Soil Quality and Tree Growth in Plantations of Forest and Agricultural Origin

Inès Nelly Moussavou Boussougou
Suzanne Brais*
Francine Tremblay
Chaire AFD
Univ. du Québec en Abitibi-Témiscamingue
445 blv Université
Rouyn-Noranda, QC, Canada J9X 5E4

Stephanne Gaussiran
Cegep de l'Abitibi-Témiscamingue
425 boulevard du Collège
Rouyn-Noranda, QC, Canada J9X 5E5

Soil organic matter loss and increased soil compaction have been identified as the factors most likely to directly impact tree growth in managed forests. We compared the soil quality of plantations established on former agricultural lands ($n = 20$) with plantations established following clear cutting of native forests ($n = 20$). Half of the plantations had been planted with jack pine (*Pinus banksiana* Lamb.) and half with white spruce [*Picea glauca* (Moench) Voss], 9 to 27 yr before the study. The old field plantations had lower (at 0–10 and 10–20 cm) mineral soil macroporosity and higher field capacity than forest plantations, indicating more severe soil compaction. The old field plantations, however, also had higher soil C content, raising the permanent wilting point and canceling compaction effects on the available water holding capacity. An indicator of organic matter quality, namely the potential net mineralization per unit of soil Kjeldahl N, was lower in the old fields. Species also affected soil quality indicators—with lower values of macroporosity and higher values of field capacity observed under white spruce. Despite significant differences in soil conditions, no significant effect ($P < 0.05$) of plantation origin on tree growth could be found. Old fields can support productive plantations of both species.

Changes in demographics and land utilization in Canadian rural regions as well as C sequestration objectives under the Kyoto accord (van Kooten et al., 2000; White and Kurz, 2005) are creating a socioeconomic environment favorable to reforestation (White and Kurz, 2005). This is the case for the Abitibi-Témiscamingue region, in northwestern Quebec, where more than 100,000 ha of abandoned agricultural land could be put back into forest production (Syndicat des Producteurs de Bois de l'Abitibi-Témiscamingue, 2000). Old field reforestation raises a number of interesting questions, however, regarding soil quality for tree growth, as decreases in soil organic matter pools and soil compaction induced by land clearing and cultivation (Murty et al., 2002; Pagliai et al., 2003) are considered the mechanisms most likely to directly impact tree growth in managed forests (Powers et al., 1990).

Changes in soil structure induced by the circulation of heavy equipment have been well documented for agricultural (Servadio et al., 2001; Pagliai et al., 2003; Hamza and Anderson, 2005) as well as forest lands (Greacen and Sands, 1980; Corns, 1988; Brais and Camiré, 1998). Compacted soils are characterized by higher bulk density, greater root penetration resistance (Gomez et al., 2002), higher microporosity (Shestak and Busse, 2005), increased water retention (Gemtos and Lellis, 1997), and lower air-filled porosity (Gomez et al., 2002; McNabb et al., 2001) than uncompacted soils. Differences in the frequency of entry and traffic patterns between forestry and agricultural operations may lead to differences in compaction severity and intensity and the area affected (Sveistrup et al., 2005). In any case, the relationships between severity of compaction and plantation growth can be tenuous because compaction may improve water retention (Gomez et al., 2002) and growth (Brais, 2001) while confounding factors such as a reduction of

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*Corresponding author (suzanne.brais@uqat.ca)..

plant competition in traffic trails may mask potential negative effects (Brais, 2001; Fleming et al., 2006).

Following harvest, surficial forest soil organic matter content can decrease (Johnson et al., 1991; Brais et al., 2002). This reduction may be caused by an increase in the decomposition rate and reduced inputs or by a redistribution of organic matter within the soil profile (Covington, 1981; Johnson et al., 1991). Differences between uncut and harvested stands were still apparent in the study area 15 yr after harvesting (Brais et al., 2002). Land clearing and soil cultivation for agricultural purposes also lead to large decreases in mineral soil organic matter (Murty et al., 2002; Franzluebbers, 2002). Reforestation, however, may promote soil C accumulation within the forest floor and upper mineral soil horizons (Richter et al., 1999). Differences in soil organic matter quality between agricultural and forest soils caused by differences in litter type are also expected (Hu et al., 1997).

Comparisons between agricultural and forest soils are challenging because historical records of land management are often lacking and differences in practices within similar land utilization are the rule rather than the exception. The Abitibi region of northwestern Quebec, however, was opened to colonization only recently (in 1911, with the construction of the transcontinental railway), agriculture was extensive rather than intensive (Tabi et al., 1990), and cultivation was of short duration in some parts of the region. Controlling for soil parent material and moisture regime using ecological classifications allows meaningful comparisons between forest plantations established after forest harvesting and plantations established on former agricultural lands.

The objectives of the study were to compare soil quality and the growth of jack pine and white spruce plantations established following clear-cutting of native forests with plantations established on former agricultural lands or old fields using indices of soil quality (Adams et al., 1998). Jack pine and white spruce are commercial boreal species with contrasting growth requirements (Dang and Cheng, 2004). White spruce is shade tolerant (Kneeshaw et al., 2006), has a high nutrient requirement, and grows better on mesic sites (Landhausser et al., 2003), while jack pine is shade intolerant and can perform well on nutrient- and water-limited sites (Hangs et al., 2003). We hypothesized that (i) soils from old field plantations would be more compacted than soils from forest plantations, (ii) soils from old field plantations would have lower organic C concentrations than soils from forest plantations, and (iii) both white spruce and jack pine would grow more rapidly in forest plantations but that jack pine growth would be less sensitive to soil conditions than white spruce.

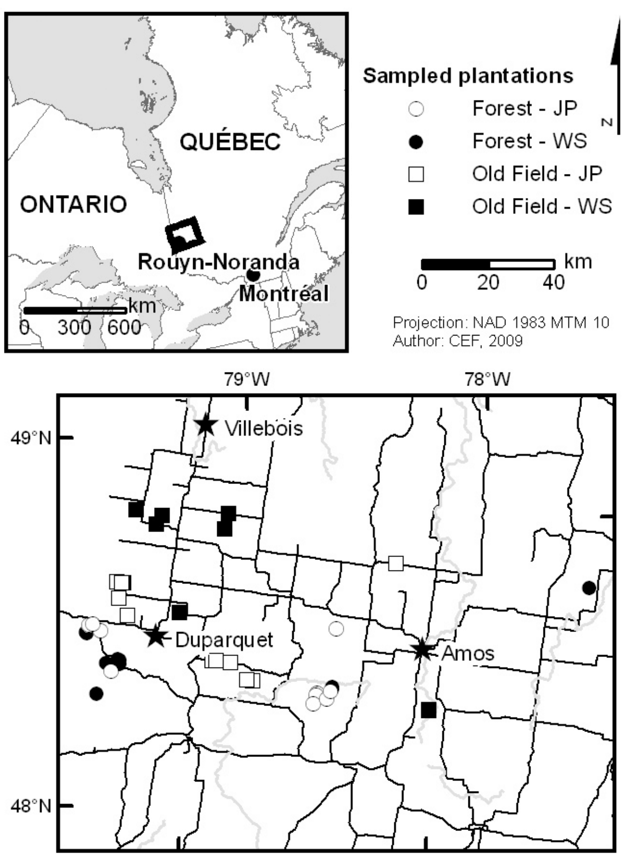

Fig. 1. Studied area and sampled site locations of jack pine (JP) and white spruce (WS) plantations.

MATERIALS AND METHODS

Study Area

The study area is located between 48 and 49° N and between 77 and 80° W (Fig. 1), in the Clay Belt region of northeastern Ontario and northwestern Quebec (Canada). The climate is continental, with a mean annual temperature of 1.2°C and a precipitation of 918 mm (Environment Canada, 2004 [www.climate.weatheroffice.ec.gc.ca; verified 6 Mar. 2010]), about half of which falls as rain between May and September inclusively. The region is situated at the southern fringe of the boreal forest and is characterized by forests of balsam fir [*Abies balsamea* (L.) Mill.], white birch (*Betula papyrifera* Marshall), and white spruce stands on mesic sites. It is part of the Precambrian Shield and its topography is generally gentle with short slopes. Most of the bedrock is covered with Quaternary deposits. The studied soils have evolved from fine clayey to fine loamy textured glaciolacustrine deposits formed by sedimentation at the bottom of glacial Lake Barlow-Ojibway (Veillette et al., 2000) under fresh to moist moisture regimes (Brais and Camiré, 1992) and are classified as Gray Luvisols or Boralfs (Agriculture Canada Expert Committee on Soil Survey, 1998).

With the construction of the Canadian transcontinental railway at the beginning of the 20th century, large tracts of land were cleared by settlers for agricultural purposes. As forestry and mining industries gained in importance, fields were abandoned (Vincent, 1995) and later converted to forest plantations. Fodder production and pasture were and are still the most common practices on agricultural land in the area (Tabi et al., 1990). Public forests occupy 93% of the land base area and forest harvesting is still mainly conducted in natural forests. Upland sites, close to towns, are logged during the summer. In the early 1980s, regeneration by plantation was just starting in Quebec; before this, different site preparation techniques were used—on clayey sites, mostly light scarification or winter windrowing. In old fields, no site preparation was required unless shrubs were abundant. In that case, the sites were also windrowed.

Field Methods

Potential plantations were first localized using the forest inventory database of the Quebec Natural Resources Ministry, which provides information such as stand type, surface deposit, moisture regime, and slope. Forest agencies were also contacted to find plantations on private agricultural land. Ten white spruce and 10 jack pine plantations on mesic (Brais and Camiré, 1992) clayey soils were located in each environment (plantation origin: old field or forest) for a total of 40 plantations. Plantation sizes ranged from 4 to 20 ha.

In each plantation and on two perpendicular transects, three circular sampling plots (100 m^2) were systematically located 50 m apart from each other. In each plot, three dominant trees were measured for total height. Trees were cored for plantation age determination. All trees with a diameter at breast height >1 cm were numbered.

In each plot, two undisturbed soil samples (100 cm^3) were taken with a double-cylinder soil sampler from the center of the 0- to 10- and 10- to 20-cm mineral soil layers for bulk density, macroporosity, and field capacity measurements. Two bulk soils samples were also taken for biochemical and permanent wilting point analyses and kept in a refrigerator (4°C) until processed (within a week). Finally, one sample was collected at the 25-cm depth for soil texture determination.

Soil Physical Properties

Soil texture was estimated by the Bouyoucos hydrometer method (Kroetsch and Wang, 2008). Soil structural properties were assessed according to Klute (1986) and Cassel and Nielsen (1986). Undisturbed soil samples (5-cm diameter, 100 cm^3) were brought to saturation under vacuum and weighed (W_1, macroporosity). Samples were set on the porous surface of a sand-box apparatus (Eijkelkamp Agrisearch Equipment, Giesbeek, the Netherlands), and brought to equilibrium at a tension of −10 kPa (field capacity). The samples were weighed again (W_2), then oven dried (105°C for 48 h) and weighed one more time (W_3). Macroporosity, bulk density (BD), and field capacity (FC) were estimated with the following:

$$\text{Macroporosity}(\%)=\frac{W_1-W_2}{100\ \text{cm}^3}100$$

$$\text{BD}=\frac{W_3}{100\ \text{cm}^3}$$

$$\text{FC}(\%\ \text{w/w})=\frac{W_2-W_3}{W_3}100$$

Bulk soil subsamples were dried and sieved (2 mm) before being submerged and brought to equilibrium with a tension of −1500 kPa (permanent wilting point) using a pressure membrane apparatus (Soilmoisture Equipment Corp., Santa Barbara, CA) and weighed (W_4). The samples were dried for 48 h at 105°C and weighed again (W_5). The permanent wilting point (PWP) and available water holding capacity (AWHC) were estimated with the following:

$$\text{PWP}(\%\ \text{w/w})=\frac{W_4-W_5}{W_5}100$$

$$\text{AWHC}(\%\ \text{w/w})=\text{FC}-\text{PWP}$$

Soil Biochemical Properties

Ground samples (250 μm) were analyzed for Kjeldahl N, including NO_2^- and NO_3^- (Bremner and Mulvaney, 1982), and for organic C by wet oxidation (Yeomans and Bremner, 1988). To assess the net potential N availability, mineral soil samples (5 g) were incubated under anaerobic conditions at 23°C for 2 wk in 50 mL of deionized water (Bundy and Meisinger, 1994). The samples were then extracted with 50 mL of 2 mol L^{-1} KCl. Initial NH_4^+ concentrations were determined on 5-g subsamples extracted with 100 mL of 1 mol L^{-1} KCl. The initial concentrations were subtracted from the final concentrations and the values were reported on a total-N basis as an index of organic matter quality and on a soil volume basis (g m^{-3}) using bulk density values.

Statistical Analyses

All statistical analyses used the MIXED, CORR, and MEANS procedures of SAS (SAS Institute, 2004). To determine whether soil clay content could be a confounding cause behind the observed effects of plantation origin or species, linear correlations between soil characteristics and clay content were assessed (n = 40). For the same reason, correlations were also conducted between soil characteristics and plantation age. Because of differences in the age range of the jack pine and white spruce plantations, however, separate analyses (n = 20) were done for each species to avoid the confounding effects of age and species.

The effects of plantation species and origin on the soil characteristics were tested by means of a mixed linear model (Littell et al., 2006), with sampling plots (n = 3) nested within plantations (n = 40). Both factors were treated as random effects, while species and plantation origin were treated as fixed effects. The significance of species, plantation origin, and their interaction was based on a Type 1 test of the hypothesis.

The effects of plantation age and origin on tree height were assessed by means of mixed linear models. Tree, plot, and plantation were treated as random effects, with individual trees (n = 3) nested within sampling plots (n = 3), and plots nested within plantations (n = 20). Age and plantation origin were treated as fixed effects. Preliminary scatter plots of tree height as a function of tree age indicated a strong linear relationship. Because tree growth was expected to show a polymorphic relationship with time (Thrower, 1987), however, a second-order polynomial model was first tested. To test for differences in growth patterns with time between plantation origins, the interaction between origin and age or origin and age squared were also included in the model. For the sake of simplicity, quadratic effects were removed from the models when not significant. The correlation between the observed and predicted values was used as a measure of explained variance (R^2).

For all regression models, Studentized residuals' normality and distribution in relation to the predicted values were visually assessed. Variables with residuals showing a horn-shaped pattern were logarithmically transformed.

RESULTS

Plantation Origin, Age, and Inherent Soil Conditions

All plantations were located on clayey to heavy clayey soils, with clay content ranging from 37 to 84% (Table 1; Fig. 2). No obvious bias was found in the range of clay contents observed for plantation origin or species (Fig. 2). Some of the jack pine

Table 1. Characteristics of sampled old field and forest plantations in the Clay Belt region of northwestern Quebec.

Species	Origin	n	Soil texture	Age	Commercial species density	Total tree density	Total height
				yr	stems ha^{-1}		m
Jack pine	forest	10	clay to heavy clay	16–21	600–2300	1133–5033	9.16
Jack pine	old field	10	clay to heavy clay	11–27	1100–3000	1367–2633	8.63
White spruce	forest	10	clay to heavy clay	10–15	1100–2900	2533–8667	5.03
White spruce	old field	10	clay to heavy clay	9–16	1500–3200	1867–6300	5.23

plantations established in old fields had higher soil clay contents than the general average, while the lowest values were observed in jack pine plantations of forest origin and white spruce plantations in old fields (Fig. 2). The sole variable showing a significant correlation with clay content was the permanent wilting point between 10 and 20 cm ($r = 0.41$, $P = 0.009$, $n = 40$); however, weak correlations were also observed for the net N mineralization rate ($r = -0.31$, $P = 0.051$, and $r = -0.27$, $P = 0.076$ at the 0–10- and 10–20-cm depths, respectively).

Plantation age ranged from 9 to 16 yr for white spruce and from 11 to 27 yr for jack pine (Table 1). Three jack pine plantations had been subjected to restocking and supported two different cohorts of trees. A permanent wilting point between 10 and 20 cm was the only soil characteristic correlated with plantation age ($r = -0.459$, $P = 0.041$ and $r = -0.461$, $P = 0.042$, $n = 20$ for jack pine and white spruce plantations, respectively).

Effects of Species and Plantation Origin on Soil Physical Properties

Average values for the 0- to 10-cm mineral soil bulk densities ranged from 0.99 to 1.04 Mg m^{-3} and were not affected by plantation origin or species (Table 2). Independent of plantation origin, bulk densities were higher under white spruce at the 10- to 20-cm depth (Table 2). Macroporosity was significantly lower in old field than in forest plantations at both soil depths and was also significantly lower under white spruce than under jack pine. In jack pine plantations, the average 10- to 20-cm macroporosity was between 2.3 and 2.5 times higher than in white spruce plantations.

Field capacity was significantly higher in old field plantations and higher under jack pine at the 10- to 20-cm depth (Table 2). Although the same trend was observed at the 0- to 10-cm soil depth, only the differences between species were significant. The soils from the old field plantations were characterized by significantly higher permanent wilting points than those of the forests at both soil depths (Table 2), and the average wilting points were also higher under white spruce than under jack pine. At both soil depths, independent of origin and species, the wilting point increased with soil organic C content ($r = 0.76$, $P < 0.001$ and $r = 0.43$, $P = 0.005$ for the 0–10- and 10–20-cm depths, respectively; $n = 40$). At both depths, the available water holding capacity was significantly lower under white spruce but was not affected by plantation origin (Table 2).

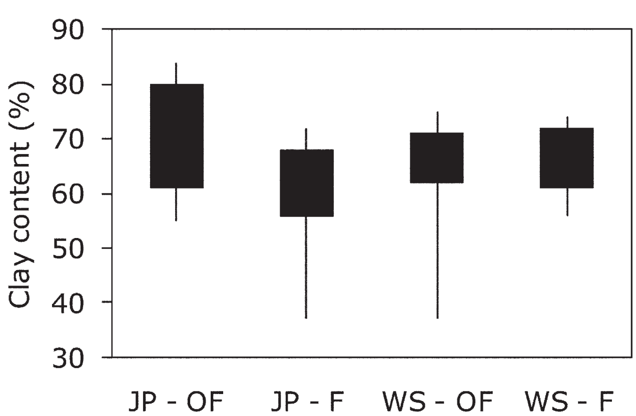

Fig. 2. Range in clay content (minimum, 25th to 75th percentiles, and maximum) of soils from jack pine (JP) and white spruce (WS) plantations established in old fields (OF) and forest clear cuts (F).

Effects of Species and Plantation Origin on Soil Chemical Properties

Organic C concentrations were between 1.4 and 1.9 times higher in the old field than the forest plantations at both soil depths (Table 2). The same trend was observed for Kjeldahl N; however, a significant interaction between species and origin was noted for Kjeldahl N at the 0- to 10-cm depth, where the difference between origins was weaker for jack pine. Species by itself had no effect on Kjeldahl N or organic C concentrations.

The C/ N ratio ranged from 20 to 27 and little difference was observed between depths (Table 2). A significant interaction was observed for the C/N ratio between plantation origin and species at the 0- to 10-cm depth. Values were higher in forest than old field plantations under white spruce, while the reverse was true for jack pine. The 10- to 20-cm-depth C/N ratio was higher under white spruce than under jack pine.

Potential net N mineralization rates at the 0- to 10-cm depth ranged from 9.6 to 27.1 g m^{-3} for 14 d and were significantly higher under white spruce than under jack pine (Table 2). At both depths, the interaction between plantation origin and species was significant: higher rates were observed in forest than old field plantations under pine and lower rates in forest than old field for spruce. The ratio of net mineralizable N/Kjeldahl N, a measure of organic matter quality, was higher under white spruce than under jack pine at the 0- to 10-cm depth and higher in forests than in old fields for both species and both soil depths (Table 2).

Effects of Plantation Origin on Tree Height

Tree height as a function of tree age followed a strong linear relationship for both species (Table 3; Fig. 3). Between 11 and 27 yr, jack pine height increased by an average of 56.3 cm yr^{-1} in forest plantations. According to the first-order model, jack pine annual height growth in old fields was reduced by 12.4 cm compared with forests; however, the difference between plantation origins was not significant (Table 3). At age 9 yr, white spruce from old field plantations were 210 cm taller than those of forest origin. Between age 9 and 16 yr, white spruce height increased

Table 2. Effects of species and plantation origin on 0- to 10- and 10- to 20-cm mineral soil properties. Mixed model analyses with sampling plot, nested within plantation, as random effects. Type 1 test of hypothesis for species, plantation origin, and their interaction. Significant effects are indicated in bold.

Property	White spruce		Jack pine		Simple effects			Interaction	
	Old field	Forest	Old field	Forest	SE†	*P* > *F* species	*P* > *F* origin	SE†	*P* > *F*
					0–10-cm mineral soil				
Bulk density, Mg m^3	1.01	1.04	0.99	0.99	0.02	0.225	0.619	0.03	0.677
Macroporosity, %	10.4	11.2	16.3	21.2	0.8	**<0.001**	**0.010**	1.1	0.062
Field capacity, %	44.2	38.0	48.0	45.2	1.9	**0.041**	0.095	2.7	0.527
Permanent wilting point, %	27.7	21.7	23.5	18.5	1.2	**0.030**	**0.002**	1.7	0.758
AWHC‡, %	17.3	17.2	22.3	25.3	1.6	**0.004**	0.510	2.20	0.483
Organic C, g kg^{-1}	45.8	29.6	37.8	27.5	0.072	0.189	<0.001	0.102	0.571
Net N mineralization, g m^{-3} in 14 d	27.1	22.9	9.6	18.2	2.1	**0.001**	0.476	3.0	**0.038**
Kjeldahl N, g kg^{-1}	2.0	1.1	1.6	1.4	0.075	0.902	**<0.001**	0.106	**0.049**
C/N ratio	22.5	26.2	23.3	19.9	0.044	0.054	0.952	0.062	**0.015**
Organic matter quality	0.011	0.017	0.004	0.009	0.140	**<0.001**	**0.002**	0.198	0.397
					10–20-cm mineral soil				
Bulk density, Mg m^3	1.16	1.23	1.10	1.06	0.03	**0.002**	0.636	0.04	0.103
Macroporosity, %	5.9	7.4	13.87	18.5	0.7	**<0.001**	**0.002**	1.0	0.102
Field capacity, %	39.1	29.4	41.8	39.1	1.5	**0.005**	**0.005**	2.1	0.107
Permanent wilting point, %	24.2	19.5	21.1	16.1	1.1	**0.034**	**0.002**	1.5	0.913
AWHC‡, %	16.1	12.8	20.7	24.0	1.2	**<0.001**	0.960	1.7	0.053
Organic C, g kg^{-1}	32.5	16.8	27.5	18.9	0.085	0.839	**<0.001**	0.121	0.244
Net N mineralization, g m^{-3} in 14 d	15.6	10.9	11.0	16.3	1.2	0.819	0.874	1.6	**0.003**
Kjeldahl N, g kg^{-1}	1.2	0.7	1.2	1.0	0.081	0.114	**<0.001**	0.115	0.100
C/N ratio	26.4	25.7	22.6	19.8	0.056	**0.012**	0.319	0.086	0.530
Organic matter quality	0.008	0.011	0.007	0.012	0.144	0.792	**0.041**	0.202	0.532

† Standard errors for Kjeldahl N, organic C, C/N ratio, and organic matter quality are in the natural log scale.

‡ Available water holding capacity.

by 74.4 cm yr^{-1} in forest plantations and by 34.9 cm yr^{-1} in old field plantations. The difference in growth rates between plantation origins was significant at the 0.060 level (Table 3).

DISCUSSION

Clayey soils from the Abitibi-Témiscamingue region have evolved from Quaternary glaciolacustrine deposits, and pedogenesis began with the retreat of Lake Ojibway 9000 yr ago (Veillette et al., 2000). These soils are richer in fine primary mineral particles than in true clay minerals (Veillette et al., 2000). The observed bulk densities in clear-cut forests were similar to those reported for unmanaged forests (Brais and Camiré, 1998), while macroporosity values were in the same range as those reported by Brais (2001) for managed forest soils of the region. According to Pagliai et al. (2004), the surficial macroporosity was within the range of values of moderately porous soils; however, the steep decrease in macroporosity with depth indicated a relatively weak pedogenetic development.

As we initially hypothesized, land clearing and subsequent cultivation induced more severe soil compaction than forest harvesting, as shown by the reduced macroporosity values in old fields at both sampled depths. Field capacity—determined on undisturbed samples—is strongly influenced by soil structure, and higher values observed at the 0- to 10-cm depth in old fields were also consistent with compaction, which, as well as breaking down larger pores, increases the proportion of smaller ones (Shestak and Busse, 2005; Wall and Heiskanen, 2003). On the other hand, the permanent wilting point, assessed on sieved soils, is strongly influenced by the organic matter content and texture. Soils in old fields were characterized by higher organic matter content than forest soils and this caused the permanent wilting point to increase (Ferreras et al., 2006; Hamza and Anderson, 2005). The available water holding capacity was not impacted by plantation origin because both field capacity and wilting point increased simultaneously.

Old field soil organic C concentrations were in the range of values reported for a number of soil series of the region under fodder production (Tabi et al., 1990); however, the higher soil organic matter concentrations of old fields, compared with that of the forest soils, was unexpected. Losses of organic matter pools in the range of 20 to 40% have been found following cultivation of virgin soils (Davidson and Ackerman, 1993); however,

Table 3. Type 1 tests of fixed effects of tree age, plantation origin, and their interaction on tree height in jack pine and white spruce plantations; first-order linear model.

Effect	df numerator	df denominator	*F* value	*P* > *F*
		Jack pine		
Tree age	1	119	190.73	< .001
Plantation origin	1	119	0.59	0.446
Age × origin	1	119	2.39	0.125
		White spruce		
Tree age	1	120	24.95	< .001
Plantation origin	1	120	0.76	0.384
Age × origin	1	120	3.62	0.060

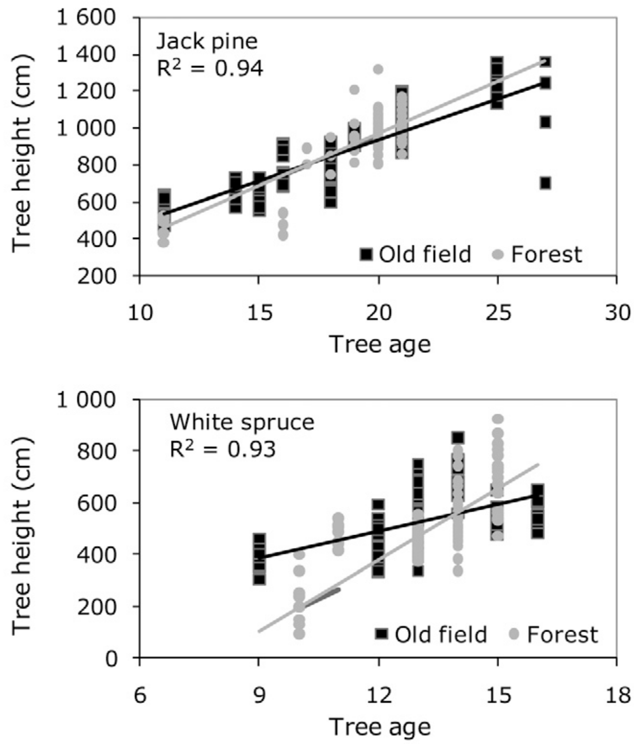

Fig. 3. Tree height in relation to age in jack pine and white spruce plantations growing in forest clear cuts and in old fields. Observed values of individual trees are indicated as dots. Parameters of the linear relationship (solid lines) between height and age were obtained from mixed linear regression models.

those losses occur mostly within the first few years following cultivation (Davidson and Ackerman, 1993). By contrast, large root litter inputs from cultivated plants, with high lignin content and slow decomposition rates (Puget and Drinkwater, 2001), can contribute to increases in soil C. By maintaining a permanent or semipermanent cover, fodder production and pasture may have promoted soil organic matter accumulation (Pulleman et al., 2000) in the years preceding plantation establishment as well as in the subsequent years. The lower quality of soil organic matter observed in the old fields reflects lower mineralization rates and can result in soil organic C accumulation. Post and Kwon (2000) have found average rates of C accumulation of 33.4 g m^{-2} yr^{-1} in agricultural soils following reversion to permanent vegetation cover for a wide range of bioclimatic regions. Assuming lesser accumulation values (15 g m^{-2} yr^{-1}), considering the regional climatic conditions of our study, it would take 66 yr to increase soil organic C concentrations by 10 g kg^{-1} m^{-2} in the 10-cm depth increment. On the other hand, forest site preparation before plantation has been shown to reduce organic C concentrations of forest clay soils of the region (Brais et al., 2002) and could also have contributed to the lower organic C values observed in the forest soils.

Despite large differences in soil physical and nutritional characteristics between forest and old field plantations, little evidence of significant differences in growth patterns was found between plantation origins. A number of factors other than soil conditions may influence growth patterns, including the initial height of seedlings and competition for light and nutriments. As well, white spruce seedlings are vulnerable to spring frost damage, which kills apical buds (Groot and Carlson, 1996) and reduces annual height growth. Height of the dominant trees was retained as a measurement of site productivity, as it has been shown to be fairly independent of competition and initial spacing (Skovsgaard and Vanclay, 2008). The high correlations observed between tree age and height indicates that, despite all the possible sources of variation in initial plantation growth conditions, height growth remained predictable during the study period. Divergences in growth patterns between plantation origins for white spruce were statistically marginal and need to be investigated on a larger number of plantations and for a longer period of time because they may have been caused by differences in initial seedling height. White spruce is a more nutrient-demanding species than jack pine and could be more susceptible to the lower net N mineralization rates observed in the old fields.

Tree species were included in the models as a means of controlling statistical variation. Considering the age of the plantations, we did not expect significant species effects on the soils; however, the effects were strong enough to warrant further investigation. All physical soil characteristics were affected by species. Under white spruce, we observed a higher permanent wilting point and lower macroporosity, indicating a shift in the pore size distribution toward smaller pores and a more massive structure, resulting in reduced aeration and available water retention. Differences in spruce and pine root distribution may account for some of these results. Roots are involved in soil structure development through mechanisms such as the pressure exerted by water extraction and inputs of organic matter that can promote soil aggregation. A spruce root system is mainly located in the 0- to 15-cm soil horizon (Safford and Bell, 1972) in contrast to the deeper more vertical rooting pattern of jack pine (Visser, 1995). Jack pine root growth capacity is also greater than that of white spruce (Grossnickle, 1988).

Large differences in the indices of net N mineralization in the 0- to 10-cm horizon were also found between species. The respective effects of jack pine and white spruce on ground vegetation dynamics following reforestation were not investigated in the current study; however, in a concurrent study on the biodiversity of old field and forest plantations, Gachet et al. (2007) found little convergence of ground vegetation dynamics between old field and forest plantations of jack pine. Differences in light transmission and the quality and quantity of litter inputs between white spruce and jack pine plantations may set underground vegetation on different successional trajectories and may explain in part the higher rates of net N mineralization under white spruce.

The clayey soils of the Abitibi region support natural stands of jack pine, while white spruce seldom forms pure stands in this part of the boreal forest; it is, however, an important component of forest succession on clayey sites. The choice of species for plantation is dependent on individual owner preferences and the seedlings availability from greenhouse producers. Jack pine is often the preferred species of private land owners because of its rapid growth. No bias in inherent site conditions (soil texture or soil moisture regime) could explain the significant differences in soil properties found between species as no differences in clay content or organic matter concentrations were found between species.

CONCLUSIONS

Increased demand for natural forest conservation, intensification of forest management in areas close to towns, as well as rising interest in forest biomass for energy purposes will lead to increased reforestation of abandoned agricultural lands. Because of the difficulties inherent in retrospective studies, comparisons between different land management histories are scarce and their inference potential regarding cause and effect relationships remain limited. The differences between forest and old field plantations found in this study, however, in terms of soil compaction and organic matter concentrations, are consistent with the literature. Similar patterns of tree growth in former forest lands and old fields, despite significant differences in soil properties, indicate that tree growth in young plantations established on rich clayey soils is not controlled by soil properties.

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REFERENCES

Adams, M.B., K. Ramakrishna, and E.A. Davidson (ed.). 1998. The contribution of soil science to the development of an implementation of criteria and indicators of sustainable forest management. SSSA Spec. Publ. 53. SSSA, Madison, WI.

Agriculture Canada Expert Committee on Soil Survey. 1998. The Canadian system of soil classification. 3rd ed. Agric. and Agri-Food Canada Publ. 1646. NRC Res. Press, Ottawa, ON.

Brais, S. 2001. Persistence of soil compaction and effects on seedling growth in northwestern Quebec. Soil Sci. Soc. Am. J. 65:1263–1271.

Brais, S., and C. Camiré. 1992. Keys to soil moisture regime evaluation for northwestern Quebec. Can. J. For. Res. 22:718–724.

Brais, S., and C. Camiré. 1998. Soil compaction induced by careful logging in the claybelt region of northwestern Quebec (Canada). Can. J. Soil Sci. 78:197–206.

Brais, S., D. Paré, C. Camiré, P. Rochon, and C. Vasseur. 2002. Nitrogen net mineralization and dynamics following whole-tree harvesting and winter windrowing on clayey sites of northwestern Québec. For. Ecol. Manage. 157:119–130.

Bremner, J.M., and C.S. Mulvaney. 1982. Nitrogen—total. p. 505–624. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Bundy, S.C., and J.J. Meisinger. 1994. Nitrogen availability Indices. p. 951–984. *In* R.W. Weaver et al. (ed.) Methods of soil analysis. Part 2. Microbiological and biochemical properties. SSSA Book Ser. 5. SSSA, Madison, WI.

Cassel, D.K., and D.R. Nielsen. 1986. Field capacity and available water capacity. p. 901–926. *In* A. Klute (ed.) Methods of soil analysis. Part 1. Physical and mineralogical methods. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Corns, I.G.W. 1988. Compaction by forestry equipment and effects on coniferous seedling growth on four soils in the Alberta foothills. Can. J. For. Res. 18:75–84.

Covington, W.W. 1981. Changes in forest floor organic matter and nutrient content following cutting in northern hardwoods. Ecology 62:41–48.

Dang, Q.-L., and S. Cheng. 2004. Effects of soil temperature on ecophysiological traits in seedlings of four boreal tree species. For. Ecol. Manage. 194:379–387.

Davidson, E.A., and I.L. Ackerman. 1993. Changes in soil carbon inventories following cultivation of previously untilled soils. Biogeochemistry 20:161–193.

Ferreras, L., E.S. Gomez, S. Toresani, I. Firpo, and R. Rotondo. 2006. Effect of organic amendments on some physical, chemical and biological properties in a horticultural soil. Bioresour. Technol. 97:635–640.

Fleming, R.L., R.F. Powers, N.W. Foster, J.M. Kranabetter, D.A. Scott, F. Ponder, Jr., et al. 2006. Effects of organic matter removal, soil compaction, and vegetation control on 5-year seedling performance: A regional comparison of long-term soil productivity sites. Can. J. For. Res. 365:529–550.

Franzluebbers, A.J. 2002. Soil organic matter stratification ratio as an indicator of soil quality. Soil Tillage Res. 66:95–106.

Gachet, S., A. Leduc, Y. Bergeron, T. Nguyen-Xuan, and F. Tremblay. 2007. Understory vegetation of boreal tree plantations: Differences in relation to previous land use and natural forests. For. Ecol. Manage. 242:49–57.

Gemtos, T.A., and T. Lellis. 1997. Effects of soil compaction, water and organic matter contents on emergence and initial plant growth of cotton and sugar beet. J. Agric. Eng. Res. 66:121–134.

Gomez, A., R.F. Powers, M.J. Singer, and W.R. Horwath. 2002. Soil compaction effects on growth of young ponderosa pine following litter removal in California's Sierra Nevada. Soil Sci. Soc. Am. J. 66:1334–1343.

Greacen, E.L., and R. Sands. 1980. Compaction of forest soils. A review. Aust. J. Soil Res. 18:163–189.

Groot, A., and D.W. Carlson. 1996. Influence of shelter on night temperatures, frost damage, and bud break of white spruce seedlings. Can. J. For. Res. 26:1531–1538.

Grossnickle, S.C. 1988. Planting stress in newly planted jack pine and white spruce: 1. Factors influencing water uptake. Tree Physiol. 4:71–83.

Hamza, M.A., and W.K. Anderson. 2005. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. Soil Tillage Res. 82:121–145.

Hangs, R.D., J.D. Knight, and K.C.J. Van Rees. 2003. Nitrogen uptake characteristics for roots of conifer seedlings and common boreal forest competitor species. Can. J. For. Res. 33:156–163.

Hu, S., D.C. Coleman, C.R. Carroll, P.F. Hendrix, and M.H. Beare. 1997. Labile soil carbon pools in subtropical forest and agricultural ecosystems as influenced by management practices and vegetation types. Agric. Ecosyst. Environ. 65:69–78.

Johnson, C.E., A.H. Johnson, T.H. Huntington, and T.G. Siccama. 1991. Whole-tree clear-cutting effects on soil horizons and organic-matter pools. Soil Sci. Soc. Am. J. 55:497–502.

Klute, A. 1986. Water retention: Laboratory methods. p. 635–662. *In* A. Klute (ed.) Methods of soil analysis. Part 1. Physical and mineralogical methods. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Kneeshaw, D.D., R.K. Kobe, D. Coates, and C. Messier. 2006. Sapling size influences shade tolerance ranking among southern boreal tree species. J. Ecol. 94:471–480.

Kroetsch, D., and C. Wang. 2008. Particle size distribution. p. 713–725. *In* M.R. Carter and E.G. Gregorich (ed.) Soil sampling and methods of analysis. 2nd ed. CRC Press, Boca Raton, FL.

Landhausser, S.M., U. Sillins, V.J. Lieffers, and W. Liu. 2003. Response of *Populus tremuloides*, *Populus balsamifera*, *Betula papyrifera* and *Picea glauca* seedlings to low soil temperature and water-logged soil conditions. Scand. J. For. Res. 18:391–400.

Littell, R.C., G.A. Milliken, W.W. Stroup, R.D. Wolfinger, and O. Schabenberger. 2006. SAS for mixed models. 2nd ed. SAS Inst., Cary, NC.

McNabb, D.H., A.D. Startsev, and H. Nguyen. 2001. Soil wetness and traffic level effects on bulk density and air-filled porosity of compacted boreal forest soils. Soil Sci. Soc. Am. J. 65:1238–1247.

Murty, D., M.U.F. Kirschbaum, R.E. McMurtrie, and A. McGilvray. 2002. Does conversion of forest to agricultural land change soil carbon and nitrogen? A review of the literature. Global Change Biol. 8:105–123.

Pagliai, M., A. Marsili, P. Servadio, N. Vignozzi, and S. Pellegrini. 2003. Changes in some physical properties of a clay soil in central Italy following the passage of rubber tracked and wheeled tractors of medium power. Soil Tillage Res. 73:119–129.

Pagliai, M., N. Vignozzi, and S. Pellegrini. 2004. Soil structure and the effect of management practices. Soil Tillage Res. 79:131–143.

Post, W.M., and K. Kwon. 2000. Soil carbon sequestration and land-use change: Processes and potential. Global Change Biol. 6:317–327.

Powers, R.F., D.H. Alban, R.E. Miller, A.E. Triarks, C.G. Wells, P.E. Avers, R.G. Cline, N.S. Loftus, Jr., and O. Fitzgerald. 1990. Sustaining productivity in

North American forests: Problems and prospects. p. 49–79. *In* S.P. Gessel et al. (ed.) Sustained productivity of forest soils. Fac. of For. Publ., Univ. of British Columbia, Vancouver, BC, Canada.

Puget, P., and L.E. Drinkwater. 2001. Short-term dynamics of root- and shoot-derived carbon from a leguminous green manure. Soil Sci. Soc. Am. J. 65:771–779.

Pulleman, M.M., J. Bouma, E.A. van Essen, and E.W. Meijles. 2000. Soil organic matter content as a function of different land use history. Soil Sci. Soc. Am. J. 64:689–693.

Richter, D.D., D. Markewitz, S.E. Trumbore, and C.G. Wells. 1999. Rapid accumulation and turnover of soil carbon in a re-establishing forest. Nature 400:56–58.

Safford, L.O., and S. Bell. 1972. Biomass of fine roots in a white spruce plantation. Can. J. For. Res. 2:169–172.

SAS Institute. 2004. SAS/STAT 9.1 user's guide. SAS Inst., Cary, NC.

Servadio, P., A. Marsili, M. Pagliali, S. Pellegrini, and N. Vignozzi. 2001. Effects on some clay soil qualities following the passage of rubber-tracked and wheeled tractors in central Italy. Soil Tillage Res. 61:143–155.

Shestak, C.J., and M.D. Busse. 2005. Compaction alters physical but not biological indices of soil health. Soil Sci. Soc. Am. J. 69:236–246.

Skovsgaard, J.P., and J.K. Vanclay. 2008. Forest site productivity: A review of the evolution of dendrometric concepts for even-aged stands. Forestry 81:13–31.

Syndicat des Producteurs de Bois de l'Abitibi-Témiscamingue. 2000. Plan régional de protection et de mise en valeur des forêts privées de l'agence de l'Abitibi. Vol. 2. Calcul de la possibilité forestière. SPBAT, Rouyn-Noranda, QC, Canada.

Sveistrup, T.E., T.K. Haraldsen, R. Langohr, V. Marcelino, and J. Kvaerner. 2005. Impact of land use and seasonal freezing on morphological and physical properties of silty Norwegian soils. Soil Tillage Res. 81:39–56.

Tabi, M., L. Tardif, D. Carrier, G. Laflamme, and M. Rompré. 1990. Inventaire des problèmes de dégradation des sols agricoles du Québec. Région agricole 9 Abitibi-Témiscamingue. Ministère de l'agriculture, des pêcheries et de l'alimentation, Québec, QC, Canada.

Thrower, J.S. 1987. Growth intercepts for estimating site quality of young white spruce plantations in north central Ontario. Can. J. For. Res. 17:1385–1389.

van Kooten, G.C., E. Krcmar-Nozic, R. van Gorkom, and B. Stennes. 2000. Economics of afforestation for carbon sequestration in western Canada. For. Chron. 76:165–172.

Veillette, J., Y. Bergeron, L. Gaudrault, F. Miron, and G. Drainville. 2000. Abitibi-Témiscamingue, de l'emprise des glaces à un foisonnement d'eau et de vie: 10,000 ans d'histoire. Editions Multimondes, Sainte-Foy, QC, Canada.

Vincent, O. 1995. Histoire de l'Abitibi-Témiscamingue. Inst. québécois de recherche sur la culture, Québec, QC, Canada.

Visser, S. 1995. Ectomycorrhizal fungal succession in jack pine stands following wildfire. New Phytol. 129:389–401.

Wall, A., and J. Heiskanen. 2003. Water-retention characteristics and related physical properties of soil on afforested agricultural land in Finland. For. Ecol. Manage. 186:21–32.

White, T.M., and W.A. Kurz. 2005. Afforestation on private land in Canada from 1990 to 2002 estimated from historical records. For. Chron. 81:491–497.

Yeomans, J.C., and J.M. Bremner. 1988. A rapid and precise method for routine determination of organic carbon in soil. Commun. Soil Sci. Plant Anal. 19:1467–1476.