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Substrate comparison for short-term success of a multispecies tree plantation in thickened tailings of a boreal gold mine

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Abstract Tree planting can accelerate the conversion of mine sites into forests after closure, thereby decreasing environmental impacts on forested landscapes. However, few studies have investigated tree planting to reclaim metalliferous mine tailings. To mitigate the restrictions to tree growth associated with mine tailings, soils and amendments can be used. A 2-year field experiment was conducted in low-sulphur thickened tailings of a gold mine under boreal conditions. We aimed to select the best substrate to establish multispecies plantations. We compared the effects of (1) increasing the topsoil volume and thickness, (2) amending tailings and overburden with greenwaste compost, and (3) direct planting in the tailings on the establishment of *Larix laricina* (Du Roi) K. Koch, *Pinus banksiana* Lamb., *Salix viminalis* L., and *P.* × *canadensis* Moench × *P. maximowiczii* A. Henry. Trees did not survive the first winter when planted directly in tailings, but compost addition to tailings increased survival through substrate structure improvement. However, survival and growth remained lower for three species planted in the compost and tailings mixture compared to soil treatments. Tree roots did not colonize tailings underlying the compost and tailings mixture, whereas roots were present in tailings underlying soil layers. In overburden amended with compost, survival and growth rates were similar to those for trees planted in topsoil of the same thickness. Adding compost to tailings or mineral soil improved the P nutrition of trees, which appeared a limiting nutrient in this study. Tree growth was influenced by topsoil thickness (50 vs. 20 cm) rather than volume (20 cm layer vs. 20 cm deep planting holes); trees grown in the thicker topsoil showed the highest N nutrition and aerial growth.

Keywords Mine revegetation · Mine wastes · Soil thickness · Compost amendment · Trace metals

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Introduction

Tree planting is a practical means to integrate reclaimed mine sites in natural forested landscapes. It also restores biodiversity and enables traditional land use by local communities. Trees accelerate the conversion of degraded lands into forests (Parrotta et al. 1997) because they facilitate the colonization of native plant species from adjacent forest ecosystems at canopy closure (Strong 2000). Trees have been used extensively worldwide to revegetate surface mine sites, particularly coal mines (Emerson et al. 2009; Bending and Moffat 1999; Macdonald et al. 2015; Maiti 2007; Mosseler et al. 2014). However, few studies have examined tree planting to reclaim metalliferous mine tailings (Bjugstad 1986; Boyter et al. 2009; Renault et al. 2008; Larchevêque et al. 2013).

Metalliferous mill tailings consist of the finely crushed ore (70–80 % of particles sized 2–80 µm, Aubertin et al. 2002) that remains after valuable metals have been removed. They are transported (mostly pumped) from the mine plant with water and deposited as slurry in tailings facilities. They are difficult to revegetate because they lack organic matter, nutrients, and soil organisms (Burger and Zipper 2002). Tailings also lack physical structure, can exhibit extreme pH, and may contain potentially phytotoxic levels of salts and heavy metals (Tordoff et al. 2000). Of the milling wastes, thickened tailings (50–70 % solids by mass when deposited) provide the material for an emerging surface deposition technology (Robinsky et al. 1991) that reduces water consumption, particularly for larger operations such as open-pit mines, which process low-grade ores, or mines that are located in arid areas. Their basic properties are similar to those of conventionally deposited (slurried) tailings (Bussière 2007), but they have a more uniform (homogeneous) grain-size distribution in the tailings facility (Al and Blowes 1999) and low hydraulic conductivities (Barbour et al. 1993).

Trees can be planted directly in low-sulphur tailings given the low metal toxicity (Tordoff et al. 2000). However, to improve tree planting success, tailings can be mixed with low-cost organic amendments such as sewage sludge, domestic refuse, peat, or topsoil (Tordoff et al. 2000; Larchevêque et al. 2012, 2013). An organic matter content of 4 % is recommended to improve the tailings structure (better infiltration rate, lower density) (Bendfeldt et al. 2001) and to promote slow, sustainable nutrient release (Dere et al. 2008; Stehouwer et al. 2006). Nowadays, topsoil (i.e., superficial soil containing organic matter) and overburden (i.e., soil overlying bedrock) are usually saved for revegetation purposes (Cooke and Johnson 2002; Macdonald et al. 2015). They are applied as layers over mine wastes to improve revegetation success, especially topsoil (Holl 2002; Kost et al. 1998). However, topsoil is often available in limited quantities, relative to the large mine surfaces to be revegetated. This limits the thickness of the applied layers and the area of treated surfaces, and may necessitate the use of complementary solutions such as overburden and amendments. If the soil volume is too low, tree survival and growth may be limited due to inadequate moisture and nutrient reserves (Tordoff et al. 2000). In boreal regions, where nutrient cycling is slow (McMillan et al. 2007) because of cold temperatures and a short growing season, nutrient reserves in the substrate may be even more critical for adequate nutrition of the planted trees. Moreover, tree root growth may be restricted to the superficial soil or amended tailings due to unsuitable structure of the underlying tailings (Larchevêque et al. 2013; Meredith and Patrick 1961; Evanylo et al. 2005; Michels et al. 2007).

A field experiment was conducted in low-sulphur thickened tailings of a gold mine under boreal conditions. The main study objectives were to compare the effects of (1) increasing the volume of topsoil, (2) the use of compost amendment to improve the tailings and overburden soil quality, and (3) direct planting in the tailings with mineral fertilization on the establishment of four species of planted trees adapted to boreal conditions (tamarack, jack pine, basket willow, and hybrid poplar). We aimed to select the best substrate for establishing multispecies plantations in order to rapidly afforest the tailings facility. Tree survival, aerial and root growth, and nutrient and trace metal concentrations were monitored for 2 years and related to the substrate structural and chemical properties.

Our working hypotheses were that (1) trees do not survive when planted directly in tailings, even with mineral fertilization; (2) root growth is restricted in tailings due to their poor structural properties (low macroporosity, high density); (3) mixing tailings with greenwaste compost to obtain 4 % organic matter improves tailings' structure and tree survival; (4) mixing mineral soil with compost (23 % DM basis) produces tree survival and growth rates similar to those for the use of topsoil; (5) the lower the soil volume (i.e., from planting holes to thin and thick soil), the lower the tree growth, with no impact on tree survival due to the low toxicity of the underlying tailings; and (6) trees will have low trace metal concentrations due to the neutral pH of the tailings.

Materials and methods

Site description

The Canadian Malartic gold mine (Malartic, Quebec, Canada, 48°13′N, 78°12′W) is a large open-pit mine that begun 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.), white 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 18–19 °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).

Tailings, soils, and compost

The ore from the Canadian Malartic mine is mineralized greywacke. The tailings have low sulphur content (around 1 % S) and contain calcite, which can neutralize acidity. The tailings consist of finely milled wastes from the gold extraction process (cyanide leaching), with 86 % particles <80 μm and a uniformity coefficient ($C_U = D_{60}/D_{10}$) of 11.1 (D_{10}: 0.003 mm and D_{60}: 0.034 mm, D_{10} and D_{60} being the size of the sieve at which 10 and 60 % of the particles pass, respectively). The tailings were deposited in the facility as thickened tailings (around 60 % of solids by mass) less than 6 months before the experiment. The tailings had been treated for cyanide destruction (using SO_2/O_2 technology), which reduced free CN^- concentrations to less than 20 mg kg^{-1}. Table 1 presents the tailings chemical characteristics. The mean trace metal concentrations are below Quebec's regulation thresholds for residential lands, except for total Cd, which is slightly above threshold.

The tailings were transported by truck from the tailings facility to the experimental site in April 2012. The experimental cell (120 m × 50 m) consisted of waste rock walls

Table 1 Characteristics of initial soils, tailings, and compost

	Overburden topsoil	Overburden mineral soil	Compost	Tailings	Regulation threshold[b] (residential lands)
pH	5.1 (0.1)	7.2 (0.1)	6.7 (0.01)	7.9 (0.1)	
Clay[a] (%)	42 (5)	33 (5)		12 (1)	
Silt[a] (%)	27 (1)	15 (1)		50 (1)	
OM[a] (%)	17 (3)	1.1 (3)	41 (1)	0.1 (2)	
C/N	22 (7)	17 (5)	20 (2)	4 (1.5)	
EC[a] (cS m^{-1})	7 (1)	10 (1)	21 (0.5)	10 (1)	
Total N (g kg^{-1})	4.3 (0.3)	0.4 (0.3)	12 (1)	0.1 (0.5)	
Total P (g kg^{-1})	0.6 (0.04)	0.6 (0.04)	2.5 (0.2)	0.7 (0.01)	
Olsen P (mg kg^{-1})	3.6 (0.7)	5.1 (0.7)	252 (7)	8 (5)	
Total K (g kg^{-1})	3.6 (0.05)	2.7 (0.05)	6.5 (0.2)	9 (0.4)	
Total Ca (g kg^{-1})	11 (1)	9 (1)	31 (1.3)	17 (2)	
Total Mg (g kg^{-1})	11 (0.1)	11 (0.1)	4 (0.01)	14 (0.6)	
Total Na (g kg^{-1})	0.3 (0.02)	0.4 (0.02)	0.4 (0.01)	0.5 (0.05)	
Total Al (g kg^{-1})	17 (1)	13 (1)	3.5 (0.3)	14 (1)	
Total Fe (g kg^{-1})	27 (2)	24 (2)	9 (0.3)	34 (2)	
Total B (mg kg^{-1})	6.3 (0.3)	3.9 (0.3)	21 (0.6)	0.8 (0.5)	
Total As (mg kg^{-1})	7.7 (0.5)	5.7 (0.5)	5 (0.8)	5.4 (1.4)	30
Total Cd (mg kg^{-1})	0.6 (0.15)	0.4 (0.15)	2 (0.07)	6 (0.2)	5
Total Co (mg kg^{-1})	5.8 (0.4)	6.0 (0.4)	1.0 (0.15)	5.9 (1.5)	50
Total Cr (mg kg^{-1})	120 (14)	116 (14)	10 (0.1)	168 (10)	250
Total Cu (mg kg^{-1})	58 (12)	31 (12)	42 (4)	52 (2)	100
Total Mn (mg kg^{-1})	344 (26)	367 (26)	427 (11)	441 (16)	1000
Total Mo (mg kg^{-1})	2.3 (0.2)	1.6 (0.3)	1.1 (0.4)	8.6 (0.6)	10
Total Ni (mg kg^{-1})	64 (7)	51 (7)	11 (1)	69 (9)	100
Total Pb (mg kg^{-1})	22 (4)	13 (4)	24 (1)	18 (100)	500
Total Zn (mg kg^{-1})	83 (5)	62 (5)	151 (5)	73 (4)	500

Mean (SE), n = 3

All values are expressed on a dry mass basis

[a] Clay: particles <2 μm, silt: particles <50 μm, *OM* organic matter, *EC* electrical conductivity

[b] Quebec Government (2014)

(0.5–1.5 m high) covered with a geotextile liner to retain the tailings while allowing water drainage.

The overburden soil used to cover the tailings was luvic gleysol (Agriculture and Agri-Food Canada 2012) obtained from a swampy area above the pit that had been previously colonized by conifers. The soil was stockpiled for 36 months in 7 m high piles with a 2.5:1 slope before use. The overburden topsoil consisted of the uppermost 30 cm of dark (organic-rich) soil (O and A horizons) that had been set aside prior to excavating the open pit. The overburden subsoil consisted of the remaining mineral sandy clay loam (several meters thick) that was excavated down to bedrock after the overburden topsoil had been removed. Overburden topsoil and mineral soil (subsoil) were stored in separated piles.

The greenwaste compost used as amendment to improve the structure of the mineral soil and tailings was obtained from the St-Henri-de-Lévis facility in Quebec (Biogénie, Varennes, QC, Canada). It was composed mainly of leaves and lawn residues as well as a small proportion of small branches and tree bark. It was passed through a 1.25 cm sieve before use. Table 1 presents the soil and compost characteristics.

Plant material and growth conditions

The conifers are native species of the surrounding forest, but fast-growing broadleaved trees were selected for boreal conditions. All trees were produced locally by the Ministère de l'Énergie et des Ressources Naturelles du Québec (MERN). Two-year-old jack pine and tamarack seedlings were grown in 200 cm^3 containers on peat substrate under field conditions, watered to maintain substrates at approximately 30 % water volumetric content, and fertilized (75 and 200 ppm of 34-0-0 each week the second year of growth for tamarack and jack pine, respectively), to reach a minimum nitrogen concentration of 1.7 % (on a dry mass basis) in the foliage before planting. Trees had mean height of 40.4 and 39.2 cm, and mean diameter of 5.8 and 5.6 mm at planting, respectively for tamarack and jack pine. Hybrid poplar and willow stock consisted of clonally propagated 1-year-old whips (1 m long cuttings with 16.4 and 17.6 mm basal diameters, respectively for willow and poplar) from *P.* × *canadensis* Moench × *P. maximowiczii* A. Henry (DN × M, 916004), and *Salix viminalis* L. (basket willow). Willow mother trees were grown in the field in sandy soils without any fertilizer addition (foliar N concentration of 2 % on average), while hybrid poplar mother trees were watered twice or once daily and fertilized with 20-20-20 mineral fertilizer once every 2 weeks until a cumulative amount of 100 kg N ha^{-1} was spread over the growing season.

The field experiment was set up on thickened tailings in mid-June 2012. Unrooted whips were planted to a depth of 30 cm in the substrates. All trees were fertilized at planting with 15 g ammonium nitrate (34.5-0-0) and 15 g triple superphosphate (0-45-0) using placed fertilization (van den Driessche 1999), where the fertilizer was inserted into a slit made with a spade near the base of each tree (20 cm from the tree and 15 cm deep). Weed cover in the tested treatments remained lower than 20 % of soil surface in July 2013, the second year after planting; thus, no weed control was needed.

Experimental design

A split-plot design was used: 18 experimental plots = 3 blocks (replicates) × 6 treatments (whole plot factor: TS50, 50 cm overburden topsoil; TS20, 20 cm overburden topsoil; TSho, planting holes filled with topsoil, MS20, 20 cm overburden mineral soil + compost; TC, tailings mixed with compost; and T, direct planting in tailings) × 4 tree species (sub-plot factor: jack pine, tamarack, DN × M poplar, basket willow) × 9 trees per factor combination. Each plot covered an 11 m × 11 m (TS50, TS20, TC, and T) or 16 m × 16 m (MS20 and TSho) area. The soils (TS50, TS20, MS20) were applied over the tailings by a mechanical shovel in May 2012. The mineral soil (MS20) was then mixed locally with 0.1 m^3 of fresh greenwaste compost (i.e., 65 kg at a proportion of 23 % on a dry mass (DM) basis) by a mechanical shovel in 1 m^2 × 20 cm deep planting holes. For the TSho treatment, planting holes (1 m^2 × 20 cm) were dug in the tailings and filled with topsoil by a mechanical shovel. The TC treatment was then applied: a 6 cm thick layer of compost was deposited over the tailings surface and mixed to a 15 cm depth by a compact loader (T110, Bobcat company, West Fargo, ND) equipped with a rotovator. The compost amendment contained 179 t ha^{-1} of dry compost at a proportion of 13 % on a dry mass basis.

Trees were spaced 1 m × 1 m apart, and a 3 m buffer zone was kept free of trees at the edge of the treatment areas. However, for the MS20 and TSho treatments, the planting holes were separated from each other by 1 m, for 2 m × 2 m tree spacing.

Measurement, sampling, and analysis

Substrate measurement

Three random samples were taken before planting (May 2012) for soil and compost characterization (Table 1). Planting substrates were then sampled at planting in mid-June 2012 to characterize each treatment. Each analyzed soil sample was a composite of four samples, one per tree species, taken at the base of the fifth tree in each plot ($N = 18$, 1 sample per plot). Soil and compost nutrients were analyzed on sieved (2 mm mesh), finely ground, oven-dried samples (50 °C) (Lakehead University Centre for Analytical Services, Thunder Bay, ON, Canada). Total N and organic C were analyzed by the Dumas combustion method (LECO CNS 2000, Mississauga, ON). Organic matter concentrations were calculated as 1.72× organic carbon (C). Following HNO_3-HCl digestion, sample concentrations of total P, K, Ca, Mg, Na, Al, As, B, Cd, Co, Cr, Cu, Fe, Mo, Mn, Ni, Pb, and Zn 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), pH was determined in a saturated paste extract, and electrical conductivity was determined in a 1:2 water solution. Soil texture was determined using the Bouyoucos hydrometer method (Bouyoucos 1962).

Undisturbed 100 cm^3 substrate samples were taken with a double cylinder soil sampler at 0–10 cm depth in each plot at the same location and date as for soil analysis, but the samples were not bulked (1 sample per tree species and treatment, $N = 72$). Water retention properties of the substrates were determined using Klute's (1986) and Cassel and Nielsen's (1986) procedures. In the lab, undisturbed substrate samples (5 cm diameter, 100 cm^3) were brought to saturation under vacuum and weighed (W1). They were then placed on the porous surface of a sand box apparatus (Eijkelkamp Agrisearch Equipment, The Netherlands) and brought to equilibrium at a tension of −10 kPa (field capacity, FC). They were then weighed (W2) and oven-dried (105 °C, 48 h) prior to final weighing (W3). Macroporosity, or air-filled porosity (%), and dry bulk density (g cm^{-3}) were estimated with the following formulas:

$$\text{Macroporosity} = (\text{W1} - \text{W2})/100\ \text{cm}^3 \times 100$$

$$\text{Field capacity} = (\text{W2} - \text{W3})/100\ \text{cm}^3 \times 100$$

$$\text{Bulk density} = \text{W3}/100\ \text{cm}^3.$$

Plant measurement

Survival, stem height, and basal diameter were measured at planting and at the end of each growing season in 2012 and 2013 for each planted tree. In July 2013, 10–20 fully matured leaves (broadleaved) or 3–5 branches of the year (conifers) were sampled on the fifth tree for each treatment × species combination ($N = 72$). Sampled leaves were oven-dried (50 °C), ground, and analyzed for total N, P, Ca, Mg, and K, and for the same total metal concentrations as for soils, using the above-mentioned analytical methods. On 23 September 2013, the fifth tree of each treatment by species combination (N = 36) was harvested for aboveground biomass assessment. Trees were separated into stems and leaves. The plant parts were then oven dried at 50 °C for 48 h and weighed.

At the end of September 2013, tree root presence was assessed in the treatment substrates and the underlying tailings by coring with an 8 cm diameter auger (core 750 cm^3) (Eijkelkamp Agrisearch Equipment, The Netherlands). The tailings alone treatment was not sampled due to tree death. The first core corresponded to the total depth of the thin soil layers (0–20 cm) MS20, TS20, and TSho, or to the tailings mixed with compost. The second core was sampled at 20–30 cm in the tailings underlying the thin treatments. Soil cores were taken on the diagonals of the square formed by the 4 central planted trees of each plot, one tree per species, at 40 cm of the tree foot. A total of 72 cores × 2 depths were sampled (3 repetitions by tree species by treatment). In the laboratory, tree roots were washed from the soil above a fine metallic grid. When weeds are occasionally present (mainly herbaceous species), they were separated manually from tree roots based on differences in colour, texture (light coloured and less lignified herbaceous roots), and smell. Scanned images of fresh roots were analyzed with Winrhizo software (regular version, Regent Instruments Inc., Sainte-Foy, QC) for root length by diameter class, and mean diameter. Then, root length density (RLD, cm cm^{-3} of substrate) of fine roots (diameter <2 mm), as well as the ratio of coarse (diameter >2 mm) to fine root length (in %), were calculated. Finally, the root samples were oven-dried at 80 °C and weighed to measure total root biomass by soil volume (root soil density, g m^{-3}).

Statistical analysis

Survival data were compared using the χ^2 test (PROC FREQ, SAS V.9.2, SAS Institute Inc., Cary, NC). Because only two trees (1 willow and 1 tamarack) survived the second year when planted in tailings, the T treatment was removed from further tree analysis. Soil characteristics data were subjected to one-way analysis of variance (treatment effect, PROC GLM). For final height and diameter (height and diameter at planting as covariables), plant element concentrations, and parameters of roots sampled at 0–20 cm (poplar and willow only), the data were subjected to two-way analysis of variance (treatment, species) (PROC GLM or MIXED). Pearson correlations between (1) substrate macroporosity and density, and (2) foliar macronutrient concentrations, versus tree growth parameters (height and diameter increments the first and second year after planting, aerial biomasses, root length, root soil densities, and root mean diameter) were analyzed (SAS, PROC CORR). All tested factors were fixed effects and the block factor was considered a random effect. When effects for a given variable were significant, least-square means were estimated (LS MEANS statement) and Tukey tests were conducted to separate the means. Overall significance for the analyses was set at alpha = 0.05.

Results

Substrate characteristics

The tailings (T) showed greater bulk density (1.33 g cm^{-3}) and lower macroporosity (6 %) compared to the other treatments, but field capacity was quite similar among all treatments (around 40 %) (Table 2). They also had much lower total N and OM concentrations compared to the other treatments. The topsoil treatments had lower pH and greater organic matter and C to N ratio than the tailings (TC) and mineral soil mixed with compost (MS20), but similar total N concentrations. Both compost and tailings were richer in total K and Mn than the soils, resulting in approximately twice the concentrations of K and slightly greater concentrations of Mn in the TC treatment compared to the other treatments. The compost also significantly enriched the mineral soil (MS20) and tailings (TC) in total P and Ca and available P compared to the topsoil treatments. In the treatments, the only trace metal that exceeded the regulation threshold for residential use was total Cd, with slightly greater total concentration in tailings and TC treatments compared to soil treatments (Table 2).

Tree survival and growth

After two growing seasons, all trees that were planted directly in the tailings (T treatment) were dead (Fig. 1). In contrast, survival rates were similar for all species, exceeding 90 % for all soil treatments (TS20, TS50, MS20, TSho), although they declined in the mixed tailings and compost treatment (TC) in the second year for both conifers, and as early as the first year for poplar. Willow survival was maximal regardless of treatment, for both years.

Regardless of species (except for jack pine height), the thicker topsoil (TS50) consistently obtained the highest final height, greatest final diameter (Fig. 2), and greatest foliar (all tree species) and shoot (broadleaved only) biomasses (results not shown) compared to all other treatments. At the opposite, the TC treatment obtained the worst values for the same parameters, with differences between TC and thin soil treatments depending on species. For all species, mineral soil + compost (MS20) obtained similar growth (height and diameter) to that for thin topsoil (TS20) and topsoil holes (TSho), except for pine diameter. In the short term, no growth difference was found between trees planted in 20 cm topsoil and in topsoil planting holes.

Conifer root development was low 2 years after planting since roots were not always found in each sampled core, especially in the mineral soil, and in tailings mixed with compost (only one core on the three sampled contained roots). On the contrary, fast-growing poplar and willow roots were nearly always found in sampled cores at 0 cm to 20 cm of each treatment, but treatments had no effect on their total biomass, mean diameter, or root length density of fine roots (diameter <2 mm) (Table 3). Poplar and willow roots were mainly fine roots (diameter <2 mm) since the ratio of coarse to fine root length always remained below 5 %. Some roots of fast-growing poplars and willows were found in the tailings under the treatments using a soil layer but not under the tailings and compost mixture.

Element concentrations in trees

Treatment effect on foliar element concentrations was similar for all tested species, except for Ca, K, Zn, and N/P ratio (significant interactions between treatment and species factors). Table 4 presents the foliar concentrations of macronutrients among treatments and species, as well as the concentrations of metals for which the treatment effect was significant (Cd, Cu, Ni, and Zn). Trees planted in the thick topsoil (TS50) had higher N concentrations than trees planted in the other treatments (except for tamarack). Trees planted in the compost mixtures (TC and MS20) had higher P concentrations compared to

Table 2 Substrate characteristics at planting (mid-June 2012) of the treatments (T: tailings, MS20: 20 cm mineral soil + compost, TC: tailings mixed with compost, TS50: 50 cm topsoil, TS20: 20 cm topsoil, TSho: topsoil holes)

	Planting substrates					
	T	MS20	TC	TS50	TS20	TSho
Bulk density (g cm^{-3})	1.3 (0.1) c	1.1 (0.1) c	0.9 (0.1) a	0.9 (0.1) a	0.9 (0.1) ab	1.0 (0.1) ab
Macroporosity (% vol.)	6 (1) a	12 (1) b	12 (1) b	15 (1) b	14 (1) b	13 (1) b
Field capacity (% vol.)	42 (1.1) ab	38 (1.1) a	45 (1.1) b	43 (1.1) ab	40 (1.1) ab	42 (1.1) ab
pH	7.9 (0.1) c	7.3 (0.1) b	7.5 (0.1) b	6.3 (0.1) a	6.6 (0.1) a	6.3 (0.1) a
OM[a] (%)	0.1 (2) a	5 (2) ab	4 (2) a	14 (2) c	12 (2) c	11 (2) bc
C/N	4 (1.5) a	18 (1.5) b	15 (1.5) b	29 (1.5) c	26 (1.5) c	31 (1.5) c
EC[a] (cS m^{-1})	10 (1) bc	10 (1) bc	13 (1) c	7 (1) ab	5 (1) a	8 (1) abc
Total N (g kg^{-1})	0.1 (0.5) a	1.7 (0.5) b	1.5 (0.5) ab	2.7 (0.5) b	2.7 (0.5) b	2.0 (0.5) b
Total P (g kg^{-1})	0.7 (0.04) b	0.7 (0.04) b	0.9 (0.04) c	0.5 (0.04) a	0.6 (0.04) a	0.5 (0.04) a
Olsen P (mg kg^{-1})	7.7 (5.4) a	33.8 (5.4) b	36.8 (5.4) b	10 (5.4) a	10 (5.4) a	10 (5.4) a
Total K (g kg^{-1})	9 (0.4) b	4 (0.4) a	9 (0.4) b	3 (0.4) a	4 (0.4) a	3 (0.4) a
Total Ca (g kg^{-1})	17 (2) b	16 (2) b	19 (2) b	8 (2) a	9 (2) a	9 (2) a
Total Mg (g kg^{-1})	14 (0.6) c	11 (0.6) a	14 (0.6) bc	12 (0.6) ab	12 (0.6) ab	12 (0.6) ab
Total Na (g kg^{-1})	0.5 (0.05) b	0.3 (0.05) a	0.5 (0.05) b	0.2 (0.05) a	0.2 (0.05) a	0.2 (0.05) a
Total Al (g kg^{-1})	14 (1) a	10 (1) a	13 (1) a	13 (1) a	13 (1) a	12 (1) a
Total Fe (g kg^{-1})	34 (2) b	23 (2) a	32 (2) b	24 (2) a	25 (2) a	25 (2) a
Total As (mg kg^{-1})	5.4 (1.4) a	3.5 (1.4) a	2.8 (1.4) a	5.9 (1.4) a	7.1 (1.4) a	3.5 (1.4) a
Total Cd (mg kg^{-1})	6.0 (0.2) b	4.1 (0.2) a	5.7 (0.2) b	4.2 (0.2) a	4.4 (0.2) a	4.4 (0.2) a
Total Co (mg kg^{-1})	5.9 (1.5) a	6.9 (1.5) a	7.0 (1.5) a	7.2 (1.5) a	7.0 (1.5) a	7.7 (1.5) a
Total Cr (mg kg^{-1})	168 (10) a	163 (10) a	155 (10) a	162 (10) a	159 (10) a	152 (10) a
Total Cu (mg kg^{-1})	52 (2) b	37 (2) a	51 (2) b	38 (2) a	40 (2) a	42 (2) a
Total Mn (mg kg^{-1})	441 (16) b	355 (16) a	447 (16) b	329 (16) a	359 (16) a	347 (16) a
Total Mo (mg kg^{-1})	8.6 (0.6) b	2.3 (0.6) a	5.9 (0.6) b	2.5 (0.6) a	2.3 (0.6) a	2.7 (0.6) a
Total Ni (mg kg^{-1})	69 (9) a	70 (9) a	64 (9) a	94 (9) a	93 (9) a	143 (9) b

Table 2 continued

	Planting substrates					
	T	MS20	TC	TS50	TS20	TSho
Total Pb (mg kg^{-1})	18 (100) a	18 (100) a	21 (100) a	29 (100) a	33 (100) a	280 (100) a
Total Zn (mg kg^{-1})	73 (4) a	67 (4) a	81 (4) a	68 (4) a	71 (4) a	67 (4) a

All values are expressed on a dry mass basis

Mean (SE), n = 3

Treatments denoted with the same lower case letter do not differ significantly at $p = 0.05$

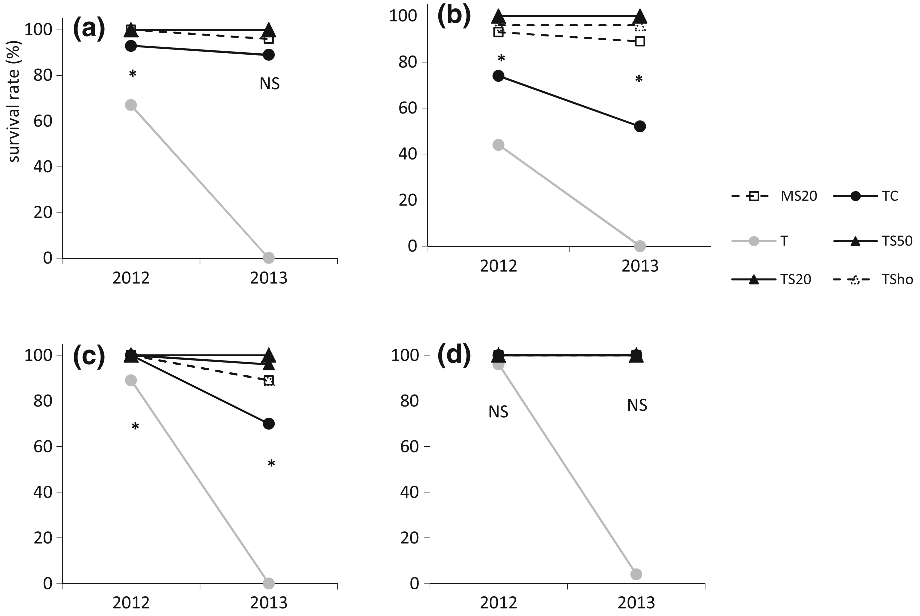

Fig. 1 Percent survival among treatments (T: tailings, MS20: 20 cm mineral soil + compost, TC: tailings mixed with compost, TS50: 50 cm topsoil, TS20: 20 cm topsoil, TSho: topsoil holes) for each growing season (2012, 1st growing season; 2013, 2nd growing season) for **a** tamarack, **b** DN × M poplar, **c** jack pine, and **d** basket willow. $n = 27$. Statistical comparisons were performed between treatments at each date: $*p < 0.05$, *NS* non-significant

topsoil treatments (except for jack pine, which showed greater Na concentration in this treatment compared to other treatments). Accordingly, N–P concentration ratio in willow leaves was the greatest in TS50 while it was the lowest in MS20 and TC. Tamarack K concentrations (MS20) and poplar K (TC) and Ca concentrations (MS20) were higher in leaves of trees planted in mixtures with compost, but did not differ significantly from those for all topsoil treatments. All tree foliage contained low trace metal concentrations [<phytotoxicity thresholds of Kabata-Pendias and Pendias (2001)], except for Zn in willow leaves of TS50 treatment, whose concentration appeared greater than in all other treatments (225 mg kg^{-1}). The same treatment with thick topsoil layer showed increased foliar

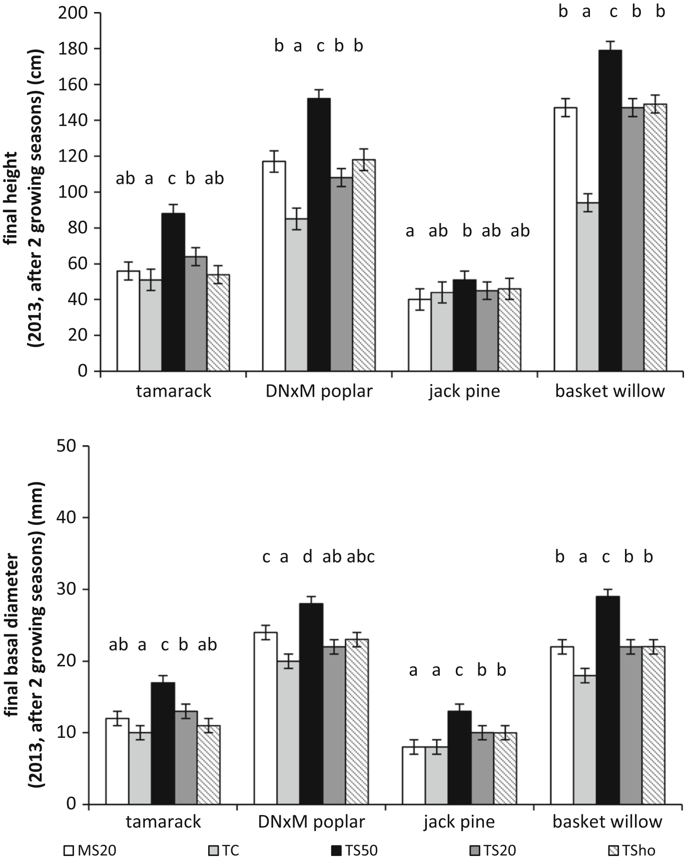

Fig. 2 Final height and basal diameter among treatments (T: tailings, MS20: 20 cm mineral soil + compost, TC: tailings mixed with compost, TS50: 50 cm topsoil, TS20: 20 cm topsoil, TSho: topsoil holes) at the end of the second growing season (2013) for *a* tamarack, *b* DN × M poplar, *c* jack pine, and *d* basket willow. $n = 27$. *Bars* denote SE. Treatments denoted by the *same letter* do not differ

concentrations of Cd and Cu for all tree species compared to others treatments, and increased Ni concentrations compared to all treatments except TSho, but these concentrations remained low.

Correlation analysis between substrate structure, foliar macronutrient concentrations, and tree growth

Substrate density was not correlated to any tree growth parameter, whereas substrate macroporosity appeared to be positively and linearly correlated to poplar above ground biomass ($p = 0.0032$, r = 0.73), foliar biomass ($p = 0.0063$, r = 0.69), and especially shoot biomass ($p = 0.0028$, r = 0.73). The linear regression between macroporosity and poplar shoot biomass is presented in Fig. 3. Among foliar macronutrients, nitrogen concentrations were positively and linearly correlated with all aboveground growth parameters of poplar ($p < 0.001$, $0.69 < r < 0.81$), with foliar biomass ($p < 0.001$, r = 0.69) and

Table 3 Poplar and willow root characteristics measured at the end of the second growing season (September 2013) among treatments (MS20: 20 cm mineral soil + compost, TC: tailings mixed with compost, TS50: 50 cm topsoil, TS20: 20 cm topsoil, TSho: topsoil holes) at 0–20 cm sampling depth

	Species	Planting substrates				
		MS20	TC	TS50	TS20	TSho
Root soil density ($g\ m^{-3}$)	Poplar	133 (104) a	42 (26) a	688 (456) a	106 (32) a	377 (271) a
	Willow	222 (46) a	86 (29) a	222 (23) a	286 (116) a	168 (94) a
Mean diameter (mm)	Poplar	0.29 (0.17) a	0.09 (0.21) a	0.43 (0.17) a	0.28 (0.17) a	0.38 (0.17) a
	Willow	0.43 (0.21) a	0.39 (0.21) a	0.54 (0.17) a	0.82 (0.17) a	0.58 (0.17) a
Fine root length density (<2 mm) ($cm\ cm^{-3}$)	Poplar	0.42 (0.05) a	0.46 (0.06) a	0.47 (0.05) a	0.48 (0.05) a	0.50 (0.05) a
	Willow	0.41 (0.06) a	0.42 (0.06) a	0.47 (0.05) a	0.36 (0.05) a	0.43 (0.05) a
Ratio of coarse to fine roots (length) (%)	Poplar	1.1 (1.0) a	1.2 (1.3) a	3.0 (1.0) a	0.7 (1.0) a	4.2 (1.3) a
	Willow	0.9 (1.3) a	0.8 (1.3) a	2.2 (1.0) a	0.8 (1.1) a	1.4 (1.0) a

Mean (SE), n = 3

Treatments denoted with the same lower case letter do not significantly differ at $p = 0.05$

2013 diameter increment of basket willow ($p < 0.001$, r = 0.84), and finally with shoot and leaf biomass ($p < 0.001$, r = 0.65 and 0.72, respectively) of jack pine.

Discussion

Trees planted directly in thickened tailings

Confirming our first hypothesis, trees—regardless of species—did not survive the first winter when planted directly in tailings. Generally, willow species planted directly at Canadian mine sites appear to survive well (Mosseler et al. 2014), and they are often first among the pioneer species that naturally invade boreal mine sites (Winterhalder 1995; Strong 2000). In our experiment, basket willow did not survive in pure tailings but showed maximal survival rate for all other treatments. The tailings showed density close to the threshold for impeding root growth ($1.4\ g\ cm^{-3}$) (Archer and Smith 1972). More importantly, tailings' air-filled porosity was lower than the minimum required for root development (10 % v/v) (Archer and Smith 1972), illustrating the inadequate tailings structure for root growth according to our second hypothesis. However, roots were present in the tailings under the soil layers, indicating that root development in the tailings was possible despite low macroporosity. Concomitantly to difficult root growth, it is possible that, despite the added N with fertilization at planting, this nutrient was poorly conserved in tailings. Low organic matter means fewer cation exchange sites, and therefore low fertilizer fixation for progressive release (Tordoff et al. 2000) (in this case ammonium ions). Because the tailings were particularly low in N compared to the other tested substrates, although this was not the case for P, the lack of fertilizer N fixation may have additionally impacted tree survival.

Table 4 Foliar concentrations in macronutrients and selected trace metals of each tree species (poplar, willow, pine, and tamarack) during the second growing season (July 2013) among treatments (T: tailings, MS20: 20 cm mineral soil + compost, TC: tailings mixed with compost, TS50: 50 cm topsoil, TS20: 20 cm topsoil, TSho: topsoil holes)

	Tree leaf				
	MS20	TC	TS50	TS20	TSho
Poplar					
Total N (g kg^{-1})	15 (0.2) a	14 (0.2) ab	**18** (**0.2**) b	16 (0.2) ab	14 (0.2) a
Total P (g kg^{-1})	**2.7** (**0.2**) b	**2.0** (**0.2**) b	1.5 (0.2) a	1.3 (0.2) a	1.3 (0.2) a
Total N/P	6 (1.4) a	7 (1.4) a	12 (1.4) a	12 (1.4) a	11 (1.4) a
Total K (g kg^{-1})	15 (0.8) ab	**18** (**0.8**) b	14 (0.8) ab	13 (0.8) a	14 (0.8) a
Total Ca (g kg^{-1})	**15** (**0.6**) b	13 (0.6) ab	11 (0.6) a	12 (0.6) ab	12 (0.6) ab
Total Mg (g kg^{-1})	3.0 (0.2) a	2.8 (0.2) a	2.9 (0.2) a	3.0 (0.2) a	3.0 (0.2) a
Total Na (g kg^{-1})	0.08 (0.04) a	0.06 (0.04) a	0.06 (0.04) a	0.07 (0.04) a	0.07 (0.04) a
Total Cd (mg kg^{-1})	0.45 (0.14) a	0.24 (0.14) a	**1.13** (**0.14**) b	0.57 (0.14) a	0.72 (0.14) a
Total Cu (mg kg^{-1})	5.0 (0.6) ab	1.8 (0.6) a	**5.1** (**0.6**) b	3.8 (0.6) a	3.4 (0.6) a
Total Ni (mg kg^{-1})	3.0 (1.7) a	0.3 (1.7) a	**5.6** (**1.7**) b	2.5 (1.7) a	**5.4** (**1.7**) b
Total Zn (mg kg^{-1})	148 (17) a	63 (17) a	143 (17) a	84 (17) a	63 (17) a
Willow					
Total N (g kg^{-1})	18 (0.2) a	17 (0.2) ab	**24** (**0.2**) b	17 (0.2) ab	20 (0.2) a
Total P (g kg^{-1})	**2.7** (**0.2**) b	**2.4** (**0.2**) b	1.3 (0.2) a	1.4 (0.2) a	1.6 (0.2) a
Total N/P	7 (1.4) a	8 (1.4) a	**19** (**1.4**) b	15 (1.4) ab	11 (1.4) ab
Total K (g kg^{-1})	19 (0.8) a	20 (0.8) a	20 (0.8) a	16 (0.8) a	17 (0.8) a
Total Ca (g kg^{-1})	9 (0.6) a	8 (0.6) a	6 (0.6) a	6 (0.6) a	8 (0.6) a
Total Mg (g kg^{-1})	3.4 (0.2) a	2.8 (0.2) a	2.7 (0.2) a	3.0 (0.2) a	3.1 (0.2) a
Total Na (g kg^{-1})	0.02 (0.04) a	0.02 (0.04) a	0.01 (0.04) a	0.01 (0.04) a	0.01 (0.04) a
Total Cd (mg kg^{-1})	0.77 (0.14) a	0.60 (0.14) a	**1.43** (**0.14**) b	1.04 (0.14) a	0.88 (0.14) a
Total Cu (mg kg^{-1})	8.7 (0.6) a	7.5 (0.6) a	**10.5** (**0.6**) b	9.9 (0.6) ab	7.5 (0.6) a
Total Ni (mg kg^{-1})	4.0 (1.7) a	1.8 (1.7) a	**7.9** (**1.7**) b	5.4 (1.7) a	**13.5** (**1.7**) b
Total Zn (mg kg^{-1})	80 (17) a	74 (17) a	**225** (**17**) b	137 (17) a	108 (17) a
Pine					
Total N (g kg^{-1})	11 (0.2) a	12 (0.2) ab	**17** (**0.2**) b	12 (0.2) ab	12 (0.2) a
Total P (g kg^{-1})	1.2 (0.2) a	1.1 (0.2) a	1.2 (0.2) a	1.2 (0.2) a	1.0 (0.2) a
Total N/P	10 (1.4) a	11 (1.4) a	15 (1.4) a	10 (1.4) a	12 (1.4) a
Total K (g kg^{-1})	5 (0.8) a	6 (0.8) a	5 (0.8) a	5 (0.8) a	5 (0.8) a
Total Ca (g kg^{-1})	9 (0.6) a	8 (0.6) a	6 (0.6) a	6 (0.6) a	8 (0.6) a
Total Mg (g kg^{-1})	2.1 (0.2) a	1.4 (0.2) a	1.9 (0.2) a	1.8 (0.2) a	1.8 (0.2) a
Total Na (g kg^{-1})	0.06 (0.04) a	**0.3** (**0.04**) b	0.05 (0.04) a	0.1 (0.04) a	0.06 (0.04) a
Total Cd (mg kg^{-1})	0.06 (0.14) a	0.01 (0.14) a	**0.08** (**0.14**) b	0.02 (0.14) a	0.02 (0.14) a
Total Cu (mg kg^{-1})	0.49 (0.6) a	0.40 (0.6) a	**2.7** (**0.6**) b	1.5 (0.6) ab	1.1 (0.6) a
Total Ni (mg kg^{-1})	1.1 (1.7) a	0.6 (1.7) a	**3.2** (**1.7**) b	1.5 (1.7) a	1.6 (1.7) a
Total Zn (mg kg^{-1})	15 (17) a	16 (17) a	61 (17) a	36 (17) a	23 (17) a
Tamarack					
Total N (g kg^{-1})	15 (0.2) a	20 (0.2) a	18 (0.2) a	16 (0.2) a	13 (0.2) a
Total P (g kg^{-1})	**1.8** (**0.2**) b	**2.1** (**0.2**) b	1.3 (0.2) a	1.1 (0.2) a	1.3 (0.2) a
Total N/P	9.3 (1.4) a	9.6 (1.4) a	13.5 (1.4) a	14.3 (1.4) a	10.3 (1.4) a

Table 4 continued

	Tree leaf				
	MS20	TC	TS50	TS20	TSho
Total K (g kg^{-1})	**13** (**0.8**) b	11 (0.8) ab	7 (0.8) a	9 (0.8) ab	10 (0.8) ab
Total Ca (g kg^{-1})	4 (0.6) a	3 (0.6) a	3 (0.6) a	3 (0.6) a	4 (0.6) a
Total Mg (g kg^{-1})	1.9 (0.2) a	1.5 (0.2) a	1.5 (0.2) a	1.4 (0.2) a	1.7 (0.2) a
Total Na (g kg^{-1})	0.16 (0.04) a	0.10 (0.04) a	0.06 (0.04) a	0.06 (0.04) a	0.07 (0.04) a
Total Cd (mg kg^{-1})	0.007 (0.14) a	0.007 (0.14) a	**0.09** (**0.14**) b	0.02 (0.14) a	0.04 (0.14) a
Total Cu (mg kg^{-1})	1.5 (0.6) a	2.8 (0.6) a	**3.1** (**0.6**) b	2.8 (0.6) ab	1.9 (0.6) a
Total Ni (mg kg^{-1})	1.2 (1.7) a	3.0 (1.7) a	**4.2** (**1.7**) b	2.2 (1.7) a	**6.7** (**1.7**) b
Total Zn (mg kg^{-1})	19 (17) a	22 (17) a	24 (17) a	22 (17) a	19 (17) a

All values are expressed on a dry mass basis

Mean (SE), n = 3

Treatments denoted with the same lower-case letter do not differ significantly at $p = 0.05$

Bolded values indicate a significant greater value of a treatment compared to other treatments

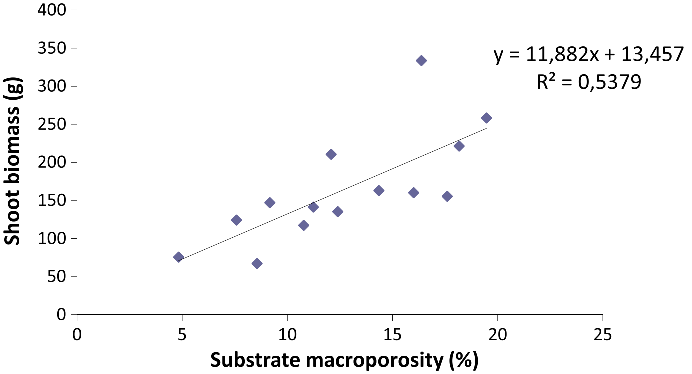

Fig. 3 Linear regression between: (1) substrates' macroporosity (% volume of pores >30 μm) and (2) poplar shoot biomass (g) developed after two growing seasons for combined treatments

Trees planted in mineral soil or tailings amended with greenwaste compost

Compost added to tailings improved the structure of the mixture by increasing the macroporosity and decreasing the bulk density to levels similar to those of the soil treatments. Better soil structure is known to create better conditions for root development by improving the three critical physical properties identified by Angers and Caron (1998) for controlling root growth: root penetration, water availability, and aeration. In our study, no relation between substrate macroporosity and root parameters was evidenced. However, substrate macroporosity was found to be positively and linearly related to hybrid poplar aerial biomass, highlighting that substrate macroporosity can also influence tree aerial development. Better tailings structure most probably enabled the trees to survive when planted in the mixture, thus corroborating our third hypothesis, although survival rates were lower than those found for the soil treatments for three of the four tested tree species.

Yet root growth of fast-growing trees was restricted to the compost and tailings mixture, which may at least partially explain that trees grown in the tailings and compost mixtures were smaller than trees grown in soils. Roots of fast-growing trees, however, were able to grow in the tailings under the soil layers. These results also demonstrate that root development in tailings is influenced by the nature of the overtopping layer.

Confirming our fourth hypothesis, when greenwaste compost was mixed with the mineral soil, thereby increasing the organic matter content, all tree species showed similar survival and growth responses in both 20 cm soils: topsoil and mineral soil + compost (except for pine diameter growth). Compost addition resulted in macroporosity levels in the mineral soil similar to those of topsoil. However, despite compost addition, bulk density values were found to be higher for mineral soil than for topsoil as well as agricultural soils of the same texture (i.e., 1 g cm^{-3}, Larchevêque et al. 2011). This can most probably be explained by transport and stockpiling conditions that would make the mineral soil highly compacted (Ramsay 1986).

Compost addition enriched the mixtures (tailings and mineral soil) in total Ca and P, but trees grown in these treatments showed significantly improved P foliar concentrations only. Since N–P concentration ratio in willow leaves concomitantly decreased when grown in compost mixtures, P may be a limiting nutrient in the used topsoil substrates, at least for willows. Foliar P concentrations in willows grown in topsoil treatments are indeed lower than optimal concentrations (0.2–0.3 % DM) reported for the same species by Labrecque and Teodorescu (2001), and reach optimal values when grown in compost mixtures. Available P (i.e., Olsen P) was also substantially increased in the mixtures (Table 2). The added compost probably contributed organic acids to the mixtures (confirmed by the lower pH after mixing), which increased P solubilization by direct ligand exchange or ligand-promoted mineral dissolution (Abrahão et al. 2014) from iron or aluminium-bound P, or by decreasing the soil solution pH, which dissolved the calcium-bound P (Zhang et al. 2001). Thus, despite P mineral fertilization at planting, improved P availability due to compost amendment allowed greater absorption of this limiting nutrient by the planted trees.

Trees planted in varying volumes of topsoil

Our fifth hypothesis was partially confirmed, as all trees were bigger when grown in the thick topsoil compared to the lower volume topsoils. However, tree aerial growth was not lower for planting holes compared to thin topsoil, despite lower available soil volume. Because trees showed greater leaf N concentrations in the bigger trees grown in thick topsoil compared to other treatments, the richer N nutrition could be responsible for the better tree growth with this treatment. Because overall mean N concentrations in leaves (1.4–2.4 % DM) were low regardless of treatment for both broadleaved species in the second year compared to the optimal concentrations reported in the literature (Hansen et al. 1988; Larchevêque et al. 2011; Labrecque and Teodorescu 2001), a small increase in N may have had a substantial effect on aerial growth. Accordingly, tree foliar concentrations in N were found to be positively related to aerial growth parameters, especially for the fast-growing poplar. Thus, even if both N and P appear as limiting nutrients in our experiment, tree growth may be rather controlled by N concentrations in leaves. N is an essential plant nutrient that significantly affects tree growth, particularly for fast-growing trees such as hybrid poplars, which have high nutritional requirements (van den Driessche 1999). Moreover, these results highlight that soil layer thickness impacts more planted tree growth and N nutrition than soil layer volume, at least at the short term. This result is surprising, as we expected that N and P fertilization of all trees planted with the three topsoil treatments would result in similar N concentrations in tree leaves across species. The proximity of water saturated tailings to roots under thin topsoil layers may be similar to more elevated water table conditions compared to thick topsoil layer. This possible hydrogeological difference did not significantly affect fine root length in the topsoils (Table 3), but may have influenced tree N nutrition (Lieffers and Macdonald 1990).

Trace metal accumulation in trees

In support of our sixth hypothesis, trace metal accumulations in all tree species were low, probably due to the neutral pH of the mine tailings and the low total trace metal concentrations. Consequently, and in line with our fifth hypothesis, trees survived when planted in soils regardless of soil volume. The only trace metal that accumulated in the tree foliage was Zn in basket willow, and only with the thick topsoil treatment. The bioaccumulation factor (i.e., Zn concentration in leaves/Zn concentration in soil) was greater than two for this species, whereas others have reported it at less than one (Rosselli et al. 2003; Vervaeke et al. 2003). In our experiment, the acidic pH of the topsoil may have increased the Zn availability to trees (Markert et al. 2000; De Nicola et al. 2003), whereas the landfill soils that Rosselli et al. (2003) investigated were calcareous, with neutral pH. Moreover, it should be noted that the accumulated Zn in the willows may not have originated primarily from the mine tailings, given that total Zn concentrations in the tailings were similar to those in the topsoil layered over the tailings. On the contrary, the proximity of the neutral tailings under thin topsoil layers may have increased the topsoil pH (Larchevêque et al. 2013), which could have participated in decreased absorption of Cd, Cu, and Ni by trees compared to thick topsoil layer (see Table 4).

Conclusions

Our results indicate that in order to establish multispecies plantations on mine tailings, a substrate consisting of layers of soil over the tailings should be preferred to tailings amended with compost. It would therefore be essential to conserve soil for reclamation purposes at the outset of mining operations. Mixing compost with tailings improved their macroporosity and tree survival, although root growth was restricted to the amended tailings, resulting in lower growth and survival rates compared to soil treatments. Topsoil can be replaced by mineral soil amended with compost to obtain 4 % organic matter without affecting survival or growth in the short term (two growing seasons). Besides improved tailings and mineral soil structure, the main effect of compost was to increase substrate P availability, resulting in greater foliar P concentrations in trees. Furthermore, substrate thickness appeared more crucial than substrate volume to maximize tree aerial growth and N nutrition as soon as possible after planting. Thus, despite higher placement costs, thicker soil layers should be preferred.

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