soil sampler in seeded and non-seeded tailings plots (3 repetitions x 3 or 4 samples x 2 treatments). In seeded plots, the samples were always cored near the vicinity of well-developed graminoids (at a maximal 10 cm distance from the centre of the grass clump), where the primer-effect of graminoid roots is supposed to be maximal for the natural colonization of seedlings whose seeds could be trapped in the vicinity of grasses. Ten additional cores were randomly sampled at the same depth in a part of the tailings facility where tailings were deposited less than six months ago. Bulk density and macroporosity (air-filled porosity, % of pores > 30 µm, Beven and Germann 1982) were determined following procedures described by Cassel and Nielsen (1986). Cores were brought to saturation under vacuum and weighed (W1). They were then set on the porous surface of a sand box apparatus (Eijkelkamp Agrisearch Equipment) and brought to equilibrium at a tension of −10 kPa (field capacity). Cores were weighed (W2) and oven-dried (105°C, 48 hours) prior to final weighing (W3). Macroporosity (%) and bulk density were estimated with the following formulas:

Macroporosity = \( \left( \frac{W_1 - W_2}{100 \ \text{cm}^3} \right) \times 100 \)
Bulk density  = $W/100 \text{cm}^3$

Graminoid development

In the greenhouse experiment, mean germination rates (%) were assessed for each pot (100 pots) two weeks after seeding as number of germinated seeds / 5 x 100. Survival rates (%) were calculated for each pot at the end of the experiment as number of living plants / number of germinated seeds x 100. Success rate (%) was calculated as germination rate x survival rate. All of the other measurements were performed, at the end of May 2014, on the ten pots (out of an available twenty) where the graminoid species showed the best aerial development after two months of growth. The selection of 10 pots with the best growth ensured enough roots were available to measure an effect. Indeed, the objective of the greenhouse study was less to quantify the root effect of graminoids on the macroporosity of tailings (since we are in ideal controlled conditions) than to demonstrate their ability to improve the macroporosity. The aboveground portion of plants was cut at ground level 24 hours after the last watering. They were weighed after oven-drying at 70°C for 48 hours (dry mass). Aerial biomass was calculated by pot and viable plant. Then all remaining tailings or peat in the pots after coring ($670 \text{ cm}^3 = 770 \text{ cm}^3 - 100 \text{ cm}^3$ of the extracted core) were used for root morphology analysis. In the laboratory, graminoid roots were washed from the substrates above a fine metallic grid. Scanned images of fresh roots were analyzed with WinRHIZO software (regular version, Regent Instruments Inc., Sainte-Foy, QC) for root length, area, diameter, volume, and tip number. Root length density (RLD, cm.cm$^{-3}$ substrate), root surface density (cm$^2$.cm$^{-3}$ substrate), root volume density (cm$^3$.cm$^{-3}$ substrate), and the density of the number of tips (nb.cm$^3$ substrate) were calculated. Root samples were then oven-dried at 70°C for 48 hours and weighed to measure root biomass (by pot and plant), root soil density (root mass by soil volume, g.cm$^{-3}$ substrate), specific root area (SRA, m$^2$.kg$^{-1}$), and specific root length (SRL, m.g$^{-1}$).
In the field experiment, plant cover was measured on June 25, 2015 in each seeded tailings plot, the third growing season after seeding. The point intercept method, which is non-destructive, was used (Jonasson 1983). A sharp rod was placed vertically every 10 cm on a 10 x 10 cm grid in four sampling squares (1 m²) by plot. At each rod position, the contact occurrence of each plant species touching the rod was noted. Percent cover of graminoids in each sampling square was calculated as number of positions where contact occurred / 100 x 100.

Statistical analysis
Germination, survival, and success rates were compared among species using the $\chi^2$ test (PROC FREQ, SAS V.9.2, SAS Institute Inc., Cary, NC). For the greenhouse experiment, data on root parameters, aerial biomass, substrate macroporosity, and density were subjected to one-way analysis of variance (species) (SAS, PROC GLM). Species factor was fixed while the block factor was considered a random effect. When species effect was significant for a given variable, least-square means were estimated (SAS, LS MEANS statement), and post-hoc Tukey’s tests were conducted to separate the means. Pearson correlations between tailings macroporosity at the end of the greenhouse experiment and root parameters were analyzed (SAS, PROC CORR). For the field experiment, substrate macroporosity, and density were subjected to one-way analysis of variance (seeding) (SAS, PROC GLM). Seeding factor was fixed while the block factor was considered a random effect. Overall significance for analyses was set at alpha = 0.05, except for the correlation analyses.

Results
Greenhouse experiment
Germination, survival, and success rates differed significantly among the five tested species (Table 2). In tailings, B. inermis and F. rubra had the best germination rates, whereas A. sativa and B.
inermis had the best survival rates. Consequently, B. inermis showed the best overall success rate of the five species, with a one in two chance for a seed to produce a viable plant. B. inermis and P. arundinacea had lower germination rates in tailings compared to peat. Survival rates of L. perenne, P. arundinacea, and F. rubra were also decreased in tailings compared to peat.

Except A. sativa, which had a productivity in the same range in tailings and in peat, all other species showed greater aboveground and root biomass by plant in peat than in tailings, with around 10 times more aboveground biomass in peat (results not shown). Regarding root biomass, L. perenne and F. rubra grown in tailings produced 60% and 30%, respectively, of the root biomass by plant that was produced in peat, while B. inermis and P. arundinacea showed the greatest decrease in root biomass with 5 to 10 times less biomass in tailings than in peat, respectively (results not shown). B. inermis showed the greatest root biomass production by plants seeded in peat (1.4 g), with much lower biomass when seeded in tailings. In tailings, A. sativa and B. inermis produced the greatest root biomass by plant (Table 3). Since B. inermis’s success was nearly twice that for A. sativa, B. inermis produced the greatest root biomass by pot of all the species seeded in tailings. However, of all the species, A. sativa produced the greatest aerial biomass by plant and by pot (Table 3). Of the tested plants, A. sativa produced the longest roots with the largest number of tips by plant, whereas P. arundinacea had the lowest root length density and the greatest root density (Table 4). B. inermis showed the largest root diameter as well as the greatest root volume by pot and by plant. However, roots of all samples had a diameter of 2 mm or less.

After two months of plant growth, the macroporosity of tailings was clearly above the threshold that is reported to impede root growth (10%). Macroporosity was the greatest in tailings with B. inermis compared to tailings of all other tested species (Table 3). The macroporosity of tailings at the end of the experiment was positively correlated with plant root biomass of all species (r = 0.46, p = 0.099),
especially for *B. inermis* \((r = 0.57, p = 0.089)\) and *A. sativa* \((r = 0.58, p = 0.099)\). The linear relation between the two variables is presented in Figure 1.

*Field experiment*

The mean graminoid cover on seeded plots reached only 36% (± 5% SE) in the third growing season. The cover of other plant types (non-graminoids) was less than 2%. In non-seeded plots, total plant cover was null (2 contact occurrences on 1,200 measurement points).

The macroporosity of tailings was similar in graminoid seeded (4.9%) and non-seeded plots (6.4%), and both remained lower than the thresholds reported to impede root growth. The density of tailings was not affected by plant development either in the greenhouse, or in the field experiment.

*Discussion*

Despite lower germination, survival, and productivity of graminoids in tailings compared to a standard substrate, all tested graminoids improved the macroporosity of tailings after only two months of growth under greenhouse conditions. However, contrary to our first hypothesis, graminoid root development was not sufficient to improve the density of tailings. As a result of the development of graminoid roots, the macroporosity of tailings exceeded the 10% threshold reported in the literature to impede plant root growth (*Archer and Smith 1972*). Hence, direct graminoid seeding has the potential to improve the macroporosity of tailings when their growing conditions are optimized in the greenhouse.

This improvement occurred despite a diameter of graminoid roots always lower than 2 mm (fine roots) for all tested plants. Yet *Bodner et al. (2014)* emphasize that roots with diameters greater than 0.42 mm and roots of perennial species have the greatest effect on substrate macroporosity increase. The thicker the roots, the greater the pressure which allows them to penetrate dense soils (*Yunusa and Newton 2003*). In our study, both the annual *A. sativa* and the
perennial *B. inermis* had a mean diameter of roots greater than 0.42 mm and succeeded in improving the macroporosity of tailings in the short term. In addition to a direct effect of coarse plant roots on macroporosity through biopore creation, root length and biomass were reported to be positively correlated to soil aggregation (*Angers and Caron 1998*). Moreover, fine and extended roots like those of graminoid species are particularly effective in forming stable aggregates (*Oades 1984, Tisdall 1991*), which may have contributed to macropore formation. Several root parameters may be implicated in macroporosity increase since the tested species showed differing root characteristics. Above all, in our study, macroporosity improvement was related to root biomass production by graminoids, as overall the two variables were positively correlated (p = 0.099). *B. inermis* was the most effective graminoid at improving the macroporosity of tailings, probably due to its greater root biomass. But its larger root diameter (*Bodner et al. 2014*) and greater root volume compared to all other species may also have participated in maximizing the improvement. *Bromus inermis* could therefore be particularly useful in seeding mixes that aim to improve the structure of tailings. *A. sativa*, an annual graminoid, was able to efficiently increase macroporosity in just one growing season through maximal root biomass, length, and number of tip production. Both *A. sativa* and *B. inermis* root biomasses were also individually positively related to the macroporosity of tailings. However, perennial graminoids are reported to be more efficient than annuals for soil structure improvement (*Angers and Caron 1998*). Thus, perennials such as *B. inermis* may show better performance over a longer period of time than two months. In another experiment, *P. arundinacea* was reported to have greater root biomass than *B. inermis* and *L. perenne* (*Bolinder et al. 2002*). However, this was not the case in our experiment, neither in peat, nor in tailings.

In the field, graminoids had a low cover even three years after seeding, and macroporosity was similar whether tailings were seeded or not. According to our third hypothesis, the process of
macroporosity improvement due to root growth may be slower under field conditions than under ideal light, temperature, and watering conditions of the greenhouse. However, we also found that the macroporosity of tailings without any plant growth was lower in the field experiment than under greenhouse conditions, which may have further restricted graminoid root development.

The values of macroporosity found in tailings freshly deposited in the facility (2.6%) were twice or more lower than in the tailings in pots under greenhouse conditions (7%), or three years after truck transport and mechanical shovel placement in the field experiment (4.9 to 6.4%). Bodner et al. (2013) showed that mechanical loosening of soils increases their macroporosity, but this effect disappears with time as soils reconsolidate. This may imply that the method of deposition influenced the macroporosity of tailings, and that aqueous slurry deposition resulted in lower macroporosity than remobilization of more drained material by mechanical shovel (field experiment) or by hand (greenhouse experiment). The macroporosity of remobilized tailings may then decrease with time, as our finding of the lower macroporosity in the field experiment after three years compared to that measured in the short term under greenhouse conditions demonstrates. Mechanical and biological improvement of the macroporosity of tailings may be complementary, but biopores created by roots may have a greater effect on fluid circulation due to a greater vertical and lateral continuity, and be more durable than porosity created through mechanical tillage (Yunusa and Newton 2003).

Other characteristics of graminoid species—in particular, their competitive ability to absorb water, nutrients, and light—should be considered to foster the development of the roots of other plant species after seeding. For example, the negative competitive effect of graminoid species vis-à-vis trees has been highlighted in studies of tree planting on mine substrates (Kost et al. 1998; Skousen et al. 2006; Halofsky and McCormick 2005). When mines are established in forested
landscapes, the seeding of graminoid species to revegetate tailings may thus slow plant succession towards forest. However, on mine tailings specifically, one study focused on graminoid–tree interactions and demonstrated a positive effect of a graminoid species, *Panicum virgatum* (Choi and Wali 1995). In mine tailings habitats where concomitant stresses are occurring, the competitive effects of seeded graminoid species for resources could thus be compensated by the decrease of some stresses in their vicinity, such as lack of air for root respiration, extreme temperatures, and wind exposure. Yet, according to the stress gradient hypothesis (Bertness and Callaway 1994), plant interactions could change from negative (competition) to positive (facilitation) when stress exposure increases, especially under cold climates (Callaway et al. 2002). *A. sativa* is often used as a nurse plant for tailings revegetation. The fact that it dies after one season may limit its competitiveness with other plants’ seedlings. On the other hand, *B. inermis*, *L. perenne*, and *P. arundinacea* grow to a higher maximal height and may be highly light-competitive with young tree seedlings.

**Conclusion**

In the controlled-environment study, plants with differing root morphologies improved tailings macroporosity, which highlights the fact that plants can modify a tailings structure through different strategies. Root biomass was directly related to improved macroporosity for all graminoid species studied. Larger root diameter, greater root volume, and increased success rate for perennial *B. inermis* resulted in maximal improvement, while annual *A. sativa* achieved similar improvements as perennial species. Thus, graminoids have the potential to be used as primer-species on mine tailings, providing that their development is adequate. In any case, perennial graminoids with low competitive ability should be selected.
The development of plant roots may represent a great challenge in freshly deposited tailings in the facility, which showed very low macroporosity, and plant development may benefit from tailings remobilization after drainage, for example by ploughing. However, graminoid development in tailings under field conditions remained low and was insufficient to improve macroporosity, compared to more favourable greenhouse conditions.

Acknowledgements

We thank Mine Canadian Malartic for providing the tailings for the experiment, as well as the Research Institute on Mines and the Environment and the Commission scolaire Harricana, Amos, Quebec, for providing laboratory and technical equipment. This research was funded by a grant to M. Guittonny-Larchevêque from the Foundation of Université du Québec en Abitibi-Témiscamingue. This research was made possible through student hosting (Y. Meddeb) from Université de Montpellier 1 (France).

References


Tables

**Table 1.** Initial tailings characteristics. Mean (SE); n = 3. All values are expressed on a dry matter basis.

<table>
<thead>
<tr>
<th></th>
<th>Tailings</th>
<th>Regulatory threshold** (residential lands)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.9 (0.4)</td>
<td></td>
</tr>
<tr>
<td>OM*</td>
<td>0.1 (0.01)</td>
<td></td>
</tr>
<tr>
<td>EC*</td>
<td>8 (1)</td>
<td></td>
</tr>
<tr>
<td>Total N</td>
<td>0.04 (0.01)</td>
<td></td>
</tr>
<tr>
<td>Total P</td>
<td>0.68 (0.03)</td>
<td></td>
</tr>
<tr>
<td>Olsen P</td>
<td>bdl*</td>
<td></td>
</tr>
<tr>
<td>Total K</td>
<td>7.7 (1.7)</td>
<td></td>
</tr>
<tr>
<td>Total Ca</td>
<td>14.4 (2.6)</td>
<td></td>
</tr>
<tr>
<td>Total Mg</td>
<td>14.8 (0.3)</td>
<td></td>
</tr>
<tr>
<td>Total Na</td>
<td>0.5 (0.2)</td>
<td></td>
</tr>
<tr>
<td>Total Al</td>
<td>13.4 (0.4)</td>
<td></td>
</tr>
<tr>
<td>Total Fe</td>
<td>32.0 (2.7)</td>
<td></td>
</tr>
<tr>
<td>Total B</td>
<td>2.4 (1.1)</td>
<td></td>
</tr>
<tr>
<td>Total Cd</td>
<td>0.1 (0.1)</td>
<td>5</td>
</tr>
<tr>
<td>Total Cr</td>
<td>194 (29)</td>
<td>250</td>
</tr>
<tr>
<td>Total Cu</td>
<td>53 (2)</td>
<td>100</td>
</tr>
<tr>
<td>Total Mn</td>
<td>442 (9)</td>
<td>1000</td>
</tr>
<tr>
<td>Total Ni</td>
<td>79 (13)</td>
<td>100</td>
</tr>
<tr>
<td>Total Pb</td>
<td>43 (23)</td>
<td>500</td>
</tr>
<tr>
<td>Total Zn</td>
<td>84 (7)</td>
<td>500</td>
</tr>
</tbody>
</table>

* OM: organic matter; EC: electrical conductivity; bdl: beyond detection limit

** Data Available online at [http://legisquebec.gouv.qc.ca/fr/ShowDoc/cr/Q-2,%20r.%2037/](http://legisquebec.gouv.qc.ca/fr/ShowDoc/cr/Q-2,%20r.%2037/)

(Government of Quebec 2014)
Table 2. Plant germination, survival, and success rates for the five tested species in tailings and peat in the greenhouse experiment. Frequencies are calculated for five seeds by pot and plant. Mean frequencies, n = 10 pots. * Significant species effect at p < 0.05

<table>
<thead>
<tr>
<th>Species</th>
<th>Germination</th>
<th>Survival</th>
<th>Success</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tailings %</td>
<td>Peat %</td>
<td>Tailings %</td>
</tr>
<tr>
<td>A. sativa</td>
<td>31</td>
<td>33</td>
<td>91</td>
</tr>
<tr>
<td>B. inermis</td>
<td>56</td>
<td>100</td>
<td>91</td>
</tr>
<tr>
<td>L. perenne</td>
<td>46</td>
<td>50</td>
<td>61</td>
</tr>
<tr>
<td>P. arundinacea</td>
<td>30</td>
<td>90</td>
<td>65</td>
</tr>
<tr>
<td>F. rubra</td>
<td>57</td>
<td>55</td>
<td>56</td>
</tr>
<tr>
<td>$\chi^2$ test</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>
Table 3. Plant root and aerial biomasses after 2 months of growth in the greenhouse experiment and associated tailings macroporosity and density in each pot for the five tested species (A. sativa, B. inermis, L. perenne, P. arundinacea, and F. rubra). Mean (SE); n = 5 pots. Within a variable, means that do not differ among species at the 0.05 level are noted with the same letter (a < b < c)

<table>
<thead>
<tr>
<th>Species</th>
<th>Root biomass by pot g</th>
<th>Root biomass by plant g</th>
<th>Aerial biomass by pot g</th>
<th>Aerial biomass by plant g</th>
<th>Macroporosity %</th>
<th>Bulk density g.cm⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. sativa</td>
<td>0.36 (0.09) a</td>
<td>0.26 (0.05) c</td>
<td>4.8 (0.31) b</td>
<td>3.2 (0.25) b</td>
<td>13.8 (0.7) a</td>
<td>1.3 (0.04) a</td>
</tr>
<tr>
<td>B. inermis</td>
<td>0.53 (0.08) b</td>
<td>0.23 (0.05) bc</td>
<td>1.1 (0.30) a</td>
<td>0.5 (0.24) a</td>
<td>14.4 (0.6) b</td>
<td>1.3 (0.04) a</td>
</tr>
<tr>
<td>L. perenne</td>
<td>0.15 (0.09) a</td>
<td>0.06 (0.05) ab</td>
<td>0.4 (0.31) a</td>
<td>0.1 (0.25) a</td>
<td>11.6 (0.7) a</td>
<td>1.4 (0.04) a</td>
</tr>
<tr>
<td>P. arundinacea</td>
<td>0.09 (0.10) a</td>
<td>0.04 (0.06) ab</td>
<td>0.4 (0.31) a</td>
<td>0.2 (0.25) a</td>
<td>12.4 (0.7) a</td>
<td>1.3 (0.04) a</td>
</tr>
<tr>
<td>F. rubra</td>
<td>0.08 (0.09) a</td>
<td>0.02 (0.07) a</td>
<td>0.4 (0.31) a</td>
<td>0.1 (0.25) a</td>
<td>13.1 (0.7) a</td>
<td>1.3 (0.04) a</td>
</tr>
</tbody>
</table>
Table 4. Plant root morphological characteristics after 2 months of growth in each pot of the greenhouse experiment for the five tested species (*A. sativa*, *B. inermis*, *L. perenne*, *P. arundinacea*, and *F. rubra*). Mean (SE); n = 5 pots. Within a variable, means that do not differ among species at the 0.05 level are noted with the same letter (a < b)

<table>
<thead>
<tr>
<th>Species</th>
<th>Root mean diameter</th>
<th>Root length density</th>
<th>Root tips number by pot</th>
<th>Root volume by pot</th>
<th>Specific root length</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>A. sativa</em></td>
<td>0.45 (0.04) a</td>
<td>0.8 (0.06) b</td>
<td>13 (1.4) b</td>
<td>1.9 (0.9) a</td>
<td>5,575 (3016) a</td>
</tr>
<tr>
<td><em>B. inermis</em></td>
<td>0.56 (0.03) b</td>
<td>0.7 (0.06) b</td>
<td>6 (1.3) a</td>
<td>6.2 (0.9) b</td>
<td>4,450 (2844) a</td>
</tr>
<tr>
<td><em>L. perenne</em></td>
<td>0.39 (0.04) a</td>
<td>0.7 (0.07) b</td>
<td>5 (1.5) a</td>
<td>0.8 (1) a</td>
<td>6,125 (3284) a</td>
</tr>
<tr>
<td><em>P. arundinacea</em></td>
<td>0.32 (0.04) a</td>
<td>0.3 (0.07) a</td>
<td>3 (1.6) a</td>
<td>0.2 (1) a</td>
<td>13,884 (3434) a</td>
</tr>
<tr>
<td><em>F. rubra</em></td>
<td>0.40 (0.04) a</td>
<td>0.5 (0.06) b</td>
<td>2 (1.5) a</td>
<td>0.6 (0.9) a</td>
<td>7,047 (3179) a</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Species</th>
<th>Root density</th>
<th>Root length by plant</th>
<th>Root tips number by plant</th>
<th>Root volume by plant</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>A. sativa</em></td>
<td>0.4 (0.05) a</td>
<td>340 (39) b</td>
<td>6,472 (770) b</td>
<td>0.9 (0.38) a</td>
</tr>
<tr>
<td><em>B. inermis</em></td>
<td>0.1 (0.05) a</td>
<td>214 (37) a</td>
<td>1,683 (725) a</td>
<td>2.0 (0.36) b</td>
</tr>
<tr>
<td><em>L. perenne</em></td>
<td>0.3 (0.06) a</td>
<td>159 (43) a</td>
<td>1,270 (838) a</td>
<td>0.2 (0.41) a</td>
</tr>
<tr>
<td><em>P. arundinacea</em></td>
<td>0.6 (0.06) b</td>
<td>82 (44) a</td>
<td>778 (876) a</td>
<td>0.1 (0.43) a</td>
</tr>
<tr>
<td><em>F. rubra</em></td>
<td>0.2 (0.06) a</td>
<td>94 (41) a</td>
<td>419 (811) a</td>
<td>0.1 (0.40) a</td>
</tr>
</tbody>
</table>
Figure captions

Figure 1. Linear regressions between tailings macroporosity (% volume of pores > 30 µm) and root biomass developed in each pot (g) for all graminoid species after two months of growth in the greenhouse experiment.
$y = 3.2531x + 12.265$

$R^2 = 0.208$