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Planting trees in soils above non-acid-generating wastes of a boreal gold mine [1]

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Abstract: Tree planting is a useful means of integrating reclaimed mine sites into natural forested landscapes. The main objective of this study was to evaluate the effect of soil thickness and nature on the establishment and metal accumulation of trees planted in low sulfur mine wastes under boreal conditions. Two field experiments were conducted to evaluate survival, growth, and nutrient and trace metal concentrations of several trees, including 2 fast-growing species (*Pinus banksiana*, *Larix laricina*, *Populus maximowiczii* × *P. balsamifera*, *P.* × *canadensis* × *P. maximowiczii*, and *Salix viminalis*), planted in soils (topsoil or subsoil, 50 or 20 cm thick) above waste rock and thickened tailings, respectively. As expected, tree growth increased (×2) in the topsoil compared to the subsoil above waste rock, despite mineral fertilization. Tree growth also decreased in thin topsoils, concomitantly with a decrease in foliar N concentrations, but soil thickness had no effect on tree survival. The basket willow appeared well adapted and multi-purpose for mine-waste revegetation over the short term since its survival remained maximal whatever the nature (topsoil or subsoil) or thickness (50 *versus* 20 cm) of the soil layer or waste type (waste rock *versus* tailings). The tamarack showed good survival and growth on both waste types (except in subsoil alone). By contrast, the survival (waste rock) and growth (thin soils above tailings) of hybrid poplars was poor under the tested conditions. On these non-acid-generating wastes with low total trace metal concentrations, none of the tree species accumulated trace metals from soil in their foliage, but basket willow survival should be followed over the longer term to check for deleterious effects of Zn accumulation.
Keywords: fast-growing trees, metal accumulation, mine revegetation, soil thickness, thickened tailings, waste rock.

Résumé: La plantation d'arbres est une bonne façon de réintégrer les sites miniers restaurés au sein des paysages forestiers naturels. L'objectif principal de cette étude était d'évaluer l'effet de l'épaisseur et de la nature du sol sur l'établissement d'arbres et leur accumulation de métaux lorsque ces arbres étaient plantés sur des rejets miniers non acides en conditions boréales. Deux expériences de terrain ont été réalisées pour évaluer la survie, la croissance et les concentrations de métaux traces et de nutriments de plusieurs espèces d'arbres, dont 2 à croissance rapide (*Pinus banksiana*, *Larix laricina*, *Populus maximowiczii* × *P. balsamifera*, *P.* × *canadensis* × *P. maximowiczii* et *Salix viminalis*), plantés dans des sols (couche de surface ou sous-sol, 50 ou 20 cm d'épaisseur) sur des roches stériles et des résidus épaissis, respectivement. Tel qu'attendu, dans l'expérience avec des roches stériles, la croissance des arbres plantés sur le sol de surface a augmenté (×2) par rapport à ceux sur le sous-sol en dépit d'une fertilisation minérale. La croissance des arbres plantés sur des sols de surface minces était réduite, parallèlement à une diminution des concentrations foliaires de N, cependant l'épaisseur de sol n'avait aucun effet sur la survie des arbres. Le saule des vanniers semblait bien adapté et polyvalent pour la végétalisation de rejets miniers à court terme puisque sa survie est restée maximale indépendamment de la nature (sol de surface ou sous-sol) ou de l'épaisseur (50 *versus* 20 cm) de sol et du type de rejets (stériles *versus* résidus). La croissance et la survie du mélèze laricin étaient bonnes sur les deux types de rejets (sauf pour le sous-sol seul). À l'opposé, les peupliers hybrides n'ont pas obtenu de bonnes performances au niveau de la survie (roches stériles) ou de la croissance (dans des sols minces sur résidus) dans les conditions étudiées. Aucune des espèces d'arbres n'a accumulé de métaux traces dans son feuillage à partir du sol dans ces conditions de croissance sur des résidus miniers non acides possédant de faibles concentrations de métaux traces, mais la survie du saule des vanniers devrait être suivie à plus long terme pour évaluer les effets délétères de l'accumulation Zn.
Mots-clés: accumulation de métal, arbres à croissance rapide, épaisseur de sol, roches stériles, végétalisation de sites miniers, résidus épaissis.

Nomenclature: USDA, NRCS, 2015.

Introduction

The frequent occurrence of mines within Canadian boreal forests would suggest that mine revegetation strategies should aim to reclaim mines with trees, not only as an attempt to restore disturbed habitats but also to increase social acceptability of the projects. In Canada, tree planting is a useful means of integrating reclaimed mine sites into natural forested landscapes, together with restoring biodiversity and increasing CO_2 sequestration to compensate

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for emissions that were generated during the mining and extraction processes. Trees accelerate the conversion of degraded lands into forests (Parrotta, Turnbull & Jones, 1997) because they can facilitate native plant species recolonization at canopy closure (Strong, 2000).

Metalliferous mine wastes, such as waste rock and mill tailings, generally cover large surface areas and are among the most difficult substrates to revegetate. First, they lack organic matter, nutrients, and soil organisms (Burger & Zipper, 2002). Second, they lack physical structure, can exhibit extreme pH values, and contain potentially phytotoxic levels of salts and heavy metals (Tordoff, Baker & Willis, 2000). Waste rock is the material that covers or surrounds economic ores; it is removed from the ground and accumulated in waste rock piles. Mill tailings consist of the finely crushed ore (70% to 80% of particles range between 2 and 80 µm; Aubertin, Bussière & Bernier, 2002) that remains after valuable metals were removed. They are transported (mostly pumped) as aqueous slurries from the mine plant and deposited in tailings facilities. Among milling wastes, thickened tailings represent an emerging technology for surface deposition (Robinsky *et al.*, 1991) that reduces water consumption, especially in larger operations such as open-pit mines, which process low-grade ores and extract large quantities of rock, or mines located in arid areas. Thickened tailings have a solid content of 50% to 70% (on a mass basis) when deposited. While their basic properties are similar to those of conventionally deposited (slurried) tailings (Bussière, 2007), they have a more uniform grain-size distribution (homogeneous) when impounded in the tailings facility (Al & Blowes, 1999). Consequently, thickened tailings have low hydraulic conductivities ($K_{sat} = 10^{-6}$ to 10^{-8} m·s^{-1}; Barbour, Wilson & St-Arnaud, 1993), which may create anoxic conditions for tree root growth (Larchevêque *et al.*, 2013). In contrast, waste rock does not retain moisture due to its heterogeneous grain size distribution (Peregoedova, Aubertin & Bussière, 2013) and, indeed, may increase drought stress in trees.

Trees have been used extensively to revegetate mine waste disposal areas, especially those of coal mines, in the United States (Drake, 1986; Kost & Vimmerstedt, 1994; Angel *et al.*, 2006; Emerson, Skousen & Ziemkiewicz, 2009), Europe (Katzur & Haubold-Rosar, 1996; Bending & Moffat, 1999; Pietrzykowski, 2010), India (Singh & Singh, 2006; Maiti, 2007), Australia (Ward & Pickersgill, 1985; Mercuri, Duggin & Grant, 2005), and Canada (Landhaüsser *et al.*, 2012; Sloan & Jacobs, 2013; Mosseler, Major & Labrecque, 2014), but fewer studies are available regarding tree planting to reclaim metalliferous mine wastes, especially tailings (Bjugstad, 1986; Renault *et al.*, 2008; Boyter, Brummer & Leininger, 2009; Asensio *et al.*, 2011; Larchevêque *et al.*, 2013). The main strategy for installing trees on mine wastes relies upon tree planting after amendments are applied to improve substrate quality or after deploying soils over the wastes.

In general, revegetation success increases with the use of soils, as does the speed of natural vegetation recovery (Marcus, 1997). Topsoil material typically contains organic matter, which improves soil structure, water infiltration, and soil nutrients (Peters, 1995; Marcus, 1997) and favours plant development. In Canada, regulations often require that operators of open-pit mines preserve the soil that has been excavated above the pit for future site reclamation, topsoil often being segregated from low organic matter mineral subsoil. Until the waste storage areas are ready to revegetate, these soils are transported and stockpiled on the mine site, which can result in severe soil compaction (Ramsay, 1986), loss of fungi (in particular, decomposers and mycorrhizae) (Cooke & Johnson, 2002), and decrease of seed viability (Rokich *et al.*, 2001). High transportation costs and limited availability of topsoil compared to subsoil imply a need to decrease the thickness of soils used to cover mine wastes, find ways to increase the usability of the subsoil, or reduce the surface of planted areas.

Non-acid-generating mine wastes may have limited toxicity toward plant roots (Bagatto & Shorthouse, 1999; Trüby, 2003). However, if the soil is too thin (<25 cm thick), survival and growth of the vegetation can be limited due to properties of the underlying wastes that are unsuitable for root growth (Meredith & Patrick, 1961; Evanylo *et al.*, 2005; Michels *et al.*, 2007) or the presence of inadequate moisture and nutrient reserves (Tordoff, Baker & Willis, 2000). In boreal regions, where nutrient cycling is slow (McMillan *et al.*, 2007) due to cold temperatures and a short growing season, soil thickness may be even more critical for ensuring sufficient nutrition of the planted trees.

Tree planting success on mine wastes varies greatly, depending upon the tree species that are being planted (Kost & Vimmerstedt, 1994). Pioneer trees, adapted to growth on primary substrates like mine wastes, perform better than late succession trees (Whitbread-Abrutat, 1997). The use of fast-growing pioneer species may be useful for rapidly achieving an aesthetic effect ("greening up"), especially when mines are close to urban areas, but their deployment is still rare. For example, hybrid poplar grows faster than other broadleaved trees or white pine (*Pinus strobus*) when it is planted on reclaimed mine sites in the Appalachian Mountains (Casselman *et al.*, 2006). However, the use of fast-growing trees for mine waste revegetation may be a riskier proposition than employing slower-growing species, since growth performance of the former is very sensitive to substrate conditions such as nutrient and water availability (van den Driessche, 1999) or weed competition (Coll *et al.*, 2007).

In the context of metalliferous mine wastes, to decrease the risk of metal contamination of the food-web, methods limiting accumulation in the aerial parts of planted trees should be assessed. Trees generally accumulate metals in their root parts (external bark, fine roots, mycorrhiza mycelia) (Bagatto & Shorthouse, 1999; Trüby, 2003), which limits the exportation of metals from soil to grazed aerial parts. However, fast-growing species of 2 genera that are among the most frequently planted for wood or biomass production, *viz.*, poplars (*Populus* spp.) and willows (*Salix* spp.), have been demonstrated to accumulate metals that originated from the substrate into their leaves (Robinson *et al.*, 2000; Hassinen *et al.*, 2009), although this accumulation may be clone- or species-dependent (Boyter, Brummer & Leininger, 2009).

Our main objective was to evaluate the effect of soil thickness and nature on the establishment and metal accumulation capabilities of trees that were planted in non-acid-generating mine wastes under boreal conditions. We sought to devise and subsequently recommend a strategy for successful revegetation of waste rock and thickened tailings with trees. Two field experiments were conducted to evaluate survival and growth, along with nutrient and trace metal concentrations, in 4 tree species: tamarack or eastern larch (*Larix laricina*), jack pine (*Pinus banksiana*), basket willow (*Salix viminalis*), and hybrid poplars (*Populus* spp.). These were planted into soils that had been deposited on top of the mine wastes. The first experiment was conducted for 3 y over waste rock, while the second planting experiment was performed above thickened tailings and lasted 2 y. The use of topsoil was compared with that of subsoil (both stockpiled); the latter was improved by mineral fertilizer or compost addition. Tree survival and growth was monitored on 50 cm- *versus* 20 cm-thick soils. Finally, the performance of several pioneer trees, *i.e.*, fast-growing broadleaved *versus* native conifers, was compared.

We had 4 working hypotheses: 1) Tree survival, short-term growth, and nutrition would be improved on topsoil compared to subsoil, especially for high nutrient-demanding, fast-growing broadleaved species; 2) Tree growth would increase with increasing soil thickness, but the latter would not affect tree survival, given the limited toxicity of the wastes being used; 3) With respect to non-acid-generating properties of the mine wastes that were used, trace metal accumulations would be low in tree foliage, and especially low in native conifers, compared to fast-growing broadleaved species; 4) Over the short-term, trees would accumulate greater concentrations of metals when grown on thinner soils, because a greater proportion of their roots would enter into contact with the wastes.

Methods

Site description

The Canadian Malartic gold mine (property of the Canadian Malartic Partnership; Malartic, Quebec, Canada; 48°13'N, 78°12'W) is a large open-pit mine that began production in 2011. It is located within the Northern Clay Belt region of Quebec and adjacent Ontario. Typical forest vegetation surrounds the mine and includes jack pine, black spruce (*Picea mariana*), trembling aspen (*Populus tremuloides*), white or paper birch (*Betula papyrifera*), tamarack, and balsam fir (*Abies balsamea*) in the canopy. In this boreal region, the growing season typically begins in mid-May and ends in early October, with a mean temperature during the 3 warmest months (June, July, and August) around 18–19 °C. 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 wastes, soils, and compost

Canadian Malartic ore is a mineralized greywacke. The waste rock and 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 sieves through which 10% and 60% of the sample weight passes, respectively). They were deposited in the facility as thickened tailings (around 60% solids by mass) less than 6 months before the experiment took place. The tailings were detoxified through a cyanide destruction process (SO_2/H_2O_2 technology), which left free CN^- concentrations lower than 20 mg·kg^{-1}. Chemical characteristics of the tailings and waste rock are summarized in Table I. Both types of Canadian Malartic wastes had mean trace metal concentrations that were below Quebec regulatory thresholds for residential lands (Government of Quebec, 2014) except for total cadmium (Cd) levels in the tailings, which appeared to be slightly higher than the threshold (see Table I).

Overburden soil that was used to cover the mine wastes was a luvic gleysol (Soil Classification Working Group, 1998) that was obtained from a swampy area above the pit that had been previously colonized by conifers. The soil was stockpiled in 7-m-high piles (2.5:1 slope) for 12 to 36 months prior to 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 the excavation of the open pit. The overburden subsoil consisted of the remaining mineral sandy clay loam soil (several metres thick), which was excavated down to bedrock after the overburden topsoil had been removed. Overburden topsoil and subsoil were saved in separate piles. Greenwaste compost came from the St-Henry-de-Lévis facility (Biogénie, Varennes, Quebec, Canada). It was mainly composed of leaves and lawn residues, together with a small proportion of small branches and tree bark. This material was sieved to pass a 1.25-cm mesh screen before use. Both soil and compost characteristics are summarized in Table I.

Plant material

Trees that were used in the experiments were native species, which were obtained from the surrounding forested region, or species adapted to boreal conditions. All trees were locally produced by the Ministère des Ressources Naturelles du Québec (MRNQ). Two-year-old seedlings were nursery-grown from seeds of native Quebec origin in 110-cm^3 containers for jack pine (seeds from 1st generation orchard, 46°15'N, 73°55'W) and tamarack (seeds from Arboretum Dablon, 48°21'N, 72°13'W). Hybrid poplar and willow stock consisted of clonally propagated 1-y-old whips (*i.e.*, 1-m-long stem cuttings) from *Populus maximowiczii* × *P. balsamifera* (M×B, 915319), *P.* × *canadensis* × *P. maximowiczii* (DN×M, 916004), and basket willow.

Experimental designs

For experiment 1, the waste rock was transported by truck from the waste rock pile to the experimental site in June 2011. Waste rock was piled to a 2 m height to construct a 10:1 slope that mirrored the truck roads covering waste rock piles (Figure 1). The pile slope was

Table I. Initial soil, mine wastes, and compost characteristics. Mean (standard error, SE); n = 3, except on waste rock. All values are expressed on a dry matter basis.

Characteristics	Units	Overburden topsoil	Overburden subsoil	Compost	Tailings	Waste rock	Regulatory threshold [b] (residential lands)
pH		5.1 (0.1)	7.2 (0.1)	6.7 (0.01)	7.9 (0.1)	6.7 to 9	
Clay [a]	%	42 (5)	33 (5)				
Silt [a]	%	27 (1)	15 (1)				
OM [a]	%	17 (3)	1.1 (3)	41 (1)	0.1 (2)		
C/N		22 (7)	17 (5)	20 (2)			
EC [a]	$cS \cdot m^{-1}$	7 (1)	10 (1)	21 (0.5)	10 (1)		
Total N	$g \cdot kg^{-1}$	4.3 (0.3)	0.4 (0.3)	12 (1)	0.1 (0.5)		
Total P	$g \cdot kg^{-1}$	0.6 (0.04)	0.6 (0.04)	2.5 (0.2)	0.7 (0.01)		
Olsen P	$mg \cdot kg^{-1}$			252 (7)	8 (5)		
Total K	$g \cdot kg^{-1}$	3.6 (0.05)	2.7 (0.05)	6.5 (0.2)	9 (0.4)	10	
Total Ca	$g \cdot kg^{-1}$	11 (1)	9 (1)	31 (1.3)	17 (2)	15	
Total Mg	$g \cdot kg^{-1}$	11 (0.1)	11 (0.1)	4 (0.01)	14 (0.6)	10	
Total Na	$g \cdot kg^{-1}$			0.4 (0.01)	0.5 (0.05)	0.2	
Total Al	$g \cdot kg^{-1}$	17 (1)	13 (1)	3.5 (0.3)	14 (1)	9.5	
Total Fe	$g \cdot kg^{-1}$	27 (2)	24 (2)	9 (0.3)	34 (2)	24	
Total B	$mg \cdot kg^{-1}$	6.3 (0.3)	3.9 (0.3)	21 (0.6)	0.8 (0.5)		
Total Cd	$mg \cdot kg^{-1}$	0.6 (0.15)	0.4 (0.15)	2 (0.07)	6 (0.2)	0.2	5
Total Cr	$mg \cdot kg^{-1}$	120 (14)	116 (14)	10 (0.1)	168 (10)	123	250
Total Cu	$mg \cdot kg^{-1}$	58 (12)	31 (12)	42 (4)	52 (2)	25	100
Total Mn	$mg \cdot kg^{-1}$	344 (26)	367 (26)	427 (11)	441 (16)	372	1000
Total Ni	$mg \cdot kg^{-1}$	64 (7)	51 (7)	11 (1)	69 (9)	57	100
Total Pb	$mg \cdot kg^{-1}$	22 (4)	13 (4)	24 (1)	18 (100)	31	500
Total Zn	$mg \cdot kg^{-1}$	83 (5)	62 (5)	151 (5)	73 (4)	63	500

[a] Clay, <2 µm; silt, <50 µm; OM, organic matter; EC, electrical conductivity.

[b] Government of Quebec (2014).

Figure 1. Experimental zone in the tailings facility of the Canadian Malartic mine (property of Canadian Malartic Partnership): experiment 1 on waste rock at the upper side, and experiment 2 on thickened tailings at the lower side.

south-facing. A 50-cm-thick layer of soil was applied by a crawler-dozer over the waste rock in July 2011, a few days before planting. A split-plot design was used: 6 experimental plots = 3 blocks (replicates) × 2 soil types (whole plot factor: overburden topsoil, overburden subsoil) × 4 tree species (sub-plot factor: jack pine, tamarack, M×B poplar, basket willow) × 16 trees per factor combination (pseudo-replicates). The 3 replicate blocks consisted of an 82- × 20- × 2-m (10:1 slope) mound of compacted waste rock. Each plot covered a 13- × 13-m area and was separated from its neighbours by a 6-m-wide buffer zone that was not covered by soil. Trees were planted within each plot in mid-July 2011 at 1 × 1 m spacing, and a 3-m-wide buffer zone was kept free of trees at the periphery of the soils.

For experiment 2, tailings were transported by truck from the tailings facility to the experimental site in April 2012. The experimental cell (120 × 50 m) consisted of waste rock walls (0.5 to 1.5 m high) that were covered with a geotextile liner, which allowed water drainage while retaining the tailings in place (Figure 1). Soils were applied onto the tailings by an excavator in May 2012. To improve the quality of the subsoil, 0.1 m^3 of fresh greenwaste compost (corresponding to 700 kg dry mass [DM]) was mixed into the soil by an excavator in 1-m^2 × 20-cm-deep planting holes. A split-plot design was also used: 9 experimental plots = 3 blocks (replicates) × 3 treatments (whole plot factor: 50- or 20-cm-thick overburden topsoil, 20 cm overburden subsoil + compost) × 4 tree species (sub-plot factor: jack pine, tamarack, DN×M poplar, basket willow) × 9 trees per factor combination (pseudo-replicates). Each plot covered an 11- × 11-m (topsoil) or 16- × 16-m (subsoil) area and was separated from the others by a 3-m-wide zone without soil. Tree species were planted at 1 × 1 m spacing in mid-June 2012 into the soils covering the mine tailings. The hybrid poplar clone that was used was DN×M, which had shown better survival than the other clone in soils covering tailings in a preliminary greenhouse experiment (Larchevêque *et al.*, 2013). For the subsoil treatment, each planting hole with compost was separated from the others by a distance of 1 m, resulting in 2 × 2 m tree spacing. For both experiments, unrooted whips were planted directly into the soil to a depth of 30 cm.

All trees were fertilized with 15 g ammonium nitrate (34.5-0-0) and 15 g triple superphosphate (0-45-0) by placed fertilization (van den Driessche, 1999), which involved fertilizer insertion into a slit made with a spade near the base of each tree (20 cm from the tree and 15 cm deep).

Measurements, sampling, and analysis

Chemical analyses and soil texture

Three random soil samples were collected for chemical characterization from both the waste rock experiment (in July 2011) and the tailings and compost experiment (in June 2012; Table I). In the waste rock experiment, soils and tree leaves were sampled in the second year after planting, in July 2012. Each soil sample was taken at the base of the sixth tree, with a composite sample of fully matured leaves being taken from the same tree (n = 24, 1 sample per tree species and treatment). In the tailings experiment, soils were sampled in July 2012. Each soil sample to be analyzed was a composite of 4 samples, 1 per tree species, which were taken at the base of the fifth tree in each plot (n = 18, 1 sample per plot). Tree leaves (fifth tree) were sampled the following year, in July 2013 (n = 72, 1 sample per tree species and treatment).

Soil and compost nutrient analyses were conducted on sieved (2 mm mesh), finely ground, oven-dried samples (50 °C) by the Lakehead University Centre for Analytical Services (Thunder Bay, Ontario, Canada). Total N and organic C were determined by the Dumas combustion method (CNS 2000, LECO Corporation, Mississauga, Ontario, Canada). 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, Mn, Ni, Pb, Sr, and Zn were determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES, Vista PRO, Varian Canada, Mississauga, Ontario, Canada). Available P was determined colorimetrically on sodium bicarbonate extracts of the soils (Olsen *et al.*, 1954). Bulk pH was determined from saturated soil pastes, while soil electrical conductivity was determined from a 1:2 (soil:water) extract. After drying (50 °C), plant leaves were analyzed for total N, P, Ca, Mg, and K, together with the same trace metals that were determined for the soils, using the previously detailed analytical methods. Soil texture was determined using the hydrometer method (Bouyoucos, 1962).

Substrate structure

In both experiments, undisturbed 100-cm^3 soil samples were taken with a double cylinder soil sampler in each plot at the same location and date as for soil analysis (1 sample per tree species and treatment, n = 24 and n = 72 for waste rock and tailings experiments, respectively). Bulk density and macroporosity (air-filled porosity, % of pores >30 µm) were determined following procedures outlined by Cassel and Nielsen (1986).

Growth measurements

In both experiments, survival, stem height, and basal diameter were measured at planting and at the end of each growing season for each planted tree. Cumulative height and diameter increments were calculated as (value at the end of the experiment – value at planting).

Statistical analyses

Survival data were compared among treatments using the χ^2 test (PROC FREQ, SAS V.9.2, SAS Institute Inc., Cary, North Carolina, USA). For soil characteristics, cumulative height and diameter increments, and plant elemental concentrations, the data were submitted to two-way analysis of variance (waste rock: soil nature, and species; tailings: treatment, species) (PROC GLM or MIXED). All factors that were tested were considered to be fixed effects, while blocks were considered to be a random effect. When effects were significant for a given variable, least-square means were estimated (LS MEANS statement) and *post hoc* Tukey tests were conducted to separate the means. Overall significance for the analyses was set to $\alpha = 0.05$.

Results

Waste rock experiment

Tree survival and growth

Tree survival was very high (90–100%) after the first growing season for all species that were tested, but decreased during subsequent years, except for willow (on topsoil or subsoil) and tamarack on the topsoil (Figure 2). Tree survival was generally greater on topsoil than on subsoil, except for willows. At least half of the M×B poplars that had been planted on both soils died by the end of the third year.

For all 4 species, cumulative height and diameter increments from 2011 to 2013 were consistently two-fold or more higher on topsoil compared to subsoil, despite N and P fertilization of all trees at planting (Figures 3 and 4).

Structure of soils

Prior to planting in 2011, macroporosity was similar and low, regardless of soil type (Table II), and close to the 10% threshold that would allow root growth, as reported by Archer and Smith (1972). Soil macroporosity generally increased to more adequate levels for root growth in 2012, at which time it was significantly higher in topsoil compared to subsoil. At planting, the bulk density of the subsoil was not adequate for root growth (*i.e.*, equal to the 1.4 $g \cdot cm^{-3}$ threshold that would impede root growth, as reported by Schuuman, 1965) and was nearly twice that of topsoil. Subsoil bulk density decreased in the second year after planting, but remained higher than that of the topsoil.

Element concentrations in trees and soils

There was no significant interaction between soil type and tree species for element concentrations in either soils or leaves; thus, the results are averaged by tree species (Table III). Topsoil pH was acidic, while subsoil pH was neutral. Organic matter concentrations were very high in the topsoil compared to the subsoil. Foliar N concentrations were significantly higher in trees that were planted in the subsoil compared to those planted in the topsoil, consistent with the lower C:N ratio in the subsoil. Concentrations of P, K, Ca, and Fe in tree leaves were similar between the 2 soil types, probably because both soil concentrations were in the same ranges. Topsoil contained more B than the subsoil, which resulted in greater B concentrations in tree leaves that had been planted in topsoil. Concentrations of trace metals were not elevated, either in the soils or in

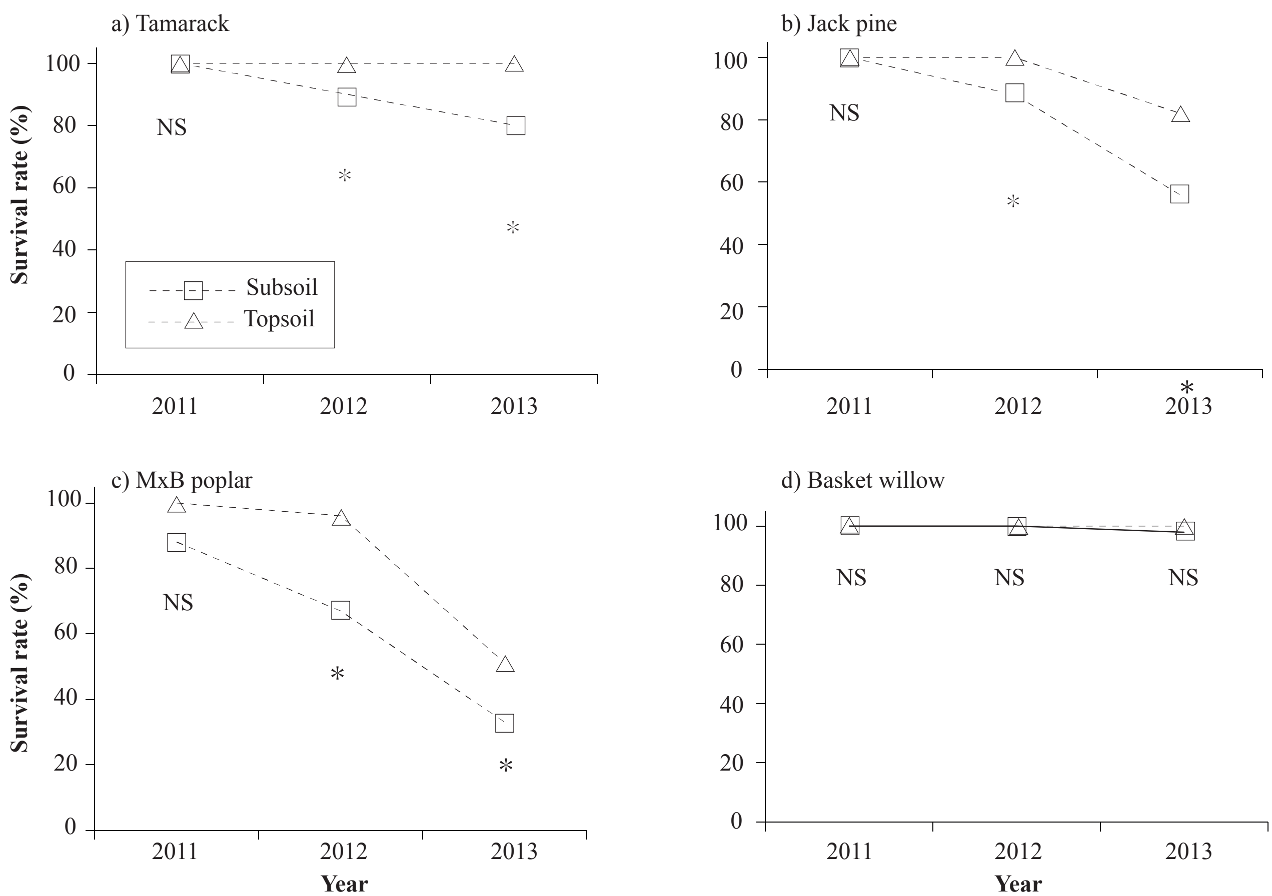

FIGURE 2. Percent survival among treatments (50-cm subsoil *versus* topsoil) at each growing season (2011, 1st growing season; 2012, 2nd growing season; 2013, 3rd growing season) in the waste rock plantation (experiment 1) for a) tamarack, b) jack pine, c) M×B poplar, and d) basket willow. Means, $n = 48$. Statistical comparisons were done among treatments for each date: *$P < 0.05$, NS: non-significant.

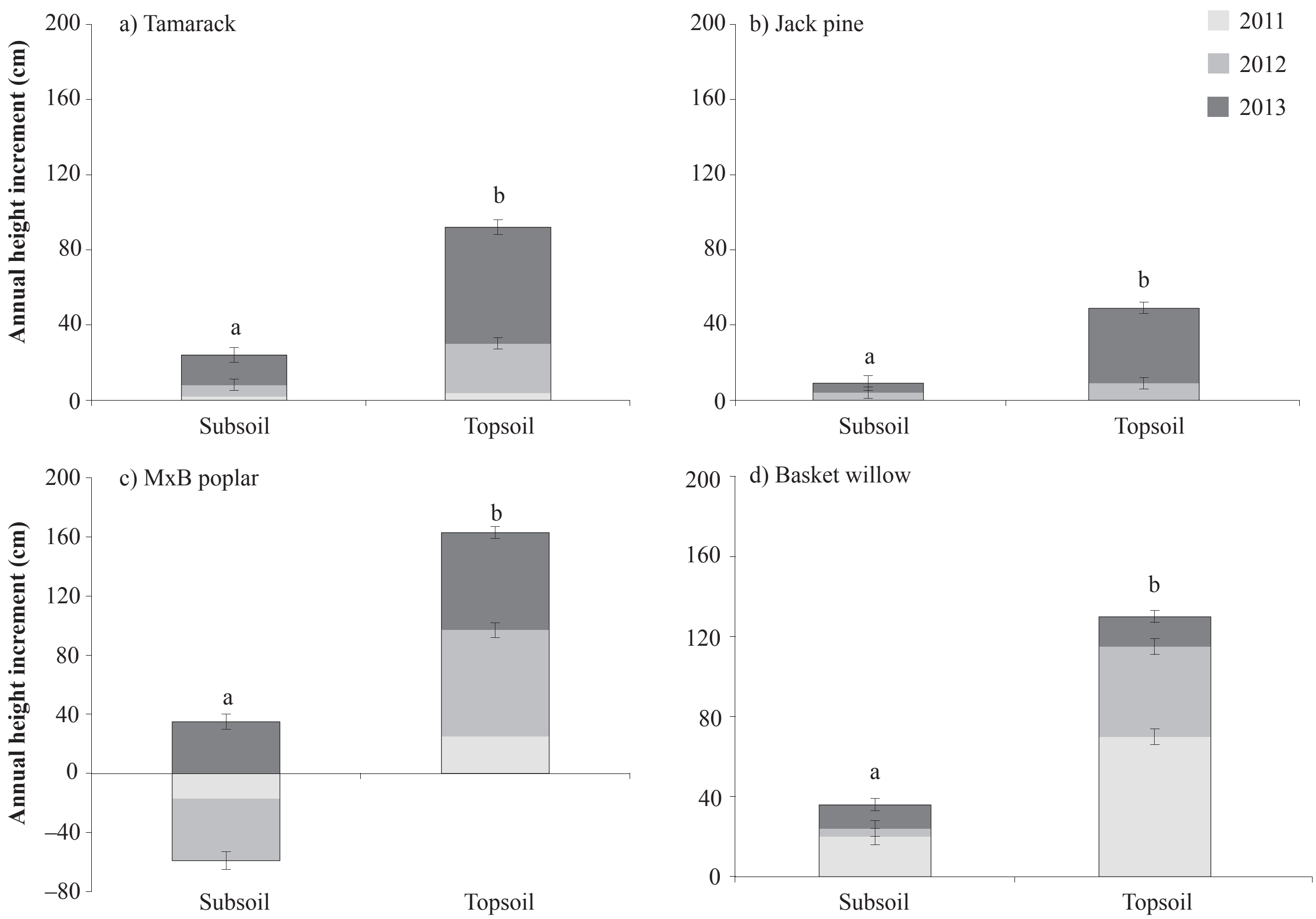

FIGURE 3. Tree height increment (cm) among treatments (50-cm subsoil *versus* topsoil) during each growing season (2011, 1st growing season; 2012, 2nd growing season; 2013, 3rd growing season) in the waste rock plantation (experiment 1) for a) tamarack, b) jack pine, c) M×B poplar, and d) basket willow. Means, n = 48. Bars denote SE. Statistical comparisons were done on cumulative height increments (final height – height at planting); treatments denoted by the same letter do not significantly differ at P = 0.05.

tree leaves, except for those of Mn and Zn. Manganese and Zn concentrations were greater in leaves of trees that were planted in topsoil compared to those planted in subsoil. No significant effect was apparent for differences among tree species regarding foliar trace metal concentrations. Willows that were planted in the 50-cm-thick topsoil had a mean Zn concentration of 175 g·kg^{-1} in their leaves.

TAILINGS EXPERIMENT

TREE SURVIVAL AND GROWTH

Survival of all of the studied tree species was high (>90%) over the short term (first and second years) and similar for the 3 soil types (Figure 5). For tamarack, poplar, and willow, the cumulative (2012–2013) height and diameter increments were consistently higher for individuals planted in the 50-cm topsoil compared to the other 2 treatments (Figures 6 and 7). DN×M poplar had very poor height increment responses in thin soils in the second year following planting (2013) compared to the thick topsoil. Cumulative height increment for jack pine growing in the 50-cm topsoil was greater than that of individuals in the subsoil only, while the 3 soil types yielded significantly different diameter increments, with the greatest and least responses on 50-cm-thick topsoil and subsoil, respectively (Figure 6).

STRUCTURE OF SOILS

Macroporosity of the 3 soils was similar and greater than the minimal threshold that would allow root growth prior to plantation establishment (Table II). Bulk density of the subsoil, when mixed with compost, was greater than that of the 50-cm topsoil, but it was lower than the threshold impeding root growth and lower than that of the subsoil that did not contain compost, which was used in the waste rock experiment.

ELEMENTAL CONCENTRATIONS IN TREES AND SOILS

The pH of the topsoil was acidic but less than that measured in the experiment on waste rock, while the combination of subsoil + compost was neutral (Table IV). Addition of compost to the subsoil increased organic matter concentrations to 5%, but this concentration remained lower than that measured in the topsoil. Nitrogen concentrations were greater in the leaves of trees that were planted in 50-cm topsoil compared to those individuals that were planted in the subsoil + compost, the 20-cm-thick topsoil having intermediate values. Total N and C:N ratios of topsoil materials were greater than those of the

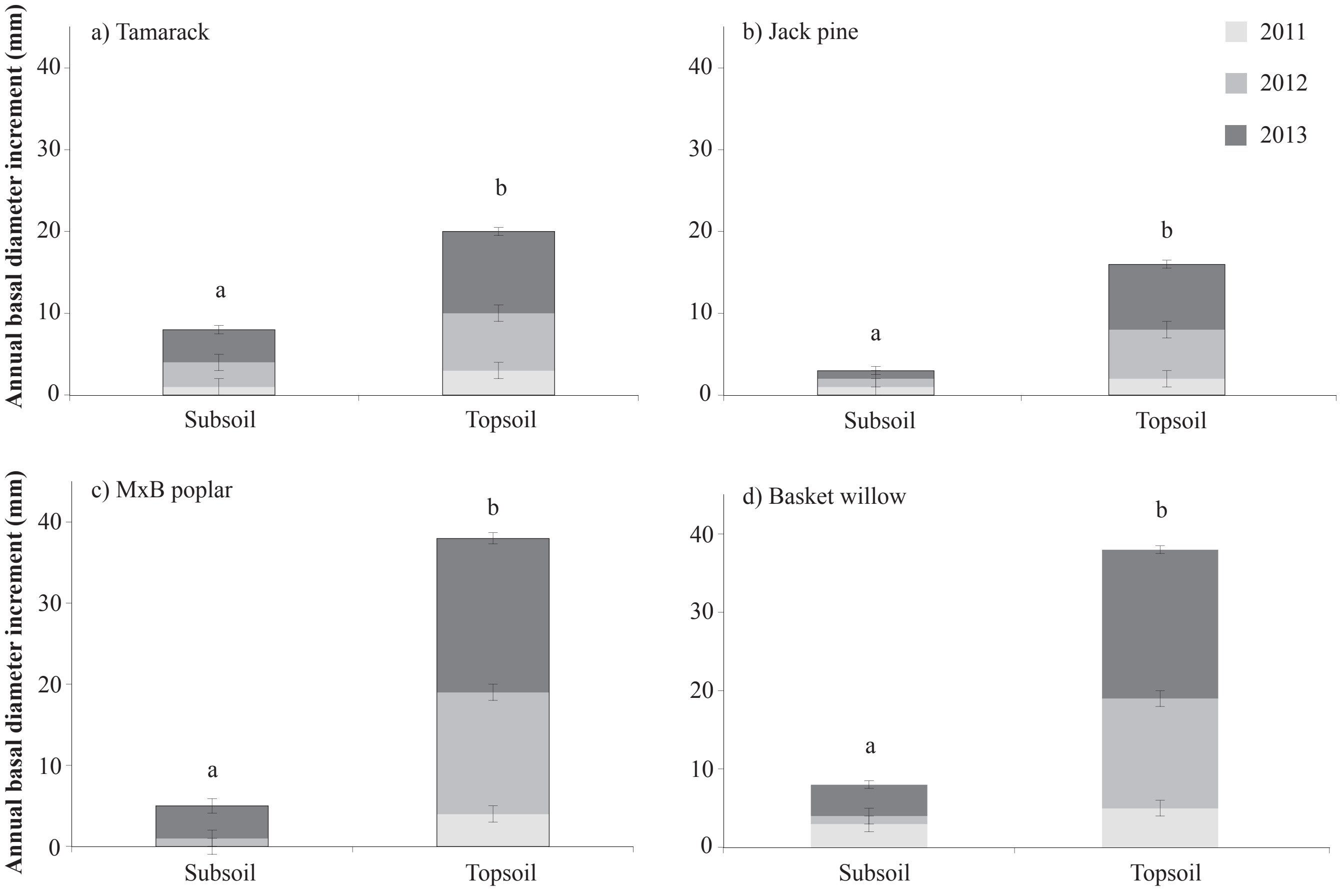

Figure 4. Tree basal diameter increment (mm) among treatments (50-cm subsoil *versus* topsoil) during each growing season (2011, 1st growing season; 2012, 2nd growing season; 2013, 3rd growing season) in the waste rock plantation (experiment 1) for a) tamarack, b) jack pine, c) M×B poplar, and d) basket willow. Means, n = 48. Bars denote SE. Statistical comparisons were done on cumulative diameter increments (final diameter – diameter at planting); treatments denoted by the same letter do not significantly differ at P = 0.05.

subsoil + compost. Foliar P and B concentrations were the greatest in trees that were planted in the subsoil + compost compared to topsoil; P availability and B total concentrations were also greater in the subsoil + compost. Despite total Cd concentrations in the tailings that were close to regulatory thresholds, this heavy metal did not significantly accumulate in trees that were planted in the mine soils. In contrast to the results of the experiment that was conducted on waste rock, foliar Mn concentrations in trees that were planted in topsoil did not differ from those planted in the subsoil + compost. Concentrations of trace metals were low in planted tree leaves, with the exception of Zn. For K, Ca, and Zn responses, interactions were apparent between soil and tree species. Potassium and Ca slightly increased respectively in tamarack and poplar in the subsoil + compost compared to both topsoils. Zn concentrations increased to 225 $\mu g \cdot g^{-1}$ in the leaves of willows that were planted in the 50-cm-thick topsoil above tailings compared to 137 and 80 $\mu g \cdot g^{-1}$ in the 20-cm-thick topsoil and subsoil + compost, respectively. Soil type did not affect the other tree species for these 3 elements. Trees that were planted in the 50-cm topsoil above tailings accumulated slightly more Cd, Ni, and Cu than those that were planted in the thinner soils.

Tree species significantly differed in terms of their foliar concentrations of Al, B, Cd, Co, Cu, Fe, Mg, Mn, Ni, P, Sr, and Zn. Concentrations were always greater in willow than in conifers, except for Zn in the subsoil + compost and Mn. Regardless of soil, DN×M poplar exhibited greater foliar concentrations of Cd, Co, Cu, and

Table II. 1) Macroporosity and bulk density of soils for the 2 treatments (subsoil *versus* topsoil) in the waste rock experiment at planting (2011) and 1 y after planting (2012). Comparisons were performed for each date; treatments with the same lowercase letter do not significantly differ at P = 0.05. 2) Macroporosity and bulk density of soils for all treatments (20- or 50-cm topsoil, or 20-cm subsoil + compost) in the tailings experiment at planting (2012); treatments with the same uppercase letter do not significantly differ at P = 0.05. Mean (SE), n = 6.

	Macroporosity (% pores >50µm)		Density ($g \cdot cm^{-3}$)	
	2011	2012	2011	2012
1) Subsoil – 50 cm	8 (3) a	16 (1) a	1.4 (0.1) b	1.2 (0.1) b
Topsoil – 50 cm	12 (3) a	20 (1) b	0.8 (0.1) a	0.7 (0.1) a
2) Topsoil – 50 cm		15 (0.9) A	0.86 (0.05) A	
Topsoil – 20 cm		14 (0.9) A	0.94 (0.05) AB	
Subsoil – 20 cm + compost		12 (0.9) A	1.13 (0.05) B	
Minimal threshold allowing root growth (Archer & Smith, 1972; Schuuman, 1965)	10	10	1.4	1.4

TABLE III. Mean (SE) basic soil characteristics and elemental concentrations (oven-dry mass) in soils over waste rock (experiment 1) and in tree leaves (all species combined) among treatments (subsoil *versus* topsoil) during the second growing season. Separate comparisons were performed for soils and foliage; treatments with the same letter do not significantly differ at $P = 0.05$.

		Soils		Tree leaves	
Soil characteristics	Units	Subsoil ($n = 12$)	Topsoil ($n = 12$)	Subsoil plantation (bulked 4 species; $n = 12$)	Topsoil plantation (bulked 4 species; $n = 12$)
pH		7.2 (0.04) b	5.3 (0.04) a		
OM [a]	%	1.2 (0.6) a	21 (0.6) b		
C/N		15 (0.7) a	27 (0.7) b		
EC [a]	$cS\cdot m^{-1}$	11.3 (0.7) b	4.2 (0.2) a		
Total N	$g\cdot kg^{-1}$	0.5 (0.1) a	4.5 (0.1) b	21 (1) b	18 (1) a
Total P	$g\cdot kg^{-1}$	0.58 (0.02) a	0.58 (0.02) a	1.3 (0.8) a	1.4 (0.8) a
Olsen P	$mg\cdot kg^{-1}$	5.1 (0.7) a	3.6 (0.7) a		
Total K	$g\cdot kg^{-1}$	3.2 (0.2) a	3.2 (0.2) a	8 (0.9) a	10 (0.9) a
Total Ca	$g\cdot kg^{-1}$	9.9 (0.4) b	8.1 (0.4) a	8 (1) a	6 (1) a
Total Mg	$g\cdot kg^{-1}$	13 (0.4) b	10 (0.4) a	3 (0.3) b	2 (0.3) a
Total Na	$g\cdot kg^{-1}$	0.4 (0.02) b	0.3 (0.02) a	0.05 (0.003) a	0.04 (0.003) a
Total Al	$g\cdot kg^{-1}$	15 (0.5) a	17 (0.5) b	0.21 (0.02) b	0.16 (0.02) a
Total Fe	$g\cdot kg^{-1}$	28 (0.8) a	26 (0.8) a	0.4 (0.04) a	0.3 (0.04) a
Total B	$mg\cdot kg^{-1}$	1.7 (0.3) a	3.9 (0.3) b	5.5 (1) a	18 (1) b
Total As [b]	$mg\cdot kg^{-1}$	5.7 (0.5) a	7.7 (0.5) b	2.1	2.4
Total Cd [b]	$mg\cdot kg^{-1}$	4.9 (0.2) a	4.8 (0.2) b	0.2	0.7
Total Co	$mg\cdot kg^{-1}$	6.0 (0.4) a	5.8 (0.4) a	0.31 (0.08) a	0.69 (0.08) b
Total Cr	$mg\cdot kg^{-1}$	130 (6) b	108 (6) a	3.1 (0.4) a	2.4 (0.4) a
Total Cu	$mg\cdot kg^{-1}$	32 (2) a	51 (2) b	5.0 (0.7) a	5.8 (0.7) a
Total Mn	$mg\cdot kg^{-1}$	433 (12) b	316 (12) a	52 (17) a	265 (17) b
Total Ni	$mg\cdot kg^{-1}$	64 (4) a	59 (4) a	2.3 (0.3) a	4.1 (0.3) b
Total Pb [b]	$mg\cdot kg^{-1}$	DL [a]	15 (1.4)	0.9	0.6
Total Sr	$mg\cdot kg^{-1}$	57 (4) a	71 (4) b	49 (10) a	71 (10) a
Total Zn	$mg\cdot kg^{-1}$	67 (3) a	77 (3) b	66 (22) a	142 (22) b

[a] OM: organic matter; EC: electrical conductivity; DL: below detection limit.

[b] As, Cd, and Pb in tree leaves: too many samples were below detection limit; thus, the mean is given for information purposes only.

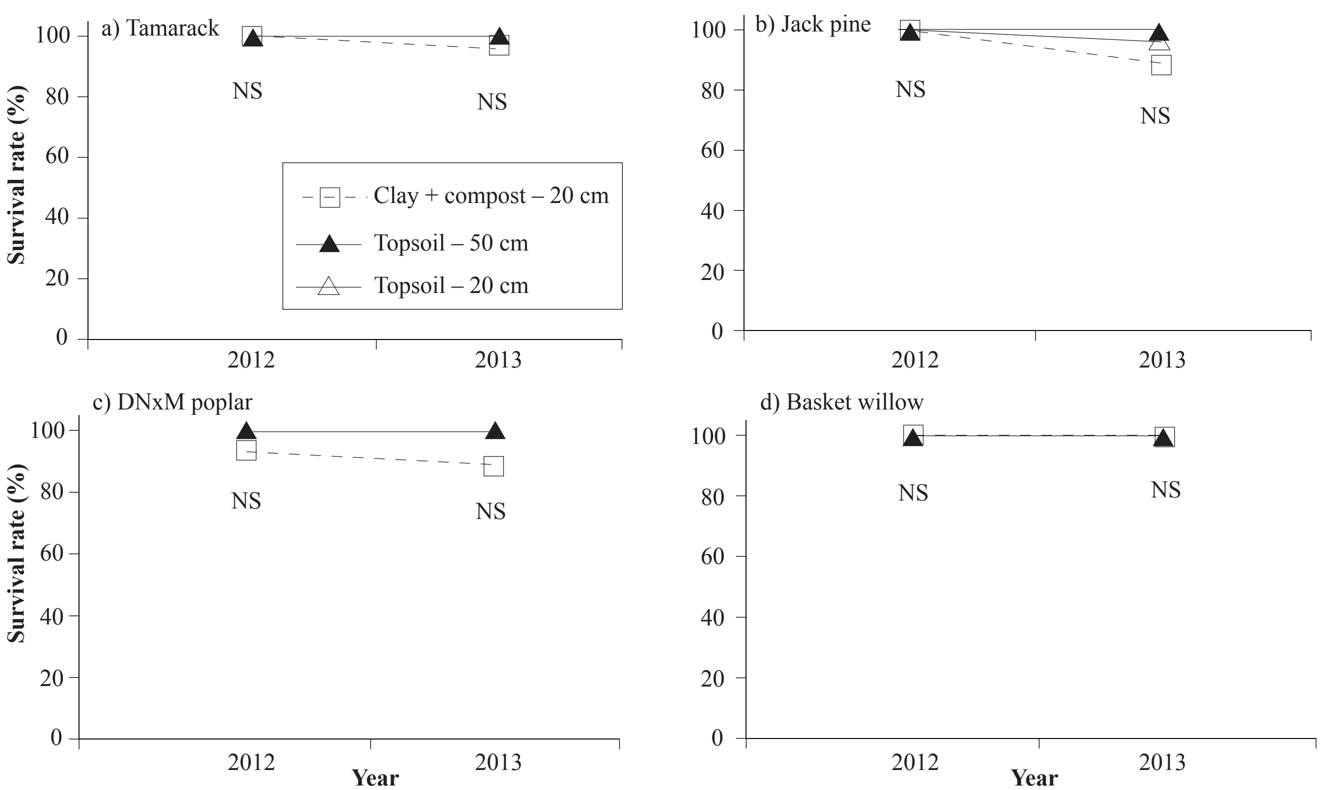

FIGURE 5. Percent survival among treatments (50- or 20-cm topsoil, or 20-cm subsoil + compost) in each growing season (2012, 1st growing season; 2013, 2nd growing season) in the tailings plantation (experiment 2) for a) tamarack, b) jack pine, c) DN×M poplar, and d) basket willow. Means, $n = 27$. Statistical comparisons were done among treatments for each date: NS: non-significant.

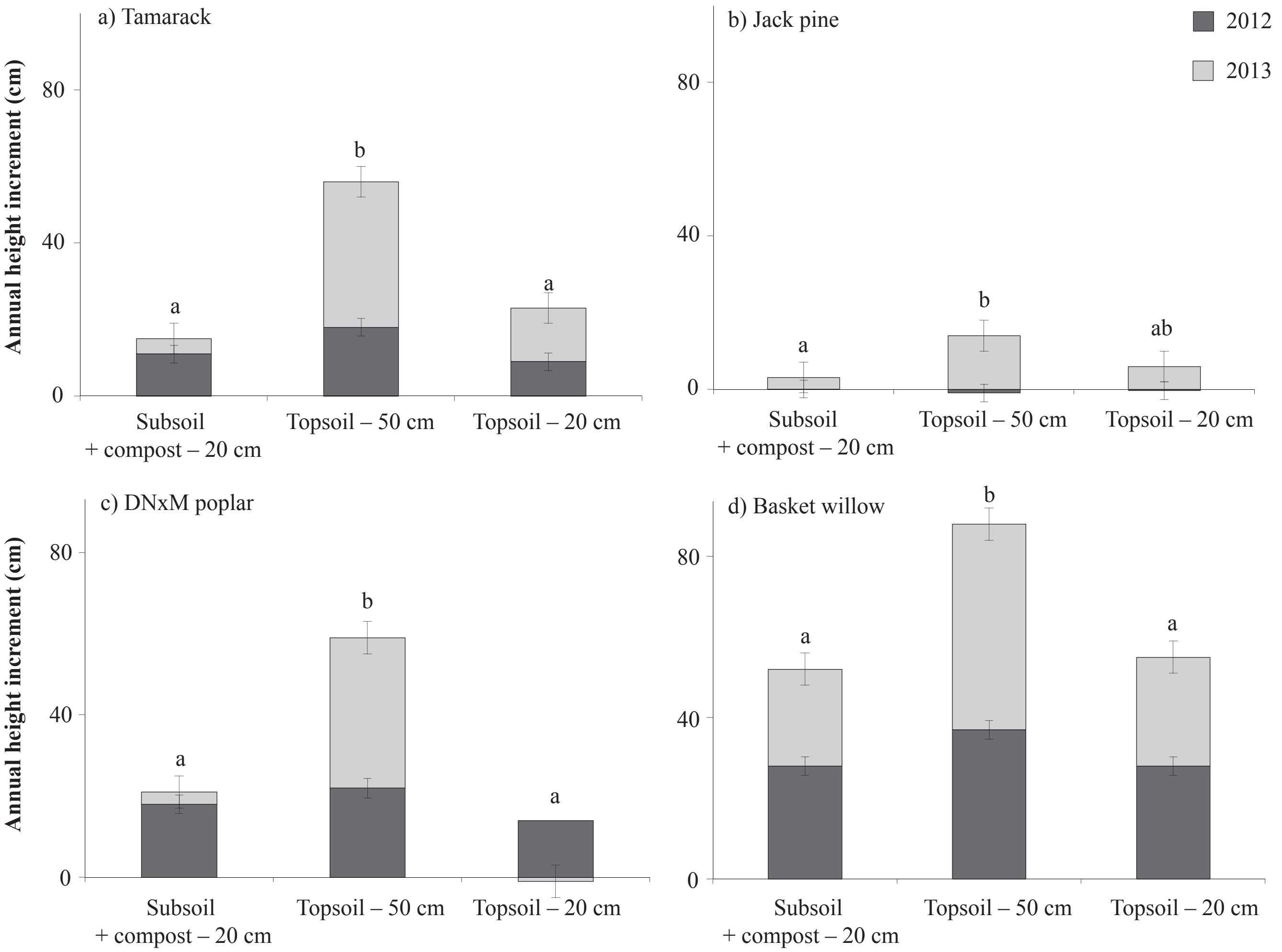

FIGURE 6. Tree height increment (cm) among treatments (50- or 20-cm topsoil, or 20-cm subsoil + compost) during each growing season (2012, 1st growing season; 2013, 2nd growing season) in the tailings plantation (experiment 2) for a) tamarack, b) jack pine, c) DN×M poplar, and d) basket willow. Means, n = 27. Bars denote SE. Statistical comparisons were done on cumulative height increments (final height – height at planting); treatments denoted by the same letter do not significantly differ at P = 0.05.

Zn (only for Zn in subsoil + compost) compared to conifers. Neither DN×M poplar nor basket willow showed any trace element accumulation behaviour since their respective foliar concentrations were far lower than those of the soils, except for Sr (×1 mean soil concentration in leaf) and Zn (×2 mean soil concentration in leaf).

Discussion

EFFECT OF SOIL QUALITY

In accordance with our first hypothesis, tree growth was greatly improved (×2) in the topsoil compared to the subsoil above waste rock, but the beneficial effects of topsoil were not more pronounced for high resource-demanding, fast-growing species. Moreover, the nature of the soil had little impact on survival after 3 y for such species, except that the poplars died more rapidly on the subsoil. The observed growth improvements on topsoil may have been unrelated to better nutrition because the corresponding trees had lower leaf N concentrations but were also bigger, and the lower foliar N may have been due to a dilution effect. On the subsoil, trees had greater leaf N concentrations, which could be due to their smaller size or to the lower C:N ratio of this material, which increased added N availability to plants (Gosz, 1984). In all likelihood, the better structure (greater macroporosity and lower bulk density) of the topsoil, which was due to its greater organic matter concentrations compared to the subsoil, improved tree growth. Better soil structure is known to create better conditions for root development, by improving the 3 critical physical properties identified by Angers and Caron (1998) for controlling root growth: root penetration, water availability, and aeration. Indeed, in the second experiment on tailings, when greenwaste compost was mixed with the subsoil, thereby increasing its organic matter content, all tree species showed similar growth responses in both 20-cm soils, *i.e.*, topsoil and subsoil + compost (except for pine diameter growth). The compost addition also enriched the subsoil in B, K, Ca, and P, which resulted in greater foliar concentrations of these elements.

The bulk density values of the subsoil were above those found in agricultural soils of the same

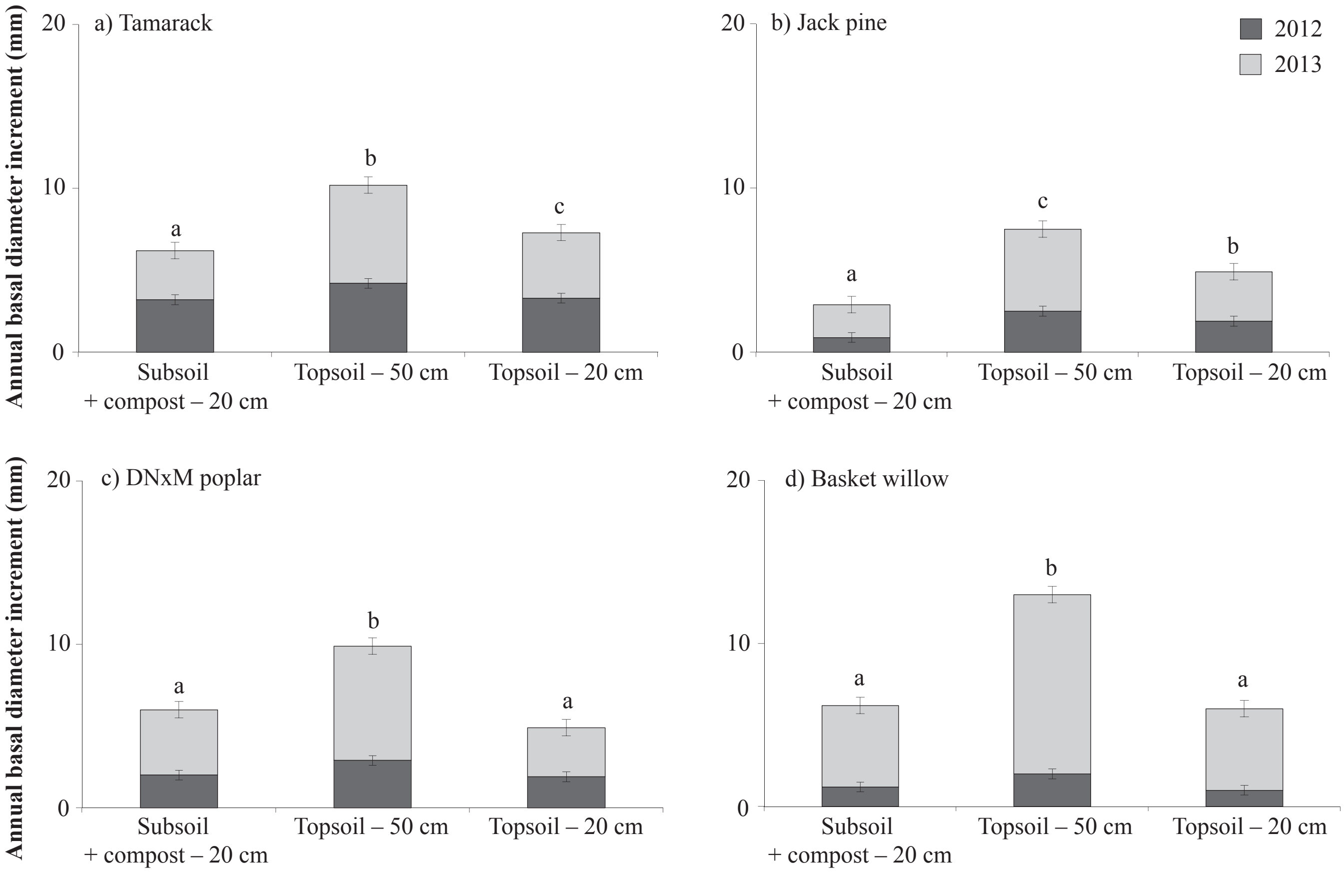

FIGURE 7. Tree basal diameter increment (mm) among treatments (50- or 20-cm topsoil, or 20-cm subsoil + compost) during each growing season (2012, 1st growing season; 2013, 2nd growing season) in the tailings plantation (experiment 2) for a) tamarack, b) jack pine, c) DN×M poplar, and d) basket willow. Means, n = 27. Bars denote SE. Statistical comparisons were done on cumulative diameter increments (final diameter – diameter at planting); treatments denoted by the same letter do not significantly differ at P = 0.05.

texture (*i.e.*, 1 g·cm^{-3}, Larchevêque, DesRochers & LaRocque, 2011). The soil used was most likely highly compacted by transport and stockpiling conditions before any layering occurred (Ramsay, 1986). In the waste rock experiment, the stockpiled subsoil reached a density threshold (1.4 g·cm^{-3}, according to Schuurman, 1965) that very likely decreased conifer root growth. Organic-matter-rich overburden topsoil was probably more resistant than the subsoil to the deleterious effects of stockpiling on bulk density and macroporosity. Soane (1990) noted that the presence of organic matter increased soil elasticity and resistance to deformation and, thus, decreased compaction ability.

EFFECT OF SOIL THICKNESS

In accordance with our second hypothesis, tree growth increased with topsoil thickness (except for jack pine height growth), but topsoil thickness had no effect on tree survival. The thinner the soil, the greater the likelihood that soil nutrients would be exhausted or that roots have less space to develop if not able to colonize the underlying mine wastes (Tordoff, Baker & Willis, 2000; Cooke & Johnson, 2002). Foliar N concentrations in both thin soils above tailings decreased (15–16 mg·g^{-1} *versus* 19 mg·g^{-1} in 50-cm topsoil) despite the trees being smaller; these lower concentrations may well explain the slow growth of the trees. The low N concentrations in the trees may have resulted from lower N availability or lower fine root biomass in the thin soils because all trees were fertilized with the same amount of N at planting. The proximity of water-saturated tailings in the thin soils may have maintained conditions of elevated moisture content and decreased aeration, which could have decreased root growth. Proximity to the water table greatly affects both the fine root growth of trees (Lieffers & Rothwell, 1987) and their nitrogen nutrition (Lieffers & Macdonald, 1990). The high nutrient-demanding hybrid poplar was the least adapted to thin soils since its height growth drastically decreased in such soils as early as the second year after planting.

COMPARISON OF TREE SPECIES PERFORMANCE

Of the fast-growing species that were tested, the 2 hybrid poplars appeared to be less adapted to mine waste revegetation with soil, while basket willow appeared to be very well adapted over the short term. Willow survival remained maximal regardless of the type (topsoil or subsoil) or thickness (50 or 20 cm) of the soil and the waste type (waste rock or tailings). Indeed, some willow species appear to perform well for the reclamation of Canadian mine sites (Mosseler, Major & Labrecque, 2014), and they are often first among the pioneer species that naturally invade boreal mine sites (Winterhalder, 1995; Strong, 2000).

Table IV. Mean (SE) basic soil characteristics and element concentrations (oven-dry mass) in the soils above tailings (experiment 2, first growing season) and in tree leaves (all species combined, second growing season) among treatments (20- or 50-cm topsoil, or 20-cm subsoil + compost). Separate comparisons were performed for soils and foliage; treatments with the same letter do not significantly differ at $P = 0.05$.

		Soils			Tree leaves		
Soil characteristics	Units	Compost – 20 cm ($n = 3$)	Topsoil – 50 cm ($n = 3$)	Topsoil – 20 cm ($n = 3$)	Subsoil + compost plantation (bulked 4 species; $n = 12$)	50-cm topsoil plantation (bulked 4 species; $n = 12$)	20-cm topsoil plantation (bulked 4 species; $n = 12$)
pH		7.3 (0.1) b	6.3 (0.1) a	6.6 (0.1) a			
OM [a]	%	5 (2) a	14 (2) b	12 (2) b			
C/N		18 (1.5) a	29 (1.5) b	26 (1.5) b			
EC [a]	$cS·m^{-1}$	10 (1) b	7 (1) ab	5 (1) a			
Total N	$g·kg^{-1}$	1.7 (0.5) a	2.7 (0.5) a	2.7 (0.5) a	15 (0.9) a	19 (0.9) b	16 (0.9) ab
Total P	$g·kg^{-1}$	0.7 (0.04) b	0.5 (0.04) a	0.6 (0.04) a	2.1 (0.1) b	1.3 (0.1) a	1.2 (0.1) a
Olsen P	$mg·kg^{-1}$	33.8 (5.4) b	10 (5.4) a	10 (5.4) a			
Total K	$g·kg^{-1}$	4 (0.4) a	3 (0.4) a	4 (0.4) a	13 (0.4)	12 (0.4)	11 (0.4)
Total Ca	$g·kg^{-1}$	16 (2) b	8 (2) a	9 (2) a	7.6 (0.3)	6.2 (0.3)	6.1 (0.3)
Total Mg	$g·kg^{-1}$	11 (0.6) a	12 (0.6) a	12 (0.6) a	2.6 (0.1) a	2.3 (0.1) a	2.3(0.1) a
Total Na	$g·kg^{-1}$	0.3 (0.05) a	0.2 (0.05) a	0.2 (0.05) a	0.11 (0.02) a	0.07 (0.02) a	0.10 (0.02) a
Total Al	$g·kg^{-1}$	10 (1) a	13 (1) a	13 (1) a	0.11 (0.001) a	0.10 (0.001) a	0.12 (0.001) a
Total Fe	$g·kg^{-1}$	23 (2) a	24 (2) a	25 (2) a	0.26 (0.02) a	0.24 (0.02) a	0.28 (0.02) a
Total B	$mg·kg^{-1}$	3.7 (0.5) b	2.1 (0.5) a	2.9 (0.5) ab	33 (2) b	16 (2) a	18 (2) a
Total As	$mg·kg^{-1}$	3.5 (1.4) a	5.9 (1.4) a	7.1 (1.4) a	2.1 (0.5) a	1.8 (0.5) a	1.3 (0.5) a
Total Cd	$mg·kg^{-1}$	4.1 (0.2) a	4.2 (0.2) a	4.4 (0.2) a	0.32 (0.07) a	0.68 (0.07) b	0.41 (0.07) a*
Total Co	$mg·kg^{-1}$	6.9 (1.5) a	7.2 (1.5) a	7.0 (1.5) a	0.82 (0.11) a	0.69 (0.11) a	0.52 (0.11) a
Total Cr	$mg·kg^{-1}$	163 (10) a	162 (10) a	159 (10) a	1.8 (0.48) a	1.32 (0.48) a	1.74 (0.48) a
Total Cu	$mg·kg^{-1}$	37 (2) a	38 (2) a	40 (2) a	3.9 (0.3) a	5.3 (0.3) b	4.5 (0.3) ab
Total Mn	$mg·kg^{-1}$	355 (16) a	329 (16) a	359 (16) a	87 (15) a	125 (15) a	107 (15) a
Total Ni	$mg·kg^{-1}$	70 (9) a	94 (9) a	93 (9) a	2.31 (0.77) a	5.22 (0.77) b	2.88 (0.77) a
Total Pb	$mg·kg^{-1}$	18 (100) a	29 (100) a	33 (100) a	0.36 (0.25) a	0.35 (0.25) a	0.27 (0.25) a
Total Sr	$mg·kg^{-1}$	102 (9) b	69 (9) a	79 (9) ab	41 (4.5) a	32 (4.5) a	33 (4.5) a
Total Zn	$mg·kg^{-1}$	67 (4) a	68 (4) a	71 (4) a	66 (8)	113 (8)	70 (8)

[a] OM: organic matter; EC: electrical conductivity.

On waste rock, M×B poplar survival was low in the third year (≤50%), regardless of treatment. A similar decrease in survival with time was also observed for jack pine, but this species declined in a less drastic manner. Foliar analyses that were performed in the second year revealed adequate but low N concentrations (18–23 $mg·g^{-1}$) in poplar leaves of the waste rock experiment, which may have increased their sensitivity to weed competition for N (Hansen, McLaughlin & Pope, 1988). Nitrogen is an essential plant nutrient that greatly affects tree growth, especially in boreal ecosystems, where N mineralization is slow due to cool temperatures (Stanturf *et al.*, 2001). Understory colonization of the plantations was low during the first year, but 23 different species, mainly grasses and a few shrubs, were found in the plantation understory during the second year (M. Lachevêque, unpubl. results). Crown closure of poplars and willows occurred as soon as the third year at 1 × 1 m spacing, and a substantial decrease in the weed cover was noted, which likely reduced competition for N. Another explanation for poplar decline in the waste rock experiment in the third year could be their increased sensitivity to drought stress with increasing size on this well-drained substrate. Among woody plants, poplars are very sensitive to water stress (Marron *et al.*, 2005). The low degree of spacing between individual poplars could also have increased intra-specific competition for water and nutrients (Benomar, DesRochers & LaRocque, 2012).

Like willow, tamarack survival was high on both waste types (except in subsoil alone). The latter species should be considered for mine site reclamation, especially on tailings. Indeed, its height growth was far better on tailings compared to waste rock, probably due to the more humid conditions in the soils covering the low drainage tailings. Tamarack is well adapted to high water table environments (Kenkel, 1987; Islam & Macdonald, 2004).

Trace metal accumulation by trees

In accordance with our third hypothesis, trace metal accumulation in the tree species that we tested was low, probably due to the neutral pH of the mine wastes and their low total concentrations of these elements. As expected, concentrations for several metals (Cd, Co, Cu, and Zn) in fast-growing broadleaved species were greater than those in native conifer species, but only in the tailings experiment; otherwise, they remained low. The only trace metal that accumulated in the foliage of trees was Zn (broadleaved species only). The bioaccumulation factor (*i.e.*, Zn concentration in leaves/Zn concentration in soil) was greater than 2 for this species, while others have reported it to be less than 1 (Rosselli, Keller & Boschi, 2003; Vervaeke *et al.*, 2003). In our experiment, the acidic pH of the topsoil may have increased Zn availability to trees (Markert *et al.*, 2000; De Nicola, Maisto & Alfani, 2003), while the landfill soils that Rosselli, Keller, and Boschi (2003) reported on were calcareous, with neutral pH. Moreover, it should be noted that the Zn accumulated in the willows may not have originated preferentially from the mine wastes, given that total concentrations of this element in the wastes were similar to those of the soils layered over top of the rock waste and tailings. Bioaccumulation in basket willow remained low, and thus this species would appear to be a good candidate for site revegetation. However, since basket willow has also been reported to be one of the willow species that is most sensitive to Cu, Ni, Cd, and Zn toxicity (Punshon & Dickinson, 1999), the performance of the planted trees should be monitored over the longer term to detect any deleterious effects of long-term Zn accumulation.

Contrary to our fourth hypothesis, some trace metals accumulated to a much greater extent in the thick 50-cm topsoil than in the thinner 20-cm soils above tailings. In trees that were planted in the 50-cm topsoil, Cd, Cu, and Ni concentrations were higher for all tested species and foliar Zn concentrations were higher in willow when compared to the thin soils. The proximity of the neutral pH tailings in the case of thin soils may have increased soil pH, which in turn would have decreased the availability of these trace metals to trees (Larchevêque *et al.*, 2013).

Conclusion

To afforest low sulfur mine wastes in the boreal region, we would recommend the use of topsoil more than 50 cm thick for fast-growing, drought-sensitive hybrid poplars. The same recommendation may be applicable to jack pine, since its survival declined on 50-cm-thick topsoil during the third year, but this should be confirmed over the longer term. Basket willow and tamarack can be planted in 20-cm-thick or lower quality (*i.e.*, mineral subsoil) soils without threatening survival over the short term, but at the expense of growth rates. Tamarack established well in the more humid conditions likely to be characteristic of thickened tailings, while basket willow performed better on waste rock in terms of its growth. Finally, to improve the structure of the subsoil for tree establishment, soil layering can be performed 1 y before planting or the subsoil can be mixed with greenwaste compost at planting.

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