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LIST OF ABBREVIATIONS

AC	Arbres cibles
AIC_c	Second-order Akaike Information Criterion
AMD	Acid mine drainage
BB	Barrière biologique
BBS	Bio-barrier species
CCBE	Covers with capillary barrier effects
CEBC	Couvertures avec effets de barrière capillaire
CI	Confidence interval
DM	Dry mass
DMA	Drainage minier acide
DSE	Dark septate endophyte
LTA	Les Terrains Aurifères
MRN	Ministère des Ressources naturelles du Québec
SD	Standard deviation
SE	Standard error
TS	Target tree species

RÉSUMÉ

La formation de drainage minier acide (DMA) reste l'un des grands problèmes environnementaux causés par les résidus de l'activité minière. La mise en place de couvertures avec effets de barrière capillaire (CEBC) est fréquemment utilisée pour la restauration de sites miniers ayant des problèmes de DMA. Toutefois la colonisation de ces sites par les végétaux, particulièrement les espèces d'arbres à racines profondes, peut compromettre l'efficacité à long terme des CEBC, à savoir la limitation de la migration de l'oxygène de l'atmosphère vers les roches acides. L'une des avenues les plus prometteuses pour améliorer la performance à long terme des CEBC est de créer une barrière biologique (BB) à l'aide d'espèces indigènes à effets allélopathiques potentiels. L'allélopathie est l'effet inhibiteur d'une espèce de plante sur la croissance et/ ou la reproduction d'une autre, directement à travers la libération de composés allélopathiques dans le sol ou, indirectement, par la compétition pour les ressources et l'espace. Cette étude vise à évaluer si les espèces suivantes, le calamagrostide du Canada (*Calamagrostis canadensis*) et le kalmia à feuilles étroites (*Kalmia angustifolia*), peuvent représenter des barrières biologiques efficaces et inhiber la croissance d'espèces d'arbres cibles (AC), représentant un risque particulier pour l'efficacité des CEBC telles que: le peuplier baumier (*Populus balsamifera*), le saule (*Salix* spp.), et l'épinette noire (*Picea mariana*). L'influence des BB sur (1) la croissance en hauteur de la tige et du diamètre basal, la biomasse (tiges, feuilles, racines et biomasse totale), et le ratio racine/tige des AC; (2) les caractéristiques de l'architecture du système racinaire des AC ont été mesurées. L'influence relative des BB sur la croissance des AC dans des conditions sèches et humides a également été évaluée. L'expérience a débuté en 2008 sur le site Les Terrains Aurifères (LTA), Malartic (Québec). Les espèces bio-barrières ont été plantées systématiquement avec les arbres cibles dans des parcelles expérimentales à l'intérieur de blocs aléatoires respectivement dans les zones sèche et humide du site LTA. Nous avons utilisé une méthode de numérisation tridimensionnelle de la racine, suivie d'une analyse avec le logiciel AMAPmod pour évaluer l'architecture des racines des AC. Les données ont été analysées à l'aide des modèles linéaires mixtes. Un effet inhibiteur important du calamagrostide sur la croissance aérienne et souterraine des trois AC (croissance en hauteur de la tige, diamètre, biomasse, profondeur maximale des racines, extension radiale des racines, longueur et volume totaux des racines, nombre de racines de 2ème et 3ème ordres) a été observé. La biomasse du calamagrostide a eu un effet négatif sur la biomasse et l'architecture du système racinaire des AC. La présence du kalmia, a eu une influence positive sur la croissance en hauteur de la tige et en diamètre, la biomasse, la profondeur maximale des racines, le volume et le nombre de racines de 2ème ordre du peuplier baumier, tandis que la croissance du saule n'a pas été affectée. À l'exception du rapport racine/ tige et du nombre de racines de 2ème ordre, la présence de kalmia a eu un effet positif sur toutes les caractéristiques de croissance de l'épinette noire. Les résultats obtenus nous permettent de conclure que le calamagrostide représente une barrière biologique plus efficace que le kalmia. Les contraintes d'adaptation sur le site LTA et le taux de mortalité élevé observé chez le kalmia, pourraient être les principales causes de sa faible performance comme barrière biologique.

Mots clés: couvertures avec effets de barrière capillaire, effet allélopathique, biomasse, architecture du système racinaire, numérisation des racines.

ABSTRACT

Acid mine drainage (AMD) generation remains one of the challenging environmental issues caused by mining industry wastes. The construction of covers with capillary barrier effects (CCBE) is frequently used as a closure plan for various mines with AMD problems. Nevertheless, colonization of vegetation on mining sites (especially deep-rooting tree species) can compromise the CCBE main function i.e. restriction of oxygen migration from the atmosphere to acid-generating rock. One of the environmentally safe solutions to improve the long-term CCBE performance is to create a bio-barrier made of native species with potential allelopathic effects. Allelopathy is the inhibiting effect of one plant species on growth and reproduction of another one, either directly through release of allelopathic compounds into the soil environment, or indirectly through the competition (resource competition, interference competition for space). This study was aimed to test whether the bio-barrier species (BBS), bluejoint reedgrass (*Calamagrostis canadensis*) and sheep laurel (*Kalmia angustifolia*), can inhibit the growth and alter the root system architecture (especially inhibition downward root growth) of the target tree species (TS), which represent a particular risk to the CCBE efficiency: balsam poplar, willow, and black spruce. The influence of BBS was assessed on (1) stem height and basal diameter increment, biomass (shoot, root, total), and root-to-shoot ratios of TS; (2) root system architecture characteristics of TS. The relative influence of BBS on TS growth in dry and wet conditions was also evaluated. The experiment started in 2008 at Les Terrains Aurifères (LTA) site located near Malartic, Québec. Bio-barrier species were planted systematically with TS in experimental plots within blocks in dry and wet zones of the LTA site. A method of three-dimensional root digitizing followed by analysis in AMAPmod software was used to determine the root architecture of TS. The data were analyzed with linear mixed models. A strong inhibiting effect of bluejoint reedgrass on above- and belowground growth of three TS (stem height and basal diameter increment, biomass, maximum root depth and root radial extension, total root length and volume, number of 2nd- and 3d-order roots) was observed. The biomass of bluejoint reedgrass had an adverse effect on biomass and root parameters of TS. In the presence of sheep laurel, stem height and basal diameter increment, biomass, maximum root depth, root volume and number of 2nd-order roots of balsam poplar increased, whereas willow was not affected. Except for the root-to-shoot ratio and number of 2nd-order roots, the presence of sheep laurel had a positive effect on all investigated characteristics of black spruce. We concluded that bluejoint reedgrass represents a more efficient bio-barrier species than sheep laurel in this study. Slow adaptation of sheep laurel to site conditions that was induced by transplant shock, possibly led to its high mortality, low phytotoxic and competitive activities.

Key words: covers with capillary barrier effects, allelopathic effect, biomass, root system architecture, root digitizing.

CHAPTER I

GENERAL INTRODUCTION

1.1 Covers with capillary barrier effects as mine site reclamation method

Québec is one of the leading Canadian provinces in exploitation of mineral resources. Nevertheless, mining operations are accompanied by the release of millions tonnes of tailings that may lead to serious ecological problems. To prevent this, the government of Québec issued the Mining Act (MNR 2014) that requires the mining companies to work towards sustainable development. Following the regulations of the Mining act, mining companies must rehabilitate tailings impoundment areas to prevent contamination of the environment, thereby obtaining social acceptance.

Nowadays, acid mine drainage (AMD) remains one of the challenging environmental issues for the mining industry (Johnson and Hallberg 2005; Bussière 2009). Acid mine drainage is produced from the oxidation of sulphide minerals, such as pyrite and pyrrhotite, contained in mine tailings (Kleinmann *et al.* 1981; Blowes *et al.* 1994). Many methods are proposed to control AMD generation (MEND 2001). In humid climates, the construction of covers with capillary barrier effects (CCBE) is frequently used as a closure plan for various mines with AMD generation (Ricard *et al.* 1997; Dagenais *et al.* 2005; Bussière *et al.* 2006). Covers with capillary barrier effects have to maintain a high degree of saturation in one (or more) of its layers in order to limit oxygen migration from the atmosphere to the mine tailings and consequently to prevent AMD generation (Nicholson *et al.* 1989; Bussière *et al.* 2003). Basically, CCBEs consist of three to five layers. Each layer is made of different materials, each having a specific function. From the bottom to the top the layers are: a support and capillary break layer made of course-grained materials; a moisture-retention layer made of fine-grained materials that serves as oxygen and water barrier; a drainage layer made of coarse-grained material to prevent water loss from evaporation; protection and surface layers to protect against erosion and bio-intrusion of the CCBE (Aubertin *et al.* 1995; Bussière *et al.* 2003). Schematic illustration of a typical CCBE is presented in Figure 1.1.

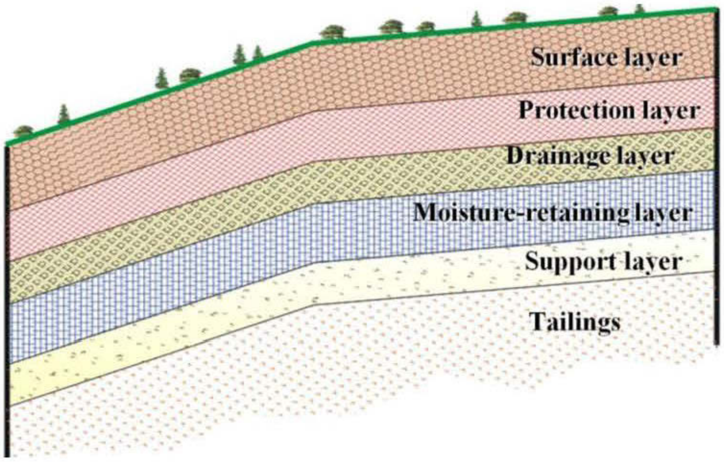

Figure 1.1 Configuration of covers with capillary barrier effects (Aubertin *et al.* 1995).

Many studies conducted in laboratory and field conditions to verify the ability of CCBE to control oxygen migration and thereby to avoid AMD generation (Aubertin *et al.* 1995, 1997; Bussière *et al.* 2004; Dagenais *et al.* 2005; Bussière *et al.* 2006). Nevertheless, long-term CCBE efficiency can be compromised in boreal contexts by the invasion of undesirable plant species, such as balsam poplar (*Populus balsamifera L.*), willow (*Salix* spp.), and black spruce (*Picea mariana* (Mill.) BSP), which colonize mining sites from nearby forest soon after CCBE construction (Trépanier 2005; Trépanier *et al.* 2006; Smirnova *et al.* 2009, 2011). The main risks associated with uncontrolled vegetation establishment on the CCBE are: (1) extraction of water from fine grained soil by plant roots, which reduces the degree of saturation and the capacity of the CCBE to constrain oxygen migration; (2) creation of macropores by roots and consequently an increase in water infiltration and oxygen migration through the cover system; and (3) physical damage to the CCBE through up-rooting of shallow-rooting trees (such as *Picea* spp.) (USDOE 1990; Handel *et al.* 1997; Hutchings 2001).

1.2 Description of root systems of undesirable tree species

Undesirable trees species, especially their root systems, can threaten the integrity of CCBE and affect their long-term performance. In the following, the root system of the potentially dangerous tree species are described and discussed.

1.2.1 Poplars

The species of the genus *Populus*, known in the boreal zone as poplar and aspen, can produce new roots from the radical, from a cutting or an abscised branch, and from the pre-existing root system in the case of suckers (Zasada and Phipps 1990). However, roots of healthy parent poplar trees rarely develop suckers without aboveground disturbance (Wan *et al.* 2006). The root system of a parent poplar trees and its suckers have different root architecture. Euphrates poplar (*Populus euphratica* Oliv.) seedlings produce one deep vertical tap root, keeping this as adult tree, and radiating coarse lateral roots that are formed from the tap root (Wiehle *et al.* 2009). Suckers have a "T"- like root system that originates from lateral roots of a parent tree. Consequently, suckers never develop a tap root but have two apparent side roots opposite from each other (Wiehle *et al.* 2009).

Trembling aspen (*Populus tremuloides* Michx.) produces strong vertically penetrating roots originating near the tree base and sinker roots that are formed from a network of lateral roots (Peterson and Peterson 1992). The lateral roots of aspen are usually within 15 to 30 cm of the soil surface, whereas the sinker roots may reach 3 m in depth (Strong and La Roi 1983b; Perala 1990). Root system morphology and depth distribution of aspen vary with stand age and site conditions (Strong and La Roi 1983a,b). Aspen roots can reach a depth of 130 cm with age but on sandy soils. On clay loam, aspen has a maximum rooting depth of 95 cm (Strong and La Roi 1983b).Maximum vertical rooting depth of aspen ranges from 1.5 to > 3 m, whereas the radial spread ranges from 14.3 to 30.5 m (see review by Stone and Kalisz 1991). In early growth of trembling aspen and balsam poplar (28-30 days after seed establishment), balsam poplar tends to produce deeper roots, compared to aspen (Wolken *et al.* 2010). Root systems of balsam poplar penetrate deeply in the soil and possess an extensive system of lateral roots on dry sites (Zasada and Phipps 1990). On wet sites, rooting depth of balsam poplar can be reduced (Zasada and Phipps 1990).

Maximum root branching order for tree species is seven (Dickmann and Pregitzer 1992; Pregitzer and Friend 1996). However, little is known about root branching pattern (total number of root orders, number of roots by orders) and root system architecture of poplar trees (total root length and volume, etc).

1.2.2 Willows

Most willows (*Salix* spp.), frequently used in ecological engineering (i.e. soil remediation, short-rotation woody crops for the biomass production, stabilization of slopes, soil erosion control), are fast-growing shrubs (Greger and Landberg 1999; Schaff *et al.* 2002; Pulford and Watson 2003; Mirck *et al.* 2005; Meers *et al.* 2007; Mickovski *et al.* 2009). The root system architecture of willow shrubs differs from willow trees. Willow shrubs are highly dependent on an efficient root system for water and nutrient uptake to maintain its high yield production (Rytter 1999). The root system of willows is characterized by a high production and turnover rate of fine roots (Rytter and Rytter 1998; Rytter 1999) and an extensive gravitropic coarse root system (Mickovski *et al.* 2009). The majority of its roots are located in the upper soil layers where soil conditions are more favorable for root penetration and growth (e.g. high nutrients availability, optimal soil density, better soil aeration) (Volk *et al.* 2001). Black willow (*Salix nigra* Marsh.), a commercially important species native to North America, is recognized as a shallow-rooting species (Pitcher and McKnight 1990).

Between 40 to 45% of fine root number and root mass of a four-year-old basket willow (*Salix viminalis* L.) plantations is located in the top 10 cm of soil with an average root depth of 25-30 cm (Rytter and Hansson 1996). According to investigation done on fine root biomass production of basket willows on irrigated and daily fertilized plantations, around 80% of the fine root biomass is concentrated in the upper 50 cm and 35% in the upper 30 cm of soil (Rytter 1999). Total number of roots of basket willow is also greatest in the upper 10 cm of soil and decreases by 24% at depth ranging between 10 to 40 cm (Mickovski *et al.* 2009). Total root length and root length per soil volume of willow are the highest at 10 to 20 cm of the soil profile (Mickovski *et al.* 2009). Willow can develop roots to depths greater than 3.5 m with radial extension of 6 to 40 m (see review by Stone and Kalisz 1991).

1.2.3 Black spruce

Spruce has a shallow root system that consists of four to six lateral roots spreading horizontally (Eis 1970; Strong and La Roi 1983a; Viereck and Johnston 1990). The roots of black spruce can reach a depth of 90 cm, however roots are rare below 30 cm (Damman 1971). The maximum root biomass of spruce is concentrated in the upper 10 cm of the ground level (Strong and La Roi 1983a; Bhatti 1998). Maximum radial root growth of black spruce is 9.1 m (Stone and Kalisz 1991). Black spruce can initiate adventitious roots when a branch or stem is in direct contact with the ground (Viereck and Johnston 1990; Krause and Morin 2005).

The root architecture of black spruce makes this species vulnerable to windthrow (Viereck and Johnston 1990; Nicoll *et al.* 2006). The potential of black spruce to create large holes after uprooting is the main reason why it represents a particular risk to CCBE efficiency. The oxygen and water can penetrate through the holes to sulphide minerals, thereby contributing to AMD formation.

1.3 Root behaviour in response to environmental stresses

Root system development in plants is under some degree of genetic control (Gale and Grigal 1987). This means that the root architecture that was described above is exhibited in normal conditions. However, roots growth is also influenced by environmental conditions. It can be limited by physical, chemical, and biological soil properties (Bengough *et al.* 2011). One of the widely recognized plant responses to changes in soil media in the presence of plant species is a shift in biomass partitioning between above- and belowground plant structures (Chapin *et al.* 1993; Wardle and Peltzer 2003). It is frequently reported that biomass allocation to the roots increases as supplies of water and/or mineral nutrients (especially P and N) become growth-limiting (Haynes and Gower 1995; Huante *et al.* 1995; Bonifas *et al.* 2005; Murphy *et al.* 2009). Biomass allocation shifts towards roots and consequently an increase in root-to-shoot ratio is induced by belowground resource competition (Gersani *et al.* 2001; Donaldson *et al.* 2006; Murphy and Dudley 2007). This response allows plants to maximize the exploitation of insufficient nutrients and water, thereby minimizing resource requirements (Chapin *et al.* 1987).

In addition to altering biomass partitioning, plants can also adjust their root architecture (López-Bucio *et al.* 2003) by producing their roots in soil patches with more favorable conditions, thereby avoiding zones that are depleted in water and nutrients (Eissenstat and Caldwell 1988; Callaway 1990; Fitter and Stickland 1991; Bilbrough and Caldwell 1995). Moreover, plants possess the ability to discriminate self from non-self-neighbours (Falik *et al.* 2003; Gruntman and Novoplansky 2004; Fang *et al.* 2013) and can segregate their root system spatially (Schenk *et al.* 1999). There is some evidence that plants can alter their root architecture in the presence and absence of neighbouring species (Krannitz and Caldwell 1995; Fang *et al.* 2013). The adaptive changes of roots to various environmental conditions can be exhibited through the alteration in total root length, root volume, and vertical root depth (Gilman *et al.* 1982; Fang *et al.* 2011, 2013). For example, plants grown with neighbours had lower shoot and root biomass, total root length, root surface area, root system volume, and higher root ramification than when they were grown alone (Fang *et al.* 2013). Hodge (2009) considered that there is no general rule to explain plant root proliferation in the presence of neighbouring species and root behaviour depends on the genetic identity of coexisting species. Nevertheless, the main strategy of plant species when they adjust their root architectural pattern is to avoid belowground competition and maximize nutrient uptake (Wardle and Peltzer 2003).

1.4 Bio-barriers to improve long-term performance of mining covers

Two approaches can be used to prevent the establishment of undesirable vegetation on the CCBE: (1) creation of a physical barrier (engineered measures) and (2) the use of a bio-barrier made of native species. Physical barrier may have substantial drawbacks, such as low durability, high implementation costs, whereas a bio-barrier has the advantage of being more environmentally safe. Plants with potential allelopathic effects can be used as bio-barrier species on the CCBE (Smirnova *et al.* 2009). Allelopathy is the inhibiting effect of one plant species on the growth and reproduction of another plant species, either directly through release of allelopathic compounds into the soil environment, or indirectly through competition (competition for resources and space) (Inderjit and del Moral 1997; Siciliano and Germida 1998; Wardle 1998). The apparent physiological effect of allelopathy can be expressed through the inhibition of stem height and basal diameter of tree seedlings (English and Hackett 1994; Yamasaki *et al.* 1998; Thiffault *et al.* 2004), reduction in root and shoot dry weights (Jobidon and Thibault 1982; Weston and Putnam 1985; Nilsson 1994), root growth, and root hair formation (Weston and Putnam 1986; Mallik 1987; Zhu and Mallik 1994). Along with abiotic stresses (i.e. water deficit, temperature stress, radiation), allelopathy is also a stress factor that can limit plant growth and development (Pedrol *et al.* 2008).

Allelopathic compounds are secondary metabolites, such as phenolics (Appel 1993; Gallet and Pellissier 1997; Inderjit and Mallik 1997a; Li *et al.* 2010), flavonoids, alkaloids (Rice 1984), which may influence nutrient cycling and rate of nutrient turnover (Appel 1993; Inderjit and Mallik 1997a; Joanisse *et al.* 2007). The occurrence of allelopathic compounds varies depending on climatic conditions. For example, phenolic compounds are very frequent in cool temperate zones, whereas terpenoids were studied extensively in arid ecosystems (see review by Reigosa *et al.* 1999).

Allelopathic compounds can suppress microbial activity, thereby reducing the decomposition rate and consequently, reducing the availability of nutrients (Siciliano and Germida 1998; Wardle *et al.* 1998). Allelochemicals are produced by all plant parts, however leaf litter decomposition is considered to be its main source (Reigosa *et al.* 1999).

Plant-plant interactions are very complex and can include both direct allelopathy (release of allelochemicals) and competition (Qasem and Hill 1989). In natural ecosystems, it is difficult to discriminate allelopathy from competition, because these two phenomena can operate simultaneously (Inderjit and del Moral 1997; Inderjit and Callaway 2003; Mallik 2008). The production of allelochemicals can be altered by biotic and abiotic stresses (Einhellig 1995; Reigosa *et al.* 1999); in particular, plants may produce more allelochemicals under water stress conditions (Galmore 1977; Pedrol *et al.* 2008), thereby causing greater damage to neighbouring plants. Thus, the inhibiting effect of leaves, litter, and soil extracts of potential allelopathic species is stronger as the soil pH becomes more acidic (Zhu and Mallik 1994).

The ecological importance of allelopathy is recognized in the boreal forest (Jobidon 1992; English and Hackett 1994; Titus *et al.* 1995; Thiffault and Jobidon 2006). The use of bio-barriers made of species with potential allelopathic effects, such as sheep laurel (*Kalmia angustifolia* L.) and bluejoint reedgrass (*Calamagrostis canadensis* (Michx.) Beauv.), was suggested as a method to protect the cover system against bio-intrusions (Smirnova *et al.* 2009).

1.4.1 Bluejoint reedgrass

Bluejoint reedgrass is a perennial grass that is commonly found in North American boreal and temperate regions (USDA 1937). This species prefers moist sites but can survive on a wide range of habitats (Haeussler *et al.* 1990). Bluejoint reedgrass is recognized as a problematic species that creates adverse conditions for the establishment and growth of tree seedlings, such as white spruce (*Picea glauca* (Moench.) Voss.) (Eis 1981; Drew 1988; Staples *et al.* 1999) and trembling aspen (*Populus tremuloides* Michx.) (Landhäusser and Lieffers 1998; Landhäusser *et al.* 2007). For example, severe mortality of white spruce was observed in the presence of bluejoint reedgrass (Eis 1981). A decrease in average height, root collar calliper growth, dry weight of stems and leaves, and an increase in root-to-shoot ratio of trembling aspen in the presence of bluejoint reedgrass was reported, but no effect on root dry weight of aspen was detected (Landhäusser and Lieffers 1998).

Experimental evidence suggests that belowground resource competition for water and nutrients is likely to be one of the main factors responsible for growth suppression of tree seedlings in the presence of perennial grasses (Nambiar and Sands 1993; Ludovici and Morris 1996,1997; Löf and Welander 2004; Collet *et al.* 2006). Bluejoint reedgrass is a nutrient-demanding species (Landhäusser and Lieffers 1994). This species produces a fibrous root system consisting of a high number of fine roots and rhizomes that allows it to consume rapidly available resources (Ludovici and Morris 1997; Balandier *et al.* 2006). It is because fine roots are capable of absorbing immobile nutrients and nutrients from a soil solution at very low concentrations (Nambiar and Sands 1993). Bluejoint reedgrass is one of the major competitors for absorption of applied fertilizer ^{15}N when planted with white spruce seedlings (Staples *et al.* 1999). Also, bluejoint reedgrass has a higher capacity for NH_4^+ and NO_3^- uptake, compared to tree species, such as white spruce, jack pine, and trembling aspen (Hangs *et al.* 2003).

Spatial distribution of root systems of tree seedlings can be shifted in the presence of grasses because the grasses are capable of creating nutrient depletion zones (Collet *et al.* 2006). Also, bluejoint reedgrass forms a root sod in the upper soil layers (5-15 cm below the soil surface) (Lieffers *et al.* 1993) and therefore, it can cause a physical obstacle to root penetration of tree seedlings (Balandier *et al.* 2006; Landhäusser et al. 2007).

The detrimental effects of bluejoint reedgrass litter on root collar caliper growth, dry weight of stems and leaves of aspen was presented (Landhäusser and Lieffers 1998). The slow rate of bluejoint reedgrass litter decomposition insulates the soil and keeps the soil cool in spring

(Hogg and Lieffers 1991). Bluejoint reedgrass can tolerate cold soil temperatures (Lieffers *et al.* 1993; Landhäusser and Lieffers 1994), whereas the emergence and growth of trembling aspen is strongly affected by cold soil temperatures (Landhäusser and Lieffers 1998; Landhäusser *et al.* 2006).

Straw extract of bluejoint reedgrass has direct allelopathic effects on seed germination (Winder and Macey 2001). Other graminoids are also capable of releasing allelochemicals and cause a detrimental effect on growth of neighbouring plants (Jobidon *et al.* 1989).

1.4.2 Sheep laurel

Sheep laurel is an ericaceous understory shrub native to the eastern Canadian boreal forests that ranges from Newfoundland to Ontario (Titus *et al.* 1995). It is very efficient at vegetative propagation: by stem base sprouting, belowground rhizomatous growth, and layering (Mallik 1993). Sheep laurel can tolerate a wide range of edaphic conditions (Damman 1971; Titus *et al.* 1995). However, this ericaceous shrub is found to be more vigorous (higher values for plant height, leaf area and specific leaf area) in partial shade, compared to open sites (clear-cut) (Mallik 1994). Earlier studies demonstrated that the presence of sheep laurel inhibits the growth of conifer seedlings, such as black spruce (English and Hackett 1994; Yamasaki *et al.* 1998; Thiffault *et al.* 2004; Thiffault and Jobidon 2006), red pine (*Pinus resinosa* Ait.) (Krause 1986), and balsam fir (*Abies balsamea* (L.) Mill.) (Thompson and Mallik 1989). A risk of conversion of productive to unproductive forest stands occupied by sheep laurel following disturbance in the boreal forest was reported (Thiffault and Jobidon 2006)

A decrease in the growth of conifers in the presence of sheep laurel was frequently attributed to direct allelopathy, competition, soil nutrient imbalance, and weak ectomyccorhization of seedlings caused by the ericaceous shrub (Inderjit and Mallik 2002). Sheep laurel produces a very extensive fine root system that provides a competitive advantage over conifers (Wallstedt *et al.* 2002). One study on the effect of direct competition for nutrients and water between sheep laurel and black spruce demonstrated that most of the available nutrients were captured by sheep laurel (Thiffault *et al.* 2004). Sheep laurel has the potential to modify soil nutrient cycling by changing the availability of different inorganic ions (Inderjit and Mallik 1996,1999). The leaves of this ericaceous shrub contain secondary metabolites (polyphenols such as tannins) (Zhu and Mallik 1994; Joanisse *et al.* 2007) that can be leached into the soil and cause a nutrient imbalance. Tannins, which released by sheep laurel litter, form complexes with proteins (Bradley *et al.* 2000; Joanisse *et al.* 2009) and inhibit the activity of acid phosphatase enzymes, thereby reducing nitrogen mineralization and microbial activity in the soil (Joanisse *et al.* 2007). The removal of sheep laurel during six consecutive years increases the level of nitrogen mineralization rates in the forest floor (LeBel *et al.* 2008).

In laboratory conditions, water extract of sheep laurel leaves, litter, roots, and soil showed a strong inhibitory effect on the primary root growth and root hair formation in black spruce seedlings (Mallik 1987; Zhu and Mallik 1994). The length of the primary roots and shoot growth of black spruce were considerably reduced by different concentrations (0, 0.5, 1, 2, and 5 mM) of eight phenolic acids that were leached from sheep laurel leaves (Zhu and Mallik 1994). The different types of phenolic acids showed different toxicities on the root growth of black spruce. Root growth inhibition that was caused by several polyphenols was observed even at the lowest concentration of 0.5 mM (Zhu and Mallik 1994).

1.5 Research context

Covers with capillary barrier effects represent an efficient measure limiting short-term production of AMD (Bussière *et al.* 2006). This Master's study was conducted to integrate a bio-barriers made of species with potential allelopathic effects in the design of CCBEs in order to protect the CCBEs against undesirable tree establishment, thereby improving its long-term efficiency. The main objective of this study was to assess whether two bio-barrier species (BBS) with potential allelopathic effects, bluejoint reedgrass (Landhäusser and Lieffers 1998; Balandier *et al.* 2006) and sheep laurel (Yamasaki *et al.* 1998; Thiffault *et al.* 2004; Joanisse *et al.* 2007), can inhibit the growth of three target tree species (TS): balsam poplar, willow, and black spruce (most problematic species in the Québec boreal context). The effects of BBS are assessed on growth increment, biomass (root, shoot, total), and root-to-shoot of three TS. Increased attention was paid to test whether BBS are able to alter the root system architecture of three TS (maximum root depth and root radial extension, total root length and volume, root branching parameters number of 2nd-and 3rd-order roots) and especially to inhibit downwards root growth of TS because tree roots represent a particular risk to CCBEs. The use of bio-barriers made of species with potential allelopathic effects is a promising ecological solution to control undesirable tree invasions since BBS are native to boreal ecosystems (no pesticides or herbicides are involved to control tree invasions on the CCBEs).

The results of the study will allow us to answer the question: does a bio-barrier made of species with potential allelopathic effects represent a reliable ecological approach to improve the long-term CCBE performance? These results are particularly important in areas where CCBEs are frequently applied, such as Québec. This study is innovative since this is the first work that involves this ecological approach (allelopathic bio-barriers) instead of using physical barriers to control this natural tree invasion on the existing CCBEs. It is also important to note that the method of three-dimensional root digitizing with consequent analyzing in AMAPmod software (Godin *et al.* 1997; Danjon *et al.* 1999a, b) that was used in this study to assess the root system architecture of TS has never been previously applied in Canada.

Direct allelopathic potential of BBS (measurement of allelochemicals concentration in the foliar and foliar-litter tissues of BBS, root exudates analyses, chemical analyses of soil below the BBS and water from shoot and root exudates collectors) was not performed in this study due to time constraints and the typical size of a Master's thesis. However, these data were collected in a larger project that integrates this Master's work; results will be presented elsewhere.

CHAPTER II

BIO-INTRUSION BARRIERS OF *CALAMAGROSTIS CANADENSIS* AND *KALMIA ANGUSTIFOLIA* HAVE SPECIFIC IMPACTS ON ROOT SYSTEM ARCHITECTURE AND GROWTH OF TREE SPECIES ESTABLISHED ON MINE COVERS

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2.1 Résumé

Les couvertures avec effets de barrière capillaire (CEBC) sont fréquemment utilisées par l'industrie minière comme une technique efficace pour prévenir le drainage minier acide (DMA). Cette méthode est basée sur la présence d'une couche saturée en eau à l'intérieur de la couverture, ce qui permet de réduire la disponibilité d'oxygène et, par conséquent, la production du DMA. Cependant, l'efficacité à long terme des CEBC peut être compromise par l'intrusion des racines (surtout des arbres) dans la couche de rétention d'eau. Les arbres représentent une menace particulière pour la performance des couvertures, car l'intrusion des racines peut réduire la capacité des couvertures à limiter la migration de l'oxygène et augmenter le risque de dommages physiques à la CEBC. L'utilisation de plantes à effets allélopathiques potentiels comme barrière biologique pour protéger le CEBC contre la colonisation des plantes indésirables a été suggérée. Dans ce projet, deux espèces communes de la zone boréale du Québec, le calamagrostide du Canada (*Calamagrostis canadensis*) et le kalmia à feuilles étroites (*Kalmia angustifolia*), ont été choisies comme barrières biologiques (BB) pour tester si elles réduisent la croissance d'espèces d'arbres cibles (AC): le peuplier baumier (*Populus balsamifera*), le saule (*Salix* spp.) et l'épinette noire (*Picea mariana*). L'impact des BB sur les AC a été évalué pour: (1) la croissance en hauteur et en diamètre de la tige; la biomasse des feuilles, tiges et racines; le ratio racine/tige des AC ; et (2) les paramètres de l'architecture du système racinaire des AC. L'influence relative du calamagrostide et du kalmia sur les AC a été également évaluée dans des zones sèche et humide de la CEBC. L'expérimentation a été amorcée en 2008 au site de Les Terrains Aurifères situé près de Malartic au Québec. Les systèmes racinaires de 192 arbres ont été numérisés en utilisant un dispositif Polhemus FASTRAK et analysés à l'aide du logiciel AMAPmod. La présence du calamagrostide a exercé une influence négative sur la croissance des AC (croissance en hauteur et en diamètre, biomasse, profondeur maximale des racines, extension radiale des racines, longueur et volume totaux des racines, nombre de racines de 2ème- et 3ème-ordres). La biomasse du calamagrostide a eu un effet négatif sur la biomasse et les caractéristiques des racines des AC. La croissance en hauteur et en diamètre, la biomasse, la profondeur, le volume et le nombre des racines du 2ème-ordre de peuplier baumier ont augmenté dans les parcelles de kalmia. La présence du kalmia n'a pas eu d'effet sur la croissance du saule. Toutes les caractéristiques de croissance de l'épinette noire, sauf le ratio racine/tige et le nombre de racines de 2ème-ordre, ont également été améliorées en présence du kalmia. Donc, on remarque que le calamagrostide représente une BB plus efficace que le kalmia. Nos travaux suggèrent que l'effet inhibiteur du calamagrostide sur la croissance des AC pourrait être le résultat de la compétition pour l'espace et les ressources plutôt que celui de l'interférence allélopathique directe (libération des substances allélochimiques). Le peu d'effet du kalmia sur la croissance des AC est probablement relié à la faible densité de cette espèce consécutive à une contrainte d'adaptation aux conditions de site.

Mots clés: couvertures avec effets de barrière capillaire, calamagrostide du Canada, kalmia à feuilles étroites, l'architecture du système racinaire, numérisation des racines

2.2 Abstract

Covers with capillary barrier effects (CCBE) are frequently used by mining companies as an effective technique to prevent acid mine drainage (AMD) generation. This method uses the unsaturated properties of soils to maintain one of its layers at a high degree of saturation, thereby reducing O_2 availability and consequently the production of the AMD. However, CCBE long-term efficiency can be affected by root intrusion (especially from trees) into the moisture-retaining layer. Tree species represent a particular threat to cover performance as their roots may reduce cover ability to limit oxygen migration (and subsequent AMD generation) and can increase the risk of physical damage to the CCBE. The use of plants with potential allelopathic effects has been suggested as a bio-barrier to protect the CCBE against colonization of undesirable plants. In this project, two species common in the boreal zone of Québec, bluejoint (*Calamagrostis canadensis*) and sheep laurel (*Kalmia angustifolia*), were selected as bio-barrier species (BBS) to test whether they reduce the growth of target tree species (TS): balsam poplar (*Populus balsamifera*), willow (*Salix* spp.), and black spruce (*Picea mariana*). Effects of BBS on TS were assessed in terms of: (1) stem height and basal diameter increment, shoot, root and total biomass, root-to-shoot ratios of TS; and (2) root system architecture parameters of TS. The relative influence of bluejoint and sheep laurel on TS under dry and wet conditions was also evaluated. In 2008, the experiment was established at mine tailings located near the town of Malartic, Québec (Canada). The coarse root systems of 192 TS were digitized using a Polhemus FASTRAK device and analyzed with AMAPmod software. The presence of bluejoint strongly decreased above- and belowground growth of TS (stem height and basal diameter increment, biomass, maximum root depth, root radial extension, total root length and volume, and number of 2^{nd}- and 3^{rd}-order roots). Bluejoint biomass negatively affected biomass and root characteristics of TS. Stem height and basal diameter increment, biomass, maximum root depth, root volume, and number of 2^{nd}-order roots of balsam poplar increased in the sheep laurel plots, whereas willow showed no response to this treatment. All characteristics of black spruce (except for root-to-shoot ratio and number of 2^{nd}-order roots) improved in the presence of sheep laurel. Thus, bluejoint was a more efficient BBS than sheep laurel. We suggest that the inhibitory effects of bluejoint on TS growth were achieved through competition for space and resources rather than direct allelopathic interference (release of allelochemicals). Low competitive and phytotoxic activity of sheep laurel could probably be attributed to its low density and transplantation stress related to site conditions.

Key words: covers with capillary barrier effects, sheep laurel, bluejoint, tree root system architecture, root digitizing

2.3 Introduction

Along with the economic benefits that are derived from the exploitation of mineral resources in Canada, the mining industry produces substantial quantities of wastes that may incur adverse environmental impacts. Acid mine drainage (AMD), which results from the oxidation of sulphide-containing minerals in mine wastes (Kleinmann *et al.* 1981; Blowes *et al.* 1994), represents one of the most challenging environmental problems for the mining industry (Bussière *et al.* 2006). Many methods have been proposed to control AMD generation (MEND 2001). Covers with capillary barrier effects (CCBE) are considered to be an efficient means of limiting oxygen migration in humid climates, thereby controlling AMD generation from mine wastes (Ricard *et al.* 1997; Bussière *et al.* 2003; Dagenais *et al.* 2005; Bussière *et al.* 2006).

Colonization of undesirable plant species, which naturally invade CCBEs from the adjacent forest, can however compromise long-term CCBE efficiency (Trépanier *et al.* 2006). The main risks that are associated with vegetation invasion of the cover system are: 1) extraction of water from fine grained soil by plant roots, which reduce the degree of saturation and the capacity of the CCBE to constrain oxygen migration; (2) creation of macropores by roots and consequently an increase in water infiltration and oxygen migration through the cover system; and (3) physical damage to the CCBE through up-rooting of shallow-rooting trees (such as *Picea* spp.) (USDOE 1990; Handel *et al.* 1997; Hutchings 2001).

Different approaches have been proposed to control vegetation invasion and its effects on CCBE performance (Cooke and Johnson, 2002), such as the addition of herbicides, the installation of an asphalt layer, or the use of other physical barriers that are constructed of compacted soil. These approaches can have substantial drawbacks, such as limited lifespans and soil contamination. In contrast, the establishment of bio-intrusion barriers that are composed of native species with potential allelopathic effects represents an interesting environmental solution for improving CCBE long-term efficiency (Smirnova *et al.* 2009). Allelopathy is defined as the inhibition or delay of germination and growth of one plant species that can be attributed to the effects of another, either directly through the release of biochemical compounds into the environment, or indirectly through competition (Inderjit and del Moral 1997; Siciliano and Germida 1998; Wardle 1998).

Bluejoint reedgrass (hereafter bluejoint; *Calamagrostis canadensis* (Michaux) Beauvois) and sheep laurel (*Kalmia angustifolia* L.) are species native to boreal ecosystems of Canada. These two species are recognized for their allelopathic effects (Zhu and Mallik 1994; Winder and Macey 2001; Joanisse *et al.* 2007) and strong competitive ability (Hangs *et al.* 2003; Thiffault *et al.* 2004). Like most perennial grasses, bluejoint can impede the growth and emergence of trees, mainly through belowground competition for space and resource capture (Landhäusser and Lieffers 1998; Balandier *et al.* 2006; Landhäusser *et al.* 2007). The presence of grasses inhibits root development of trees, i.e., root biomass, total length density, surface area, and extension rates (Ludovici and Morris 1996, 1997; Harmer and Robertson 2003; Collet *et al.* 2006).

Sheep laurel inhibits the growth of naturally and artificially established coniferous seedlings (Thompson and Mallik 1989; English and Hackett 1994; Thiffault *et al.* 2004). Earlier studies that were conducted in the boreal forest have demonstrated that sheep laurel competes with conifers for soil resources and interferes with nutrient cycling (nitrogen cycle) through the release of secondary metabolites (polyphenols, such as condensed tannins) into the soil environment (Yamasaki *et al.* 1998; Thiffault *et al.* 2004; Bloom and Mallik 2006; Joanisse *et al.* 2007; LeBel *et al.* 2008). For example, the addition of leaves, litter, roots, and soil extracts of sheep laurel can inhibit the primary root growth of black spruce (*Picea mariana* (Miller) BSP (Mallik 1987; Zhu and Mallik 1994).

Plants react to changes in the soil environment (e.g. abiotic stress, presence of competitors, among others) in various ways. For example, they can produce more allelochemicals under water-stress conditions (Galmore 1977; Pedrol *et al.* 2008), which causes greater damage to neighbouring individuals. Plants can preferentially reallocate biomass to the roots as a response to stressful belowground conditions (moisture deficiencies, resource competition, etc.) (Chapin *et al.* 1987; Haynes and Gower 1995; Donaldson *et al.* 2006; Murphy and Dudley 2007). Moreover, they can discriminate self from non-self-neighbours (Falik *et al.* 2003; Gruntman and Novoplansky 2004) and can spatially segregate their root systems (Schenk *et al.* 1999). In the presence of neighbours, plants can alter their root growth through root proliferation in soil patches where physical and chemical conditions are favourable, thereby avoiding inhibitory soil zones and zones where water and nutrients are lacking (Gilman *et al.* 1982; Callaway 1990;

Fitter and Stickland 1991). Adaptive changes in root architecture to various environmental conditions are manifested by alterations in total root length, root volume, vertical root depth, and root ramification patterns (Gilman *et al.* 1982; Fang *et al.* 2013). However, root architecture adjustments to environmental changes vary greatly amongst plant species (Godin *et al.* 1999; Danjon and Reubens 2008).

The main objective of our study was to test whether two native species can maintain effective bio-barriers against tree establishment on CCBEs that are located in boreal Québec, Canada. Effects of two bio-barrier species (BBS), bluejoint and sheep laurel, were examined with respect to both the aboveground component and root growth of three target tree species (TS): balsam poplar (*Populus balsamifera* L.), willow (*Salix* spp.), and black spruce. The target tree species that had been selected were identified as potentially detrimental to CCBE performance because they are common and widely distributed throughout northwestern Québec, including our study area (Trépanier *et al.* 2006; Smirnova *et al.* 2009, 2011). The study specifically assessed BBS effects on: (1) height and diameter increment, biomass (root, shoot, total), and root-to-shoot ratios of TS (target tree species); and (2) the root architecture of TS. Furthermore, (3) the relative influence of BBS on TS was tested under both dry and wet soil conditions.

We hypothesized that BBS are capable of inhibiting TS growth, especially downward TS root growth. We predicted: (1) a decrease in height and diameter increment and biomass, and an increase in root-to-shoot ratios for TS; (2) a shift from vertical root distribution to lateral root expansion and proliferation of roots in the upper soil layers, together with a decrease in total root length and volume, and an increase of root ramification; and 3) a stronger inhibitory effect of BBS on TS growth in the dry, compared to the wet zone.

This study is the first attempt to introduce BBS onto an existing CCBE in a boreal context. Data that are obtained in this study will aid in evaluating the use of BBS as an ecological approach for improving CCBE long-term efficiency. This study also increases our understanding of tree root development in the presence of neighbouring species, given that the effects of BBS on TS root system architecture have not been previously investigated.

2.4 Materials and methods

2.4.1 Study site

The study was conducted on the site of Les Terrains Aurifères (LTA), which is located in Fournière and Dubuisson Townships near Malartic, Québec (48°06'55" N; 78°00'31" W; Figure 2.1). Les Terrains Aurifères was bordered on the east by an old Malartic Goldfield tailings impoundment, which belongs to Ministère des Ressources Naturelles du Québec (MRN).

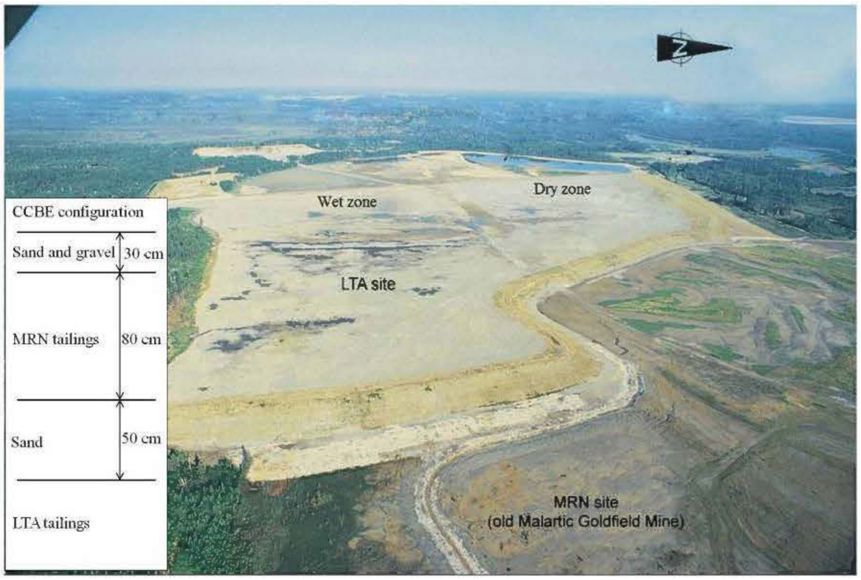


Figure 2.1 Les Terrains Aurifères site, which is located in Fournière and Dubuisson Townships (Québec, Canada). Modified from Bussière *et al.* 2006.

The tailings impoundment that was created on Les Terrains Aurifères covers an area of about 60 ha (Bussière *et al.* 2006). Around 8 mega-tonnes of acid-generating tailings (12 m-thick layer) were spread over half of the surface of the Malartic Goldfield site, where 10 mega-tonnes of non-acid generating carbonaceous tailings (5 m-thick layer) had been accumulated following the initial mining operation (MEND 2000; Bussière *et al.* 2003, 2006).

Covers that incorporated capillary barrier effects (CCBE) had been constructed in 1995-1996. The cover system consisted of three layers that were composed of different materials: (1) a layer of sand (0.5 m) that was placed directly upon the tailings, which was used as a support and as a capillary break layer; (2) a moisture-retention layer (0.8 m) composed of the fine materials (non-reactive tailings); and (3) a layer of sand and gravel (0.3 m) that was spread over top of layers 1 and 2 as protection against erosion and bio-invasion into the CCBE (Ricard *et al.* 1999). The principal role of the cover system is to control the movement of atmospheric O_2 into the acid-generating tailings beneath the CCBE. For the CCBE to be effective, a high degree of saturation must be maintained in the moisture-retention layer, which can be attributed to capillary barrier effects at the interfaces with the two sand layers. It is recognized that if more than 85% of the soil pores are filled with water, oxygen flux is low enough to control acid generation. More detailed information about CCBEs can be found in Aubertin *et al.* (1995) and Bussière *et al.* (2006).

Two zones (dry and wet) were identified at the LTA site (Figure 2.2). In the dry zone, the water table was typically more than one meter below the bottom of the sand layer of the CCBE (capillary break layer). In the wet zone, the water table was near saturation in the bottom capillary break layer and in the moisture-retention layer (Bussière *et al.* 2006).

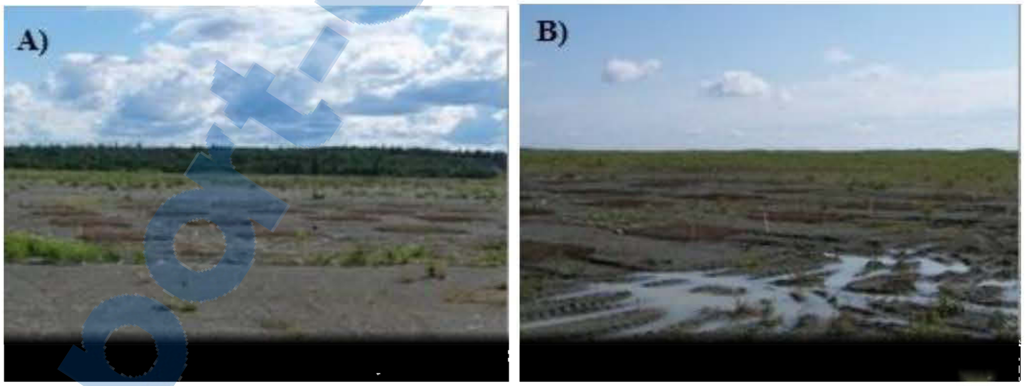


Figure 2.2 Photographs representing A) dry and B) wet zones that were identified at Les Terrains Aurifères (Québec).

2.4.2 Experimental design and treatment

Three TS (balsam poplar, willow, and black spruce) and two BBS (bluejoint and sheep laurel) were used for this study. In 2008, six blocks replicated three times per zone were established. (Figure 2.3). Each block contained three main plots, to which one of each TS was randomly attributed; the main plots were further divided in three sub-plots containing a systematic distribution of the two BBS and a control (no BBS). The plot surfaces were raked, manually weeded, and the cobbles were removed. In 2008, topsoil was added to the site. The soil amendment was loamy sand with low organic matter (50 to 54 g/kg) and nutrient content (10-16 mg N/kg, 38-41 mg P/kg, 31-41 mg K/kg, 468-779 mg Ca/kg, 35-48 mg Mg/kg). At the beginning of the 2009 growing season, a mixture of sand and clay (1m3/1 m2) was added, which had higher organic matter (506-514 g/kg) and macronutrient concentrations (30-47 mg N/kg, 43-56 mg P/kg, 42-48 mg K/kg, 1560-2420 mg Ca/kg, 235-368 mg Mg/kg) than the previous amendment.

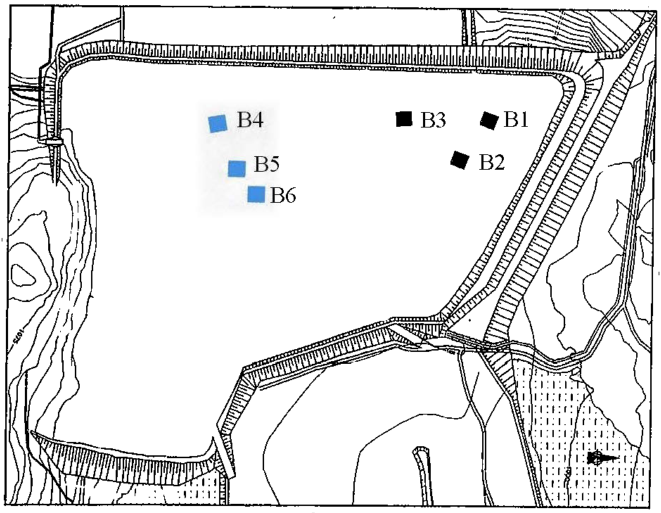


Figure 2.3 Locations of experimental blocks within the Les Terrains Aurifères site. Blocks B1, B2 and B3 were in the dry zone; B4, B5 and B6 were in the wet zone.

In 2008, balsam poplar and willow seedlings were transplanted directly from the LTA site into the main plots). Individuals of these two species were selected off-block on the basis of their stem height (30 ± 10 cm) and excavated with a mechanical shovel to prevent root damages. Two-year-old containerized black spruce seedlings were obtained from a local nursery. Stem height, basal diameter and root characteristics (number of roots per order, length of first-order roots, the diameter of roots at the collar, direction of root growth) of TS were measured prior planting.

The experimental design thus consisted of experimental blocks each divided into three main plots that were divided into three subplots of 1m^2 each (Figure 2.4). The tree seedlings were planted within each 1m^2 subplot. In total, six blocks with 18 main plots that consisted of 54 experimental subplots were involved to this study. The TS were grown either without BBS (control), or in presence of BBS (sheep laurel, bluejoint, respectively).

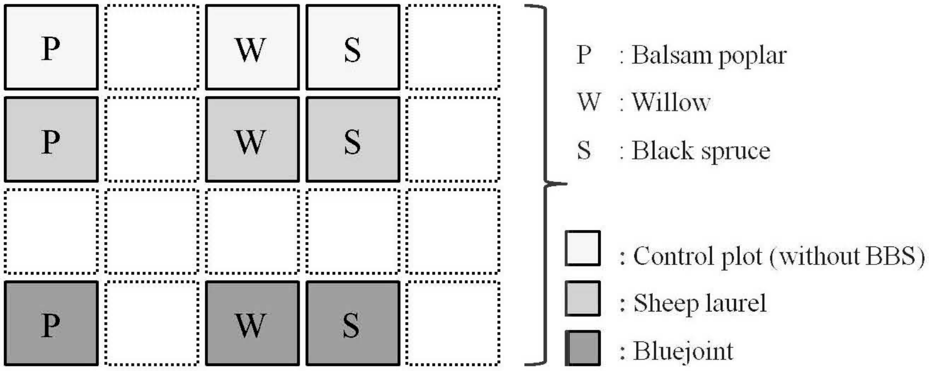


Figure 2.4 Example of one experimental block illustrating the plot arrangement. Each treatment was replicated three times within each block. White quadrates signify the experimental plots where additional species were planted but not involved to this study.

Sheep laurel was transplanted at the LTA site in 2008. The root rhizomes were collected in an open site, located along power transmission lines, adjacent to the forest and approximately 50 km away from the LTA site. The collection site had a sandy soil with an organic horizon of about 2 cm. Bluejoint seed was purchased from a nursery and sown in 2010. Bluejoint had a low survival rate. Consequently, bluejoint seedlings were planted in 2011 at a density of about 40 plants/m^2.

2.4.3 Seedling measurements and sampling

Stem height (cm) and basal diameter (root collar diameter, cm) of each TS were measured within each experimental 1 m^2 subplot once at the end of each growing season (2009-2012) in the control and sheep laurel plots, and once per 2011-2012 growing seasons in the bluejoint plots. In total, the root systems of 192 TS distributed among the 54 subplots were excavated with a high-pressure water jet in August 2012 (see Tarroux and DesRochers 2010) (Appendix A). The reference direction (north) was marked on the TS stem prior TS excavation. Broken coarse roots (> 2 mm in diameter) were collected during TS excavation and reattached at their appropriate locations for further measurements. Percent cover of the BBS was determined for each subplot as the area that was occupied by the vertical projection of BBS leaves onto the soil surface (Mallik *et al.* 2012). The BBS surrounding the TS (within the entire1 m^2 subplot) were excavated.

Each TS was separated into shoots and roots in the laboratory. Shoots were further divided into foliar components, and branches. The material was oven-dried 48 h at 65°C and weighed (± 0.01 g). Roots of the TS were washed; fine roots (< 2 mm in diameter) were clipped off and were not considered in further analyses. Thereafter, coarse roots were digitized (details presented below). After digitizing, coarse roots were dried at 65°C and weighed.

Fifty grams of each BBS component (leaves, stems, and roots) per sample was collected and oven-dried at 65°C for 48 h. These subsamples were used to estimate sample gravimetric moisture content and the remaining dry biomass of BBS (Smirnova *et al.* 2008).

2.4.4 Root architecture measurements and analyses

Coarse root systems of TS were digitized in three dimensions with a Polhemus Fastrak low-magnetic field digitizer (Polhemus, Colchester, VT, USA; http://polhemus.com/) and PiafDigit software (Danjon and Reubens 2008) following the method described by Danjon *et al.* (1999a). The root systems were positioned according to the reference direction (north). Since metal might interfere with the magnetic field and measurements (Danjon *et al.* 1999b; Nicoll *et al.* 2006), digitizing was performed outdoors and far away from large metallic objects. The topology, Cartesian XYZ coordinates, and diameter of each digitized point were simultaneously recorded. The diameter corresponding to the first digitized point was measured in two directions (north-south and east-west), considering that the roots had oval cross-sectional areas (Danjon *et al.* 2005; Nicoll *et al.* 2006). Measurements along the length of the roots were taken at 2 cm intervals when the root was straight and every 0.5 cm when the root was highly curved or when its diameter changed abruptly. Appendix B shows some examples of how coarse root systems were digitized from August to September 2012 at the Lac Duparquet Research Station of UQAT.

Multi-scale tree graph coding (Godin *et al.* 1997; Godin 2000) was used to represent the hierarchical structure of the root system (Danjon *et al.* 1999b, 2005). The data that were obtained from the digitizing were analyzed with AMAPmod software (Godin *et al.* 1997, 1999;

Danjon *et al.* 1999a). Maximum root depth (cm) and root radial extension (cm), total root length (cm) and root volume (cm^3), and the total number of 2^{nd}- and 3^{rd}-order roots were computed from the AMAPmod routines. Computations of root characteristics were performed at various scales, viz., at the segment- and axis-levels, and at the entire root system level. The procedure for the calculations has been detailed by Danjon *et al.* (1999a) and Nicoll *et al.* (2006).

2.4.5 Statistical analyses

Characteristics of TS (stem height and basal diameter increment; above-, belowground, and total dry mass; root-to-shoot ratio; root architectural characteristics) were analyzed in R (Version 2.15.2, R Development Core Team 2012) with linear mixed effects models (Zuur *et al.* 2009). Each TS and treatment (BBS) was analyzed separately. Homoscedasticity and normality of residuals were verified for all data prior to analysis. Data were ln- transformed whenever necessary. The block and treatment-within block were treated as random effects.

Two candidate models were identified to assess the effects of BBS on height and diameter increment of TS during the experimental period 2011-2012 for bluejoint and 2009-2012 for sheep laurel. The models included the fixed effects of zone (wet vs. dry), treatment (control, bluejoint, and sheep laurel) and their interaction (zone × treatment). The respective reference levels for these categorical variables were dry zone and control plot. Effects of zone, treatment, dry mass of BBS (aboveground, belowground, and total), and their interactions (zone × treatment, zone × BBS dry mass) on TS dry mass and root characteristics were assessed. The correlated parameters, such as the treatment and BBS dry mass, were not included in the same model.

Models were ranked based on the second-order Akaike Information Criterion (i.e., AIC_c), using the *modavg.lme* function of the *AIC_cmodavg* package (Mazerolle 2006). Akaike weights and Δ AIC_c were computed to determine the strength of evidence for each model (Burnham and Anderson 2002). Model averaging was performed to obtain parameter estimates, unconditional standard errors (SE) and 95% unconditional confidence intervals (CI).

2.5 Results

2.5.1 Bio-barrier species responses

We observed a high cover of bluejoint in the experimental plots with the three TS (> 60%) (Table 2.1). The establishment of bluejoint was better in the plots planted with deciduous trees: balsam poplar and willow (> 86%) (Table 2.1).

Table 2.1 Mean (± SE) percent cover (%) and dry mass of roots, shoots, total biomass dry weight of bio-barrier species (g) when grown in the plots with target tree species at Les Terrains Aurifères site, Québec.

Bio-barrier species	Target tree	Percent cover, %	Shoot dry mass, g	Root dry mass, g	Total dry mass, g
Bluejoint	Balsam poplar	88 (8)	75.8 (26.4)	45.9 (26.2)	121.7 (46.9)
	Willow	86 (7)	85.2 (23.2)	33.7 (18.4)	118.9 (69.5)
	Black spruce	60 (15)	34.7 (16.0)	27.9 (5.6)	62.6 (34.1)
Sheep laurel	Balsam poplar	19 (11)	182.5 (97.4)	144.8 (47.2)	327.3 (140.1)
	Willow	17 (11)	205.2 (105.8)	183.4 (133.8)	388.6 (211.3)
	Black spruce	33 (14)	213.4 (94.5)	140.8 (59.4)	354.1 (143.8)

Note. Values are shown as the mean with standard deviation in the parentheses.

Sheep laurel had a high mortality rate and low percent cover in the plots with three TS by the end of the experiment (August, 2012) (Table 2.1). The mean percent cover of sheep laurel was < 24%. Sheep laurel had a lower percent cover than bluejoint (Table 2.1), but biomass measurements showed the opposite. We obtained a higher biomass for sheep laurel than bluejoint (Table 2.1).

2.5.2 Target tree species mortality

The survival of TS varied among treatments. Bluejoint had a strong detrimental effect on TS survival one year after the grass was planted. Mortality of balsam poplar and willow reached 42% in the bluejoint experimental plots in both zones. For black spruce, about 8% of mortality was observed in the dry and 17% in the wet zones, respectively, in the presence of bluejoint. No significant tree mortality was observed in the control, except for 8% of dead willow observed in the dry zone and in the sheep laurel plots.

2.5.3 Target tree species growth

2.5.3.1 Bluejoint

One-year stem height increment (2011-2012) was 90% lower for balsam poplar, 75% lower for willow, and 62% lower for black spruce, when the target tree species were growing in the presence of bluejoint, compared to the control plots (balsam poplar, $\text{estimate}_{\text{bluejoint}} = -2.90$, 95% CI: -3.23, -2.57; willow, $\text{estimate}_{\text{bluejoint}} = -5.65$, 95% CI: -7.93, -3.37; black spruce, $\text{estimate}_{\text{bluejoint}} = -3.59$, 95% CI: -7.00, -0.18; Figure 2.5). On average, basal diameter increment of balsam poplar and willow was four times lower in the bluejoint plots, compared to the controls (balsam poplar, $\text{estimate}_{\text{bluejoint}} = -0.16$, 95% CI: -0.25, -0.07; willow, $\text{estimate}_{\text{bluejoint}} = -0.13$, 95% CI: -0.21, -0.04). For black spruce, basal increment decreased by 80% when planted in the bluejoint plots, compared to the control plots ($\text{estimate}_{\text{bluejoint}} = -0.17$, 95% CI: -0.22, -0.13). Stem height increment of balsam poplar was lower in the wet zone, compared to the dry zone ($\text{estimate}_{\text{wet zone}} = -0.51$, 95% CI: -0.84, -0.18) (Figure 2.5). We detected no other effect of zone.

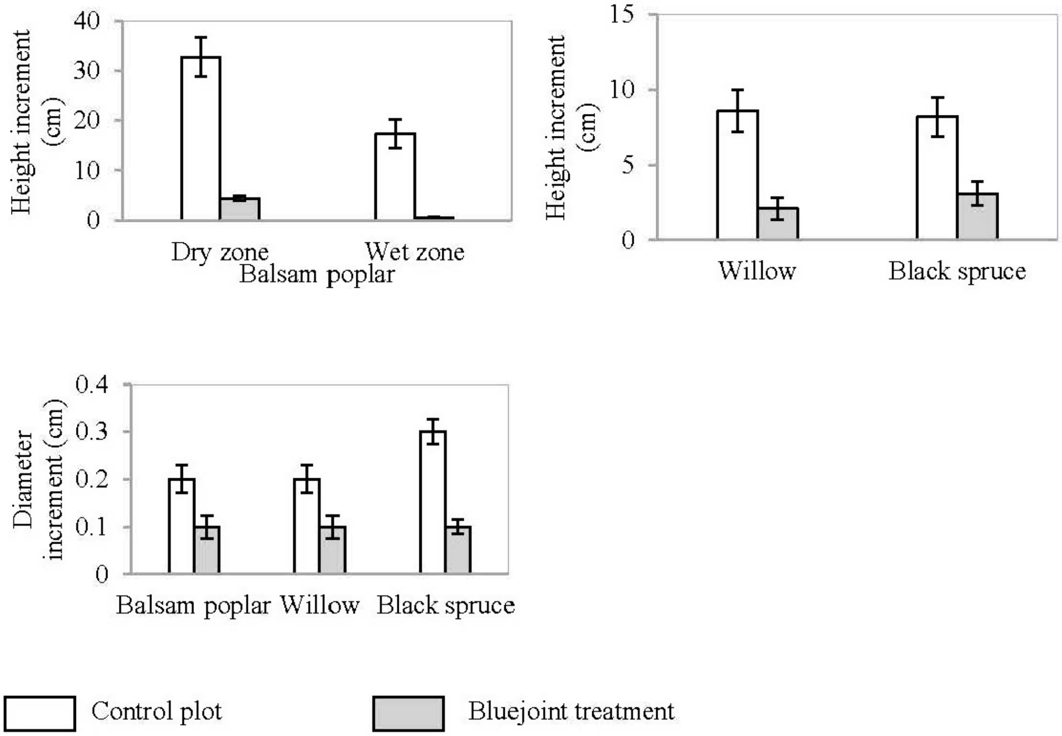


Figure 2.5 One-year (2011-2012) stem height and basal diameter increment (cm) of target tree species in the control and bluejoint plots at Les Terrains Aurifères site (Québec). Data are presented as mean (± SE).

2.5.3.2 Sheep laurel

Growth characteristics of the TS varied among treatments (Appendices E and F). In both zones, the presence of sheep laurel improved height and diameter growth for balsam poplar ($\text{estimate}_{\text{sheep laurel}}$ = 0.48, 95% CI: 0.15, 0.88; $\text{estimate}_{\text{sheep laurel}}$ = 0.48, 95% CI: 0.15, 0.80) and black spruce ($\text{estimate}_{\text{sheep laurel}}$ = 0.84, 95% CI: 0.52, 1.16; $\text{estimate}_{\text{sheep laurel}}$ = 0.29, 95% CI: 0.05, 0.52) over the four growing seasons (2009-2012). Stem height and basal diameter increment of balsam poplar were respectively 45% and 55% higher in the sheep laurel plots, compared to the controls (Figure 2.6). Three-year stem height increment for black spruce that was grown in the sheep laurel plots was twice that observed in the control plots, whereas the respective basal diameter increment was 29% higher in the sheep laurel plots (Figure 2.6). The presence of sheep laurel did not influence willow growth, as the unconditional 95% CI around the model-averaged estimate largely included 0 (Appendix F, Figure 2.6).

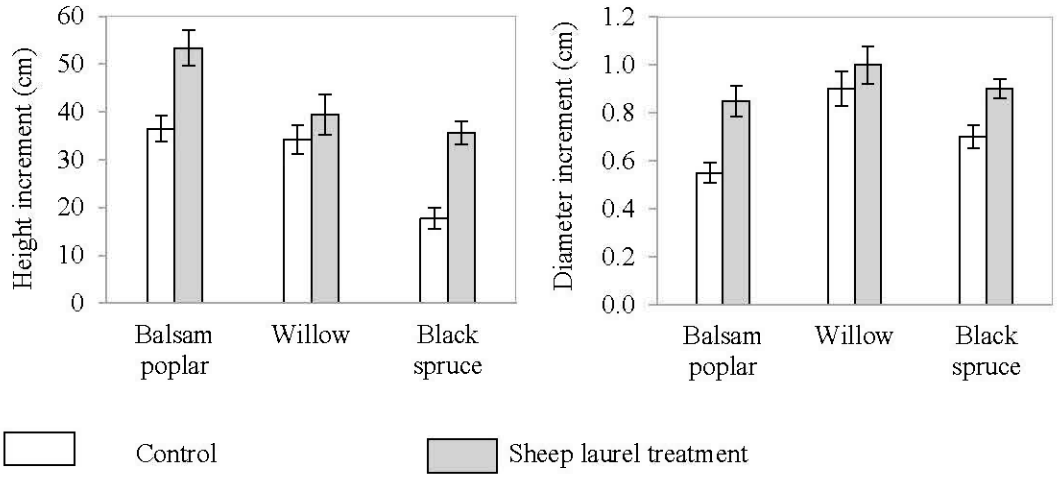


Figure 2.6 Three-year (2009-2012) stem height and basal diameter increment (cm) of target tree species in the control and sheep laurel plots at Les Terrains Aurifères site (Québec). Data are presented as mean (± SE).

2.5.4 Target tree species biomass and root-to-shoot ratios

2.5.4.1 Bluejoint

Variation in TS biomass (dry mass, DM) was well explained by the model that included the main effects of bluejoint and zone (Appendix G). Mean (± SE) shoot (2.8 ± 0.4 g), root (2.2 ±

0.4 g), and total (5.0 ± 0.7 g) biomass of balsam poplar in the bluejoint plots was 14 times lower than that measured in the control plots (Table 2.2). Willow biomass was about five times higher in the control plots (shoot, 31.2 ± 7.1 g; root, 25.4 ± 5.1 g; total, 56.6 ± 3.0 g) than in the presence of bluejoint (shoot, 6.1 ± 0.6 g; root, 4.4 ± 0.5 g; total, 10.5 ± 1.0 g). Black spruce biomass (shoot, 11.7 ± 1.9 g; root, 3.3 ± 0.6 g; total, 15.0 ± 2.4 g) was four times lower in the bluejoint plots, compared to the controls (shoot, 45.5 ± 5.5 g; root, 11.9 ± 1.6 g; total, 57.5 ± 7.1 g). The biomass of bluejoint had adverse effect on black spruce biomass (Table 2.2). No explanatory variable influenced the root-to-shoot ratio of TS (Table 2.2).

Table 2.2 Parameter estimates for root, shoot, total dry mass, and root-to-shoot ratios of target tree species in response to the bluejoint treatment at Les Terrains Aurifères site, Québec.

Response variable	Explanatory variable	Estimate	SE	Upper and lower 95% CI
	I. Balsam poplar			
Shoot dry mass	Wet zone	0.14	0.23	-0.30, 0.58
	Bluejoint	**-2.66**	0.22	**-3.09, -2.33**
Root dry mass	Wet zone	-0.26	0.34	-0.40, 0.93
	Bluejoint	**-2.57**	0.25	**-3.06, -2.07**
Total dry mass	Wet zone	0.17	0.23	-0.28, 0.61
	Bluejoint	**-2.60**	0.21	**-3.02, -2.18**
Root-to-shoot ratio	Wet zone	0.05	0.18	-0.29, 0.40
	Bluejoint	0.10	0.17	-0.23, 0.43
	Shoot dry mass of bluejoint	0.00	0.00	0.00
	Root dry mass of bluejoint	0.00	0.00	0.00
	Total dry mass of bluejoint	0.00	0.00	0.00
	II. Willow			
Shoot dry mass	Wet zone	-0.40	0.41	-1.20, 0.40
	Bluejoint	**-2.10**	0.35	**-2.77, -1.42**
Root dry mass	Wet zone	0.17	0.43	-1.01, 0.68
	Bluejoint	**-2.51**	0.38	**-3.25, -1.76**
Total dry mass	Wet zone	-0.30	0.41	-1.10, 0.50
	Bluejoint	**-2.27**	0.35	**-2.95, -1.58**
Root-to-shoot ratio	Wet zone	0.07	0.21	-0.34, 0.47
	Bluejoint	-0.06	0.14	-0.33, 0.22
	Shoots dry mass of bluejoint	0.00	0.00	0.00
	Root dry mass of bluejoint	0.00	0.00	0.00
	Total dry mass of bluejoint	0.00	0.00	0.00

Response variable	Explanatory variable	Estimate	SE	Upper and lower 95% CI
III. Black spruce				
Shoots dry mass	Wet zone	-0.27	0.27	-0.80, 0.26
	Bluejoint	**-1.36**	0.15	**-1.65, -1.06**
	Shoot dry mass of bluejoint	**-0.04**	0.005	**-0.05, -0.03**
	Root dry mass of bluejoint	**-0.04**	0.007	**-0.05, -0.03**
	Total dry mass of bluejoint	**-0.02**	0.003	**-0.03, -0.01**
Root dry mass	Wet zone	-0.46	0.35	-1.14, 0.22
	Bluejoint	**-1.39**	0.20	**-1.78, -1.00**
	Shoot dry mass of bluejoint	**-0.04**	0.01	**-0.05, -0.02**
	Root dry mass of bluejoint	**-0.04**	0.01	**-0.06, -0.02**
	Total dry mass of bluejoint	**-0.02**	0.01	**-0.03, -0.01**
Total dry mass	Wet zone	-0.31	0.28	-0.87, 0.25
	Bluejoint	**-1.36**	0.16	**-1.67, -1.05**
	Shoot dry mass of bluejoint	**-0.04**	0.01	**-0.05, -0.02**
	Root dry mass of bluejoint	**-0.04**	0.01	**-0.05, -0.02**
	Total dry mass of bluejoint	**-0.02**	0.01	**-0.03, -0.01**
Root-to-shoot ratio	Wet zone	0.03	0.10	-0.17, 0.22
	Bluejoint	0.06	0.10	-0.14, 0.26
	Shoot dry mass of bluejoint	0.00	0.00	0.00
	Root dry mass of bluejoint	0.00	0.00	0.00
	Total dry mass of bluejoint	0.00	0.00	0.00

Notes. The reference levels in the mixed model were dry zone and control plot. The values in boldface type signify that 95% unconditional confidence interval for a given parameter excludes zero.

2.5.4.2 Sheep laurel

Four models had strong support (high Akaike weights) for explaining variation in DM and the root-to-shoot ratios of three TS. The "best" models, which encompassed more than 95% of total Akaike weights, contained the main effects of zone, sheep laurel treatment, and DM of sheep laurel (Appendix H). The shoot, root, and total DM of balsam poplar were higher in the presence of sheep laurel by 72%, 53%, and 64%, respectively, compared to in its absence (shoot, $\text{estimate}_{\text{sheep laurel}}$ = 0.63, 95% CI: 0.20, 1.07; root, $\text{estimate}_{\text{sheep laurel}}$ = 0.52, 95% CI: 0.10, 0.95; total, $\text{estimate}_{\text{sheep laurel}}$ = 0.59, 95% CI: 0.17, 1.01) (Figure 2.7)

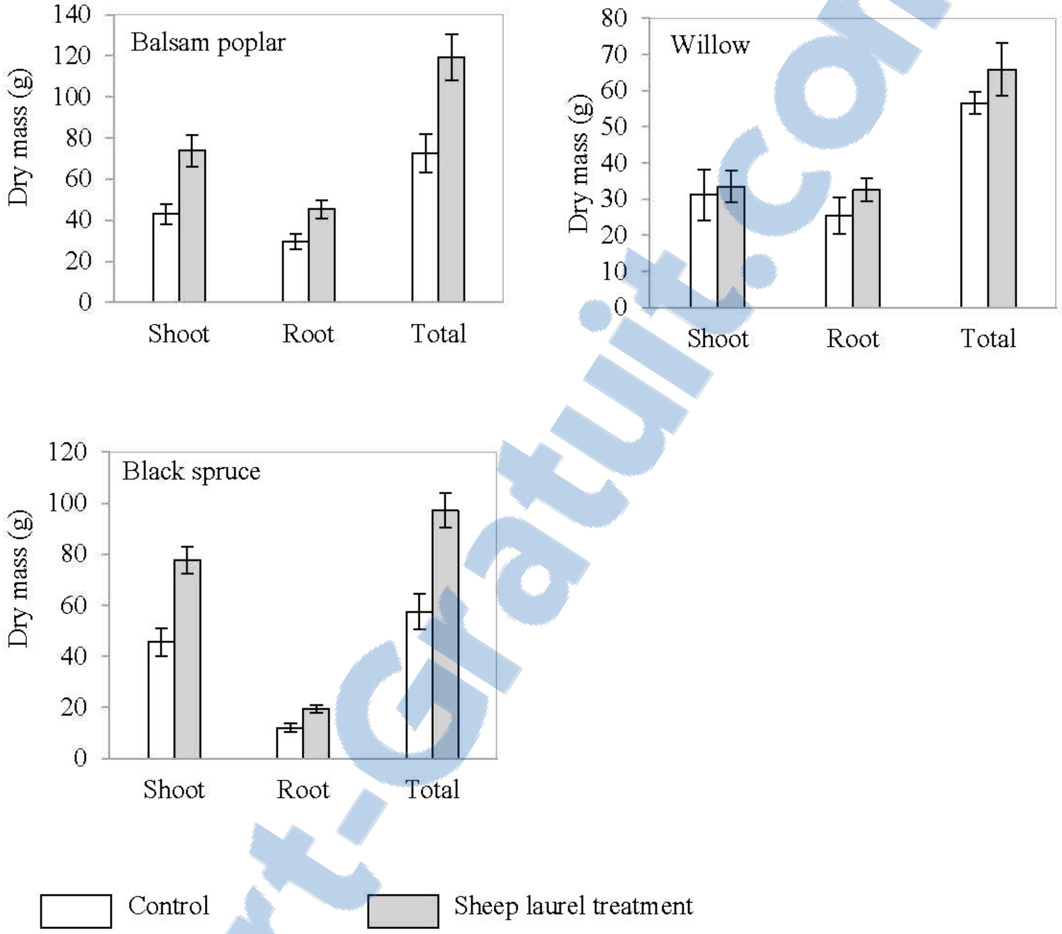


Figure 2.7 Dry mass of target tree species in the control and sheep laurel plots at Les Terrains Aurifères site (Québec). Data are presented as mean (± SE)

In the presence of sheep laurel, the shoot, root, and total DM of black spruce increased by 71%, 62%, and 69%, respectively (shoot, $\text{estimate}_{\text{sheep laurel}}$ = 0.64, 95% CI: 0.34, 0.95; root, $\text{estimate}_{\text{sheep laurel}}$ = 0.60, 95% CI: 0.24, 0.96; total, $\text{estimate}_{\text{sheep laurel}}$ = 0.63, 95% CI: 0.32, 0.95).

The biomass of willow and the root-to-shoot ratios of the three TS did not vary among treatments (sheep laurel vs. control) and zones (dry vs. wet) (Appendix I).

2.5.5 Target tree species root system architecture

2.5.5.1 Bluejoint

Bluejoint had a strong detrimental effect on root architecture characteristics of three TS (Tables 2.3 and 2.4). In the presence of bluejoint, maximum root depth, root radial extension, total root length, and the root volume of balsam poplar decreased by > 80%, compared to control conditions. The number of 2nd- and 3rd-order roots of balsam poplar decreased respectively by 68% and 77% in the bluejoint plots, compared to control plots. Shoot and total DM of bluejoint had an adverse effect on total root length and root volume of balsam poplar (Table 2.3). The total number of 2nd- and 3rd-order roots of balsam poplar was detrimentally affected by the biomass of bluejoint.

Maximum root depth and root radial extension, the total number of 2nd- and 3rd-order roots of willow were reduced by bluejoint treatment by 72%, 87%, 83%, and 84%, respectively, compared to control conditions (Tables 2.3 and 2.4). Total root length and root volume of willow decreased by 93% in the presence of bluejoint, compared to the control plots. Root DM of bluejoint had a detrimental effect on the number of 2nd-order roots of willow.

Maximum root depth, maximum root radial extension, and the number of 3rd-order roots of black spruce decreased in the presence of bluejoint, compared to control conditions (Tables 2.3 and 2.4). Total root volume and the number of 3rd-order roots were detrimentally affected by the biomass of bluejoint. Mean total root volume ($\pm$ SE) was 43.8 ± 5.9 cm^3 vs. 14.5 ± 3.2 cm^3, whereas the total number of 3rd-order roots was 2.8 ± 0.3 in the controls versus 1.0 ± 0.3 in the bluejoint plots. Shoot and total DM of bluejoint had an adverse effect on maximum root radial extension and total root length of black spruce (Tables 2.3 and 2.4). The number of 2nd-order roots of black spruce was negatively affected by root and total DM of bluejoint (Tables 2.3 and 2.4). The three-dimensional representation of first-, second- and third-order root systems of TS that were grown in the control and in the presence of bluejoint is illustrated in Figure 2.8

Model-averaging revealed no main effect of zone on root characteristics of three TS, except for maximum root depth of balsam poplar (Tables 2.3 and 2.4). Balsam poplar roots extended more deeply in dry zone than in the wet zone. Poplar roots were 17 cm (37%) and 1 cm (11%) deeper in the dry zone, in the control and bluejoint plots, respectively, compared to the wet zone. Bluejoint had a strong detrimental effect on root architecture characteristics of three TS (Tables 2.3 and 2.4).

2.5.5.2 Sheep laurel

As observed in the bluejoint plots, only one root characteristic, i.e., maximum root depth of balsam poplar, varied among zones ($\text{estimate}_{\text{wet zone}}$ = -0.36, 95% CI: -0.61, -0.12). When compared to the dry zone, the maximum root depth of balsam poplar in the wet zone was 37% (17 cm) and 23% (13.4 cm) lower in the control and sheep laurel plots, respectively (Table 2.4). In the presence of sheep laurel, the maximum root depth of balsam poplar increased by 38% ($\text{estimate}_{\text{sheep laurel}}$ = 0.32, 95% CI: 0.09, 0.55) and its total root volume was 57% greater, compared to the control plot ($\text{estimate}_{\text{sheep laurel}}$ = 0.57, 95% CI: 0.08, 1.07). The number of 2nd-order roots of balsam poplar in the sheep laurel plots was 36% greater than in the control ($\text{estimate}_{\text{sheep laurel}}$ = 1.63, 95% CI: 0.37, 2.88). No difference between plots was observed for maximum root radial extension, total root length, and the number of 3rd-order roots of balsam poplar (Table 2.4, Appendix L).

The maximum root depth of willow varied among zones ($\text{estimate}_{\text{wet zone}}$ = 6.23, 95% CI: 2.96, 9.50). In comparison with the dry zone, maximum root depth of willow in the wet zone was 11% (3.1 cm) and 44% (9.5 cm) greater in the control and sheep laurel plots, respectively. Other root architecture characteristics of willow were not affected by the presence of sheep laurel (Table 2.4, Appendix L).

The sheep laurel treatment increased maximum root depth of black spruce by 23% ($\text{estimate}_{\text{sheep laurel}}$ = 0.25, 95% CI: 0.15, 0.35) (Table 2.4). Root radial extension and total root length of black spruce were 28% greater in the sheep laurel plots, compared to the control (root radial extension, $\text{estimate}_{\text{sheep laurel}}$ = 0.31, 95% CI: 0.15, 0.46; total root length, $\text{estimate}_{\text{sheep laurel}}$ = 0.36, 95% CI: 0.15, 0.57). Total root volume and the number of 3rd-order roots of black spruce increased by 58% and 55%, respectively, in presence of sheep laurel ($\text{estimate}_{\text{sheep laurel}}$ = 0.58, 95% CI: 0.21, 0.95; $\text{estimate}_{\text{sheep laurel}}$ = 1.25, 95% CI: 0.63, 1.87). The number of 2nd-order roots did not vary among control and sheep laurel plots (Appendix L). Several examples of AMAPmod images of TS root systems that were excavated from the control and the sheep laurel plots are presented in Figure 2.8.

Table 2.3 Parameter estimates for the root system architecture characteristics of target tree species in response to the bluejoint treatment at Les Terrains Aurifères site, Québec.

Response variable	Explanatory variable	**Balsam poplar**			**Willow**			**Black spruce**		
		Estimate	SE	95% CI	Estimate	SE	95% CI	Estimate	SE	95% CI
Maximum root depth	Wet zone	-0.26	0.1	**-0.47, -0.06**	-0.07	0.27	-0.60, 0.46	-0.14	0.08	-0.30, 0.01
	Bluejoint	-1.48	0.1	**-1.68, -1.28**	-1.59	0.26	**-2.11, -1.08**	-0.52	0.08	**-0.67, -0.37**
Maximum root radial extension	Wet zone	-0.06	0.2	-0.45, 0.33	-0.11	0.46	-1.00, 0.79	-0.09	0.21	-0.51, 0.33
	Bluejoint	-2.47	0.2	**-2.86, -2.09**	-2.05	0.29	**-2.62, -1.49**	-1.29	0.11	**-1.51, -1.07**
	Shoot dry mass of bluejoint	-	-	-	-	-	-	-0.03	0.01	**-0.04, -0.03**
	Total dry mass of bluejoint	-	-	-	-	-	-	-0.02	0.002	**-0.02, -0.01**
Total root length	Wet zone	0.32	0.44	-0.56, 1.19	0.09	0.54	-0.98, 1.15	-0.28	0.19	-0.65, 0.09
	Bluejoint	-2.31	0.35	**-3.00, -1.62**	-2.85	0.47	**-3.77, -1.94**	-	-	-
	Shoot dry mass of bluejoint	-0.03	0.01	**-0.04, -0.02**	-	-	-	-0.03	0.004	**-0.04, -0.02**
	Total dry mass of bluejoint	-0.02	0.01	**-0.02, -0.01**	-	-	-	-0.02	0.002	**-0.02, -0.01**
Total root volume	Wet zone	0.19	0.47	-0.73, 1.12	-0.36	0.57	-1.47, 0.75	-0.3	0.28	-0.85, 0.25
	Bluejoint	-2.45	0.38	**-3.18, -1.71**	-3.23	0.49	**-4.2, -2.26**	-	-	-
	Shoot dry mass of bluejoint	-0.03	0.01	**-0.04, -0.02**	-	-	-	-0.04	0.01	**-0.05, -0.03**
	Root dry mass of bluejoint	-	-	-	-	-	-	-0.04	0.01	**-0.06, -0.03**
	Total dry mass of bluejoint	-0.02	0.01	**-0.02, -0.01**	-	-	-	-0.02	0.003	**-0.03, -0.02**

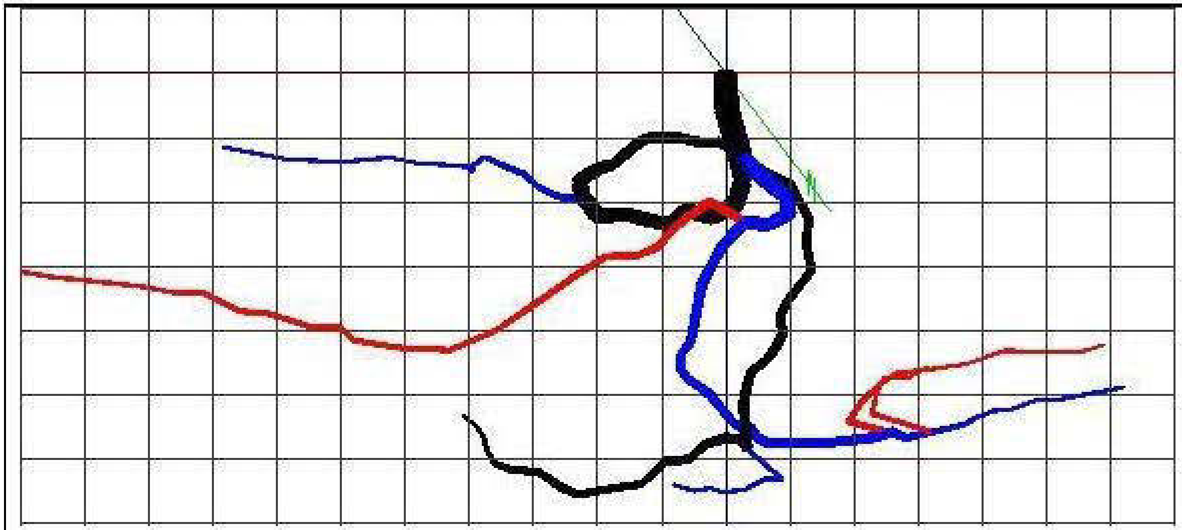
Response variable	Explanatory variable	Balsam poplar			Willow			Black spruce		
		Estimate	SE	95% CI	Estimate	SE	95% CI	Estimate	SE	95% CI
Number of 2nd-order roots	Wet zone	0.7	0.77	-0.80, 2.21	0.35	1.5	-2.59, 3.28	-0.34	0.6	-1.51, 0.83
	Bluejoint	-2.78	0.68	**-4.11, -1.46**	-5.48	0.85	**-7.15, -3.82**	-	-	-
	Shoot dry mass of bluejoint	-0.03	0.01	**-0.05, -0.01**	-	-	-	-	-	-
	Root dry mass of bluejoint	-0.04	0.01	**-0.07, -0.02**	-0.14	0.02	**-0.18, -0.11**	-0.1	0.01	**-0.13, -0.07**
	Total dry mass of bluejoint	-0.02	0.01	**-0.03, -0.01**	-	-	-	-0.05	0.01	**-0.06, -0.03**
Number of 3rd-order roots	Wet zone	0.02	0.4	-0.77, 0.81	-0.6	0.59	-1.76, 0.55	-0.38	0.42	-1.20, 0.44
	Bluejoint	-0.82	0.39	**-1.58, -0.05**	-2.6	0.47	**-3.52, -1.68**	-1.75	0.21	**-2.17, -1.33**
	Shoot dry mass of bluejoint	-0.01	0.005	**-0.02, 0**	-	-	-	-0.05	0.01	**-0.06, -0.03**
	Root dry mass of bluejoint	-0.014	0.007	**-0.03, 0**	-	-	-	-0.05	0.01	**-0.07, -0.03**
	Total dry mass of bluejoint	-0.006	0.003	**-0.01, 0**	-	-	-	-0.03	0.004	**-0.03, -0.02**

Notes. The reference levels in the linear mixed models were dry zone and control plot. The values in boldface type signify that 95% unconditional confidence interval for a given parameter excludes zero.

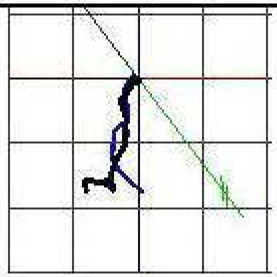
Table 2.4 Mean (± SE) root system characteristics of target tree species among treatments (control vs. bluejoint, sheep laurel) at Les Terrains Aurifères site, Québec.

Target tree species	Treatment	Maximum root depth (cm)		Maximum root radial extension (cm)		Total root length (cm)		Total root volume (cm^3)		Number of 2nd-order roots		Number of 3rd-order roots	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Balsam poplar	Control (dry/ wet)	46.2/ 29.2	5.4/ 6.2	100.1	10.6	382.4	39.4	86.4	11.7	4.4	0.4	1.3	0.3
	Bluejoint (dry/ wet)	8.5/ 7.5	1.4/ 1.2	7.4	0.9	41.5	9.9	6.4	1.7	1.4	0.5	0.3	0.1
	Sheep laurel (dry/ wet)	58.8/ 45.4	6.6/ 5.6	118.7	5.8	506.9	36.4	135.6	10	6.0	0.3	2.1	0.3
Willow	Control (dry/wet)	27.4/ 30.5	3.7/ 4.6	52.2	6.0	370.8	57.6	73.2	15.5	6.8	0.8	2.8	0.7
	Bluejoint	8.0	1.3	6.6	1.2	27.0	6.3	5.2	1.4	1.1	0.3	0.2	0.1
	Sheep laurel (dry/ wet)	21.8/ 31.3	1.7/ 3.0	63.1	6.7	527.6	63.2	89.3	8.2	7.8	0.7	3.3	0.6
Black spruce	Control	16.7	0.5	52.0	5.0	309.3	29.6	43.8	5.9	7.6	0.5	2.8	0.3
	Bluejoint	10	0.6	14.7	1.9	105.0	16.2	14.5	3.2	4.7	0.5	1.0	0.3
	Sheep laurel	21.3	0.9	68.6	4.9	423.6	27.5	70.8	6.1	8.3	0.5	4.0	0.4

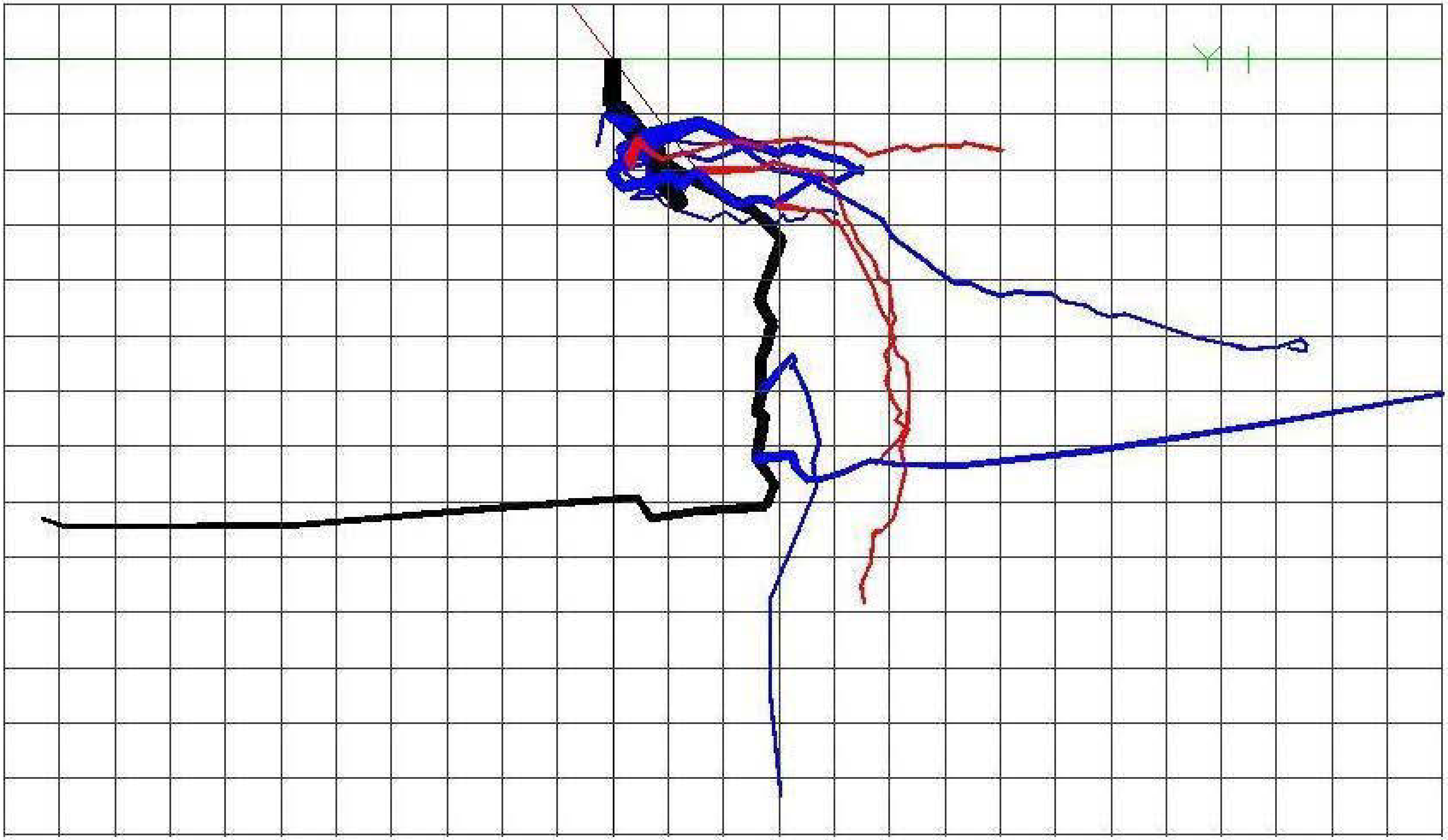
Balsam poplar



Control plot. Maximum root depth = 32.8 cm, maximum root radial extension = 49.1 cm, total root length = 328.0 cm, total root volume = 93.9 cm3, number of 2nd-order roots = 3, number of 3rd-order roots = 3.

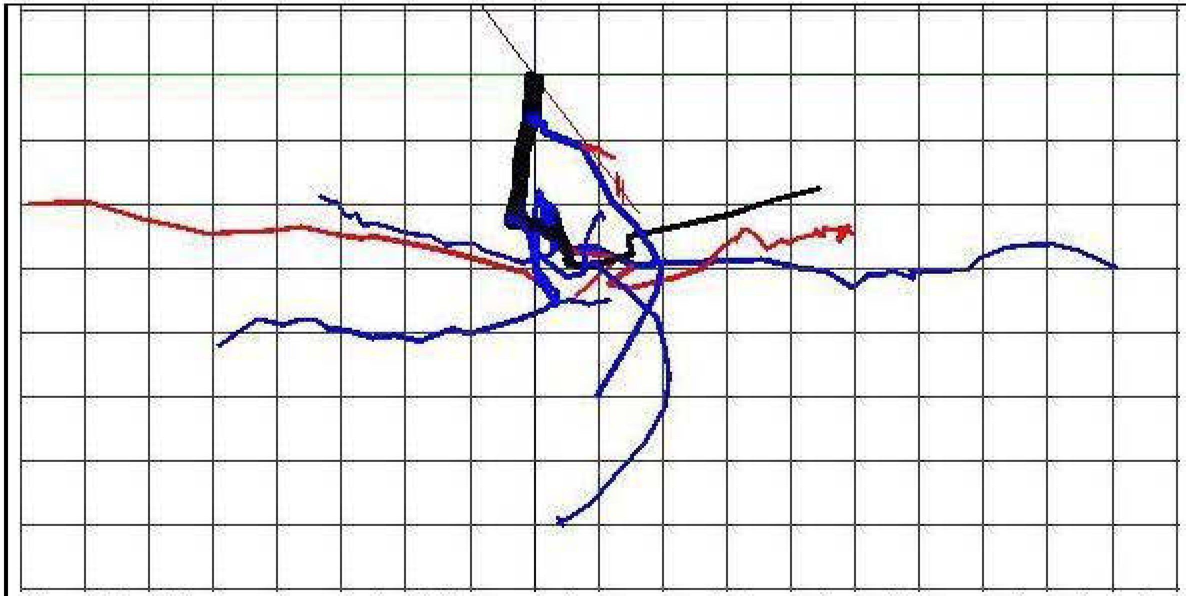


Bluejoint treatment. Maximum root depth = 8.5 cm, maximum root radial extension = 7.0 cm, total root length = 37.0 cm, total root volume = 2.7 cm^3, number of 2nd-order roots = 1, number of 3rd-order roots = 0.

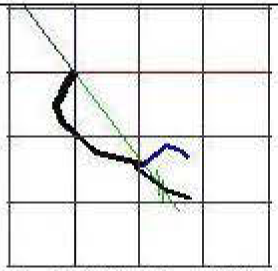


Sheep laurel treatment. Maximum root depth = 66.5cm, maximum root radial extension = 72.8 cm, total root length = 657.6 cm, total root volume = 188.5 cm^3, number of 2nd-order roots = 7, number of 3rd- order roots = 3.

Willow

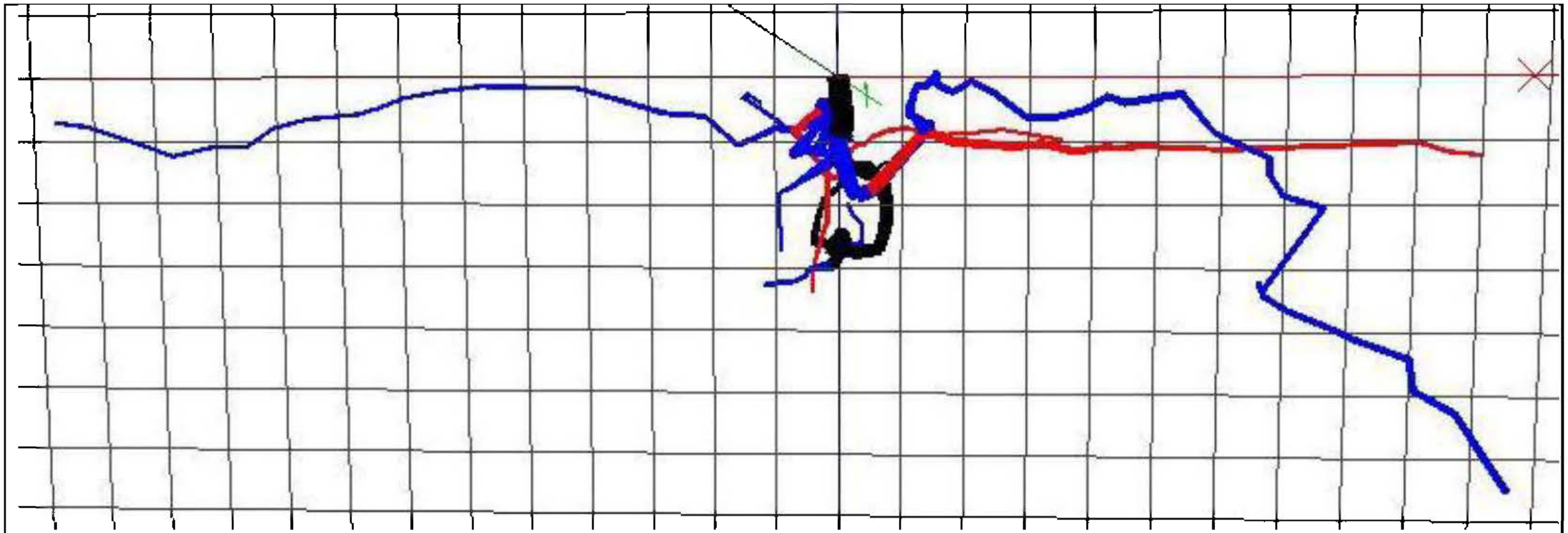


Control plot. Maximum root depth = 34.7 cm, maximum root radial extension = 45.0 cm, total root length = 412.1 cm, total root volume = 51.8 cm^3, number of 2nd-order roots = 8, number of 3rd-order roots = 4

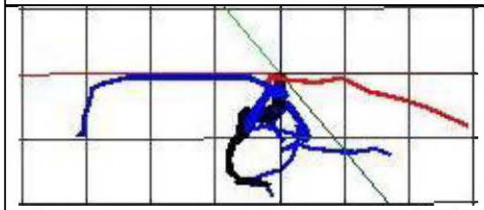


Bluejoint treatment. Maximum root depth = 9.1 cm, maximum root radial extension = 9.4 cm, total root length = 22.1 cm, total root volume = 1.8 cm^3, number of 2nd-order roots = 1 number of 3rd-order roots = 0

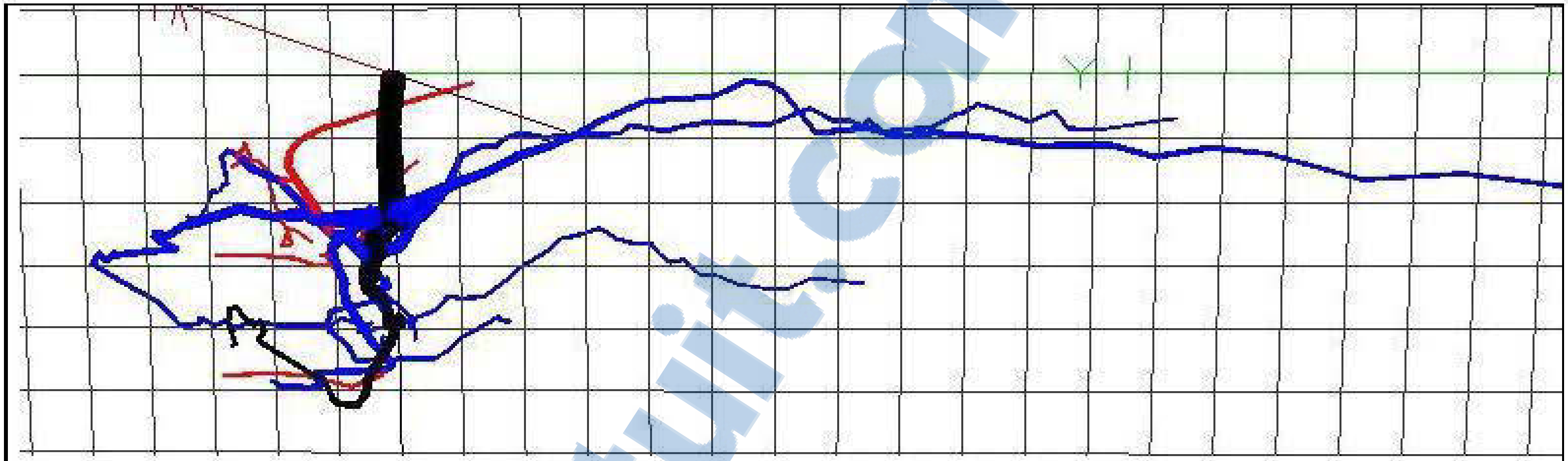
Black spruce



Control plot. Maximum root depth = 17.0 cm, maximum root radial extension = 68.0 cm, total root length = 411.9 cm, total root volume = 92.3 cm3, number of 2nd-order roots = 6, number of 3rd-order roots = 3.



Bluejoint treatment. Maximum root depth = 8.8 cm, maximum root radial extension = 19.7 cm, total root length = 124.5 cm, total root volume = 13.6 cm^3, number of 2nd-order roots = 6, number of 3rd-order roots = 1.



Sheep laurel treatment. Maximum root depth = 25.2 cm, maximum root radial extension = 113.7 cm, total root length = 7321.5 cm, total root volume = 153.9 cm^3, number of 2nd-order roots = 9, number of 3rd-order roots = 6.

Figure 2.8 Three-dimensional AMAPmod representations of root systems (side view) of target tree species excavated from the experimental plots at Les Terrains Aurifères site, Québec. The roots were coloured according to their category: black, first-order roots; blue, second-order roots; and red, third-order roots. Grid squares have 5-cm sides.

2.6 Discussion

2.6.1 Influence of bluejoint on above- and belowground growth of target trees

We measured high mortality and strong growth suppression of balsam poplar, willow, and black spruce in the plots that were colonized by bluejoint at the LTA site (Tables 2.2 to 2.4; Figure 2.5). Previous studies have reported that perennial grasses detrimentally affect tree seedlings by modifying environmental conditions (Balandier *et al.* 2006; Collet *et al.* 2006; Landhäusser *et al.* 2007). Interference competition for space with the bluejoint may be responsible for this substantial reduction in aboveground (growth increment, shoot biomass) and belowground structures (root and total biomass, maximum root depth, maximum root radial extension, total root length, total root volume, total number of 2nd- and 3rd-order roots) of the three TS. The dense sod that was formed by roots and rhizomes of bluejoint could represent a physical obstacle to root penetration and growth of the three TS (Landhäusser *et al.* 2007). Indeed, plant root growth decreases in dense substrates (Landhäusser *et al.* 1996). A detrimental effect of root biomass of bluejoint was observed for some of the root architectural characteristics of TS, viz., root ramification parameters of three TS and the root volume of black spruce. High bluejoint cover estimates (Table 2.1) on plots with TS also demonstrated that bluejoint is an aggressive competitor for space. Together with limiting root growing space, the presence of dense bluejoint roots could decrease aeration of and rainfall penetration into the soil (see Balandier *et al.* 2006). Plant growth may decrease if rooting space is physically restricted, regardless of the presence of abundant supplies of nutrients and water to the plant (Young et al. 1997, Schenk et al. 1999).

Direct resource competition for nutrients and water between TS and bluejoint could also occur and cause TS growth inhibition, since bluejoint is very nutrient-demanding (Landhäusser and Lieffers 1994; Hangs *et al.* 2003). Previous studies have frequently reported that grass-induced resource competition (mainly for water and nitrogen) decreased stem height and basal diameter, and leaf and root biomass of tree species (Collet *et al.* 1996; Landhäusser and Lieffers 1998; Coll *et al* 2004). Reductions in the biomass of roots, root system size and the number of roots (Collet *et al.* 2006), together with root extension rates and root length density (Ludovici and Morris 1996, 1997) of trees affected by grass competition were detected.

Shoot biomass of bluejoint (Table 2.1) exerted an adverse effect on shoot biomass of black spruce. Cover estimates of bluejoint in plots that contained deciduous trees and black spruce were > 80% and 60%, respectively. These responses suggest that bluejoint could have competed for light with TS, thereby further inhibiting their growth (Eis 1981). Survival and growth of black spruce was greater than for balsam poplar and willow in the bluejoint plots. These results are consistent with the findings of Messier *et al.* (2009), who showed that late-successional tree species are less affected by grass competition than early successional species, which require high levels of resources (e. g. light and nutrients) to maintain their fast rates of growth.

In addition, bluejoint litter has an insulating effect on the soil and contributes in maintaining cool soil temperatures throughout the growing season (Hogg and Lieffers 1991; Landhäusser *et al.* 2006), which is known to detrimentally affect tree seedling growth (Tryon an Chapin 1983). Direct allelopathic effects (release of allelochemicals) have been reported for other graminoid species (Jobidon *et al.* 1989; Winder and Macey 2001). However, allelopathic interference by bluejoint, if present, was unlikely to be the sole cause of high tree mortality and strong inhibition of tree seedling growth in this study. Production of chemical compounds by the BBS was beyond the scope of this study, but some measurements (Smirnova *et al.,* unpublished results) were performed that confirmed no significant allelochemical release by bluejoint reedgrass into the test plots.

2.6.2 Influence of sheep laurel on above- and belowground growth of target trees

Earlier studies have reported a strong inhibitory effect of sheep laurel on tree seedling growth in both natural ecosystems and in experimental field manipulations (Titus *et al.* 1995; Inderjit and Mallik 2002; Thiffault *et al.* 2004; LeBel *et al.* 2008). In our study, the effects of sheep laurel on growth of the TS were tested solely under experimental conditions at the LTA site. Target tree species showed high survival and adaptation capacity to site conditions, whereas sheep laurel had to be planted several times in the experimental plots due to high mortality during the first growing season (2008). Thus, sheep laurel likely suffered high stress levels from transplantation into the site. Sheep laurel is more vigorous (greater plant height, leaf area and specific leaf area) under partial shade conditions, compared to open sites (Mallik 1994, Mallik *et al.* 2012). The LTA is an open site that is subject to direct insolation and strong winds. Soil temperature was measured in the experimental plots (control and sheep laurel plots) in a parallel study (Smirnova *et al.* 2012); soil temperature at a depth of 10 cm varied between 16.0 and 19.5℃ during the vegetative season at the LTA site. In comparison, in nearby black spruce and trembling aspen stands, average soil temperature was 13.4 ± 1.5℃ (Fréchette *et al.* 2011). Thus, microclimatic conditions at the LTA site did not contribute to successful growth of sheep laurel. At the end of the experiment, the density of sheep laurel in the sample plots was relatively low (on average, < 20% of sheep laurel cover in plots with balsam poplar and willow; 24% in black spruce plots; see Table 2.1). This likely resulted in small surface accumulations of leaf litter, which is recognized as a major source of allelochemicals (see review by Reigosa *et al.* 1999). In comparison, Mallik *et al.* (2012) reported that sheep laurel cover measured in black spruce forest in Newfoundland was > 34.5 ± 9.0% in open sites, 44.0 ± 14.3% under low shade conditions, 34.5 ± 6.0% in medium shade, and 36.6 ± 9.5% in deep shade sites. In the present study, the level of allelopathic compounds that were produced by sheep laurel was probably too low to exert measurable phytotoxic effects. This assumption is reinforced by the work of Smirnova *et al.* (unpublished results), who reported that sheep laurel produced polyphenols at a lower concentrations in the LTA site than was reported by Joanisse *et al.* (2009) in natural boreal forest stands.

Previous studies have revealed that plant root system development is altered in the presence of neighbouring plant species (Nord *et al.* 2011; Fang *et al.* 2013) in order to maximize their growth (Gersani *et al.* 2001). In our experiment, stem height and basal diameter increment, together with the shoot, root, and total dry mass of balsam poplar, was enhanced in the presence of sheep laurel. This effect is assumed to be the result of optimization in root growth. Balsam poplar adjusted its root growth in the presence of sheep laurel by increasing vertical growth of coarse roots, root ramification (number of 2nd-order roots), and root volume. These results are consistent with Nord *et al.* (2011), who found that the presence of neighbours can stimulate plants to produce fewer roots in the uppermost soil layers and more roots in the subsoil layers that are free of competitor roots, to place fewer roots in soil patches near roots of neighbours, and to increase root length. Hence, balsam poplar appears to have minimized resource competition with sheep laurel by producing more roots below the zones of sheep laurel root proliferation. A deeper root system with greater ramification possibly allowed the balsam poplar to better explore available growth space and improve its resource capture (mainly water), thereby improving aboveground growth in presence of neighbouring sheep laurel.

Although they are in the same family (*Salicaceae*), willow and balsam poplar have adopted different plant growth forms, i.e., shrubs and trees, which responded in different ways to the presence of sheep laurel. The presence of sheep laurel had no effect on the growth of willow. Neutral responses of willow might be attributable to its well-developed fine root system (Rytter and Rytter 1998; Rytter 1999), which allowed nutrient and water uptake without altering root system architecture in the plots containing sheep laurel.

The root systems of shrubs tend to be shallower in dry conditions and spread laterally, whereas trees have vertical root systems that are strongly developed downwards (Schenk and Jackson 2002). Our results support this idea, as a similar trend was observed in the two zones at the LTA site. Willow shrubs produced roots that were deeper in the wet zone, compared to the dry one. Balsam poplar had more shallowly developed roots in the wet zone. This response is likely to be an adaptive response of different plant growth forms to survive in water-limited conditions. The roots of willow need an abundant and continuous water supply (Pitcher and McKnight 1990); therefore, willow mainly used rainfall that infiltrated the upper soil layers of the dry zone. Greater depth penetration of balsam poplar roots in the dry zone gave them access to moisture reserves in deeper soil layers.

Black spruce also showed good potential for minimizing resource competition when grown in the plots with sheep laurel. All parameters that were measured for black spruce, i.e., stem height and basal diameter increment, biomass (root, shoot, total), and root architecture characteristics, increased in the presence of sheep laurel, relative to the control, except for the root-to-shoot ratio and the number of 2nd-order roots. In addition, we observed that sheep laurel and black spruce that were grown at the LTA site were both colonized by common dark septate endophyte (DSE), *Phialocephala fortinii* Wang and Wilcox (Appendix M). The presence of this endophyte indicates that sheep laurel, which had been transplanted earlier to LTA site from its natural habitat, might share symbionts with black spruce that stimulated the latter's growth. To date, the role of DSE in natural ecosystems is poorly defined (see Jumpponen 2001). However, the enhanced growth of gymnosperm plant species that were colonized by *Phialocephala fortinii* has been reported (Jumpponen and Trappe 1998; Alberton *et al.* 2010; Newsham 2011). Microbiological analyses that were performed on the roots of balsam poplar and willow did not reveal the presence of DSE (unpublished data).

2.7 Conclusion

A multilayered cover system was demonstrated to be a technically feasible and effective mining site reclamation method, which could be used to restrict oxygen flux into spoil materials and eliminate acid generation over the short-term (Ricard *et al.* 1997; Dagenais *et al.* 2005; Bussière *et al.* 2006). The risks that were associated with rapid and uncontrolled establishment of vegetation on CCBE (Trépanier *et al.* 2006) provided the impetus for developing this experimental study, which was aimed at improving long-term CCBE efficiency. We tested whether an ecological approach that was based on BBS could be used as a countermeasure for controlling tree invasion onto CCBE. In this study, tree root system architecture was emphasized. This unique experimental study quantified root development of balsam poplar, willow, and black spruce on a tailings impoundment that had been rehabilitated using a CCBE.

Our results showed that bluejoint is a more efficient BBS than sheep laurel. They suggest that strong suppression of above- and belowground growth of three TS by bluejoint was achieved mainly through competition (Landhäusser and Lieffers 1998; Hangs *et al.* 2003; Balandier *et al.* 2006). Allelopathic potential of sheep laurel (Yamasaki *et al.* 1998; Joanisse *et al.* 2007) was not detected at the LTA site over the 2009-2012 experimental periods. Moreover, enhanced growth of balsam poplar and black spruce was observed when trees grew with sheep laurel. Low competitiveness and phytotoxic activity of sheep laurel could be explained by its low density and the stress that is incurred in transplantation to the site. Although sheep laurel was not demonstrated to be an appropriate BBS in this experiment, data related to root adjustments that were made by the trees in the presence of this ericaceous species on the CCBE are unique. From these data, we can conclude that trees exhibited a high degree of root system plasticity that optimized their growth when they were grown with roots of neighbouring species. Increased root biomass allocation relative to shoots has been frequently reported regarding conditions of belowground competition and water stress (Chapin *et al.* 1987; Haynes and Gower 1995; Donaldson *et al.* 2006; Murphy and Dudley 2007), but this response was not detected in our study. In contrast, alterations to root system architecture was found to be the primary response of trees growing in the presence of neighbouring plant roots (Lynch and Ho 2005; Nord *et al.* 2011; Fang *et al.* 2013).With respect to future research, efforts should be oriented towards testing whether it is possible to improve the establishment and growth of sheep laurel on CCBE. It could be preferable to introduce various allelopathic BBS, such as *Rhododendron groenlandicum* (Oeder) Kron & Judd (Inderjit and Mallik 1997), onto the CCBE to increase the heterogeneity of the plant cover as well as its biodiversity.

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CHAPTER III

GENERAL CONCLUSION AND RESEARCH PERSPECTIVES

3.1 Summary and conclusion

In Québec, mining tailings accumulation areas must be rehabilitated to protect the environment from AMD production (MRN 2014). Covers with capillary barrier effects are recognized as one of the most effective engineered methods to rehabilitate AMD generating mining sites (Dagenais *et al.* 2005; Bussière *et al.* 2006). Nevertheless, the rapid establishment of tree species and shrubs on CCBEs was a cause of concern since uncontrolled vegetation can reduce long-term CCBE efficiency (Trépanier *et al.* 2006; Smirnova *et al.* 2009). This project was developed to improve the ability of CCBEs to control AMD production. The main objective of this study was to introduce two native species with potential allelopathic effects (bluejoint and sheep laurel) at the LTA tailings impoundment, which was rehabilitated with a CCBE in order to test whether these species can be used as effective BBS that are able to impede the growth of undesirable TS (balsam poplar, willow, and black spruce).

The assessment of TS growth in the presence of the BBS (compared to the control plots) was performed based on changes in TS growth increment over the experimental period (2009 -2012 for the bluejoint and 2011 - 2012 for sheep laurel plots), biomass (shoot, root, and total), root-to-shoot ratio, and root system architecture parameters. The effects of BBS biomass on TS characteristics was also tested (except for the growth increment data). In total, 192 TS were involved in this investigation. A method of three-dimensional root digitizing allowed us to obtain precise data concerning topological and geometrical structures of TS coarse root systems (Danjon and Reubens 2008). To succeed in digitizing them, TS root systems had to be completely excavated in order to be touched by a hand-held receiver and then, the data sets that were obtained from the digitizing had to be processed with AMAPmod software (Godin *et al.* 1997; Danjon *et al.* 1999a) for subsequent calculations of TS root architecture parameters. In fact, the part of this project that was dedicated to TS root architecture was time-consuming and contained at least 4 steps: root excavation, root system digitizing, root analysis with AMAPmod software and finally, statistical analysis in order to evaluate whether there was BBS effect on root characteristics of TS. It was very important to assess whether there were some changes in TS root system architecture in the BBS plots because: (1) TS roots were recognized as a particular threat to CCBE performance (USDOE 1990; Handel *et al.* 1997; Hutchings 2001); (2) root system architecture has been proven to be a critical factor in plant survival and growth (López-Bucio *et al.* 2003). Several root characteristics were assessed from the root analysis: maximum root depth and root radial extension, total root length and volume, number of 2^{nd}-and 3^{d}-order roots.

In this study, bluejoint was shown to be an efficient BBS. It took bluejoint one year to cause high tree seedling mortality and a strong inhibiting effect on above-and belowground structures of surviving TS (Tables 2.2 – 2.4, Figure 2.5). Detrimental effects of bluejoint on TS growth was mainly caused through competition (interference competition for space, resource competition) (Landhäusser and Lieffers 1998; Hangs *et al.* 2003; Balandier *et al.* 2006).

Strong allelopathic potential of sheep laurel (Yamasaki *et al.* 1998; Joanisse *et al.* 2007) was not demonstrated in this study. Moreover, our experiment showed improved growth of balsam poplar and black spruce in the sheep laurel plots (Figures 2.6 and 2.7, Tables 2.4). In the case of black spruce, sheep laurel shared with this tree species a representative of DSE (*Phialocephala fortinii*) that potentially contributed to spruce growth (Appendix M). Although ecological conditions on the CCBE promote the natural establishment of some plant species (Smirnova *et al.* 2011), sheep laurel, being transplanted from its natural habitat, had an adaptation stress to the LTA site conditions. This adaptation stress led to low competitive and phytotoxic activities of sheep laurel. Thus, it is likely that the substrate that was added to the LTA site was not appropriate and probably too rich for optimal growth and high allelochemicals production of sheep laurel. Sheep laurel grows abundantly on nutrient-poor to medium quality boreal forest (Titus *et al.* 1995). Sites colonized by sheep laurel in Newfoundland were characterized by high soil acidity (pH 2.8 to 4.5), and phytotoxic effect of sheep laurel on plants growth (especially on their roots) in laboratory conditions was higher at soil pH 3.0 (Zhu and Mallik 1994).

We detected no increase in root-to-shoot ratio of the three TS in the BBS plots. An increased biomass allocation to TS roots was expected as a response to competition caused by BBS

(Cannell 1985; Chapin *et al.* 1987; Schenk and Jackson 2002; Mokany *et al.* 2006). However, root system architecture of TS was substantially altered in the presence of BBS (except for willows that were grown with sheep laurel). Results from this study demonstrated that the TS root architecture adjustment plays a greater role in belowground competition responses than previously thought. Alteration of root architecture of tree species in response to neighbouring plants may probably reduce belowground competition and represents a greater plasticity than changes in biomass allocation (Lynch and Ho 2005; Nord *et al.* 2011; Fang *et al.* 2013). It is more likely that the primary response of plant species to the presence of neighbouring plants is an adjustment of root architecture rather the reallocate plant biomass (Nord *et al.* 2011).

3.2 Avenues for future research

Bluejoint has proved its potential as a BBS on the CCBE, but monospecific planting in large areas, such as LTA site (60 ha), is not a good option in terms of biodiversity conversation in the boreal zone. To achieve a successful restoration, care should be taken not only to control pollution, but also to maintain the ecological stability of the ecosystem that is artificially created on mining sites (Bradshaw 1997; Cooke and Johnson 2002). It might be a better solution to introduce various BBS onto the CCBE to increase the species richness. The combinations of patches that are made of various plants can increase the heterogeneity of plant cover on the CCBE, thereby maximizing the ecological sustainability of the rehabilitated area and increase social acceptability.

Generally, this study demonstrated that the use of a natural mechanism (at least competition) can be a promising method for mining site restoration in a CCBE context. Although, the experiment with sheep laurel did not prove our expectations, this study allowed us to obtain unique data concerning root behaviour in the presence of neighbouring BBS on the existing CCBE. Additional investigations can be performed to develop the option to use allelopathic species as BBS. Investigations can also be extended for other representatives of ericaceous plants, such as Labrador tea (*Rhododendron groenlandicum* (Oeder) Kron & Judd) (Inderjit and Mallik 1997b). Efforts can be directed to improve the establishment of ericaceous plants on the CCBE. It might be interesting to verify whether some associated species can improve ericaceous plant adaptation and growth in the relatively harsh environmental conditions that are presented on the CCBE. It could be also appropriate to investigate what kind of substrate and planting density contribute to the establishment of ericaceous plants on the CCBE. Further studies that could be devoted to introducing the ericaceous plants on the CCBE should include biochemical analyses of the soil and different plants parts to evaluate the production of phytotoxins by allelopathic species. More microbiological analyses should be done on the presence of mutualistic microorganisms on the root hairs of both undesirable tree species and ericaceous plants. To evaluate more precisely belowground competition for space between BBS and TS, other explanatory variables could be involved in statistical analysis, for example BBS root density and root surface area (Casper and Jackson 1997).

More investigations could also be done to prevent the germination of seeds of undesirable plant species on the CCBE. It would be interesting to know whether allelopathic and/ or highly competitive species can be used as BBS against tree seed germination. Also, it could be important to conduct long-term investigations to obtain detailed information on how long BBS can delay the growth and seed germination of undesirable vegetation.

Another question is whether tree growth retardants can be effective to hinder seed germination and tree species growth on the CCBE. However, the method of using growth retardants can have a disadvantage of being not environmentally safe. All advantages and drawbacks of mine restoration methods should be accounted because the restoration needs to be achieved as effectively and as cheaply as possible (Cooke and Johnson 2002).

APPENDIX A

ROOT EXCAVATION AT LES TERRAINS AURIFÈRES SITE, QUÉBEC


B2
P15 KALMIA
7.08.12


BLOCK5
P13 KALMIA
8.08.12

APPENDIX B

ROOT DIGITIZING AT THE LAC DUPARQUET RESEARCH STATION OF UQAT

Symbols were used at the pictures:

B - block number;

Target tree species: **P** - balsam poplar, **W** - willow, and **S** - black spruce;

Treatment: **C** - control, **K** - sheep laurel (*Kalmia*), and **G** - bluejoint (*Gramineae*)


B4W5K


B4W4G


B1S9C


B3S9K
23.08.12


B5S6G

APPENDIX C

SUMMARY OF LINEAR MIXED EFFECTS MODELS SELECTION BASED ON AIC$_C$ FOR ONE-YEAR STEM HEIGHT AND BASAL DIAMETER INCREMENT OF TARGET TREE SPECIES IN RESPONSE TO THE BLUEJOINT TREATMENT AT LES TERRAINS AURIFÈRES SITE, QUÉBEC

Candidate models	K[1]	AIC$_c$	Δ AIC$_c$	AIC$_c$ Wt[2]
I. Stem height of balsam poplar				
Zone + Bluejoint	6	41.56	0.00	1.00
Zone + Bluejoint + Zone × Bluejoint	7	71.50	29.94	0.00
II. Basal diameter of balsam poplar				
Zone + Bluejoint	6	15.76	0.00	1.00
Zone + Bluejoint + Zone × Bluejoint	7	44.59	28.84	0.00
III. Stem height of willow				
Zone + Bluejoint	6	79.63	0.00	1.00
Zone + Bluejoint + Zone × Bluejoint	7	97.85	18.22	0.00
IV. Basal diameter of willow				
Zone + Bluejoint	6	6.62	0.00	1.00
Zone + Bluejoint + Zone × Bluejoint	7	22.46	15.84	0.00
V. Stem height of black spruce				
Zone + Bluejoint	6	87.32	0.00	1.00
Zone + Bluejoint + Zone × Bluejoint	7	103.70	16.39	0.00
VI. Basal diameter of black spruce				
Zone + Bluejoint	6	-6.05	0.00	1.00
Zone + Bluejoint + Zone × Bluejoint	7	12.18	18.24	0.00

Notes. [1]Number of estimated parameters, [2]Akaike weights

APPENDIX D

PARAMETER ESTIMATES FOR ONE-YEAR STEM HEIGHT AND BASAL DIAMETER INCREMENT OF TARGET TREE SPECIES IN RESPONSE TO THE BLUEJOINT TREATMENT AT LES TERRAINS AURIFÈRES SITE, QUÉBEC.

Response variable	Explanatory variable	Estimate	SE	Lower 95% CI	Upper 95% CI
I. Balsam poplar					
Height increment	Wet zone	**-0.51**	0.17	**-0.84**	**-0.18**
	Bluejoint	**-2.9**	0.17	**-3.23**	**-2.57**
Diameter increment	Wet zone	-0.01	0.05	-0.1	0.08
	Bluejoint	**-0.16**	0.05	**-0.25**	**-0.07**
II. Willow					
Height increment	Wet zone	1.68	1.29	-0.84	4.21
	Bluejoint	**-5.65**	1.16	**-7.93**	**-3.37**
Diameter increment	Wet zone	-0.03	0.04	-0.11	0.06
	Bluejoint	**-0.13**	0.04	**-0.21**	**-0.04**
III. Black spruce					
Height increment	Wet zone	-0.74	1.74	-4.15	2.67
	Bluejoint	**-3.59**	1.74	**-7**	**-0.18**
Diameter increment	Wet zone	0.04	0.03	-0.01	0.09
	Bluejoint	**-0.17**	0.02	**-0.22**	**-0.13**

Notes. The reference levels in the mixed model were dry zone and control plot. The values in boldface type signify that 95% unconditional confidence interval for a given parameter excludes zero

APPENDIX E

SUMMARY OF LINEAR MIXED EFFECTS MODELS SELECTION BASED ON AIC$_C$ FOR THREE-YEAR STEM HEIGHT AND BASAL DIAMETER INCREMENT OF TARGET TREE SPECIES IN RESPONSE TO THE SHEEP LAUREL TREATMENT AT LES TERRAINS AURIFÈRES SITE, QUÉBEC

Candidate models	K[1]	AIC$_c$	Δ AIC$_c$	AIC$_c$ Wt[2]
I. Stem height of balsam poplar				
Zone + Sheep laurel	6	40.81	0.00	1.00
Zone + Sheep laurel + Zone × Sheep laurel	7	53.20	12.39	0.00
II. Basal diameter of balsam poplar				
Zone + Sheep laurel	6	34.36	0.00	1.00
Zone + Sheep laurel + Zone × Sheep laurel	7	46.89	12.53	0.00
III. Stem height of willow				
Zone + Sheep laurel	6	32.84	0.00	0.99
Zone + Sheep laurel + Zone × Sheep laurel	7	41.52	8.68	0.01
IV. Basal diameter of willow				
Zone + Sheep laurel	6	29.64	0.00	0.89
Zone + Sheep laurel + Zone × Sheep laurel	7	33.80	4.17	0.11
V. Stem height of black spruce				
Zone + Sheep laurel	6	38.54	0.00	1.00
Zone + Sheep laurel + Zone × Sheep laurel	7	51.71	13.17	0.00
VI. Basal diameter of black spruce				
Zone + Sheep laurel	6	25.27	0.00	1.00
Zone + Sheep laurel + Zone × Sheep laurel	7	38.21	12.94	0.00

Notes. [1] Number of estimated parameters, [2] Akaike weights

APPENDIX F

PARAMETER ESTIMATES FOR THREE-YEAR STEM HEIGHT AND BASAL DIAMETER INCREMENT OF TARGET TREE SPECIES IN RESPONSE TO THE SHEEP LAUREL TREATMENT AT LES TERRAINS AURIFÈRES SITE, QUÉBEC.

Response variable	Explanatory variable	Estimate	SE	Lower 95% CI	Upper 95% CI
I. Balsam poplar					
Height increment	Wet zone	-0.30	0.26	-0.81	0.21
	Sheep laurel	0.48	0.20	**0.08**	**0.88**
Diameter increment	Wet zone	0.10	0.19	-0.27	0.46
	Sheep laurel	0.48	0.17	**0.15**	**0.80**
II. Willow					
Height increment	Wet zone	-0.02	0.17	-0.34	0.31
	Sheep laurel	0.15	0.17	-0.17	0.48
Diameter increment	Wet zone	-0.04	0.14	-0.32	0.24
	Sheep laurel	-0.02	0.14	-0.30	0.26
III. Black spruce					
Height increment	Wet zone	-0.02	0.27	-0.54	0.50
	Sheep laurel	0.84	0.16	**0.52**	**1.16**
Diameter increment	Wet zone	-0.02	0.12	-0.26	0.21
	Sheep laurel	0.29	0.12	**0.05**	**0.52**

Notes. The reference levels in the mixed model were dry zone and control plot. The values in boldface type signify that 95% unconditional confidence interval for a given parameter excludes zero

APPENDIX G

SUMMARY OF LINEAR MIXED EFFECTS MODELS SELECTION BASED ON AIC$_C$ FOR ROOT, SHOOT AND TOTAL DRY MASS, ROOT-TO-SHOOT RATIOS OF TARGET TREE SPECIES IN RESPONSE TO THE BLUEJOINT TREATMENT AT LES TERRAINS AURIFÈRES SITE, QUÉBEC

Candidate models	K[1]	AIC$_c$	Δ AIC$_c$	AIC$_c$ Wt[2]
I. Shoot dry mass of balsam poplar				
Zone + Bluejoint	6	39.55	0	0.99
Zone + Shoot dry mass of bluejoint	6	49.46	9.91	0.01
Zone + Bluejoint + Zone × Bluejoint	7	50.23	10.68	0
Zone + Total dry mass of bluejoint	6	52.88	13.33	0
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	53.77	14.22	0
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	58.85	19.3	0
Zone + Root dry mass of bluejoint	6	60.04	20.49	0
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	72.5	32.95	0
II. Root dry mass of balsam poplar				
Zone + Bluejoint	6	43.03	0	0.82
Zone + Shoot dry mass of bluejoint	6	47.18	4.15	0.1
Zone + Total dry mass of bluejoint	6	47.83	4.79	0.07
Zone + Root dry mass of bluejoint	6	55.34	12.3	0
Zone + Bluejoint + Zone × Bluejoint	7	55.76	12.73	0
Zone + Shoot dry mass of bluejoint + Zone ×Shoot dry mass of bluejoint	7	56.42	13.39	0
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	56.66	13.63	0
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	68.33	25.29	0

Candidate models	K[1]	AIC_c	$\Delta\ \text{AIC}_c$	AIC_c Wt[2]
III. Total dry mass of balsam poplar				
Zone + Bluejoint	6	39.08	0	0.98
Zone + Shoot dry mass of bluejoint	6	47.85	8.77	0.01
Zone + Bluejoint + Zone × Bluejoint	7	50.45	11.37	0
Zone + Total dry mass of bluejoint	6	50.46	11.38	
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	53.88	14.8	0
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	57.42	18.34	0
Zone + Root dry mass of bluejoint	6	57.94	18.86	0
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	70.57	31.5	0
IV. Root-to-shoot ratio of balsam poplar				
Zone + Root dry mass of bluejoint	6	33.2	0	0.32
Zone + Bluejoint	6	33.72	0.51	0.25
Zone + Total dry mass of bluejoint	6	33.95	0.75	0.22
Zone + Shoot dry mass of bluejoint	6	34.03	0.83	0.21
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	44.4	11.19	0
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	44.61	11.41	0
Zone + Above biomass of Reedgrass + Zone × Total dry mass of bluejoint	7	44.69	11.49	0
Zone + Bluejoint + Zone × Bluejoint	7	46.04	12.83	0
V. Shoot dry mass of willow				
Zone + Bluejoint	6	51.14	0.00	0.91
Zone + Total dry mass of bluejoint	6	57.96	6.82	0.03
Zone + Root dry mass of bluejoint	6	58.19	7.04	0.03
Zone + Shoot dry mass of bluejoint	6	58.24	7.10	0.03
Zone + Bluejoint + Zone × Bluejoint	7	64.34	13.19	0.00
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	65.70	14.55	0.00
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	67.41	16.26	0.00
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	70.53	19.38	0.00

Candidate models	K[1]	AIC$_c$	Δ AIC$_c$	AIC$_c$ Wt[2]
VI. Root dry mass of willow				
Zone + Bluejoint	6	53.78	0.00	0.97
Zone + Total dry mass of bluejoint	6	62.90	9.13	0.01
Zone + Shoot dry mass of bluejoint	6	63.05	9.27	0.01
Zone + Root dry mass of bluejoint	6	63.30	9.53	0.01
Zone + Bluejoint + Zone × Bluejoint	7	66.96	13.18	0.00
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	71.09	17.32	0.00
Zone + Total dry mass b of Reedgrass + Zone × Total dry mass of bluejoint	7	72.78	19.00	0.00
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	75.65	21.87	0.00
VII. Total dry mass of willow				
Zone + Bluejoint	6	51.83	0	0.95
Zone + Total dry mass of bluejoint	6	59.89	8.06	0.02
Zone + Shoot dry mass of bluejoint	6	60.09	8.26	0.02
Zone + Root dry mass of bluejoint	6	60.23	8.4	0.01
Zone + Bluejoint + Zone × Bluejoint	7	65.01	13.19	0
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	67.77	15.94	0
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	69.54	17.71	0
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	72.62	20.79	0
VIII. Root-to-shoot ratio of willow				
Zone + Root dry mass of bluejoint	6	33.36	0.00	0.27
Zone + Bluejoint	6	33.46	0.10	0.25
Zone + Total dry mass of bluejoint	6	33.59	0.23	0.24
Zone + Shoot dry mass of bluejoint	6	33.62	0.26	0.24
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	44.91	11.54	0.00
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	45.10	11.74	0.00
Zone + Bluejoint + Zone × Bluejoint	7	45.17	11.81	0.00
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	45.45	12.09	0.00

Candidate models	K^1	AIC_c	Δ AIC_c	AIC_c Wt^2
IX. Shoot dry mass of black spruce				
Zone + Shoot dry mass of bluejoint	6	39.70	0.00	0.34
Zone + Total dry mass of bluejoint	6	39.83	0.12	0.32
Zone + Bluejoint	6	40.34	0.64	0.25
Zone + Root dry mass of bluejoint	6	42.70	3.00	0.08
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	50.47	10.77	0.00
Zone + Bluejoint + Zone × Bluejoint	7	50.56	10.86	0.00
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	52.07	12.37	0.00
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	55.46	15.75	0.00
X. Root dry mass of black spruce				
Zone + Bluejoint	6	44.99	0.00	0.42
Zone + Shoot dry mass of bluejoint	6	46.16	1.16	0.24
Zone + Total dry mass of bluejoint	6	46.46	1.46	0.20
Zone + Root dry mass of bluejoint	6	48.36	3.37	0.08
Zone + Bluejoint + Zone × Bluejoint	7	49.17	4.17	0.05
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	54.83	9.84	0.00
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	57.06	12.07	0.00
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	59.94	14.95	0.00
XI. Total dry mass of black spruce				
Zone + Shoot dry mass of bluejoint	6	40.97	0.00	0.32
Zone + Bluejoint	6	41.05	0.09	0.31
Zone + Total dry mass of bluejoint	6	41.16	0.19	0.29
Zone + Root dry mass of bluejoint	6	43.78	2.82	0.08
Zone + Bluejoint + Zone × Bluejoint	7	50.17	9.20	0.00
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	51.24	10.27	0.00
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	53.07	12.10	0.00
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	56.30	15.33	0.00

Candidate models	K[1]	AIC$_c$	Δ AIC$_c$	AIC$_c$ Wt[2]
XII. Root-to-shoot ratio of black spruce				
Zone + Root dry mass of bluejoint	6	20.66	0.00	0.27
Zone + Bluejoint	6	20.85	0.19	0.25
Zone + Total dry mass of bluejoint	6	20.99	0.32	0.23
Zone + Shoot dry mass of bluejoint	6	21.16	0.50	0.21
Zone + Bluejoint + Zone × Bluejoint	7	26.14	5.47	0.02
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	26.75	6.09	0.01
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	28.03	7.37	0.01
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	29.43	8.77	0.00

Notes. [1]Number of estimated parameters, [2] Akaike weights

APPENDIX H

SUMMARY OF LINEAR MIXED EFFECTS MODELS SELECTION BASED ON AIC$_C$ FOR ROOT, SHOOT, TOTAL DRY MASS AND ROOT-TO-SHOOT RATIOS OF TARGET TREE SPECIES IN RESPONSE TO THE SHEEP LAUREL TREATMENT AT LES TERRAINS AURIFÈRES SITE, QUÉBEC

Candidate models	K^1	AIC$_c$	Δ AIC$_c$	AIC$_c$ Wt^2
I. Shoot dry mass of balsam poplar				
Zone + Sheep laurel	6	39.84	0.00	0.31
Zone + Shoot dry mass of sheep laurel	6	40.25	0.40	0.25
Zone + Total dry mass of sheep laurel	6	40.32	0.47	0.24
Zone + Root dry mass of sheep laurel	6	40.82	0.98	0.19
Zone + Sheep laurel + Zone × Sheep laurel	7	52.25	12.41	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	53.18	13.34	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	53.30	13.46	0.00
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	53.43	13.59	0.00
II. Root dry mass of balsam poplar				
Zone + Sheep laurel	6	39.32	0.00	0.33
Zone + Root dry mass of sheep laurel	6	40.02	0.70	0.23
Zone + Total dry mass of sheep laurel	6	40.05	0.74	0.23
Zone + Shoot dry mass of sheep laurel	6	40.27	0.95	0.21
Zone + Sheep laurel + Zone × Sheep laurel	7	51.62	12.30	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	52.79	13.48	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	53.19	13.88	0.00
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	53.47	14.15	0.00

Candidate models	K[1]	AIC$_c$	Δ AIC$_c$	AIC$_c$ Wt[2]
III. Total dry mass of balsam poplar				
Zone + Sheep laurel	6	39.22	0.00	0.33
Zone + Total dry mass of sheep laurel	6	39.87	0.64	0.24
Zone + Shoot dry mass of sheep laurel	6	39.92	0.70	0.23
Zone + Root dry mass of sheep laurel	6	40.16	0.93	0.20
Zone + Sheep laurel + Zone × Sheep laurel	7	51.57	12.35	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	52.67	13.44	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	52.92	13.70	0.00
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	53.12	13.89	0.00
IV. Root-to-shoot ratio of balsam poplar				
Zone + Total dry mass of sheep laurel	6	0.01	0.00	0.29
Zone + Root dry mass of sheep laurel	6	0.06	0.06	0.28
Zone + Shoot dry mass of sheep laurel	6	0.07	0.06	0.28
Zone + Sheep laurel	6	1.34	1.33	0.15
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	13.14	13.13	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	13.15	13.14	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	13.22	13.21	0.00
Zone + Sheep laurel + Zone × Sheep laurel	7	14.47	14.46	0.00
V. Shoot dry mass of willow				
Zone + Sheep laurel	6	42.54	0.00	0.43
Zone + Shoot dry mass of sheep laurel	6	43.46	0.92	0.27
Zone + Total dry mass of sheep laurel	6	44.35	1.81	0.17
Zone + Root dry mass of sheep laurel	6	44.95	2.41	0.13
Zone + Sheep laurel + Zone × Sheep laurel	7	53.27	10.73	0.00
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	56.57	14.03	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	57.31	14.77	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	57.65	15.11	0.00

Candidate models	K^1	AIC_c	Δ AIC_c	AIC_c Wt^2
VI. Root dry mass of willow				
Zone + Sheep laurel	6	35.53	0.00	0.45
Zone + Shoot dry mass of sheep laurel	6	36.56	1.02	0.27
Zone + Total dry mass of sheep laurel	6	37.60	2.06	0.16
Zone + Root dry mass of sheep laurel	6	38.37	2.84	0.11
Zone + Sheep laurel + Zone × Sheep laurel	7	42.19	6.66	0.02
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	49.11	13.57	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	49.95	14.41	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	50.40	14.86	0.00
VII. Total dry mass of willow				
Zone + Sheep laurel	6	39.47	0.00	0.43
Zone + Shoot dry mass of sheep laurel	6	40.40	0.92	0.92
Zone + Total dry mass of sheep laurel	6	41.36	1.89	0.17
Zone + Root dry mass of sheep laurel	6	41.98	2.51	0.12
Zone + Sheep laurel + Zone × Sheep laurel	7	49.16	9.68	0.00
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	53.41	13.94	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	54.14	14.67	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	54.41	14.93	0.00
VIII. Root-to-shoot ratio of willow				
Zone + Shoot dry mass of sheep laurel	6	25.01	0.00	0.41
Zone + Total dry mass of sheep laurel	6	25.35	0.34	0.35
Zone + Root dry mass of sheep laurel	6	26.68	0.18	0.18
Zone + Sheep laurel	6	28.67	0.07	0.07
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	38.19	0.00	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	38.34	0.00	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	38.78	0.00	0.00
Zone + Sheep laurel + Zone × Sheep laurel	7	41.87	0.00	0.00

Candidate models	K[1]	AIC_c	Δ AIC_c	AIC_c Wt[2]
IX. Shoot dry mass of black spruce				
Zone + Sheep laurel	6	35.68	0.00	0.43
Zone + Total dry mass of sheep laurel	6	37.13	1.45	0.21
Zone + Root dry mass of sheep laurel	6	37.34	1.66	0.19
Zone + Shoot dry mass of sheep laurel	6	37.45	1.78	0.18
Zone + Sheep laurel + Zone × Sheep laurel	7	48.87	13.20	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	50.32	14.64	0.00
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	50.50	14.82	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	50.50	14.82	0.00
X. Root dry mass of black spruce				
Zone + Sheep laurel	6	40.01	0.00	0.33
Zone + Root dry mass of sheep laurel	6	40.23	0.22	0.29
Zone + Total dry mass of sheep laurel	6	40.83	0.83	0.22
Zone + Shoot dry mass of sheep laurel	6	41.45	1.44	0.16
Zone + Sheep laurel + Zone × Sheep laurel	7	53.15	13.14	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	53.41	13.41	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	53.73	13.73	0.00
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	54.02	14.01	0.00
XI. Total dry mass of black spruce				
Zone + Sheep laurel	6	36.44	0.00	0.41
Zone + Total dry mass of sheep laurel	6	37.77	1.32	0.21
Zone + Root dry mass of sheep laurel	6	37.79	1.35	0.21
Zone + Shoot dry mass of sheep laurel	6	38.17	1.73	0.17
Zone + Sheep laurel + Zone × Sheep laurel	7	49.63	13.19	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	50.97	14.53	0.00
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	51.14	14.69	0.00

Candidate models	K^1	AIC$_c$	Δ AIC$_c$	AIC$_c$ Wt^2
XII. Root-to-shoot ratio of black spruce				
Zone + Root dry mass of sheep laurel	6	18.97	0.00	0.25
Zone + Total dry mass of sheep laurel	6	18.97	0.00	0.25
Zone + Shoot dry mass of sheep laurel	6	18.98	0.01	0.25
Zone + Sheep laurel	6	19.08	0.11	0.24
Zone + Sheep laurel + Zone × Sheep laurel	7	31.03	12.06	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	31.57	12.60	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	31.58	12.61	0.00
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	31.64	12.67	0.00

Notes. [1]Number of estimated parameters, [2]Akaike weights

APPENDIX I

PARAMETER ESTIMATES FOR ROOT, SHOOT, TOTAL DRY MASS, AND ROOT-TO-SHOOT RATIOS OF TARGET TREE SPECIES IN RESPONSE TO THE SHEEP LAUREL TREATMENT AT LES TERRAINS AURIFÈRES SITE, QUÉBEC.

Response variable	Explanatory variable	Balsam poplar			Willow			Black spruce		
		Estimate	SE	95% CI	Estimate	SE	95% CI	Estimate	SE	95% CI
Shoot dry mass	Wet zone	-0.24	0.23	-0.69, 0.21	0.03	0.26	-0.48, 0.53	-0.08	0.21	-0.50, 0.33
	Sheep laurel	**0.63**	0.22	**0.20, 1.07**	0.42	0.25	-0.06, 0.91	**0.64**	0.16	**0.34, 0.95**
	Shoot dry mass of sheep laurel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Root dry mass of sheep laurel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total dry mass of sheep laurel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Root dry mass	Wet zone	-0.09	0.22	-0.53, 0.35	0.24	0.20	-0.16, 0.64	-0.11	0.25	-0.59, 0.38
	Sheep laurel	**0.52**	0.22	**0.10, 0.95**	0.34	0.17	-0.01, 0.68	**0.60**	0.19	**0.24, 0.96**
	Shoot dry mass of sheep laurel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Root dry mass of sheep laurel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total dry mass of sheep laurel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Response variables	Explanatory variables	Balsam poplar			Willow			Black spruce		
		Estimate	SE	95% CI	Estimate	SE	95% CI	Estimate	SE	95% CI
Total dry mass	Wet zone	-0.18	0.22	-0.62, 0.25	0.12	0.23	-0.32, 0.57	-0.09	0.22	-0.51, 0.34
	Sheep laurel	**0.59**	0.22	**0.17, 1.01**	0.38	0.22	-0.05, 0.80	**0.63**	0.16	**0.32, 0.95**
	Shoot dry mass of sheep laurel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Root dry mass of sheep laurel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total dry mass of sheep laurel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Root-to-shoot ratio	Wet zone	0.09	0.06	-0.03, 0.21	0.22	0.21	-0.21, 0.64	-0.11	0.09	-0.29, 0.07
	Sheep laurel	-0.06	0.03	-0.12, 0.01	0.14	0.1	-0.05, 0.33	-0.33	0.09	-0.21, 0.15
	Shoot dry mass of sheep laurel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Root dry mass of sheep laurel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total dry mass of sheep laurel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Notes. The reference levels in the mixed model were dry zone and control plot. The values in boldface type signify that 95% unconditional confidence interval for a given parameter excludes zero.

APPENDIX J

SUMMARY OF LINEAR MIXED EFFECTS MODELS SELECTION BASED ON AIC$_C$ FOR ROOT SYSTEM ARCHITECTURE PARAMETERS OF TARGET TREE SPECIES IN RESPONSE TO THE BLUEJOINT TREATMENT AT LES TERRAINS AURIFÈRES SITE, QUÉBEC

Candidate models	K[1]	AIC$_c$	Δ AIC$_c$	AIC$_c$ Wt[2]
I. Maximum root depth of balsam poplar				
Zone + Bluejoint	6	21.45	0.00	0.99
Zone + Bluejoint + Zone × Bluejoint	7	31.21	9.76	0.01
Zone + Shoot dry mass of bluejoint	6	35.93	14.48	0.00
Zone + Total dry mass of bluejoint	6	37.02	15.57	0.00
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	42.01	20.56	0.00
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	43.26	21.81	0.00
Zone + Root dry mass of bluejoint	6	43.41	21.96	0.00
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	55.50	34.06	0.00
II. Maximum root radial extension of balsam poplar				
Zone + Bluejoint	6	36.82	0.00	0.99
Zone + Shoot dry mass of bluejoint	6	48.29	11.47	0
Zone + Bluejoint + Zone × Bluejoint	7	49.95	13.12	0
Zone + Total dry mass of bluejoint	6	50.32	13.5	0
Zone + Root dry mass of bluejoint	6	56.99	20.16	0
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	58.75	21.93	0
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	59.73	22.9	0
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	69.49	32.66	0

Candidate models	K[1]	AIC_c	ΔAIC_c	AIC_c Wt[2]
III. Total root length of balsam poplar				
Zone + Bluejoint	6	50.98	0.00	0.57
Zone + Total dry mass of bluejoint	6	52.85	1.87	0.22
Zone + Shoot dry mass of bluejoint	6	53.42	2.45	0.17
Zone + Root dry mass of bluejoint	6	56.57	5.59	0.03
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	61.90	10.93	0.00
Zone + Bluejoint + Zone × Bluejoint	7	62.46	11.48	0.00
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	62.83	11.86	0.00
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	69.33	18.35	0.00
IV. Total root volume of balsam poplar				
Zone + Bluejoint	6	52.54	0.00	0.60
Zone + Shoot dry mass of bluejoint	6	54.77	2.23	0.20
Zone + Total dry mass of bluejoint	6	54.96	2.43	0.18
Zone + Root dry mass of bluejoint	6	59.17	6.64	0.02
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	63.65	11.12	0.00
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	63.93	11.40	0.00
Zone + Bluejoint + Zone × Bluejoint	7	64.28	11.74	0.00
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	71.95	19.41	0.00
V. Total number of 2nd-order roots of balsam poplar				
Zone + Bluejoint	6	66.68	0	0.57
Zone + Total dry mass of bluejoint	6	69.19	2.5	0.16
Zone + Root dry mass of bluejoint	6	69.71	3.02	0.13
Zone + Shoot dry mass of bluejoint	6	69.98	3.3	0.11
Zone + Bluejoint + Zone × Bluejoint	7	73.39	6.7	0.02
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	75.77	9.09	0.01
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	77.5	10.82	0
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	80.52	13.84	0

Candidate models	K[1]	AIC_c	Δ AIC_c	AIC_c Wt[2]
VI. Total number of 3rd-order roots of balsam poplar				
Zone + Shoot dry mass of bluejoint	6	52.98	0.00	0.30
Zone + Total dry mass of bluejoint	6	53.13	0.15	0.28
Zone + Bluejoint	6	53.55	0.57	0.23
Zone + Root dry mass of bluejoint	6	54.02	1.04	0.18
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	64.22	11.24	0.00
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	65.23	12.24	0.00
Zone + Bluejoint + Zone × Bluejoint	7	65.36	12.37	0.00
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	67.21	14.23	0.00
VII. Maximum root depth of willow				
Zone + Bluejoint	6	44.08	0.00	0.98
Zone + Root dry mass of bluejoint	6	53.81	9.74	0.01
Zone + Total dry mass of bluejoint	6	54.46	10.38	0.01
Zone + Shoot dry mass of bluejoint	6	54.89	10.82	0.00
Zone + Bluejoint + Zone × Bluejoint	7	56.90	12.82	0.00
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	61.58	17.50	0.00
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	62.76	18.68	0.00
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	64.94	20.86	0.00
VIII. Maximum root radial extension of willow				
Zone + Bluejoint	6	51.41	0.00	0.97
Zone + Total dry mass of bluejoint	6	60.44	9.03	0.01
Zone + Root dry mass of bluejoint	6	60.57	9.15	0.01
Zone + Shoot dry mass of bluejoint	6	60.62	9.21	0.01
Zone + Bluejoint + Zone × Bluejoint	7	64.36	12.95	0.00
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	67.83	16.41	0.00
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	69.63	18.21	0.00
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	72.63	21.22	0.00

Candidate models	K[1]	AIC_c	ΔAIC_c	AIC_c Wt[2]
IX. Total root length of willow				
Zone + Bluejoint	6	58.58	0.00	0.93
Zone + Total dry mass of bluejoint	6	66.03	7.45	0.02
Zone + Root dry mass of bluejoint	6	66.11	7.53	0.02
Zone + Shoot dry mass of bluejoint	6	66.32	7.73	0.02
Zone + Bluejoint + Zone × Bluejoint	7	71.63	13.05	0.00
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	76.00	17.41	0.00
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	77.06	18.48	0.00
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	78.98	20.39	0.00
X. Total root volume of willow				
Zone + Bluejoint	6	60.12	0	0.96
Zone + Total dry mass of bluejoint	6	68.78	8.66	0.01
Zone + Shoot dry mass of bluejoint	6	68.98	8.86	0.01
Zone + Root dry mass of bluejoint	6	69.07	8.95	0.01
Zone + Bluejoint + Zone × Bluejoint	7	73.31	13.19	0
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	77.67	17.54	0
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	79.12	18.99	0
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	81.63	21.51	0
XI. Total number of 2nd-order roots of willow				
Zone + Bluejoint	6	75.89	0.00	0.73
Zone + Root dry mass of bluejoint	6	79.15	3.27	0.14
Zone + Total dry mass of bluejoint	6	80.63	4.75	0.07
Zone + Shoot dry mass of bluejoint	6	81.60	5.71	0.04
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	84.78	8.90	0.01
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	85.69	9.81	0.01
Zone + Bluejoint + Zone × Bluejoint	7	89.08	13.20	0.00
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	89.60	13.72	0.00

Candidate models	K[1]	AIC_c	Δ AIC_c	AIC_c Wt[2]
XII. Total number of 3rd-order roots of willow				
Zone + Bluejoint	6	57.87	0.00	0.76
Zone + Total dry mass of bluejoint	6	62.12	4.25	0.09
Zone + Shoot dry mass of bluejoint	6	62.31	4.44	0.08
Zone + Root dry mass of bluejoint	6	62.74	4.87	0.07
Zone + Bluejoint + Zone × Bluejoint	7	70.19	12.31	0.00
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	73.39	15.51	0.00
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	73.80	15.93	0.00
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	75.50	17.63	0.00
XIII. Maximum root depth of black spruce				
Zone + Bluejoint	6	14.47	0.00	0.84
Zone + Bluejoint + Zone × Bluejoint	7	18.21	3.73	0.13
Zone + Shoot dry mass of bluejoint	6	22.49	8.02	0.02
Zone + Total dry mass of bluejoint	6	23.51	9.03	0.01
Zone + Root dry mass of bluejoint	6	25.46	10.99	0.00
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	29.69	15.22	0.00
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	33.03	18.56	0.00
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	36.08	21.61	0.00
XIV. Maximum root radial extension of black spruce				
Zone + Shoot dry mass of bluejoint	6	33.14	0.00	0.48
Zone + Bluejoint	6	34.39	1.25	0.26
Zone + Total dry mass of bluejoint	6	34.61	1.47	0.23
Zone + Root dry mass of bluejoint	6	39.27	6.13	0.02
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	45.50	12.35	0.00
Zone + Bluejoint + Zone × Bluejoint	7	46.79	13.64	0.00
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	47.74	14.60	0.00
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	52.47	19.33	0.00

Candidate models	K^1	AIC_c	Δ AIC_c	AIC_c Wt^2
XV. Total root length of black spruce				
Zone + Shoot dry mass of bluejoint	6	32.72	0.00	0.49
Zone + Total dry mass of bluejoint	6	33.02	0.30	0.42
Zone + Root dry mass of bluejoint	6	36.99	4.27	0.06
Zone + Bluejoint	6	38.20	5.48	0.03
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	42.34	9.62	0.00
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	44.75	12.03	0.00
Zone + Bluejoint + Zone × Bluejoint	7	48.84	16.12	0.00
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	49.55	16.83	0.00
XVI. Total root volume of black spruce				
Zone + Total dry mass of bluejoint	6	42.25	0.00	0.44
Zone + Shoot dry mass of bluejoint	6	42.31	0.06	0.43
Zone + Root dry mass of bluejoint	6	45.14	2.89	0.10
Zone + Bluejoint	6	47.72	5.47	0.03
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	52.56	10.31	0.00
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	54.37	12.12	0.00
Zone + Bluejoint + Zone × Bluejoint	7	57.70	15.45	0.00
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	57.97	15.72	0.00
XVII. Total number of 2nd-order roots of black spruce				
Zone + Root dry mass of bluejoint	6	60.97	0.00	0.74
Zone + Total dry mass of bluejoint	6	63.38	2.41	0.22
Zone + Shoot dry mass of bluejoint	6	67.09	6.12	0.03
Zone + Bluejoint	6	73.18	12.21	0.00
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	73.51	12.54	0.00
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	74.77	13.81	0.00
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	77.03	16.06	0.00
Zone + Bluejoint + Zone × Bluejoint	7	84.51	23.55	0.00

Candidate models	K[1]	AIC$_c$	Δ AIC$_c$	AIC$_c$ Wt[2]
XVIII. Total number of 3rd-order roots of black spruce				
Zone + Total dry mass of bluejoint	6	49.40	0.00	0.32
Zone + Bluejoint	6	49.43	0.04	0.31
Zone + Shoot dry mass of bluejoint	6	50.46	1.07	0.19
Zone + Root dry mass of bluejoint	6	50.54	1.14	0.18
Zone + Bluejoint + Zone × Bluejoint	7	61.09	11.70	0.00
Zone + Total dry mass of bluejoint + Zone × Total dry mass of bluejoint	7	62.30	12.91	0.00
Zone + Shoot dry mass of bluejoint + Zone × Shoot dry mass of bluejoint	7	62.60	13.20	0.00
Zone + Root dry mass of bluejoint + Zone × Root dry mass of bluejoint	7	63.70	14.30	0.00

Notes. [1]Number of estimated parameters, [2]Akaike weights

APPENDIX K

SUMMARY OF LINEAR MIXED EFFECTS MODELS SELECTION BASED ON AIC_C FOR ROOT SYSTEM ARCHITECTURE PARAMETERS OF TARGET SPECIES IN RESPONSE TO THE SHEEP LAUREL TREATMENT AT LES TERRAINS AURIFÈRES SITE, QUÉBEC

Candidate models	K^1	AIC_c	ΔAIC_c	AIC_c Wt^2
I. Maximum root depth of balsam poplar				
Zone + Sheep laurel	6	24.60	0.00	0.61
Zone + Root dry mass of sheep laurel	6	26.54	1.94	0.23
Zone + Total dry mass of sheep laurel	6	28.22	3.62	0.10
Zone + Shoot dry mass of sheep laurel	6	29.14	4.55	0.06
Zone + Sheep laurel + Zone × Sheep laurel	7	37.24	12.65	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	39.41	14.81	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	40.65	16.05	0.00
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	41.44	16.84	0.00
II. Maximum root radial extension of balsam poplar				
Zone + Sheep laurel	6	36.64	0.00	0.31
Zone + Root dry mass of sheep laurel	6	37.16	0.53	0.24
Zone + Total dry mass of sheep laurel	6	37.25	0.61	0.23
Zone + Shoot dry mass of sheep laurel	6	37.37	0.73	0.22
Zone + Sheep laurel + Zone × Sheep laurel	7	49.58	12.94	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	50.23	13.60	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	50.43	13.79	0.00
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	50.57	13.93	0.00

Candidate models	K[1]	AIC$_c$	Δ AIC$_c$	AIC$_c$ Wt[2]
III. Total root length of balsam poplar				
Zone + Sheep laurel	6	35.11	0.00	0.37
Zone + Root dry mass of sheep laurel	6	36.12	1.01	0.22
Zone + Total dry mass of sheep laurel	6	36.20	1.09	0.21
Zone + Shoot dry mass of sheep laurel	6	36.34	1.23	0.20
Zone + Sheep laurel + Zone × Sheep laurel	7	46.32	11.21	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	48.49	13.38	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	49.14	14.03	0.00
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	49.49	14.37	0.00
IV. Total root volume of balsam poplar				
Zone + Sheep laurel	6	43.03	0	0.43
Zone + Root dry mass of sheep laurel	6	44.38	1.35	0.22
Zone + Total dry mass of sheep laurel	6	44.65	1.62	0.19
Zone + Shoot dry mass of sheep laurel	6	44.95	1.92	0.16
Zone + Sheep laurel + Zone × Sheep laurel	7	55.46	12.43	0
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	57.39	14.36	0
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	57.85	14.82	0
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	58.09	15.05	0
V. Total number of 2nd-order roots of balsam poplar				
Zone + Sheep laurel	6	65.28	0.00	0.36
Zone + Shoot dry mass of sheep laurel	6	65.99	0.71	0.25
Zone + Total dry mass of sheep laurel	6	66.30	1.02	0.22
Zone + Root dry mass of sheep laurel	6	66.97	1.69	0.15
Zone + Sheep laurel + Zone × Sheep laurel	7	71.65	6.36	0.01
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	75.38	10.09	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	77.01	11.73	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	77.95	12.67	0.00

Candidate models	K[1]	AIC$_c$	Δ AIC$_c$	AIC$_c$ Wt[2]
VI. Total number of 3rd-order roots of balsam poplar				
Zone + Shoot dry mass of sheep laurel	6	55.89	0.00	0.30
Zone + Total dry mass of sheep laurel	6	56.17	0.29	0.26
Zone + Sheep laurel	6	56.30	0.41	0.24
Zone + Root dry mass of sheep laurel	6	56.71	0.83	0.20
Zone + Sheep laurel + Zone × Sheep laurel	7	69.07	13.19	0.00
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	69.07	13.19	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	69.23	13.34	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	69.41	13.53	0.00
VII. Maximum root depth of willow				
Zone + Sheep laurel	6	87.58	0	0.33
Zone + Root dry mass of sheep laurel	6	88.14	0.56	0.25
Zone + Total dry mass of sheep laurel	6	88.67	1.1	0.19
Zone + Shoot dry mass of sheep laurel	6	89.26	1.68	0.14
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	91.05	3.47	0.06
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	92.7	5.13	0.03
Zone + Sheep laurel + Zone × Sheep laurel	7	95.53	7.96	0.01
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	96.51	8.94	0
VIII. Maximum root radial extension of willow				
Zone + Sheep laurel	6	32.28	0.00	0.40
Zone + Shoot dry mass of sheep laurel	6	33.64	1.37	0.20
Zone + Total dry mass of sheep laurel	6	33.65	1.37	0.20
Zone + Root dry mass of sheep laurel	6	33.67	1.39	0.20
Zone + Sheep laurel + Zone × Sheep laurel	7	45.19	12.91	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	46.50	14.22	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	46.67	14.39	0.00
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	46.83	14.55	0.00

Candidate models	K[1]	AIC_c	Δ AIC_c	AIC_c Wt[2]
IX. Total root length of willow				
Zone + Shoot dry mass of sheep laurel	6	42.12	0.00	0.50
Zone + Sheep laurel	6	43.34	1.22	0.27
Zone + Total dry mass of sheep laurel	6	44.52	2.40	0.15
Zone + Root dry mass of sheep laurel	6	45.90	3.78	0.08
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	54.17	12.05	0.00
Zone + Sheep laurel + Zone × Sheep laurel	7	56.36	14.24	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	57.59	15.47	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	58.84	16.72	0.00
X. Total root volume of willow				
Zone + Sheep laurel	6	40.32	0.00	0.39
Zone + Shoot dry mass of sheep laurel	6	41.22	0.90	0.25
Zone + Total dry mass of sheep laurel	6	41.79	1.47	0.19
Zone + Root dry mass of sheep laurel	6	42.21	1.89	0.15
Zone + Sheep laurel + Zone × Sheep laurel	7	47.45	7.13	0.01
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	53.11	12.79	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	53.87	13.55	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	54.42	14.10	0.00
XI. Total number of 2nd-order roots of willow				
Zone + Sheep laurel	6	76.96	0.00	0.31
Zone + Shoot dry mass of sheep laurel	6	77.13	0.17	0.28
Zone + Total dry mass of sheep laurel	6	77.67	0.71	0.21
Zone + Root dry mass of sheep laurel	6	77.85	0.89	0.20
Zone + Sheep laurel + Zone × Sheep laurel	7	88.66	11.70	0.00
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	90.33	13.37	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	90.59	13.63	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	90.73	13.77	0.00

Candidate models	K[1]	AIC_c	ΔAIC_c	AIC_c Wt[2]
XII. Total number of 3rd-order roots of willow				
Zone + Sheep laurel	6	67.92	0	0.22
Zone + Shoot dry mass of sheep laurel	6	68.21	0.29	0.19
Zone + Total dry mass of sheep laurel	6	68.26	0.34	0.19
Zone + Root dry mass of sheep laurel	6	68.36	0.44	0.18
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	68.67	0.75	0.15
Zone + Sheep laurel + Zone × Sheep laurel	7	70.76	2.83	0.05
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	74.48	6.55	0.01
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	78.08	10.16	0.00
XIII. Maximum root depth of black spruce				
Zone + Sheep laurel	6	5.02	0.00	0.52
Zone + Root dry mass of sheep laurel	6	6.20	1.18	0.29
Zone + Total dry mass of sheep laurel	6	7.85	2.83	0.13
Zone + Shoot dry mass of sheep laurel	6	9.44	4.42	0.06
Zone + Sheep laurel + Zone × Sheep laurel	7	16.38	11.36	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	18.95	13.93	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	19.65	14.63	0.00
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	20.20	15.18	0.00
XIV. Maximum root radial extension of black spruce				
Zone + Root dry mass of sheep laurel	6	26.75	0.00	0.29
Zone + Total dry mass of sheep laurel	6	26.97	0.22	0.26
Zone + Sheep laurel	6	27.02	0.27	0.25
Zone + Shoot dry mass of sheep laurel	6	27.44	0.69	0.20
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	39.88	13.13	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	40.16	13.41	0.00
Zone + Sheep laurel + Zone × Sheep laurel	7	40.18	13.43	0.00
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	40.47	13.72	0.00

Candidate models	K[1]	AIC_c	$\Delta\ AIC_c$	AIC_c Wt[2]
XV. Total root length of black spruce				
Zone + Sheep laurel	6	28.38	0.00	0.34
Zone + Root dry mass of sheep laurel	6	28.85	0.47	0.27
Zone + Total dry mass of sheep laurel	6	29.21	0.83	0.22
Zone + Shoot dry mass of sheep laurel	6	29.69	1.30	0.18
Zone + Sheep laurel + Zone × Sheep laurel	7	41.54	13.15	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	42.03	13.64	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	42.34	13.96	0.00
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	42.59	14.21	0.00
XVI. Total root volume of black spruce				
Zone + Root dry mass of sheep laurel	6	39.65	0.00	0.35
Zone + Sheep laurel	6	39.95	0.30	0.30
Zone + Total dry mass of sheep laurel	6	40.62	0.97	0.21
Zone + Shoot dry mass of sheep laurel	6	41.44	1.79	0.14
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	52.84	13.19	0.00
Zone + Sheep laurel + Zone × Sheep laurel	7	53.15	13.49	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	53.53	13.88	0.00
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	53.98	14.33	0.00
XVII. Total number of 2nd-order roots of black spruce				
Zone + Total dry mass of sheep laurel	6	62.61	0.00	0.28
Zone + Root dry mass of sheep laurel	6	62.64	0.03	0.27
Zone + Shoot dry mass of sheep laurel	6	62.72	0.10	0.26
Zone + Sheep laurel	6	63.49	0.87	0.18
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	73.50	10.89	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	73.50	10.89	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	73.52	10.90	0.00
Zone + Sheep laurel + Zone × Sheep laurel	7	75.21	12.59	0.00

Candidate models	K[1]	AIC_c	Δ AIC_c	AIC_c Wt[2]
XVIII. Total number of 3rd-order roots of black spruce				
Zone + Sheep laurel	6	50.90	0.00	0.61
Zone + Root dry mass of sheep laurel	6	53.09	2.19	0.20
Zone + Total dry mass of sheep laurel	6	54.30	3.40	0.11
Zone + Shoot dry mass of sheep laurel	6	55.26	4.36	0.07
Zone + Sheep laurel + Zone × Sheep laurel	7	62.75	11.85	0.00
Zone + Root dry mass of sheep laurel + Zone × Root dry mass of sheep laurel	7	64.57	13.67	0.00
Zone + Total dry mass of sheep laurel + Zone × Total dry mass of sheep laurel	7	67.26	16.36	0.00
Zone + Shoot dry mass of sheep laurel + Zone × Shoot dry mass of sheep laurel	7	68.46	17.56	0.00

Notes. [1]Number of estimated parameters, [2]Akaike weight

APPENDIX L

PARAMETER ESTIMATES FOR ROOT CHARACTERISTICS OF TARGET SPECIES IN RESPONSE TO THE SHEEP LAUREL TREATMENT AT LES TERRAINS AURIFÈRES SITE, QUÉBEC.

Response variable	Explanatory variable	Balsam poplar			Willow			Black spruce		
		Estimate	SE	95% CI	Estimate	SE	95% CI	Estimate	SE	95% CI
Maximum root depth	Wet zone	-0.36	0.12	**-0.61, -0.12**	6.23	1.67	**2.96, 9.50**	-0.01	0.006	-0.12, 0.10
	Sheep laurel	0.32	0.12	**0.09, 0.55**	-2.52	1.62	-5.69, 0.65	0.25	0.05	**0.15, 0.35**
	Shoot dry mass of sheep laurel	-	-	-	-0.01	0.01	-0.02, 0.01	0.00	0.00	0.00, 0.00
	Root dry mass of sheep laurel	0.00	0.00	0.00, 0.00	-0.01	0.01	-0.02, 0.00	0.00	0.00	0.00, 0.00
	Total dry mass of sheep laurel	0.00	0.00	0.00, 0.00	0.00	0.00	-0.01, 0.00	0.00	0.00	0.00, 0.00
Maximum root radial extension	Wet zone	-0.05	0.22	-0.48, 0.38	0.14	0.17	-0.19, 0.47	-0.01	0.19	-0.39, 0.37
	Sheep laurel	0.27	0.17	-0.06, 0.60	0.20	0.16	-0.12, 0.52	0.31	0.08	**0.15, 0.46**
	Shoot dry mass of sheep laurel	0.00	0.00	0.00, 0.00	0.00	0.00	0.00, 0.00	0.00	0.00	0.00, 0.00
	Root dry mass of sheep laurel	0.00	0.00	0.00, 0.00	0.00	0.00	0.00, 0.00	0.00	0.00	0.00, 0.00
	Total dry mass of sheep laurel	0.00	0.00	0.00, 0.00	0.00	0.00	0.00, 0.00	0.00	0.00	0.00, 0.00
Total root length	Wet zone	-0.11	0.19	-0.48, 0.26	0.02	0.29	-0.54, 0.59	-0.10	0.17	-0.43, 0.23
	Sheep laurel	0.34	0.18	-0.02, 0.69	0.43	0.24	-0.04, 0.89	0.36	0.11	**0.15, 0.57**
	Shoot dry mass of sheep laurel	0.00	0.00	0.00, 0.00	0.00	0.00	0.00, 0.00	0.00	0.00	0.00, 0.00

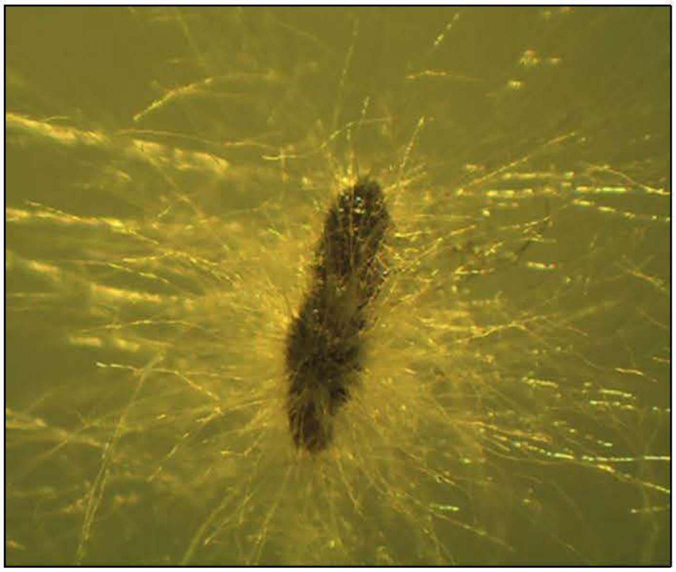
Response variable	Explanatory variable	Balsam poplar			Willow			Black spruce		
		Estimate	SE	95% CI	Estimate	SE	95% CI	Estimate	SE	95% CI
Total root length	Root dry mass of sheep laurel	0.00	0.00	0.00, 0.00	0.00	0.00	0.00, 0.00	0.00	0.00	0.00, 0.00
	Total dry mass of sheep laurel	0.00	0.00	0.00, 0.00	0.00	0.00	0.00, 0.00	0.00	0.00	0.00, 0.00
Total root volume	Wet zone	-0.26	0.27	-0.78, 0.26	0.04	0.24	-0.44, 0.51	-0.02	0.24	-0.49, 0.45
	Sheep laurel	0.57	0.25	**0.08, 1.07**	0.33	0.22	-0.10, 0.75	0.58	0.19	**0.21, 0.95**
	Shoot dry mass of sheep laurel	0.00	0.00	0.00, 0.00	0.00	0.00	0.00, 0.00	0.00	0.00	0.00, 0.00
	Root dry mass of sheep laurel	0.00	0.00	0.00, 0.01	0.00	0.00	0.00, 0.00	0.00	0.00	0.00, 0.01
	Total dry mass of sheep laurel	0.00	0.00	0.00, 0.00	0.00	0.00	0.00, 0.00	0.00	0.00	0.00, 0.00
Number of 2nd-order roots	Wet zone	0.31	0.67	-1, 1.62	1.87	1.06	-0.21, 3.94	-0.40	0.58	-1.53, 0.73
	Sheep laurel	1.63	0.64	**0.37, 2.88**	1.00	1.04	-1.04, 3.04	0.73	0.59	-0.43, 1.90
	Shoot dry mass of sheep laurel	0.01	0.00	0.00, 0.01	0.00	0.00	0.00, 0.01	0.00	0.00	0.00, 0.01
	Root dry mass of sheep laurel	0.01	0.00	0.00, 0.02	0.00	0.00	-0.01, 0.01	0.01	0.00	0.00, 0.01
	Total dry mass of sheep laurel	0.00	0.00	0.00, 0.01	0.00	0.00	0.00, 0.01	0.00	0.00	0.00, 0.01
Number of 3rd-order roots	Wet zone	-0.36	0.44	-1.22, 0.51	0.98	0.72	-0.44, 2.39	0.14	0.39	-0.63, 0.91
	Sheep laurel	0.78	0.44	-0.08, 1.64	0.60	0.71	-0.80, 2.00	1.25	0.32	**0.63, 1.87**
	Shoot dry mass of sheep laurel	0.00	0.00	0.00, 0.01	0.00	0.00	0.00, 0.01	-	-	-
	Root dry mass of sheep laurel	0.00	0.00	0.00, 0.01	0.00	0.00	0.00, 0.01	0.01	0.00	0.00, 0.01
	Total dry mass of sheep laurel	0.00	0.00	0.00, 0.00	0.00	0.00	0.00, 0.00	0.00	0.00	0.00, 0.00

Notes. The reference levels in the linear mixed models were dry zone and control plot. The values in boldface type signify that 95% unconditional confidence interval for a given parameter excludes zero

APPENDIX M

ROOT TIPS OF BLACK SPRUCE COLONIZED BY *PHIALOCEPHALA FORTINII*

Spruce root collected at Les Terrain Aurifères tailings impoundment



Mycelium growth on black spruce root tips shown above

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