Effect of soil quality and planting material on the root architecture and the root anchorage of young hybrid poplar plantations on waste rock slopes

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Abstract

Tree planting can facilitate the rehabilitation of forested landscapes on mine waste rocks. However, because of their physical and chemical nature, waste rocks are difficult to revegetate and can restrict tree root growth. On waste rock slopes, trees with inadequate root development could be prone to uprooting. The anchorage of trees is mainly determined by the architecture of the root systems that drive their mechanical interactions with the soil. The success of tree planting can be improved if performed after spreading soil over waste rock slopes. However, there is limited knowledge on the influence of soil quality on tree root development and stability. The objective of this study was to evaluate the effects of soil quality (50 cm of topsoil versus 40 cm of mineral soil + 10 cm of topsoil) and of different planting materials (whips, cuttings, and bareroots) on the architecture and resistance to shear stress of root systems of hybrid poplars four years after they were initially planted. The study was conducted in an open-pit-gold mine located in the boreal forest of Malartic, Quebec, Canada. A hybrid poplar plantation was established in 2013 on 33% soil-covered waste rock slopes, using a randomized complete block design, i.e. 3 replicated blocks × 3 planting materials × 2 soil qualities. During the fourth growing season, the stability of the hybrid poplars (resistance to uprooting) was evaluated using lateral traction tests. Complete excavations were performed to characterize their coarse root

(> 4 mm) architecture. Results showed no significant differences between treatments in terms of the maximum resistance force to uprooting, which varied between 7142 and 8989 N. After four growing seasons, no significant effects due to soil quality or planting material were observed in the number of lateral roots, mean root diameter, root biomass, aboveground biomass, and shoot/root ratio. The maximum height and basal diameter also did not differ among treatments. These findings indicate that the coarse root architecture of the planted trees and their associated root anchorage were not affected, in a four-years-old plantation of hybrid poplars, by soil quality or planting material.

Keywords: mine site revegetation, tree planting, coarse root development, uprooting tests, topsoil, overburden.

1. Introduction

In forested areas, the revegetation of mine sites after closure often involves planting trees on waste storage facilities that need to remain geotechnically stable over long periods of time. The resistance of trees to uprooting is, therefore, important to ensuring the stability of these waste facilities, which are often exposed to strong winds, particularly on slopes. Metal mining generates large volumes of solid wastes, and in particular, waste rocks, which consist of the uneconomic material that is extracted to reach the ore body. Waste rocks are usually stored at the surface in the form of piles of several tens of meters high called waste rock piles (Aubertin *et al.*, 2002). Typically, these structures are difficult to revegetate due to their physical and chemical characteristics (Mench et al., 2003); specifically, waste rock piles lack the proper physical structures, nutrients, organic matter (OM), and microorganisms to support plant growth (Burger and Zipper, 2002; Tordoff et al. 2000). The geometry of sites can also be a challenge for establishment of vegetation, especially where there are higher angle slopes and overall elevations.

To facilitate their revegetation, waste rock piles are usually covered with soil layers. Soil quality (in particular organic matter concentration) is an important determinant of tree growth (Zipper et al., 2011), and especially root growth. Therefore, when available, topsoil (i.e. A horizon) is used to improve soil productivity and biological functionality (Tordoff et al., 2000). However, the quantity of topsoil available at mine sites can be limited. In these cases, topsoils may be replaced by or combined with mineral soils, which are low in OM content and have poorer fertility, but are available in greater quantities.

Hybrid poplar plantations on soil-covered waste rock slopes have previously shown good survival and growth rates (Babi et al., 2019; Remaury et al. 2019; Larchevêque et al. 2014; Casselman et al., 2006; McGill et al., 2004; Clark Ashby, 1995). However, hybrid poplars are sensitive to changes in environmental conditions and known to respond to variations in the availability of nutrients and water in the soil depending on the plantation design (Babi et al., 2019; Zandalinas *et al.*, 2018; Dickmann, 2001). Thus, these fast-growing trees can be used as model plants to study the establishment of trees on mine tailings, including the effect of factors related to the design of plantations on the root development of trees and their stability.

Root systems provide both physiological and mechanical functions for plants. The absorption of water and nutrients is primarily performed by fine roots (d < 2 mm), whereas coarse roots (d > 2 mm) provide anchorage for the tree (Gyssels et al. 2005; James et al., 2006; Stokes *et al.*, 2005). Coarse root architecture is essentially represented by the spatial configuration of the roots (Gregory, 2006) and plays a major role in the root anchorage of the tree, wherein stability is defined as the capacity of a tree's root system to resist uprooting (Khuder *et al*. 2007; Stokes et al. 2007). The resistance force of a tree varies with its root architecture (Bell *et al.*, 1991). Moreover, the angles between roots, the number of roots, root diameters, root system symmetry, and root depths are all known to have significant impacts on anchorage and tree stability (Garrett et al, 2009; Gregory 2006; Nicoll et al., 2006; Godin 2000; Godin et al. 1999; Ruel, 1995; Fitter 1991; Harper et al.1991). Despite the importance of these parameters, relatively few belowground investigations have been conducted to evaluate the effects of planting design on root development, especially in the context of revegetation of waste rock slopes.

Although root system architectures are usually genetically predetermined (Kano-Nakata et al., 2019; Das and Chaturvedi, 2008), environmental factors, including soil texture (Drénou, 2006) and structure, can also affect root distribution (Lebourgeois and Jabiol, 2002; Coutts et al. 1999. For example, Moore (2000) showed that the mechanical resistance of pine depended on soil quality, with trees growing on clay soils showing greater maximum resistances to bending moments than those growing in non-cohesive soils. Root growth has been shown to increase with the presence of pores, thus allowing for balanced water storage and air transmission in the soil (Dexter, 2004; Oades, 1984), and root distribution was shown to depend on the content of OM and nutrients in the soil (Sainju and Good, 1993). Roots develop more (number, length, and diameter) in environments where water and nutrients are abundant (Hutchings and John, 2003). Organic matter influences soil structure by increasing total porosity (Tejada and Gonzalez, 2003; Marinari *et al.*, 2000), which can result in an increased water retention capacity (Celik *et al.*, 2004; Khaleel *et al.*, 1981). Root density is generally positively related to OM content (Strong and La Roi, 1985), therefore, trees may be more stable in soils richer in OM where root development would otherwise not be optimal. In fine-textured soils, root systems are generally denser and comprised of smaller roots because they are more able to penetrate into cracks (Nagarajah, 1987; Lévy, 1968). In coarse-textured soils roots are usually longer and more numerous (Nagarajah, 1987; Lévy, 1968). The depth and colonization intensity of the rooting zone also depends on the physical constraints of the soil (Curt et al., 2001), which restrict root elongation and can modify the root architecture of the plant (Ludovici, 2004) as well as its stability.

Planting material choice is an integral part of plantation establishment (Davis et al., 2010; Burdett, 1990). The type of planting material can affect aboveground tree growth, physiology, and survival (Desrochers and Tremblay, 2009; Jutras *et al*. 2007; Mohammed *et al*. 2001), and thus the overall success of plantations (e.g. Johansson et al., 2007). Nonetheless, the influence of planting material on root development and tree anchorage still requires further research. In Québec, Canada, planting materials of large sizes are generally used to produce hybrid poplars and to overcome weed competition for light (Réseau Ligniculture Québec, 2011). Materials such as bareroot seedlings, cuttings, and whips can be considered as viable options. Each type of material has advantages and disadvantages (Balleux and Van Lerberghe, 2001) (supplementary materials) according to differences in size as well as imbalances in the shoot/root ratio, which influences the water budget and, therefore, the aboveground as well as belowground growth and survival of trees (Grossnickle, 2005).

The main objective of the present study was to check whether topsoil could be saved by combining it with mineral soil, while allowing an adequate rooting and anchorage of trees, for differing planting materials in a hybrid poplar plantation on waste rock slopes (3H:1V, 33%) covered with 50 cm of soil. More specifically, this study examines the effects of using different planting materials (whip, cuttings, and bareroot) and soil qualities (50 cm of topsoil or 40 cm of mineral soil + 10cm of topsoil) on survival rates, aboveground growth, root architecture and mechanical resistance to uprooting of planted trees four years after planting. Lateral traction tests of hybrid poplars were conducted until uprooting as well as a complete excavation method to relate anchorage to the root architectural characteristics. The study is based on the following hypotheses:

i) Only bareroots seedlings have roots at planting. Therefore, the growth and survival of trees will be highest for bareroots.

ii) The growth and survival of hybrid poplars will decrease when the topsoil is combined with mineral soils as compared to using topsoil only.

iii) The root architecture of unrooted plants (cuttings and whips) will be less developed (number and diameter of roots; maximum rooting depth) than rooted plants (bareroots) and its development will increase with the diameter of the planting material (bareroots > whips > cuttings). Therefore, the resistance to uprooting of cuttings will be the lowest.

iv) Higher topsoil quantities will foster more developed root systems (in terms of number, length, and diameter of roots), thus, allowing for higher resistances to uprooting forces.

2. Materials and methods

2.1. Site description

The study site was located at the Canadian Malartic mine in the Abitibi-Temiscamingue region of Quebec, Canada (48° 08′ 00″ N 78° 08′ 00″ W). Canadian Malartic is a an open pit gold mine (average grade 1g/t) that exploits an orebody a rate of approximately 55,000t/day. The ore to waste rock ratio at the mine is typically between 2 to 4, and thus mining operations at Canadian Malartic generate significant quantities of solid wastes.

The forest vegetation that surrounds the site is mainly comprised of stands of black spruce (*Picea mariana),* jack pine (*Pinus banksiana)*, and larch (Larix spp.) mixed with white birch (*Betula papyrifera*) and trembling aspen (*Populus tremuloides*). The mean annual air temperature is 1.5 °C and the mean annual precipitation is approximately 930 mm (Government of Canada, 2015). The average length of the growing season ranges between 120 and 130 days and the mean number of frost-free days is 97 (Agriculture and Agri-Food Canada, 2014).

2.2. Experimental design

The experimental design, shown in Figure 1, included eighteen (18) experimental plots organized in a randomized complete block design that included three replication blocks and two tested factors (2 × 3 factorial design): 1) three plant types (whips, bareroots, and cuttings of the hybrid poplar MxB 915318); and 2) two substrates (50 cm of topsoil versus 40 cm of mineral soil + 10 cm of topsoil). Each of the eighteen experimental plots contained 25 trees (pseudoreplicates) with a spacing of 2 × 2 m. The plots were separated by 4-m-wide buffer zones. Two lines of fast-growing willows (*Salix miyabeana* Seemen, clone Sx64) were planted in the upper half to limit soil erosion and water run-off.

2.3. Planting material and growing conditions

The experimental plots were established in May 2013 on 3H:1V (33% or 18°) slopes of mine waste rocks covered with 50 cm of soil. The topsoil was a Grey Luvisol soil (Agriculture and Agri-Food Canada, 2010) from a swampy area that was located above the actual open pit. The topsoil consisted of the O and A horizons; i.e., the first 30 cm, which were dark in color and rich in organic matter (~ 20% OM content). The mineral soil consisted of the remaining sandy clay that was excavated down to the bedrock after the overburden topsoil had been removed. The soil texture was composed of 42% clay particles, 27% silt particles, and 31% sand particles, and contained ~1% OM. The topsoil and mineral soil were stored for 30-36 months before use in 7-m-high piles with a slope of 2.5:1. One composite sample (consisting of two samples per plot; 0-10 cm depth) was used for chemical characterization during planting (May 2013). Soil 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 nitrogen (N) and sulphur (S) were determined by the Dumas combustion method (CNS 2000, LECO Corporation, Mississauga, ON), and organic carbon (C) was determined using the thermogravimetric method (LECO TGA, Mississauga, Ontario). A conversion factor of 1.72 was used to convert organic carbon content to organic matter content (Nelson and Sommers 1982). Following an HNO_3-HCl digestion, bulk P, K, Ca, Mg, Na, Al, As, B, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Sr, and Zn concentrations were determined by inductively coupled plasma atomic emission spectrometry (ICP-AES, Vista PRO, Varian Canada, Mississauga, ON). Available phosphorous (P) was determined colorimetrically on sodium bicarbonate extracts of the soils (Olsen 1954). Bulk pH was determined from saturated soil pastes, while soil electrical conductivity was determined in a 1:2 (soil:water) mixture. Soil texture was determined using the hydrometer method (Bouyoucos, 1962) (supplementary materials). All measured soil and waste rock metal concentrations were below relevant regulatory thresholds.

A physical characterization of the same soil (topsoil and mineral soil) was determined in other studies (Larchevêque et al., 2016; Larchevêque and Pednault, 2016; Larchevêque et al. 2014). Briefly, these studies showed a greater macroporosity (15-20%) and lower density in the topsoil (0.7-0.9 g·cm^{-3}) relative to the mineral soil (macroporosity: 12-16%; density: 1.1-1.2 g·cm–3). Both the topsoil and mineral soil were found to have macroporosities above the 10% threshold that would allow root growth (Archer and Smith, 1972). The density of the two soils is also adequate for root growth (Schuuman, 1965).

The planting material used in this study was a semi-exotic hybrid poplar clone (*Populus maximowiczii* A. Henry × *Populus balsamifera* L. (M × B) - clone 915318), locally produced by the Quebec Ministry of Energy and Natural Resources (MERN). This poplar selected was based on its rapid growth and establishment from vegetative material.

Three planting materials were used (Figure 2): bareroot plants (mean length above ground = 131 cm and mean diameter = 11 mm); whip plants (mean length above ground= 93 cm and mean diameter = 15 mm), and cuttings (mean length above ground= 33 cm and mean diameter = 11 mm). Whips and cuttings are generally one year-old shoots, while bareroot plants are produced from 12-15 cm cuttings that are grown in the field for one growing season. The mean lengths and diameters of the planting materials were initial measurements taken just after planting. These measurements exclude the 20-30 cm of stems/roots buried in the soil.

2.4. Measurements, sampling, and analysis

Initial growth measurements (maximum height and basal diameter) were conducted at the planting in spring 2013, as well as at mortality. This inventory was repeated in the fall in 2013, 2014, 2015, and 2016.

According to climate data for 2016, monthly precipitation and temperature over the growing season (May–October) was similar to normal mean values calculated for the past 30 years.

2.4.1. Coarse root observations

In this study, only roots with a diameter > 4 mm were considered coarse, structural roots (Danjon and Reubens, 2008). Observation trenches were dug after four growing seasons (June 2016) under the second tree of the second line from the bottom of the slope, approximately ten centimeters from the stem. These $1 \times 1 \times 1\ \mathrm{m}^3$ trenches were dug with a mechanical shovel (Figure 3) for each plot (N = 18). The maximum rooting depth was noted for each treatment.

2.4.2. Root extraction

In June 2016 (fourth growing season), the root systems of eighteen trees (one tree in the center of each plot for each treatment), were excavated with a high-pressure water jet using a hydraulic pump (PUMP 2 " MULTIQUIP, N Series: 2H-7348). The structure of the root system was photographed, described, and schematized (360° distribution, vertical distribution). The overall description of the root systems was complemented by the following quantitative measurements: the number of main lateral roots (roots with a diameter > 10 mm), the number of branches from each main root, the diameter of each main root every 50 cm (until there was no more change in the diameter), the total length of the main roots until reaching a diameter < 4 mm, the angles between main lateral roots of the upslope side and the line separating upper and lower slope, and the number of sinker roots (in-depth). Measurements were performed from the collar (origin of all roots) in the direction of growth. Prior to excavation, the stem basal diameter (diameter of the base of the stem) and maximum height were measured for the eighteen studied hybrid poplars. For each excavated tree, the aboveground biomass and belowground biomass was measured. The material was oven-dried at 90 °C for 48 h for the aboveground parts and for 72 h for the roots. Once dried, the samples were weighed.

A root anchorage index was calculated to integrate some of the key measured root architectural parameters (Figure 4) for each plot. These included:

- Angles between the main lateral roots (A_n): the sum of the angles between each main lateral root on the upslope side and the line separating upper and lower slope was calculated for each excavated tree (one tree per plot, twelve in total).
- Diameters of the lateral roots on the upslope side (d; mm): the diameter of each lateral root was measured at the collar of each excavated tree.
- The length of the main lateral roots[1] (L; cm):
- The maximum rooting depth (roots with a diameter > 4 mm) (P; cm): measured for each excavated tree.

Two indexes were calculated and compared:

***I*$_1$** (cm) normalized by the sum of the diameters of the upslope roots.

***I*$_2$** (cm^2) multiplied by maximum root depth and divided by soil depth.

$$\textbf{Stability index 1}(\mathbf{I_1}) = \frac{\sum_0^n (x_n d_n)}{\sum_0^n d_n}$$

$$= \frac{\sum_0^n (L\, d_n \sin A_n)}{\sum_0^n d}$$

$$\textbf{Stability index 2 }(\mathbf{I_2}) = \sum_0^n (x_n d_n)\left(\frac{P}{\text{soil depth}}\right)$$

$$= \sum_0^n (L\, d_n \sin A_n)\left(\frac{P}{\text{soil depth}}\right)$$

The concept is based on the balance of forces in a 2-D plane. The following hypotheses were considered:

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[1] The length was considered constant with L: 50 cm. According to field observations, the diameter of the main structural roots decreases rapidly after 50 cm, thus it is chosen to consider a maximum length of 50 cm and constant in the calculations. It is considered that the maximum root reinforcement occurs at this level, close to the trunk.

- Hypothesis 1: the traction force exerted on the lower trunk is transferred to the upslope roots as a tensile force. If we assume that the force exerted is in the direction of the y-axis, only the y component of the roots will resist the exerted force. We also consider that everything happens in a 2-D plane.
- Hypothesis 2: the downslope roots are in compression and have a negligible impact on the resistance of the roots to the uprooting force exerted by the winch.
- Hypothesis 3: for the first index (I_1), it is assumed that the influence of the roots is limited to a certain length[1]. It is also assumed that the root diameter has an influence on its ability to resist the tension exerted.

2.4.3. Lateral uprooting tests

In July 2016 (fourth growing season), lateral traction tests were performed for eighteen hybrid poplars (one tree in the center of each plot) using methods adapted from previous studies (Thiffault, 2010; Sheedy, 1996; Grouard, 1995). Before the uprooting tests, maximum height and basal diameter of the stem were measured for each tree.

The point of attachment was determined by preliminary tests in order to have a significant force on the root systems and not cause curvature of the stems. Our study aimed to characterize the anchoring of young trees with a test where shear was the main mechanical stress applied to the tree. Our objective was not to reproduce the effect of the wind on tree stability but to evaluate the strength of root anchorage associated to differing planting designs. The objective was to compare the anchorage of trees to select the design (s) that minimized the risks of planted trees' uprooting that could affect the integrity of revegetated mine berms. Thus, for the pullout tests performed, the cable used for the lateral uprooting tests was attached as low as possible on the stem (at the base of the tree). Therefore, the response corresponds to the maximum resistance of the root system to a shear force. An automatic winch (WARN Pro Vantage 2500SCE 4200 lb) was used. It was attached to an optimum dynamometer scale model OP 926 (Optima Led Digital Hanging Scale 2000 lb), which was in turn attached to the tree with a sling and chain around the base of the trunk. The force was measured by the dynamometer and the readings were converted to Newtons. A lateral force (0-8811N) was exerted down the slope, parallel to the slope. The applied force (N) and the displacement (cm) of the tree (displacement of the stem compared to the initial state) were noted each minute until the root system was removed from the soil.

2.5. Statistical tests

Results from the lateral uprooting tests (maximum resisting force); root architecture observations (mean root diameter, mean number of roots, mean number of root branches); biomass analyses (aboveground and belowground biomass, shoot to root ratio); maximum measured rooting depths; and calculated root anchorage indexes were analyzed using mixed linear models created with R (ver.3.1.0). The fixed effects were planting material and soil quality, and the random effect was block. An ANOVA with repeated measures was used for tree height, basal diameter, and diameter at breast height. The normality of the response variables and the ANOVA assumptions were verified. The Tukey multiple comparison test was used when an effect was significant. A significance level of 5% was considered for the statistical analyses performed in this study. Correlations between the maximum resisting force and the stability indices (I_1 and I_2) were tested with Pearson's correlation analyse.

3. Results

3.1. Growth, survival, and poplar biomass

After four growing seasons, survival was high (95-100%) for all treatments (Table1). The maximum height of the trees was lower for the cuttings compared to the other two types of planting materials until autumn 2015 for the topsoil only treatment and autumn 2014 for the topsoil + mineral soil treatment (Figure 5). However, at the end of the fourth growing season, none of the treatments were statistically different in terms of the aboveground and belowground development of trees (maximum height, basal diameter, diameter at breast height, root biomass, aboveground biomass, aboveground/belowground ratio, aboveground/total biomass and belowground/total biomass; Table2). No interactions were observed between planting material and soil quality. In the fourth growing season, mean tree height ranged from 327 to 471 cm and the basal diameter ranged from 50 to 78 mm.

Aboveground biomass (1791-2672 g) was four times greater than the root biomass (379-566 g).

3.2. Root architecture

Four years after planting, there was no significant difference between the topsoil only and topsoil + mineral soil treatments in terms of the main quantitative variables describing the root system structure (Table3). These included the: mean root number, mean root diameter, maximum rooting depth, and number of sinker roots. Similarly, the planting material had no significant effect on the same variables. There was no interaction between planting material and the quality of soil. Hybrid poplars showed herringbone root structure (figure 6) characterized by a dominant vertical axis (main shoot of the planting material that was pulled down 30cm-deep in the soil at planting for whips and cuttings), with lateral roots distributed on this axis every 10-20 cm. For each tree, the vertical axis diameter was constant vertically. The main roots (lateral roots) were ramified and could extend to lengths of more than 2 m (horizontally). The diameter of these roots varied between 11 and 26 mm at a maximal distance of 1 m from the trunk. The diameter of the lateral roots decreased rapidly after a length of 50 cm.

For all root parameters, the results showed that the two calculated root anchorage indexes did not change significantly with planting material or soil quality. There was no interaction between the two evaluated factors (planting material and soil quality). (Figure7).

3.3. Lateral uprooting tests

For both the aboveground and belowground parameters, soil quality and tree planting material did not significantly affect the maximum resistance to uprooting and there was no significant interaction between the two tested factors. The measured maximum resistance force to uprooting varied between 7351 and 8851 N (Figure8), with the following mean values for the topsoil treatment (whip: 7320 N, cutting: 8767 N, and bareroot: 8046 N) and topsoil + mineral soil treatment (whip: 7049 N, cutting: 8587 N, and bareroot: 8026 N).

Figure 9 shows the evaluation of the uprooting force relative to the displacement of the tree; all treatment curves had similar uprooting speeds. The trees were generally uprooted after 30 cm of displacement when the force reached approximately 8000 N.

The Pearson correlation between root anchorage index 1 (I_1) and the maximum resisting force is 0.92 (P= <.0001). The Pearson correlation coefficient between index (I_2) and maximum resisting force is 0.89 (P= <.0001).

4. Discussion

To the best of our knowledge, this trial is one of a kind study that examines the effect of planting material and soil quality on the anchorage of trees planted on waste rock slopes.

Tree stability can be greatly influenced by the distribution of biomass between the aboveground and belowground parts. Contrary to the authors' first hypothesis, there were no statistically significant differences between the six treatments in terms of aboveground biomass, belowground biomass, and root/shoot ratios. Prior experiments by DesRochers and Tremblay (2009) compared four planting materials (bareroots, rootstocks, whips, and cuttings) of hybrid poplars in a clayey soil. They observed significant differences in the root/shoot ratio that were attributed to the different planting types, but only in the first growing season. Thus, the difference between rooted and unrooted planting materials can disappear over successive growing seasons (Sidhu and Dhillon, 2007). At the end of growth monitoring in the present study (autumn 2016), the trees from cuttings were the same sizes as those from the bareroots and whips, despite their height being much smaller at the beginning of the experiment. This could be explained by a higher growth rate in the cuttings (Desrochers and Tremblay, 2009; McNabb and Vanderschaaf, 2005). Results from the present study also indicated similar mean diameters for the three tested planting materials after four growing seasons, despite the initial mean diameter of the whips being higher than that of the cuttings and bareroot seedlings. Similarly, previous studies did not find a positive relationship between initial dimensions of plants and growth (Robison and Raffa 1996, hybrid poplar; Haissig, 1984, *Pinus banksiana*). However, studies that examined other tree species, such as black spruce (*Picea mariana*), white spruce (*Picea glauca)*, Olga Bay larch (*Larix olgensis*), douglas-fir (*Pseudotsuga menziesii)*, western hemlock (*Tsuga heterophylla*), and Sitka spruce (*Picea sitchensis)*, have noted that initial plant size parameters, especially diameter, influence survival and growth performance (Thiffault et al., 2014; Li et al. 2011; Jobidon et al. 2003; Newton et al. 1993). Cuttings with large initial diameters can contain more non-structural carbohydrates and thus provide a greater energy reserve, improving the likelihood of rooting success (Landhausser et al. 2012; Tschaplinski and Blake, 1989). However, it appears that the effect of carbohydrate reserves on rooting ability depends on the site-specific environmental conditions and on the tree species (Thiffault et al. 2014; Pinto et al. 2011).

The difference in root/shoot ratio has a significant effect on growth because of its implications for water uptake and water loss in trees (Grossnickle, 2000). The survival and growth of cuttings and whips were as high as bareroot seedlings despite the fact that they needed to develop new roots to access soil resources. Bareroot plants already have a root system at planting and therefore have rapid access to water and nutrients. However, bareroot plant roots could have poor contact with the soil (air pockets between root and soil) (Grossnickle, 2000). Moreover, bareroot plants have to support large aboveground parts and must regenerate new roots to facilitate water and nutrient uptake. The buried portion of the stem of poplar cuttings and whips can develop roots from their stems when conditions are appropriate (DeBell and Harrington, 1997; Hansen et al., 1993; Friend et al., 1991). Other studies have reported varying performances among planting material types (Douglas et al., 2016; MacDonald et al. 2015; Thiffault, 2004; Newton et al. 1993). Additionally, Duddles and Owston (1990) indicated that the site conditions could have more impact on growth and survival than the planting material type. The rate of survival and height growth of the tested hybrid poplar clone (26 – 143 cm. yr^{-1}) were similar or superior to those observed for the same poplar clone in plantations on other sites with similar boreal conditions (40 cm. yr^{-1}, Benomar et al., 2012; Larchevêque et al., 2011). It appears that, with the use of a 50-cm-thick layer of overburden soil, hybrid poplar planting could be appropriate for the revegetation of waste rock slopes under both short- and medium-term conditions.

Soil quality directly influences tree development and survival. Notably, the presence of organic matter influences many functions in the soil (Rezaei and Gilkes 2005; Doran and Parkin, 1994). Moreover, prior studies have shown a positive effect of soil thickness on tree growth and survival (Larchevêque and Pednault, 2016; Tordoff et al. 2000). Contrary to the authors' second hypothesis, there were no significant differences in the growth and survival of trees when the topsoil (and the organic matter) quantity increased. The development of the hybrid poplar tested in this study was equivalent in 50 cm of topsoil as in a combination of 40 cm of mineral soil and 10 cm of topsoil. This could be explained by the improvement of the quality of the mineral soil after the four years of planting. In particular, the establishment of herbaceous plants can constitute a source of organic matter by providing litter (Zhou et al. 2008; Li et al. 2006).

The anchorage of a tree is controlled by the architecture of its root system, as well as its interactions with the soil. Root architecture has an important influence on the tensile forces mobilized in the roots (Dupuy et al., 2005). In the present study, neither the planting material diameter nor the soil quality influenced the root architecture of the tested hybrid poplar. Both rooted (bareroots) and unrooted plants (cuttings and whips) developed coarse root system with similar architectures after four growing seasons. In particular, there was no difference observed between treatments in terms of the quantitative variables used to evaluate and describe the root system structures. Thiffault (2010) measured stability (resistance to winching) of large containerized and bareroot black spruce (*Picea mariana*) seedlings in the seventh growing season and characterized their root architecture. Their results showed no significant effects due to planting material on the trees' stabilities or root architectures. In light of the results of the present study, which showed that there was no significant difference between the six treatments in terms of the maximum resistance to the uprooting, the second and third hypotheses were dismissed. Indeed, it is especially the lateral roots located in the first horizons of the soil that intervene in the anchoring (Ennos et al. 1993; Danjon et al. 2005). A homogeneous distribution of these roots is essential to form the soil root plate around the stem to ensure anchorage. After four growing seasons however, the studied poplars were too young to observe a well-developed root-plate. Moreover, during a mechanical stress, if the 360° distribution of the roots is homogeneous, tension will be applied in a homogeneous way, which will increase the tree's resistance to an uprooting force (Danjon and Reubens, 2008).

The establishment of the root architecture during the development of the plant is a complex process (Pagès and Pellerin 1996). The physical properties of the soil (structure and texture) play a major role in the anchorage resistance of the plant. Depending on the nature and texture of the soil, the anchorage of the plant can be modified (Dupuy et al. 2007; Quine et al. 1991). Root development could be affected by constraints encountered in certain soils, such as rocks (Danjon et al. 1999; Quine et al. 1991). Research has shown that root systems are more mechanically resistant in clays than in sandy soils (Dupuy et al. 2007). Prior works also show that soil moisture conditions can affect plant stability. However, the effect of the degree of saturation of soil on plant stability depends on the type of soil and remains poorly understood (Kamimura et al. 2012). Contrary to the authors' fourth hypothesis, the results of this study showed a similar effect of both tested soils in terms of tree stability. For the studied hybrid poplar, there were no significant differences between the two soil qualities in terms of the number of roots, diameter of the roots, maximum rooting depth, the number of sinker roots (in-depth). In the present study, it appears that the thickness of the soil above waste rocks, rather than its quality, could have mostly controlled the root development and, therefore, the anchorage of the trees. Indeed, maximum rooting depths were lower than the soil thickness of 50 cm for all treatments (no coarse roots observed in the underlying waste rocks).

In line with the results of the maximum resistance to the uprooting, root architecture, shoot/root ratio, and plant size measurements showed no significant differences due to either planting material or soil quality. This was reflected in the two calculated root anchorage indexes. The two root anchorage indexes are strongly correlated to the maximum resistance to the uprooting. The use of these indexes appears to be an interesting option for evaluating the root anchorage of trees without using lateral uprooting tests. The first index (*I1*) integrates the 180º distribution of the root system and could allow evaluating the stability of older trees, as well as for species with a branched root system for which anchorage is achieved mainly by the distribution of the roots (Bailey et al. 2002). The second index (*I2*) also integrates the vertical distribution of roots and would be more interesting to use for species growing in deeper soils for which anchorage depends mainly on taproots (Danquechin Dorval et al. 2016; Toral et al. 2011).

5. Conclusion

This study demonstrated that the root anchorage of a four-year-old plantation of hybrid poplar was not affected by soil quality (variable topsoil thickness) or by planting material (variable shoot/root ratio) when 50 cm of overburden soil was used to cover waste rock slopes. Results indicated that there was no significant difference between treatments in terms of: the maximum resistance to uprooting, number of lateral roots, mean root diameter, root biomass, aboveground biomass, shoot/root ratio, maximum height, and basal diameter. This finding is interesting as it demonstrates that the performance of cuttings (in terms of stability, root development, aboveground growth, and survival) is as high as that of whips and bareroot plants, while the costs related to their production are lower. Moreover, in the short term, there was no significant difference between hybrid poplars planted on a 50 cm topsoil layer or on a soil layer comprised of 10 cm of topsoil and 40 cm of mineral soil in terms of survival, growth, root development, and tree stability. Therefore, lower quantities of topsoil could be used, thus reducing the challenge that mining companies face in finding sufficient quantities of soil for the revegetation of sites.

In the future, it is believed that these results will be maintained. Four years after planting, the root architecture of hybrid poplars is already defined and, without change due to external environmental factors, the root distribution will only become more complex over time. However, it could be interesting to evaluate the effect of soil quality and planting material on native species and species with different root systems, or to examine greater soil thicknesses over waste rocks.

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References

Agriculture and Agri-Food Canada, 2014. Length of Growing Season in Quebec, Baseline: 1971-2000. http://www.agr.gc.ca/eng/science-and innovation/agriculturalpractices/ climate/future-outlook/climate-change-scenarios/length-of-growingseason- in-quebec/?id=1363104198111 (accessed 05 December 2019).

Archer, J. R., & Smith, P. D. (1972). The relation between bulk density, available water capacity, and air capacity of soils. Journal of Soil Science, 23(4), 475-480.

Aubertin, M., Bussiere, B., Bernier, L. (2002). Environnement et gestion des résidus miniers. CD, Les Editions de l'Ecole Polytechnique de Montréal.

Babi, K., Guittonny, M., Larocque, G. R., & Bussière, B. (2019). Effects of spacing and herbaceous hydroseeding on water stress exposure and root development of poplars planted in soil-covered waste rock slopes. *Écoscience*, *26*(2), 149-163.

Bailey, P. H., Currey, J. D., & Fitter, A. H. (2002). The role of root system architecture and root hairs in promoting anchorage against uprooting forces in Allium cepa and root mutants of Arabidopsis thaliana. Journal of Experimental Botany, 53(367), 333-340.

Balleux, P., & Van Lerberghe, P. (2001). *Boisement des terres agricoles: guide technique*. Forêt privée française.

Bell, H. L., Dawson, C.J., Wright, C.J. (1991). Tree stability. *In Hodge: Research for practical arboriculture,* York, 2-4 April 1990.

Benomar, L., DesRochers, A., & Larocque, G. R. (2012). The effects of spacing on growth, morphology and biomass production and allocation in two hybrid poplar clones growing in the boreal region of Canada. *Trees*, *26*(3), 939-949.

Block, R. M., Knight, J. D., Booth, N. W., & Van Rees, K. C. (2009). Nursery stock type, nitrogen fertilization and shoot pruning effects on the growth of juvenile hybrid poplar in Saskatchewan. *Canadian journal of plant science*, *89*(2), 289-301.

Burger, J. A., C. E. Zipper, (2002). How to restore forests on surface-mined land: Reclamation guidelines for surfacemined land in Southwest Virginia. Virginia Cooperative Extension, Powell River Series, Publication 460–123.

Casselman, C. N., Fox, T. R., Burger, J. A., Jones, A. T., & Galbraith, J. M. (2006). Effects of silvicultural treatments on survival and growth of trees planted on reclaimed mine lands in the Appalachians. *Forest Ecology and Management*, *223*(1-3), 403-414.

Celik, I., Ortas, I., & Kilic, S. (2004). Effects of compost, mycorrhiza, manure and fertilizer on some physical properties of a Chromoxerert soil. *Soil and Tillage Research*, *78*(1), 59-67.

Charnet, F. (2003). L'enracinement des arbres et les propriétés physiques des sols. Forêt-entreprise. 154 :3 7-43.

Clark Ashby, W. (1995). Hybrid Populus in reclamation. *International Journal of Surface Mining and Reclamation*, *9*(2), 69-71.

Coutts, M. P., Nielsen, C. C. N., & Nicoll, B. C. (1999). The development of symmetry, rigidity and anchorage in the structural root system of conifers. *Plant and soil*, *217*(1-2), 1-15.

CROOK, M. J., & Ennos, A. R. (1993). The mechanics of root lodging in winter wheat, Triticum aestivum L. Journal of Experimental Botany, 44(7), 1219-1224.

Curt, T., Lucot, E., & Bouchaud, M. (2001). Douglas-fir root biomass and rooting profile in relation to soils in a mid-elevation area (Beaujolais Mounts, France). *Plant and Soil*, *233*(1), 109-125.

Danjon, F., Fourcaud, T., & Bert, D. (2005). Root architecture and wind-firmness of mature Pinus pinaster. New Phytologist, 168(2), 387-400.

Danjon, F., & Reubens, B. (2008). Assessing and analyzing 3D architecture of woody root systems, a review of methods and applications in tree and soil stability, resource acquisition and allocation. Plant and Soil, 303(1-2), 1-34.

Danjon, F., Sinoquet, H., Godin, C., Colin, F., & Drexhage, M. (1999). Characterisation of structural tree root architecture using 3D digitising and AMAPmod software. Plant and soil, 211(2), 241-258.

Danquechin Dorval, A., Meredieu, C., & Danjon, F. (2016). Anchorage failure of young trees in sandy soils is prevented by a rigid central part of the root system with various designs. Annals of botany, 118(4), 747-762.

Das, D. K., & Chaturvedi, O. P. (2008). Root biomass and distribution of five agroforestry tree species. *Agroforestry systems*, *74*(3), 223.

Davis, V., Burger, J., Rathfon, R., Zipper, C., & Miller, C. (2012). Selecting tree species for reforestation of Appalachian mined land. US Office of Surface Mining, Appalachian Regional Reforestation Initiative, Forest Reclamation Advisory Number 9.DeBell, D. S., & Harrington, C. A. (1997). Productivity of Populus in monoclonal and polyclonal blocks at three spacings. *Canadian journal of forest research*, *27*(7), 978-985.

DesRochers, A., & Tremblay, F. (2009). The effect of root and shoot pruning on early growth of hybrid poplars. *Forest ecology and management*, *258*(9), 2062-2067.

DesRochers, A., Thomas, B. R., & Butson, R. (2004). Reclamation of roads and landings with balsam poplar cuttings. *Forest ecology and management*, *199*(1), 39-50.

Dexter, A. R. (1988). Advances in characterization of soil structure. *Soil and tillage research*, *11*(3-4), 199-238.

Dexter, A. R. (2004). Soil physical quality: Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. *Geoderma*, *120*(3-4), 201-214.

Douglas, G. B., McIvor, I. R., & Lloyd-West, C. M. (2016). Early root development of field-grown poplar: effects of planting material and genotype. *New Zealand Journal of Forestry Science*, *46*(1), 1.

Drénou, C. (2006). *Les racines: face cachée des arbres*. Forêt privée française.

Doran, J. W., & Parkin, T. B. (1994). Defining and assessing soil quality. *Defining soil quality for a sustainable environment*, *35*, 1-21.

Duddles, R. E., & Owston, P. W. (1990, August). Performance of conifer stock types on national forests in the Oregon and Washington Coast Ranges. In *eds), Target Seedling Symposium: Proccedings, Combined Meeting of the Western Forest Nursery Association* (pp. 263-268).

Dupuy, L., Fourcaud, T., & Stokes, A. (2007). A numerical investigation into the influence of soil quality and root architecture on tree anchorage. In Eco-and ground bio-engineering: The use of vegetation to improve slope stability (pp. 175-189). Springer, Dordrecht.

Dupuy, L., Fourcaud, T., & Stokes, A. (2005). A numerical investigation into factors affecting the anchorage of roots in tension. *European Journal of Soil Science*, *56*(3), 319-327.

Ennos, A. R., Crook, M. J., & Grimshaw, C. (1993). A comparative study of the anchorage systems of Himalayan balsam Impatiens glandulifera and mature sunflower Helianthus annuus. Journal of Experimental Botany, 44(1), 133-146.

Fitter, A.H. (1991). The ecological significance of root system architecture: an economic approach. In: Atkinson, D. (ed.). Plant root growth. An ecological perspective. Blackwell Scientific Publications,Oxford. 229–243.

Friend, A. L., Scarascia-Mugnozza, G., Isebrands, J. G., & Heilman, P. E. (1991). Quantification of two-year-old hybrid poplar root systems: morphology, biomass, and 14C distribution. Tree Physiology, 8(2), 109-119.

Garrett, H. E., Rietveld, W. J., & Fisher, R. F. (2009). North American agroforestry: An integrated science and practice . Madison, WI, USA: American Society of Agronomy.

Godin, C. (2000). Representing and encoding plant architecture: a review. *Annals of forest science*, *57*(5), 413-438.

Godin, C., Costes, E., & Sinoquet, H. (1999). A method for describing plant architecture which integrates topology and geometry. *Annals of botany*, *84*(3), 343-357.

Gregory, P. J. (2006). Plant roots: Growth, activity and interaction with soils., (Blackwell Publishing: Oxford, UK).

Grossnickle, S. C. (2000). Ecophysiology of northern spruce species: the performance of planted seedlings. NRC Research Press.

Grossnickle, S. C. (2005). Importance of root growth in overcoming planting stress. *New Forests*, *30*(2-3), 273-294.

Guittonny-Larchevêque, M., & Pednault, C. (2016). Substrate comparison for short-term success of a multispecies tree plantation in thickened tailings of a boreal gold mine. New forests, 47(5), 763-781.

Guittonny-Larchevêque, M., Bussière, B., & Pednault, C. (2016). Tree–substrate water relations and root development in tree plantations used for mine tailings reclamation. Journal of environmental quality, 45(3), 1036-1045.

Gyssels, G., Poesen, J., Bochet, E., & Li, Y. (2005). Impact of plant roots on the resistance of soils to erosion by water: a review. *Progress in physical geography*, *29*(2), 189-217.

Haissig, B. E. (1984). Carbohydrate accumulation and partitioning in Pinus banksiana seedlings and seedling cuttings. *Physiologia plantarum*, *61*(1), 13-19.

Hansen, E. A., Netzer, D., & Toldsted, D. N. (1993). Guideline for Establishing Poplar Plantations in the North-West US.

Headlee, W. L., Zalesny Jr, R. S., & Hall, R. B. (2019). Coarse root biomass and architecture of hybrid aspen ‘Crandon’(Populus alba L.× P. grandidenta Michx.) grown in an agroforestry system in central Iowa, USA. Journal of Sustainable Forestry, 38(1), 18-30.

Hansen, E., Moore, L., Netzer, D., Ostry, M., Phipps, H., & Zavitkovski, J. (1983). Establishing intensively cultured hybrid poplar plantations for fuel and fiber. *General Technical Report NC-78. St. Paul, MN: US Dept. of Agriculture, Forest Service, North Central Forest Experiment Station*, *78*.

Harper, J.L., Jones, M., Sackville-Hamilton, N.R. (1991). The evolution of roots and the problems of analysing their behaviour. In: Atkinson, D. (ed.). Plant root growth. An ecological perspective. Blackwell Scientific Publications, Oxford. p. 3–22.

Hutchings, M. J., & John, E. A. (2003). Distribution of roots in soil, and root foraging activity. In *Root ecology* (pp. 33-60). Springer, Berlin, Heidelberg.

Kamimura, K., Kitagawa, K., Saito, S., & Mizunaga, H. (2012). Root anchorage of hinoki (Chamaecyparis obtuse (Sieb. Et Zucc.) Endl.) under the combined loading of wind and rapidly supplied water on soil: analyses based on tree-pulling experiments. European Journal of Forest Research, 131(1), 219-227.

Kano-Nakata, M., Nakamura, T., Mitsuya, S., & Yamauchi, A. (2019). Plasticity in root system architecture of rice genotypes exhibited under different soil water distributions in soil profile. *Plant Production Science*, 1-9.

Khaleel, R., Reddy, K. R., & Overcash, M. R. (1981). Changes in soil physical properties due to organic waste applications: a review. *Journal of Environmental Quality*, *10*(2), 133-141.

Khuder, H., Stokes, A., Danjon, F., Gouskou, K., & Lagane, F. (2007). Is it possible to manipulate root anchorage in young trees?. *Plant and soil*, *294*(1-2), 87-102.

James, K. R., Haritos, N., & Ades, P. K. (2006). Mechanical stability of trees under dynamic loads. American journal of Botany, 93(10), 1522-1530.

Jobidon, R., Roy, V., & Cyr, G. (2003). Net effect of competing vegetation on selected environmental conditions and performance of four spruce seedling stock sizes after eight years in Québec (Canada). Annals of Forest Science, 60(7), 691-699.

Johansson, K., Nilsson, U., & Allen, H. L. (2007). Interactions between soil scarification and Norway spruce seedling types. *New Forests*, *33*(1), 13-27.

Jutras, S., Thiffault, N., & Munson, A. D. (2007). Comparing large bareroot and container stock: water stress as influenced by peat and soil water availability. *Tree Planter's Notes Is Back!*.

Landhäusser, S. M., Rodriguez-Alvarez, J., Marenholtz, E. H., & Lieffers, V. J. (2012). Effect of stock type characteristics and time of planting on field performance of aspen (Populus tremuloides Michx.) seedlings on boreal reclamation sites. *New Forests*, *43*(5-6), 679-693.

Larchevêque, M., Desrochers, A., Bussière, B., & Cimon, D. (2014). Planting trees in soils above non-acid-generating wastes of a boreal gold mine. *Écoscience*, *21*(3-4), 217-231.

Larchevêque, M., Desrochers, A., & Larocque, G. R. (2011). Comparison of manure compost and mineral fertilizer for hybrid poplar plantation establishment on boreal heavy clay soils. *Annals of forest science*, *68*(4), 849-860.

Lebourgeois., F. & Jabiol., B. (2002). Enracinements comparés du chêne sessile, du chêne pédoncule et de hêtre. Réflexions sur l'autoécologie des essences. Revue Forestière Française (LIV). 1 :17-42.

Levy, G. (1968). Importance des propriétés du sol pour l'enracinement de Picea excelsa et de Pinus sylvestris. In *Annales des Sciences Forestières* (Vol. 25, No. 3, pp. 157-188). EDP Sciences.

Li, G. L., Liu, Y., Zhu, Y., Yang, J., Sun, H. Y., Jia, Z. K., & Ma, L. Y. (2011). Influence of initial age and size on the field performance of Larix olgensis seedlings. New Forests, 42(2), 215-226.

Li, X. R., Jia, X. H., & Dong, G. R. (2006). Influence of desertification on vegetation pattern variations in the cold semi-arid grasslands of Qinghai-Tibet Plateau, North-west China. *Journal of arid environments*, *64*(3), 505-522.

Ludovici, K. H. (2004). SOIL BIOLOGY AND TREE GROWTH| Tree Roots and their Interaction with Soil.

Macdonald, S. E., Landhäusser, S. M., Skousen, J., Franklin, J., Frouz, J., Hall, S., ... & Quideau, S. (2015). Forest restoration following surface mining disturbance: challenges and solutions. *New Forests*, *46*(5-6), 703-732.

Marinari, S., Masciandaro, G., Ceccanti, B., & Grego, S. (2000). Influence of organic and mineral fertilisers on soil biological and physical properties. *Bioresource technology*, *72*(1), 9-17.

McGill, D. W., Ford, V. L., & McNeel, J. F. (2004, April). Early development of a species test established on surface mines thirty years post-reclamation. In *Proceedings of the national meeting of the American society for surface mining and reclamation. Lexington, KY: American Society for Surface Mining and Reclamation* (pp. 1227-1238).

Mc Nabb, K., & VanderSchaaf, C. (2005). Growth of graded sweetgum 3 years after root and shoot pruning. *New forests*, *29*(3), 313-320.

Mench, M., Bussiere, S., Boisson, J., Castaing, E., Vangronsveld, J., Ruttens, A., Manceau, A. (2003). Progress in remediation and revegetation of the barren Jales gold mine spoil after in situ treatments. *Plant and Soil*, *249*(1), 187-202.

Meunier, S., Ruel, J. C., Laflamme, G., & Achim, A. (2002). Résistance comparée de l'épinette blanche et du sapin baumier au renversement. *Canadian journal of forest research*, *32*(4), 642-652.

Mohammed, G.H., McLeod, G.R., Menes, P.A., & Timmer, V.R. (2001). A comparison of bareroot and container stock. Dans R.G. Wagner et S.J. Colombo (eds.). Regenerating the Canadian Forest: Principles and Practices for Ontario. pp. 343–348. Fitzhenry & Whiteside, Markham, ON.

Moore, J. R. (2000). Differences in maximum resistive bending moments of Pinus radiata trees grown on a range of soil types. Forest Ecology and Management, 135(1-3), 63-71.

Nagarajah, S. (1987). Effects of soil texture on the rooting patterns of Thompson Seedless vines on own roots and on Ramsey rootstock in irrigated vineyards. *American journal of enology and viticulture*, *38*(1), 54-59.

Newton M, Cole EC, & White DE. (1993). Tall planting stock for enhanced growth and domination of brush in the Douglas-fir region. New Forest 7(2):107–121.

Nicoll, B. C., Gardiner, B. A., Rayner, B., & Peace, A. J. (2006). Anchorage of coniferous trees in relation to species, soil quality, and rooting depth. *Canadian Journal of Forest Research*, *36*(7), 1871-1883.

Oades, J. M. (1984). Soil organic matter and structural stability: mechanisms and implications for management. *Plant and soil*, *76*(1-3), 319-337.

Pagès, L., & Pellerin, S. (1996). Study of differences between vertical root maps observed in a maize crop and simulated maps obtained using a model for the three-dimensional architecture of the root system. Plant and soil, 182(2), 329-337.

Peltola, H., Kellomäki, S., Hassinen, A., & Granander, M. (2000). Mechanical stability of Scots pine, Norway spruce and birch: an analysis of tree-pulling experiments in Finland. *Forest Ecology and Management*, *135*(1-3), 143-153.

Phillips, C. J., Marden, M., & Suzanne, L. M. (2014). Observations of root growth of young poplar and willow planting types. New Zealand Journal of Forestry Science, 44(1), 15.

Pinto, J. R., Dumroese, R. K., Davis, A. S., & Landis, T. D. (2011). Conducting seedling stocktype trials: a new approach to an old question. Journal of Forestry, 109(5), 293-299.

Quine, C. P., Burnand, A. C., Coutts, M. P., & Reynard, B. R. (1991). Effects of mounds and stumps on the root architecture of Sitka spruce on a peaty gley restocking site. Forestry: An International Journal of Forest Research, 64(4), 385-401.

Rezaei, S. A., & Gilkes, R. J. (2005). The effects of landscape attributes and plant community on soil chemical properties in rangelands. *Geoderma*, *125*(1-2), 167-176.

Réseau Ligniculture Québec. (2011). Le Guide de Populiculture au Québec - Un guide pratique sur la culture du peuplier hybride.

Riemenschneider, D. E., & Bauer, E. O. (1997). Quantitative genetic analysis of adventitious root forming ability in Populus trichocarpa (TORR ET. GRAY). In *Biology of root formation and development* (pp. 193-201). Springer, Boston, MA.

Robison, D.J., Raffa, K.F., 1996. Importance of cutting diameter and method of production on early growth of hybrid poplar. Tree Planters' Notes 47, 76–80.

Sainju, U. M., & Good, R. E. (1993). Vertical root distribution in relation to soil properties in New Jersey Pinelands forests. *Plant and Soil*, *150*(1), 87-97.

Schuurman, J. J. (1965). Influence of soil density on root development and growth of oats. Plant and Soil, 22(3), 352-374.

Scott, R. E., & Mitchell, S. J. (2005). Empirical modelling of windthrow risk in partially harvested stands using tree, neighbourhood, and stand attributes. *Forest Ecology and Management*, *218*(1-3), 193-209.

Sidhu, D. S., & Dhillon, G. P. S. (2007). Field performance of ten clones and two sizes of planting stock of Populus deltoides on the Indo-gangetic plains of India. New Forests, 34(2), 115-122.

Stokes, A., Spanos, I., Norris, J. E., & Cammeraat, E. (Eds.). (2007). Eco-and Ground Bio-engineering: the Use of Vegetation to Improve Slope Stability: Proceedings of the First International Conference on Eco-engineering 13-17 September 2004 (Vol. 103). Springer Science & Business Media.

Strong, W. L., & La Roi, G. H. (1985). Root density-soil relationships in selected boreal forests of central Alberta, Canada. *Forest ecology and management*, *12*(3-4), 233-251.

Tejada, M., & Gonzalez, J. L. (2007). Influence of organic amendments on soil structure and soil loss under simulated rain. *Soil and Tillage Research*, *93*(1), 197-205.

Thiffault, N. (2010). Stabilité mécanique et caractéristiques racinaires de plants de fortes dimensions de Picea mariana produits en récipients ou à racines nues. The Forestry Chronicle, 86(4), 469-476.

Thiffault, N. (2004). Stock type in intensive silviculture: a (short) discussion about roots and size. *The Forestry Chronicle*, *80*(4), 463-468.

Thiffault, N., Jobidon, R., & Munson, A. D. (2014). Comparing large containerized and bareroot conifer stock on sites of contrasting vegetation composition in a non-herbicide scenario. New forests, 45(6), 875-891.

Tordoff, G. M., A. J. M. Baker & A. J. Willis, 2000. Current approaches to the revegetation and reclamation of metalliferous mine wastes. Chemosphere, 41: 219–228.

Toral, M., Bown, H. E., Mañon, A., Alvarez, J., & Navarro-Cerrillo, R. (2011). Wind-induced leaning (toppling) in young Pinus radiata plantations in Chile Inclinación por viento en plantaciones juveniles de Pinus radiata, en Chile.

Tschaplinski, T. J., & Blake, T. J. (1989). Correlation between early root production, carbohydrate metabolism, and subsequent biomass production in hybrid poplar. *Canadian Journal of Botany*, *67*(7), 2168-2174.

Zipper, C. E. Burger, J.A. Skousen, J.G.Angel, P.N. Barton, C.D. Davis, V, Franklin, J.A. (2011). Restoring forests and associated ecosystem services on Appalachian coal surface mines. Environ manage 47: 751-765.

Zhou, R. L., Li, Y. Q., Zhao, H. L., & Drake, S. (2008). Desertification effects on C and N content of sandy soils under grassland in Horqin, northern China. *Geoderma*, *145*(3-4), 370-375.