



# Species-specific responses to forest soil inoculum in planted trees in an abandoned agricultural field



Annick St-Denis<sup>a,\*</sup>, Daniel Kneeshaw<sup>a</sup>, Nicolas Bélanger<sup>b</sup>, Suzanne Simard<sup>c</sup>,  
Isabelle Laforest-Lapointe<sup>a</sup>, Christian Messier<sup>a,d</sup>

<sup>a</sup> Centre for Forest Research (CFR), Department of Biological Sciences, Université du Québec à Montréal, Montréal, QC H3C 3P8, Canada

<sup>b</sup> Centre for Forest Research (CFR), UER Science et Technologie, TELUQ, Université du Québec, Montréal, QC H2S 3L5, Canada

<sup>c</sup> Department of Forest Sciences, University of British Columbia, Vancouver, BC V6T 1Z4, Canada

<sup>d</sup> Institute of Temperate Forest Sciences (ISFORT), Department of Natural Sciences, Université du Québec en Outaouais, Ripon, QC J0V 1V0, Canada

## ARTICLE INFO

### Article history:

Received 1 April 2016

Received in revised form 27 December 2016

Accepted 29 December 2016

Available online 6 January 2017

### Keywords:

Abandoned agricultural field

Ecological restoration

Forest soil inoculation

Tree seedlings

Tree growth

Mycorrhizae

## ABSTRACT

Tree plantations are commonly used to restore abandoned agricultural fields with varying degrees of success. Agricultural soils differ from forest soils in nutrient availability and microbial communities. The objective of this study was to test the effect of adding small amounts of forest soil on the survival, growth and rates of mycorrhizal fungal colonization of trees planted in an abandoned agricultural field over the crucial first three growing seasons. Seedlings of two arbuscular mycorrhizal (AM) and two ectomycorrhizal (EM) tree species were planted in an abandoned agricultural field. Soil inocula were taken from four forest stands, each dominated by one of the planted species. Half of the soil samples were sterilized before inoculation to distinguish microbial from nutrient effects. The effect of the quantity of soil inoculum added was tested using 300 and 1500 ml of forest soil. Tree mortality was low and did not vary between treatments. The growth of EM tree species responded, positively or negatively, to forest soil inoculation. A negative feedback was detected on the growth of red oak seedlings inoculated with red oak soil. Seedlings inoculated with EM sterilized soils were smaller than control seedlings, presumably due to lower nutrient availability of EM forest soils compared to agricultural field soil. The majority of the effects, either positive or negative, were observed the first year. After three seasons of growth, only yellow birch seedlings that had received 1500 ml of non-sterilized red oak soil still benefited from soil inoculation. More research is needed in nutrient-limited soils to determine whether inoculation would have greater or longer term benefits on tree survival and growth.

© 2017 Elsevier B.V. All rights reserved.

## 1. Introduction

Long-term intensive agricultural activities may decrease soil organic carbon, nutrient availability as well as microbial biomass (Dick, 1992; Lal, 2004; Rosenzweig et al., 2016). A reduction in mycorrhizal diversity and mycelium abundance has also been reported in such sites (Helgason et al., 1998; Alguacil et al., 2008). It has recently been suggested that soil microbial communities could be manipulated to enhance the success of ecological restoration

(Heneghan et al., 2008; Harris, 2009; Hoeksema et al., 2010). Mycorrhizal fungal and bacterial inoculations have been previously tested to improve the survival and growth of outplanted nursery-produced tree seedlings (Trappe, 1977; Kropp and Langlois, 1990; Torrey, 1992). However, plant response (e.g. biomass) to inoculation could be greater if instead of using a single mycorrhizal fungus, several mycorrhizal fungal species and non-mycorrhizal microbes are present in the inoculum, or whole-community soil is used as an inoculum (Hoeksema et al., 2010; Urgiles et al., 2014). In effect, mycorrhizal function and behaviour are generally stimulated by an array of soil organisms, although some inhibitory interactions are possible (Fitter and Garbaye, 1994).

A simple method to inoculate trees would be to add soil containing desirable mycorrhizal fungal spores to a site that is deficient in these fungi (Schwartz et al., 2006), such as forest vs agricultural soils. Diversities of arbuscular mycorrhizal (AM) and ectomycorrhizal (EM) fungi are higher in forest soils than in

\* Corresponding author at: Department of Biological Sciences, Université du Québec à Montréal, C.P.8888 Succursale Centre-ville Montréal (Québec), H3C 3P8, Canada.

E-mail addresses: [st-denis.annick.2@courrier.uqam.ca](mailto:st-denis.annick.2@courrier.uqam.ca) (A. St-Denis), [kneeshaw.daniel@uqam.ca](mailto:kneeshaw.daniel@uqam.ca) (D. Kneeshaw), [nicolas.belanger@teluq.ca](mailto:nicolas.belanger@teluq.ca) (N. Bélanger), [suzanne.simard@ubc.ca](mailto:suzanne.simard@ubc.ca) (S. Simard), [isabelle.laforest.lapointe@gmail.com](mailto:isabelle.laforest.lapointe@gmail.com) (I. Laforest-Lapointe), [messier.christian@uqam.ca](mailto:messier.christian@uqam.ca) (C. Messier).

agricultural soils, but AM fungi are more abundant than EM fungi in agricultural soils (Helgason et al., 1998; Berman and Bledsoe, 1998; Dickie and Reich, 2005). Moreover, soils with high carbon levels and well-balanced nutrients generally have a positive impact on tree nutrition (Pinno et al., 2010; Ens et al., 2013). Therefore, adding a small amount of forest soil to an abandoned agricultural field could potentially create planting microsites that optimize tree survival and growth.

Most studies exploring the effects of forest soil inoculum on tree seedlings have used pot studies and/or have conducted short-term (<1 year) experiments (Packer and Clay, 2000; O'Brien et al., 2011; Urgiles et al., 2014; Dulmer et al., 2014). In pot studies, effects of forest soil transfer were observed on seedling growth, but the soil inoculum was mixed with a sterilized substrate (Borchers and Perry, 1990; O'Brien et al., 2011; Urgiles et al., 2014). Thus, tree seedlings had access to an environment in which the added microbes were not competing with field microbes. Previous field experiments using soil transfer to tree seedlings usually showed an increase in EM fungal colonization, but the presence or absence of effects on growth depended on soil provenance, field conditions, and tree species (Amaranthus and Perry, 1987; Helm and Carling, 1993; Berman and Bledsoe, 1998; Dickie et al., 2007).

The main objective of this study was to evaluate the effects of adding forest soil to tree seedlings planted in an abandoned agricultural field and to follow their survival and growth over three growing seasons. The specific objective was to compare the responses of two ectomycorrhizal (EM) tree species and two arbuscular mycorrhizal (AM) tree species to different soil inoculation treatments. Since associations with EM fungi usually confer more benefits to tree seedlings than associations with AM fungi (van der Heijden and Horton, 2009; Bradford, 2014) and AM fungi should be more abundant than EM fungi in agricultural soils, a greater response from EM tree seedlings was expected. We also questioned the effect of host specificity and soil provenance: does soil inoculum collected under a mature tree of the same species have effects similar to that of inoculum collected under a different species on the receiving seedling? Since many mycorrhizal fungi are not host specific (van der Heijden and Horton, 2009), we hypothesised no effect of soil provenance.

## 2. Materials and methods

### 2.1. Study area

The experiment was conducted at the city of Montréal's tree nursery, in the suburb of L'Assomption (45°48'38"N; 73°26'26"W). The region is characterized by a humid continental climate. For the 1981–2010 period, the average annual temperature recorded at the nearest weather station (Verchères, 45°46'N; 73°22'W) is 6.6°C, with monthly means of 21°C in July and –10°C in January while average annual precipitation is 984 mm, of which almost 20% falls as snow (Environment Canada, 2015). The experiment was established on two adjacent abandoned agricultural fields separated by a 5 m wide buffer of young Norway spruce (*Picea abies*). Soil is a fine to very fine sandy loam (IRDA, 2008). Fields were mown once or twice a year since the end of agricultural crop production more than 15 years ago. Mowing promoted ruderal herbaceous vegetation dominated by grass and clover species which are hosts of arbuscular mycorrhizal species.

### 2.2. Experimental design

This controlled field experiment began in May 2012 and the last growth measurements were taken at the end of the third growing season in August 2014. Four 12 × 36 m blocks were delineated in the largest abandoned field. Another block of the same size was

delineated in the smallest abandoned field. Blocks were located at least 5 m away from a forested strip and more than 30 m from the road to avoid edge effects. Each block was divided into two sections: the first for AM tree species and the second for EM tree species. Two AM tree species, red ash (*Fraxinus pennsylvanica* Marshall) and red maple (*Acer rubrum* L.), and two EM tree species, yellow birch (*Betula alleghaniensis* Britton) and northern red oak (*Quercus rubra* L.), were planted. Each half block was divided into 9 plots using a random split-plot design. For the first half of each block, the treatments were: (1) soil quantities (0 ml, 300 ml or 1500 ml of loose soil); (2) soil sterilization (sterilized or not, hereinafter named live soil); (3) soil provenance (red ash or red maple forest soils) and (4) tree species (red ash or red maple) (Fig. 1a). For the other half of the blocks, the first two factors were the same, but the soil provenance and tree species treatments were replaced by the EM species yellow birch and red oak (Fig. 1b). In each plot, 3 seedlings of the same species (9 plots, 5 blocks, 4 species) were planted (total of 540 seedlings).

These four hardwood species were selected because they are native to the area and seedlings are readily available. All four species have intermediate shade tolerance (Niinemets and Valladares, 2006). Container-produced one year-old seedlings were provided by the Berthierville nursery of the Quebec Ministry of Forests, Wildlife and Parks. This nursery does not inoculate seedlings with any microbes. Once delivered, seedlings were kept in a dark room (4°C, 90% humidity) before planting. Seedlings were manually planted at 2 m spacing on May 14 and 15, 2012 after the herbaceous vegetation was mowed.

Following planting, a white 50 × 50 cm polyester and polypropylene felt mulch (Arbo-Pro, Texel, Saint-Elzéar-de-Beauce, Canada) was placed around each tree seedling to reduce herb competition and maintain a stable climate while allowing water to penetrate the soil. In the rows between seedlings, vegetation was mowed every month during the summer. Each tree seedling was protected from small mammal predation using a plastic tree protector (Timm Enterprises Ltd, Milton, Canada). Tree protectors were 30 cm high for red ash, red maple and red oak seedlings, and 20 cm for the smaller yellow birch seedlings. No signs of herbivory were observed.

### 2.3. Soil collection and inoculation

Soils were collected in forest stands located within a 100 km radius of the study area between May 7 and 9, 2012. AM forest soil samples were collected in the forests in proximity to the island of Montréal, whereas EM forest soils were collected in the Lower Laurentians, starting about 60 km north of Montréal where the EM species are more abundant. More specifically, soil supporting red ash trees was collected in a woodlot outside the city of Laval, in an agricultural setting, approximately 35 km southwest of the study area (45°40'36"N; 73°43'39"W). The woodlot is composed of many broadleaf species, but the soil was taken in a section dominated by more than 70% mature red ash trees. The soil has a high activity of earthworms (A. St-Denis, pers. obs.) due to its neutral pH (calcareous glacial till). It developed into a Melanic Brunisol (Soil Classification Working Group, 1998) or Eutric Cambisol (IUSS Working Group WRB, 2015).

Soil supporting red maple trees was collected in a relatively pure red maple stand bordering a river, near the city of Boisbriand, located about 50 km southwest of the study area (45°35'52"N; 73°50'04"W). The soil developed from a fluvial deposit and transitions from Gleysols to Gray Brown Luvisol (or Albic Luvisol) (Soil Classification Working Group, 1998; IUSS Working Group WRB, 2015), depending on drainage. Soil has high P content due to previous agricultural land use on the uphill portion of the site.

Arbuscular mycorrhizal (AM) tree species							
1500 ml of Sterilized soil	<i>Red ash (RA) forest soil</i>			<i>Red maple (RM) forest soil</i>			1500 ml of Non-sterilized soil
	RA tree	RA tree	RA tree	RA tree	RA tree	RA tree	
	RM tree	RM tree	RM tree	RM tree	RM tree	RM tree	
	<i>Red maple (RM) forest soil</i>			<i>Red ash (RA) forest soil</i>			
	RA tree	RA tree	RA tree	RM tree	RM tree	RM tree	
	RM tree	RM tree	RM tree	RA tree	RA tree	RA tree	
300 ml of Sterilized soil	<i>Red maple (RM) forest soil</i>			<i>Red ash (RA) forest soil</i>			300 ml of Non-sterilized soil
	RA tree	RA tree	RA tree	RA tree	RA tree	RA tree	
	RM tree	RM tree	RM tree	RM tree	RM tree	RM tree	
	<i>Red ash (RA) forest soil</i>			<i>Red maple (RM) forest soil</i>			
	RM tree	RM tree	RM tree	RM tree	RM tree	RM tree	
	RA tree	RA tree	RA tree	RA tree	RA tree	RA tree	
No soil added	<i>Control AM tree species</i>			<i>Control EM tree species</i>			No soil added
	RA tree	RA tree	RA tree	RO tree	RO tree	RO tree	
	RM tree	RM tree	RM tree	YB tree	YB tree	YB tree	
Ectomycorrhizal (EM) tree species							
1500 ml of Non-sterilized soil	<i>Yellow birch (YB) forest soil</i>			<i>Yellow birch (YB) forest soil</i>			1500 ml of Sterilized soil
	RO tree	RO tree	RO tree	YB tree	YB tree	YB tree	
	YB tree	YB tree	YB tree	RO tree	RO tree	RO tree	
	<i>Red oak (RO) forest soil</i>			<i>Red oak (RO) forest soil</i>			
	YB tree	YB tree	YB tree	YB tree	YB tree	YB tree	
	RO tree	RO tree	RO tree	RO tree	RO tree	RO tree	
300 ml of Sterilized soil	<i>Yellow birch (YB) forest soil</i>			<i>Yellow birch (YB) forest soil</i>			300 ml of Non-sterilized soil
	YB tree	YB tree	YB tree	YB tree	YB tree	YB tree	
	RO tree	RO tree	RO tree	RO tree	RO tree	RO tree	
	<i>Red oak (RO) forest soil</i>			<i>Red oak (RO) forest soil</i>			
	RO tree	RO tree	RO tree	YB tree	YB tree	YB tree	
	YB tree	YB tree	YB tree	RO tree	RO tree	RO tree	

Fig. 1. Example of the split-plot design used in block #1.

Soils supporting yellow birch and red oak were collected at the *Station de biologie des Laurentides* of the *Université de Montréal*, in Saint-Hippolyte, 95 km northwest of the study area. The Precambrian Shield from which the yellow birch and red oak soils were sampled is characterized by thin glacial till soils derived from felsic (acidic) rocks (Bélanger et al., 2012) that generally develop into Orthic Humo-Ferric Podzols (Soil Classification Working Group, 1998, or Orthic Podzols, IUSS Working Group WRB, 2015). For yellow birch, soil was sampled in a sugar maple – yellow birch stand (45°58'51.3"N; 74°00'52.7"W) located on a gentle slope. For red oak, soil was collected in a sugar maple – red oak stand (45°58'17.0"N; 73°59'53.4"W) located on a hilltop. In these two stands, sugar maple was the dominant species while yellow birch was the co-dominant species in the first one and red oak, in the other.

As microbe species and abundance could change during the growing season, another soil collection was conducted on August 16, 2012, at the same sites, but in areas undisturbed by the previous soil collection. In each forest type, soil samples were collected from under at least six mature trees (stems with DBH > 20 cm) of the target species in an area where the other tested species of the same mycorrhizal association was not present. Coarse woody debris and surface litter were removed before collecting soil (0–25 cm depth) between 0.5 and 1 m from a mature tree. To avoid contamination, collection tools were washed with a bleach solution (10% of sodium hypochlorite) and rinsed with water between each forest soil collection. All soil samples from a given forest site were combined into a single bulk sample. Bulk samples were sieved using a 1 cm mesh, but fine root segments were kept. Half of the bulk samples

were immediately stored in a cool dark room (4°C, 90% of humidity) for a few days before being brought to the planting site. The other half of the bulk samples received a gamma irradiation treatment at the Nordion's Gamma Centre (Laval, Québec) to eliminate invertebrates, fungi and other microorganisms (McNamara et al., 2003). The first batch of soils was sterilised May 10 to 14, 2012, with a minimal dose of 51.1 kGy and a maximal dose of 73.9 kGy. The second batch was sterilised August 17 to 21, 2012, with a minimal dose of 54.7 kGy and a maximal dose of 80.5 kGy.

Inoculum instead of inocula if you put was instead of were of 100 ml or 500 ml of live or sterilized soils was added in three steps for a total of 300 ml or 1500 ml of soil added. The first soil inoculum (100 or 500 ml) was placed in the planting hole just before the seedling was planted and the second was applied at the soil surface around the seedling ( $\approx 300\text{ cm}^2$ ) immediately after planting. The third application was also at the soil surface around the seedling but three months after planting (August 16 and 21, 2012). In each block, the controls (three individuals per species) did not receive any soil inoculum.

#### 2.4. Soil analyses

Subsamples of each soil type were air-dried and sieved at 2 mm before determining sand, silt and clay fractions using the hydrometer method Done (Kroetsch and Wang, 2008) and soil pH in water (soil:solution ratio of 1:2.5). Organic C, total N and S were determined on finely ground samples by combustion and infrared detection (CNS 2000, LECO Corporation, MI). Phosphorus,

K, Ca, Mg, Mn, Al, Fe and Na were extracted from these samples using an unbuffered Mehlich III solution (Ziadi and Sen Tran, 2007) and measured by inductively coupled plasma emission spectroscopy (Optima 7300DV, PerkinElmer, MA). Effective cation exchange capacity (CEC) was operationally defined as the sum of Ca, Mg, K, Na, Al, Fe and Mn, whereas base saturation was expressed as the sum of Ca, Mg, K and Na on CEC (Hendershot et al., 2007).

## 2.5. Data collection

Survival, height and diameter at 5 cm above the ground were measured three weeks after planting (June 4, 2012), at the end of the first (September 19, 2012) and second (October 4, 2013) growing seasons, and on August 5, 2014. On September 24, 2014, 15 seedlings per species (1 seedling per block (5 blocks) in plots where 1500 ml of live soil collected in one forest was inoculated, 1 seedling per block in plots where 1500 ml of live soil from the second forest was inoculated and 1 seedling per block the control plots) were randomly excavated using a side-digger which can excavate 60 cm wide and 50 cm deep. Roots were stored in a freezer at  $-14^{\circ}\text{C}$  until analysed.

Roots were gently washed under tap water and examined for mycorrhizal fungal colonization. For AM tree species, 25–30 root tips per seedling (approximately 1.5 cm long) were randomly selected. The ink and vinegar staining technique developed by Vierheilig et al. (1998) was adapted to clear and stain red ash and red maple roots. Roots were cleared by soaking them in 10% KOH at  $90^{\circ}\text{C}$  for 10 min for red ash roots and 3 h for coriaceous red maple roots. After being rinsed with tap water, they were bleached with 3%  $\text{H}_2\text{O}_2$  for 10 and 60 min for red ash and red maple roots, respectively. Roots were acidified in vinegar (5% acetic acid) for 10 and 60 min for red ash and red maple roots. They were soaked in a solution of 5% black ink (Sheaffer Skrip #94231, Sheaffer Manufacturing Co., Fort Madison, IA) and 95% vinegar overnight at room temperature. Roots were rinsed several times with tap water acidified with a few drops of acetic acid. They were then placed in a destain solution made of 50% glycerol, 45% distilled water and 5% of HCl (1%) solution for one week. Arbuscular colonization (AC) and hyphae colonization (HC) were assessed following McGonigle et al. (1990). Arbuscules are produced by mycorrhizal fungi while hyphae may be produced by both mycorrhizal and non-mycorrhizal fungi (McGonigle et al., 1990). Each of the 25 to 30 root tips per seedling were examined under a compound microscope ( $200\times$  magnification) at three locations, for a total of 75 to 90 locations examined per sample.

For EM tree species, approximately one hundred 1 cm root tips were randomly selected among all roots collected per excavated seedling and examined under a dissecting microscope ( $10\text{--}50\times$ ). EM fungal colonization for red oak and yellow birch seedlings was assessed as the proportion of root tips with mycorrhizal structures (identified by color, branching, shape, texture and presence of emanating hyphae) over the total number of root tips evaluated. A subset of 15–25 root tips/seedling was observed under a compound microscope ( $100\text{--}400\times$ ) to confirm the presence of a Hartig net for EM tree species.

## 2.6. Statistical analyses

Chi-square tests were used to assess seedling survival. Analyses of variance for repeated measurements (ANOVAR) and univariate analyses of variance (ANOVA) were performed for each species to evaluate the effects of soil inoculum quantity, soil sterilization, soil provenance, time and their interactions on seedling height and diameter. Analyses were performed following a split-plot design ( $3 \times 2$  factorial model): Block (random)  $\times$  Soil inoculum quantity  $\times$  Soil sterilization  $\times$  Soil provenance. The data satisfied the assumptions of homoscedasticity and normality. Student's *t*-test and Tukey tests were used as *post-hoc* tests. The statistical design was not balanced if the control plots (no soil added) were included in the analyses of variance. We thus used a  $9 \times 1$  factorial model which includes 8 soil treatment combinations (for example: "300 ml of sterilized yellow birch soil") + the control. To correct for multiple comparisons, the Dunnett method was used as a *post-hoc* test to evaluate whether treatment means were significantly different from control means. Levels of mycorrhizal fungal colonization were compared using ANOVAs and correlated to final tree height and diameter with Pearson correlations. All statistical analyses were performed using JMP 10.0. Statistical significance was determined at  $p=0.05$ .

## 3. Results

### 3.1. Soil characteristics

Basic physical and chemical characteristics of forest and agricultural field soils are presented in Table 1. On the one hand, very high and high levels of extractable (Mehlich III) P were measured for the agricultural soil ( $68\text{ mg kg}^{-1}$ ) and for red maple soil ( $40\text{ mg kg}^{-1}$ ), respectively, compared to the other forest soil types (ranging from 6 to  $23\text{ mg kg}^{-1}$ ). On the other hand, the

**Table 1**  
Soil characteristics of the experimental abandoned agricultural field and four forest types (under mature trees of red ash, red maple, yellow birch and red oak).

Soil types	Sterilized?	Sand %	Silt %	Clay %	Organic C %	Total N %	Total S %	P Mehlich mg/kg	Exch. Ca cmol (+)/kg	Exch. Al cmol (+)/kg	C.E.C cmol (+)/kg	Base saturation (%)	pH
Agricultural field	–	62	27.5	10.5	1.44	0.13	0.03	68.2	5.12	23.6	31.4	19.8	6.18
Red ash soil	No	36.2	38.8	25	7.08	0.52	0.07	8.39	29.9	12.1	45.8	71.1	7.22
	Yes	40	28.8	31.2	8.39	0.64	0.10	22.8	28.5	10.5	42.70	73.0	7.28
Red maple soil	No	5	56.2	38.8	2.93	0.32	0.07	40.5	7.92	23.3	36.7	31.2	4.87
	Yes	13.8	41.2	45	3.02	0.33	0.08	40.0	7.80	23.9	37.1	30.2	5.07
Yellow birch soil	No	66.2	23.8	10	12.8	0.61	0.13	5.99	2.01	40.9	44.7	6.13	4.43
	Yes	65	22.5	12.5	11.8	0.55	0.11	10.4	2.03	44.4	48.7	5.61	4.43
Red oak soil	No	60	28.8	11.2	13.0	0.63	0.13	7.00	1.18	43.7	46.6	3.91	4.50
	Yes	58.8	30	11.2	11.7	0.61	0.11	11.6	2.03	44.0	47.9	5.88	4.74

Exch. is exchangeable; C.E.C. is effective cation exchange capacity.

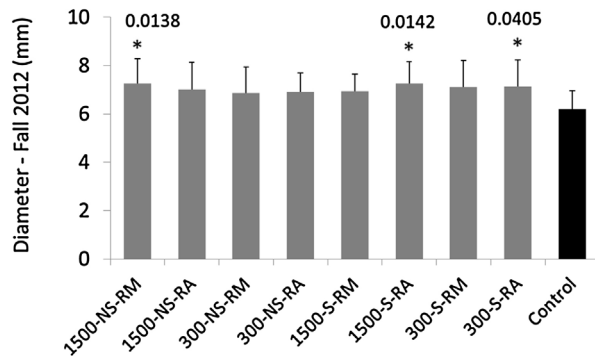
agricultural field soil had the lowest organic C (1.44%) and total N (0.13%) levels and some of the lowest exchangeable Ca (5.12  $\text{cmol}_{(+)}$   $\text{kg}^{-1}$ ), CEC (31.4  $\text{cmol}_{(+)}$   $\text{kg}^{-1}$ ) and base saturation (19.8%) values in comparison to forest soils (2.93–13.0% for organic C; 0.32–0.64% for total N; 1.18–29.9  $\text{cmol}_{(+)}$   $\text{kg}^{-1}$  for exchangeable Ca; 10.5–44.4  $\text{cmol}_{(+)}$   $\text{kg}^{-1}$  for CEC and 3.91–73.0% for base saturation). The molar N (total): P (Mehlich) ratio of the agricultural field soil (42.2) was much lower than all other forest soils (174–2257) (results not shown). The red ash and red maple soils showed higher exchangeable Ca, base saturation and pH than the yellow birch and red oak soils. Soils collected under mature red ash trees had the

highest exchangeable Ca (28–30  $\text{cmol}_{(+)}$   $\text{kg}^{-1}$ ), base saturation (71–73%) and pH (7.25). The red ash and red maple soils had relatively high silt and clay content, whereas the more acidic yellow birch and red oak soils had coarser texture (i.e. sandy loam).

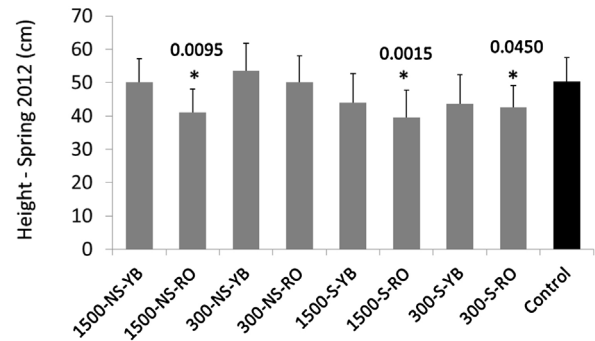
### 3.2. Survival

Seedling survival was high, with no mortality for red ash seedlings, and one red maple and five red oak seedlings that died. Mortality was too low for chi-square tests, except for the EM species yellow birch (22 dead seedlings). However, neither soil

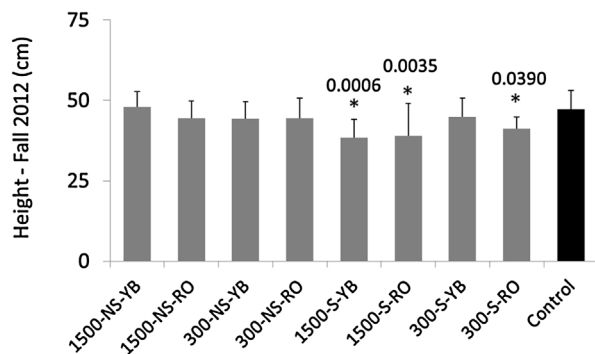
a) Red ash diameter (1<sup>st</sup> year)



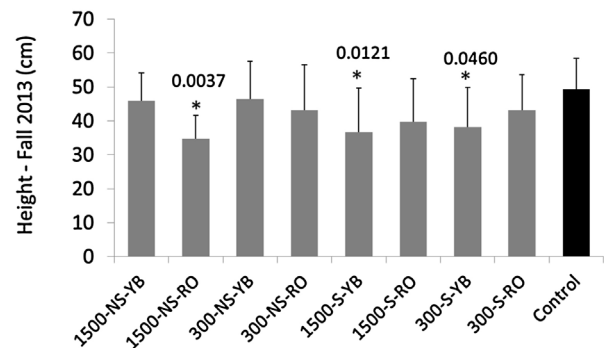
d) Red oak height (1<sup>st</sup> year)



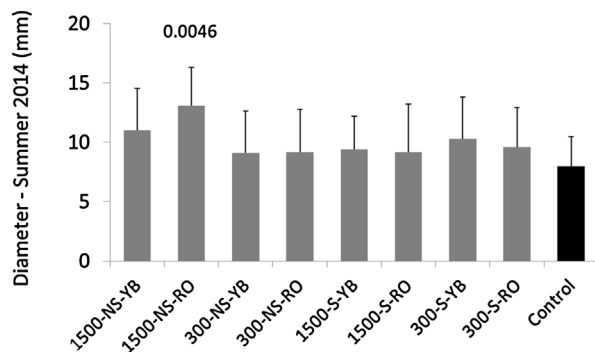
b) Yellow birch height (1<sup>st</sup> year)



e) Red oak height (2<sup>nd</sup> year)



c) Yellow birch diameter (3<sup>rd</sup> year)



**Fig. 2.** Mean ( $\pm$  sd) of (a) red ash diameter in fall of 2012 ( $n = 135$ ); (b) yellow birch height in fall of 2012 ( $n = 132$ ); (c) yellow birch diameter in summer of 2014 ( $n = 113$ ); (d) red oak height in fall of 2012 ( $n = 135$ ) and (e) in fall of 2013 ( $n = 132$ ). An asterisk (followed by the  $p$ -value) indicates that the mean for the combined soil treatments differs from the control (Dunnett's test). Only significant results are presented. See appendices for other results (Fig. A.1–A.4). Combined soil treatments: Inoculation with 1500 ml (**1500**) or 300 ml (**300**) of forest soil, with live soil (**NS** = non sterilized) or sterilized soil (**S**); and with soil collected under mature red maple trees (**RM**), mature red ash trees (**RA**), mature yellow birch trees (**YB**) and mature red oak trees (**RO**).

inoculum quantity ( $\chi^2 = 0.374$ ;  $p = 0.5410$ ), sterilization ( $\chi^2 = 1.016$ ;  $p = 0.3135$ ) nor soil provenance treatment ( $\chi^2 = 1.330$ ;  $p = 0.2488$ ) affected survival.

### 3.3. Effects of soil treatments on AM tree species growth

AM tree species did not show consistent or persistent responses to the addition of forest soil. None of the factors tested affected red ash height and diameter (Tables A.1–A.2, Fig. A.1). However, after the first growing season (in the fall of 2012), the diameter of red ash seedlings receiving 1500 ml of live red maple soil ( $p = 0.01$ ) and 300 or 1500 ml of sterilized red ash soil ( $p = 0.04$  and  $p = 0.01$ , respectively) was larger than the diameter of seedlings that did not receive forest soil (Fig. 2a). These effects did not persist with time ( $F = 0.74$ ,  $p = 0.74$ ; Table A.1).

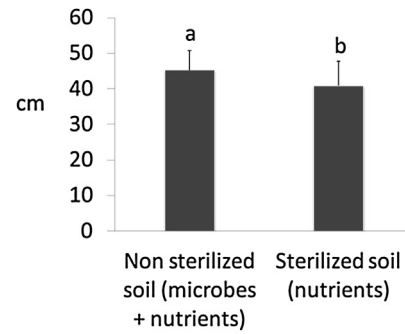
The growth of red maple seedlings inoculated with forest soil was similar to the growth of seedlings in the control (Fig. A.2). However, a significant “soil inoculum quantity”  $\times$  “soil sterilization”  $\times$  “soil provenance” interaction ( $F = 10.99$ ,  $p = 0.001$ ) was detected for red maple height at the end of the first growing season (Table A.2). Red maple seedlings inoculated with 1500 ml of live red ash soil were taller than seedlings receiving 300 ml, and taller than those inoculated with 1500 ml of live red maple soil. Conversely, red maple seedlings inoculated with soil collected under conspecific trees were taller than those inoculated with red ash soil, but only when 300 ml of live soil was added. These contrasting results do not provide strong evidence for positive effects of forest soil inoculation on red maple seedlings.

### 3.4. Effects of soil treatments on EM tree species growth

The EM birch seedlings inoculated with sterilized soil (1500 ml of yellow birch soil, 300 or 1500 ml of red oak soil) were smaller than control seedlings at the end of the first growing season (Fig. 2b). Furthermore, yellow birch seedlings inoculated with live soil were taller and had a larger diameter during the first year ( $F = 32.49$ ,  $p = 0.005$  and  $F = 18.20$ ,  $p = 0.01$ , respectively) than those inoculated with sterilized soil for all soil quantities and types combined (Fig. 3; Table A.2), but they were not taller than control seedlings (Fig. 2b). The effect on height was greater when 1500 ml of soil was added vs 300 ml ( $F = 13.55$ ,  $p = 0.02$ ; Table A.2). In contrast to height, yellow birch seedlings inoculated with yellow birch soil (sterilized or not) had a larger diameter when 300 ml of soil was added instead of 1500 ml ( $F = 90.21$ ,  $p = 0.002$ ; Table A.2). This was only observed after one growing season. By the end of the third season, results had reversed such that diameter growth of birch seedlings inoculated with 1500 ml of live soil was greater than with 300 ml ( $F = 14.49$ ;  $p = 0.02$ ). Moreover, after the third year of growth, seedlings receiving 1500 ml of live red oak soil had a larger diameter than controls ( $p = 0.005$ ; Fig. 2c). These effects coupled with the first year effects suggest some benefits of adding live red oak soil to yellow birch seedlings when planting this species in an abandoned agricultural field.

Positive and negative feedbacks were observed on the growth of red oak seedlings. Oak seedlings inoculated with live (1500 ml) or sterilized red oak soil (300 or 1500 ml) were smaller than control seedlings after the first and second growing seasons (Fig. 2d,e). As with the other EM species, red oak seedlings were taller when inoculated with live soil vs sterilized soil after the first year ( $F = 11.31$ ,  $p = 0.03$ ; Fig. 4a; Table A.2). Also, they were tallest when a small quantity of soil was added ( $F = 27.77$ ,  $p = 0.006$ ; Fig. 4b). First year red oak seedlings inoculated with red oak soil were smaller than those inoculated with yellow birch soil ( $F = 27.29$ ,  $p = 0.006$ ; Fig. 4c). At the end of the third summer, red oak seedling diameters were larger when inoculated with 1500 ml of soil instead of 300 ml ( $F = 11.21$ ,  $p = 0.03$ ). In contrast to height growth, diameter growth

#### a) Height of yellow birch seedlings (1<sup>st</sup> year of growth)



#### b) Diameter of yellow birch seedlings (1<sup>st</sup> year of growth)

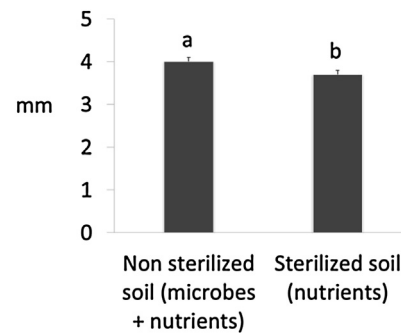


Fig. 3. (a) Height and (b) diameter (mean  $\pm$  sd) of yellow birch seedlings after one season of growth (fall 2012) according to sterilization: non sterilized (live) soil vs sterilized soil ( $n = 117$ ).

did not differ between the soil treatments and the control (Fig. A.4). In summary, for red oak seedlings, we observed: (1) a positive effect of adding live compared to sterilized soil; (2) a positive effect of adding yellow birch soil compared to red oak soil (although there were no significant benefits of adding forest soil compared to the control) (Fig. A.4); and finally (3) a negative effect of red oak soil on red oak seedling height.

### 3.5. Mycorrhizal fungal colonization

We observed >75% hyphae colonization (HC) for ash and maple seedlings. Forest soil inoculation did not increase arbuscular colonization (AC) of red ash (34 to 51%;  $F = 1.09$ ,  $p = 0.38$ ) and red maple seedlings (68 to 70%;  $F = 1.89$ ,  $p = 0.95$ ) nor the EM fungal colonization of yellow birch (40 to 60%;  $F = 0.94$ ,  $p = 0.43$ ) or red oak seedlings (30 to 43%;  $F = 2.02$ ,  $p = 0.19$ ). Hypha of EM fungi observed on EM tree roots were less than 5 cm long. Mycorrhizal fungal colonization was not correlated to tree height ( $p > 0.19$ ) and diameter ( $p > 0.22$ ).

## 4. Discussion

### 4.1. AM vs. EM tree species response

We hypothesized a greater response from EM tree seedlings than AM tree seedlings and no effect of soil provenance because many mycorrhizal fungi are not host specific (van der Heijden and Horton, 2009) and because AM fungi should be more abundant than EM fungi due to the presence of grasses in the abandoned old field that we studied. As expected, forest soil inoculum had more effects on EM than on AM tree species. On the one hand, only few temporary, weak or divergent effects were observed for the growth

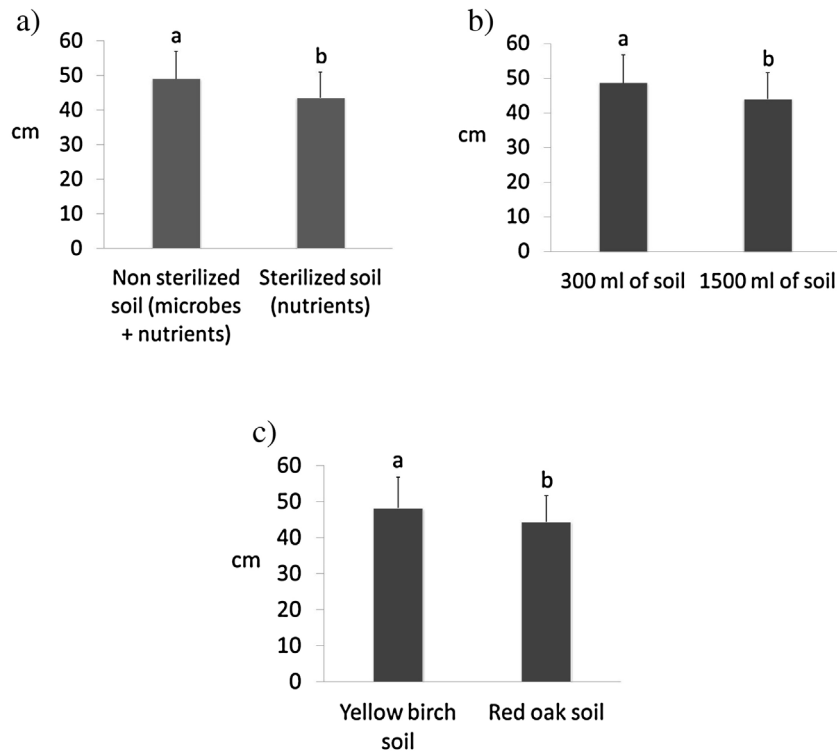


Fig. 4. Height (mean  $\pm$  sd) of red oak seedlings after one growing season (fall 2012) according to a) sterilization; b) soil quantity; and c) soil type; (n=120).

of both AM tree species. On the other hand, yellow birch and red oak seedlings responded positively to the inoculation of live soil compared to sterilized soil in the first growing season, suggesting a possible microbial feedback. However, those first year seedlings did not have better growth than control seedlings. Only birch seedlings receiving 1500 ml of live soil collected under the trees of the other EM species (red oak) had a greater diameter than control seedlings after three growing seasons. This effect could be driven by microbes since birch seedlings inoculated with nutrient poor sterilized red oak soil were smaller than control seedlings after one growing season.

The increase in yellow birch diameter was noted despite similar rates of mycorrhizal infection measured in the third growing season. In fact, adding forest soil did not influence mycorrhizal infection of any AM or EM tree species. The number of seedlings excavated might have been too few (5 per species per treatment) to detect an effect, especially since, in some cases, mycorrhizal fungal colonization varied considerably within a treatment. Furthermore, tree seedlings produced in nurseries can be naturally colonized by spore inoculation, but tree seedlings growing in forests may have more and different mycorrhizal fungal species (Gagnon et al., 1991; Southworth et al., 2009). As we conducted our study as a restoration project to test whether forest soil inoculation would affect tree survival and growth, we did not identify the mycorrhizal fungal species. Also, we did not measure the mycorrhizal fungal colonization within the first year. The differences in mycorrhizal infection between soil treatments might be greater after one season of growth and then fade with time (Dickie et al., 2007). This could explain the first year effects identified on EM tree species which benefited from live forest soil inoculation compared to the addition of sterilized soil.

The greater responses of EM tree species than AM tree species are consistent with the literature. First, the density of AM fungi increases with time since abandonment until a shift occurs in the plant community from herbaceous vegetation to woody ectomycorrhizal hosts (Johnson et al., 1991). Thus, AM fungi are suspected

to be more abundant than EM fungi in old fields. Second, EM tree species usually benefit more from mycorrhizal fungal associations than AM tree species, because exchange between mycorrhizal fungi and trees are greater for EM species than AM species (van der Heijden and Horton, 2009; Bradford, 2014). Third, soil nutrient availability in the field may have been more beneficial to EM fungi than AM fungi. Mycorrhizal fungal colonization increases and provides more benefits for seedlings in nutrient-limited environments, particularly in soils with low P availability in the case of AM species and in soils with low N availability in the case of EM species (Jonsson et al., 2001; Wiseman and Wells, 2005; Reynolds et al., 2005; Smith and Read, 2008). Although the low organic C and total N levels of the agricultural soil was expected, we did not anticipate such a high level of extractable P (i.e. 68 mg P kg<sup>-1</sup>, whereas Sawyer et al. (2002) proposed that relative yields of most crops are expected to be optimal between 26 and 35 mg P kg<sup>-1</sup>, Mehlich III). As a whole, the low molar N:P ratio of the agricultural soil suggests a low availability in N relative to P. This may explain the few positive effects of forest soil inoculation, principally for AM tree species, as well as the lack of positive correlations between mycorrhizal fungal infection and tree growth. Furthermore, when a productive soil has low C levels, plant growth can be slightly reduced because the C demand of mycorrhizal fungi and mycorrhizal associations can shift from a mutualistic to a parasitic relationship (e.g. Johnson et al., 1997).

The study site was covered by AM grass and clover species. Since AM fungi are not host specific (Klironomos, 2000; van der Heijden and Horton, 2009), AM tree seedlings may have been colonized by AM fungi present in the agricultural field abandoned for more than 15 years. In addition, the generalist red ash and red maple species are well adapted to these environments as they are among the first to invade abandoned fields in our area (D'Orangeville et al., 2008). Open fields may contain ectomycorrhizal propagules, but ectomycorrhizas (EM) are more abundant and diverse in forests (Berman and Bledsoe, 1998). Our results suggest that restoration of EM tree species in abandoned agricultural fields

may benefit more from forest soil additions than AM tree species. Similarly, the growth of an AM tree species (western red cedar seedlings) was improved by AM mycorrhizal inoculum when planted in ectomycorrhizal-dominated hemlock-amabilis fir clearcuts (Guichon, 2015).

#### 4.2. The effects of soil provenance

Contrary to our initial hypothesis, soil provenance somewhat influenced the results such as a positive effect of red oak soil on yellow birch seedlings. Conversely, one EM tree species responded negatively to the addition of forest soil collected under conspecific trees. Red oak seedlings inoculated with red oak soil were smaller than those inoculated with yellow birch soil and control seedlings. This negative feedback on red oak seedling height was also observed when sterilized red oak soil was added, probably due to its low P content, 8 times lower than that of the agricultural field soil, as well as lower exchangeable Ca, base saturation and pH (<5). The negative effect observed in the first year following the inoculation of live red oak soil persisted through the second growing season. In addition to its lower nutrient availability, it may be due to its pathogens because seedlings inoculated with 1500 ml of live red oak soil were smaller than those in the control, whereas those that had received 1500 ml of sterilized oak soil were no longer different from the control in the second year of growth.

This negative conspecific effect on red oak height was not as strong as what Packer and Clay (2000) observed for the survival of *Prunus serotina* seedlings grown in pots filled with soils collected under conspecific trees and affected by soil pathogens *Pythium* spp. Our result, observed on one out of 4 species, provides only weak support for the Janzen–Connell hypothesis (JCH). The JCH stipulates that mature individuals of a same tree species increase the abundance in their vicinity of common enemies potentially inducing a negative feedback on seedling survival and growth (Janzen, 1970; Connell, 1971). The effect is considered to be mainly driven by soil microbes (Bever et al., 2010; Mangan et al., 2010). Conversely, positive interactions due to ectomycorrhizal fungi were observed on seedlings grown in soils collected under conspecific trees (Dickie et al., 2007; O'Brien et al., 2011). In our experiment, the absence of significant effects for some tree species may be related to a balance between the negative effects due to soil pathogens and the positive effects due to mutualist species such as mycorrhizal fungi and N-fixing bacteria.

#### 4.3. The effects of soil inoculum quantity, nutrient availability, and time

Generally, stronger (positive or negative) effects were observed with 1500 ml of forest soil inoculum instead of 300 ml. The impact of soil inoculum quantity on tree growth could be explained by the level of nutrient availability found in the forest soils compared to the agricultural field soil. For example, the negative effects observed on EM tree growth when sterilized soil was added could be due to the lower nutrient availability in EM forest soils, i.e. when more forest soil was added, seedling roots likely had lower access to nutrients than the field soil due to a “dilution” effect. In contrast, red maple seedlings inoculated with 1500 ml of live red ash forest soil, which has higher pH, Ca levels and base saturation than the agricultural soil, were taller after one season of growth than those that received only 300 ml.

A slight increase in red ash diameter following the addition of 1500 ml of live red maple soil or the addition of sterilized red ash soil was also observed. In these cases, growth responses may have been influenced by P levels in the added soils. Red maple soil (sterilized or not) has high levels of extractable P (i.e. 40 mg kg<sup>-1</sup>) and sterilized red ash soil (23 mg kg<sup>-1</sup>, near optimal range)

contains more extractable P than the live red ash soil (8 mg kg<sup>-1</sup>, within very low range) (see Sawyer et al. (2002) for reference P levels (Mehlich III) for most crops). The difference in P levels between live and sterilized red ash soil could be related to gamma irradiation which is highly effective for sterilization, but may have some effects on soil chemical properties such as an increase in exchangeable soil P levels (McNamara et al., 2003). The impact of gamma irradiation on forest soil was higher for red ash soil probably due to the high activity of earthworms and microbes in this Melanic Brunisol. On the one hand, following soil sterilization the dead earthworms and microbes decomposed and thus likely increased soil P availability by creating a short-term pulse. On the other hand, microbial recolonization of the soil will be required to promote mobilization of bound P reserves.

The effect of soil inoculum quantity varied over time for EM tree growth. After one growing season, negative effects on birch and oak seedlings were observed when 1500 ml of live soil was added, but after three growing seasons, those seedlings had a larger diameter. Dickie et al. (2007) also observed that oak seedling responses varied with the quantity of forest soil added as well as time. They showed that first year seedlings receiving 2 l of forest soil (instead of 200 ml or 0 ml) had a higher EM infection rate but a lower shoot biomass, while third year seedlings had similar EM infection but a higher leaf mass. The effect on initial aerial growth may be due to resource allocation to roots and mycorrhizas.

Most effects observed after the first growing season did not persist. Generally, by the third year, tree growth was similar in all treatments. In contrast to pot studies, inoculated microbes could have been outcompeted by field microbes. The lack of persistent effects may also be due to tree roots extending with time beyond the area where forest soil was added. Mechanical site preparation effects on EM tree seedling growth have been found to disappear when roots grew beyond the modified patches in undisturbed soils covered by AM herbaceous plants (Simard et al., 2003). In our study, third year growth effects were only observed for yellow birch seedlings, the species with the smallest root system (A. St-Denis, pers. obs.), previously inoculated with 1500 ml of live red oak soil.

## 5. Conclusions

Adding live forest soil to tree seedlings planted in abandoned agricultural fields did not affect tree survival. Some positive effects of forest soil inoculation were observed for EM tree growth compared to the addition of sterilized soil whereas few effects were observed on AM tree growth. The more important effect was an increase in diameter after three growing seasons for yellow birch seedlings inoculated with 1500 ml of red oak soil. Only one species responded negatively to the addition of forest soil collected under conspecific trees. Future research should evaluate the reasons behind the negative effect of conspecific soil on red oak growth by isolating and identifying soil pathogens. We suggest that the lack of persistent effects of forest soil inoculation on tree seedlings was due to (1) the possible presence of mycorrhizal fungal spores in agricultural soil and in the seedling potting-mix; (2) the conflicting positive and negative effects of adding soil containing both possible beneficial and antagonistic microorganisms; (3) the low organic C and high P levels of the agricultural soil; and (4) the nutrient dilution effect of adding a soil inoculum with lower nutrients to the bulk soil with higher nutrient availability. Because the effects of facilitation tend to increase as site fertility decreases, notably in soils with low P availability in the case of AM species (Smith and Read, 2008; Brooker et al., 2008), a similar experiment may show more benefits if it was repeated on soils with lower P availability (or lower nutrient availability in general) or on soils with low water retention capacity (ex. sand or loamy



sand soils with a very low clay fraction). Nevertheless, this study supports the idea that planting EM tree species in abandoned agricultural field soils could benefit more from the inoculation of forest soil microbes than AM tree species.

## Acknowledgements

We are grateful to three anonymous reviewers for their comments and advice on the manuscript. We thank J.A. Fortin for advice at the beginning of our experiment and S. Guichon for laboratory guidance. We acknowledge the assistance of personnel at the City of Montreal Nursery (in particular M. Gaudet). We thank S. Daigle for advice on data analyses, the Laurentian Forestry Centre (D. Paré) for soil analyses, as well as many field and lab assistants. Funding was provided by the National Science and Engineering Research Council in Canada (NSERC, Ottawa, Canada), the Fonds de recherche du Québec – Nature et technologies and NSERC/Hydro-Québec research Chair on tree growth by NSERC-Hydro-Québec Industrial Research Chair on Control of Tree Growth (FQRNT, Québec, Canada), WSP Canada Inc. and the NSERC/Hydro-Québec research Chair on tree growth.

## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.apsoil.2016.12.008>.

## References

- Alguacil, M.M., Lumini, E., Roldan, A., Salinas-Garcia, J.R., Bonfante, P., Bianciotto, V., 2008. The impact of tillage practices on arbuscular mycorrhizal fungal diversity in subtropical crops. *Ecol. Appl.* 18, 527–536.
- Amaranthus, M.P., Perry, D.A., 1987. Effect of soil transfer on ectomycorrhiza formation and the survival and growth of conifer seedlings on old: nonreforested clear-cuts. *Can. J. For. Res.* 17, 944–950.
- Bélanger, N., Holmden, C., Courchesne, F., Cote, B., Hendershot, W.H., 2012. Constraining soil mineral weathering  $^{87}\text{Sr}/^{86}\text{Sr}$  for calcium apportionment studies of a deciduous forest growing on soils developed from granitoid igneous rocks. *Geoderma* 185, 84–96.
- Berman, J.T., Bledsoe, C.S., 1998. Soil transfers from valley oak (*Quercus lobata* Nee) stands increase ectomycorrhizal diversity and alter root and shoot growth on valley oak seedlings. *Mycorrhiza* 7, 223–235.
- Bever, J.D., Dickie, I.A., Facelli, E., Facelli, J.M., Klironomos, J., Moora, M., Rillig, M.C., Stock, W.D., Tibbett, M., Zobel, M., 2010. Rooting theories of plant community ecology in microbial interactions. *Trends Ecol. Evol.* 25, 468–478.
- Borchers, S.L., Perry, D.A., 1990. Growth and ectomycorrhiza formation of Douglas-fir seedlings grown in soils collected at different distances from pioneering hardwoods in southwest Oregon clear-cuts. *Can. J. For. Res.* 20, 712–721.
- Bradford, M.A., 2014. Ecology: good dirt with good friends. *Nature* 505, 486–487.
- Brooker, R.W., Maestre, F.T., Callaway, R.M., Lortie, C.L., Cavieres, L.A., Kunstler, G., Liancourt, P., Tielbörger, K., Travis, J.M.J., Anthelme, F., Armas, C., Coll, L., Corcket, E., Delzon, S., Forey, E., Kikvidze, Z., Olofsson, J., Pugnaire, F., Quiroz, C.L., Saccone, P., Schippers, K., Seifan, M., Touzard, B., Michalet, R., 2008. Facilitation in plant communities: the past, the present, and the future. *J. Ecol.* 96, 18–34.
- Connell, J.H., 1971. On the role of natural enemies in preventing competitive exclusion in some marine animals and in rain forest trees. In: den Boer, P.J., Gradwell, G.R. (Eds.), *Dynamics of Populations*. PUDOC, Wageningen, pp. 298–312.
- D'Orangeville, L., Bouchard, A., Cogliastro, A., 2008. Post-agricultural forests: landscape patterns add to stand-scale factors in causing insufficient hardwood regeneration. *Forest Ecol. Manag.* 255, 1637–1646.
- Dick, R.P., 1992. A review: long-term effects of agricultural systems on soil biochemical and microbial parameters. *Agr. Ecosyst. Environ.* 40, 25–36.
- Dickie, I.A., Reich, P.B., 2005. Ectomycorrhizal fungal communities at forest edges. *J. Ecol.* 93, 244–255.
- Dickie, I.A., Montgomery, R.A., Reich, P.B., Schnitzer, S.A., 2007. Physiological and phenological responses of oak seedlings to oak forest soil in the absence of trees. *Tree Physiol.* 27, 133–140.
- Dulmer, K.M., LeDuc, S.D., Horton, T.R., 2014. Ectomycorrhizal inoculum potential of northeastern US forest soils for American chestnut restoration: results from field and laboratory bioassays. *Mycorrhiza* 24, 65–74.
- Ens, J., Farrell, R.E., Bélanger, N., 2013. Effects of edaphic conditions on site quality for *Salix purpurea* 'Hotel' plantations across a large climatic gradient in Canada. *New For.* 44, 899–918.
- Environment Canada, 2015. Canadian Climate Normals 1981–2010 Environment Canada. (accessed 15.05.15) [http://climate.weather.gc.ca/climate\\_normals/](http://climate.weather.gc.ca/climate_normals/).
- Fitter, A., Garbaye, J., 1994. Interactions between mycorrhizal fungi and other soil organisms. *Plant Soil* 159, 123–132.
- Gagnon, J., Langlois, C.G., Garbaye, J., 1991. Growth and ectomycorrhiza formation of container-grown red oak seedlings as a function of nitrogen fertilization and inoculum type of *Laccaria bicolor*. *Can. J. For. Res.* 21, 966–973.
- Guichon, S.H.A., 2015. Mycorrhizal fungi: unlocking their ecology and role for the establishment and growth performance of different conifer species in nutrient-poor coastal forests. PhD thesis. University of British Columbia, Vancouver.
- Harris, J., 2009. Soil microbial communities and restoration ecology: facilitators or followers? *Science* 325, 573–574.
- Helgason, T., Daniell, T.J., Husband, R., Fitter, A.H., Young, J.P.W., 1998. Ploughing up the wood-wide web? *Nature* 394, 431.
- Helm, D.J., Carling, D.E., 1993. Use of soil transfer for reforestation on abandoned mined lands in Alaska: II. Effects of soil transfers from different successional stages on growth and mycorrhizal formation by *Populus balsamifera* and *Alnus crispa*. *Mycorrhiza* 3, 107–114.
- Hendershot, W.H., Lalonde, H., Duquette, M., 2007. Ion exchange and exchangeable cations. In: Carter, M.R., Gregorich, E.G. (Eds.), *Soil Sampling and Methods of Analysis*. 2nd ed. CRC Press, Boca Raton, pp. 197–206.
- Heneghan, L., Miller, S.P., Baer, S., Callahan, M.A., Montgomery, J., Pavao-Zuckerman, M., Rhoades, C.C., Richardson, S., 2008. Integrating soil ecological knowledge into restoration management. *Restor. Ecol.* 16, 608–617.
- Hoeksema, J.D., Chaudhary, V.B., Gehring, C.A., Johnson, N.C., Karst, J., Koide, R.T., Pringle, A., Zabinski, C., Bever, J.D., Moore, J.C., Wilson, G.W.T., Klironomos, J.N., Umbanhowar, J., 2010. A meta-analysis of context-dependency in plant response to inoculation with mycorrhizal fungi. *Ecol. Lett.* 13, 394–407.
- IRDA, 2008. *Études pédologiques* Institut de recherche et de développement en agroenvironnement (IRDA). (accessed 12.12.12) <http://www.irda.qc.ca/fr/Études-pédologiques>.
- IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, Update 2015. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. World Soil Resources Reports No. 106. FAO, Rome.
- Janzen, D.H., 1970. Herbivores and the number of tree species in tropical forests. *Am. Nat.* 104, 501–528.
- Johnson, N.C., Zak, D.R., Tilman, D., Pfleger, F.L., 1991. Dynamics of vesicular-arbuscular mycorrhizae during old field succession. *Oecologia* 86, 349–358.
- Johnson, N.C., Graham, J.H., Smith, F.A., 1997. Functioning of mycorrhizal associations along the mutualism–parasitism continuum\*. *New Phytol.* 135, 575–585.
- Jonsson, L.M., Nilsson, M.C., Wardle, D.A., Zackrisson, O., 2001. Context dependent effects of ectomycorrhizal species richness on tree seedling productivity. *Oikos* 93, 353–364.
- Klironomos, J.N., 2000. Host-specificity and functional diversity among arbuscular mycorrhizal fungi. In: Bell, C.R., Brylinski, M., Johnson-Green, P. (Eds.), *Microbial Biosystems: New Frontiers*. Proceedings of the 8th International Symposium of Microbial Ecology. Atlantic Canada Society for Microbial Ecology, Halifax, pp. 845–851.
- Kroetsch, D., Wang, C., 2008. Particle size distribution. In: Carter, M.R., Gregorich, E.G. (Eds.), *Soil Sampling and Methods of Analysis*. 2nd ed. CRC Press, Boca Raton, pp. 713–726.
- Kropp, B.R., Langlois, C.G., 1990. Ectomycorrhizae in reforestation. *Can. J. For. Res.* 20, 438–451.
- Lal, R., 2004. Soil carbon sequestration impacts on global change and food security. *Science* 304, 1623–1627.
- Mangan, S.A., Edward, A.H., Bever, J.D., 2010. Specificity between Neotropical tree seedlings and their fungal mutualists leads to plant–soil feedback. *Ecology* 91, 2594–2603.
- McGonigle, T.P., Miller, M.H., Evans, D.G., Fairchild, G.L., Swan, J.A., 1990. A new method which gives an objective measure of colonization of roots by vesicular-arbuscular mycorrhizal fungi. *New Phytol.* 115, 495–501.
- McNamara, N.P., Black, H.I.J., Beresford, N.A., Parekh, N.R., 2003. Effects of acute gamma irradiation on chemical, physical and biological properties of soils. *Appl. Soil Ecol.* 24, 117–132.
- Niinemetts, Ü., Valladares, F., 2006. Tolerance to shade, drought, and waterlogging of temperate Northern Hemisphere trees and shrubs. *Ecol. Monogr.* 76, 521–547.
- O'Brien, M.J., Gomola, C.E., Horton, T.R., 2011. The effect of forest soil and community composition on ectomycorrhizal colonization and seedling growth. *Plant Soil* 341, 321–331.
- Packer, A., Clay, K., 2000. Soil pathogens and spatial patterns of seedling mortality in a temperate tree. *Nature* 404, 278–281.
- Pinno, B.D., Thomas, B.R., Bélanger, N., 2010. Predicting the productivity of a young hybrid poplar clone under intensive plantation management in northern Alberta, Canada using soil and site characteristics. *New For.* 39, 89–103.
- Reynolds, H.L., Hartley, A.E., Vogelsang, K.M., Bever, J.D., Schultz, P.A., 2005. Arbuscular mycorrhizal fungi do not enhance nitrogen acquisition and growth of old-field perennials under low nitrogen supply in glasshouse culture. *New Phytol.* 167, 869–880.
- Rosenzweig, S.T., Carson, M.A., Baer, S.G., Blair, J.M., 2016. Changes in soil properties, microbial biomass, and fluxes of C and N in soil following post-agricultural grassland restoration. *Appl. Soil Ecol.* 100, 186–194.
- Sawyer, J.E., Mallarino, A.P., Killorn, R., Barnhart, S.K., 2002. General Guide for Crop Nutrient Recommendations in Iowa Pm-1688. Iowa State University Extension, Ames, IA.
- Schwartz, M.W., Hoeksema, J.D., Gehring, C.A., Johnson, N.C., Klironomos, J.N., Abbott, L.K., Pringle, A., 2006. The promise and the potential consequences of the global transport of mycorrhizal fungal inoculum. *Ecol. Lett.* 9, 501–515.

- Simard, S.W., Jones, M.D., Durall, D.M., Hope, G.D., Stathers, R.J., Sorensen, N.S., Zimonick, B.J., 2003. Chemical and mechanical site preparation: effects on *Pinus contorta* growth physiology, and microsite quality on steep forest sites in British Columbia. *Can. J. For. Res.* 33, 1495–1515.
- Smith, S.E., Read, D.J., 2008. *Mycorrhizal Symbiosis*, 3rd ed. Academic Press, New York, NY.
- Soil Classification Working Group, 1998. *The Canadian System of Soil Classification*, 3rd ed. Research Branch, Agricultural and Agri-Food Canada, Publication 1646; NRC Research Press, Ottawa, ON.
- Southworth, D., Carrington, E.M., Frank, J.L., Gould, P., Harrington, C.A., Devine, W.D., 2009. Mycorrhizas on nursery and field seedlings of *Quercus garryana*. *Mycorrhiza* 19, 149–158.
- Torrey, J.G., 1992. Can plant productivity be increased by inoculation of tree roots with soil microorganisms? *Can. J. For. Res.* 22, 1815–1823.
- Trappe, J.M., 1977. Selection of fungi for ectomycorrhizal inoculation in nurseries. *Annu. Rev. Phytopathol.* 15, 203–222.
- Urgiles, N., Strauß, A., Loján, P., Schüßler, A., 2014. Cultured arbuscular mycorrhizal fungi and native soil inocula improve seedling development of two pioneer trees in the Andean region. *New For.* 45, 859–874.
- Vierheilig, H., Coughlan, A.P., Wyss, U., Piché, Y., 1998. Ink and vinegar: a simple staining technique for arbuscular-mycorrhizal fungi. *Appl. Environ. Microbiol.* 64, 5004–5007.
- Wiseman, P.E., Wells, C., 2005. Soil inoculum potential and arbuscular mycorrhizal colonization of *Acer rubrum* in forested and developed landscapes. *J. Arboric.* 31, 296–302.
- Ziadi, N., Sen Tran, T., 2007. Melhich 3 extractable elements. In: Carter, M.R., Gregorich, E.G. (Eds.), *Soil Sampling and Methods of Analysis*. 2nd ed. CRC Press, Boca Raton, pp. 81–88.
- van der Heijden, M.G.A., Horton, T.R., 2009. Socialism in soil? The importance of mycorrhizal fungal networks for facilitation in natural ecosystems. *J. Ecol.* 97, 1139–1150.