Short-term effects of organic matter scalping on the growth and nutrition of black spruce and jack pine seedlings planted in the boreal forest

by Nelson Thiffault[1]

ABSTRACT

Scarification contributes to creating planting microsites for reforestation by mixing organic matter (OM) with the upper layers of mineral soil. However, on some boreal sites characterized by a thick humus layer and dominated by ericaceous shrubs, competition seems to limit the benefits of scarification. A potential solution would be to remove OM completely through scalping. The objective of our study was to compare the short-term effects of scarification and scalping on the growth of *Picea mariana* and *Pinus banksiana* on such sites. After three growing seasons, we explored the relationships between seedling growth, groups of competing vegetation species, planting depth and distance to the nearest OM accumulation. The two treatments had similar effects on these variables. Growth on plots subjected to scalping was independent from the distance to OM. Planting depth had a nil or positive effect on seedling growth. *Pinus* seedlings largely outgrew *Picea* seedlings. However, the lack of short-term difference between scarification and scalping must be interpreted with caution, given the potential mid- and long-term effects of OM exportation on soil fertility, erosion and seedling nutrition.

Key words: reforestation, plantation, site preparation, *Picea mariana*, *Pinus banksiana*

RÉSUMÉ

Le scarifiage contribue à créer des microsites pour le reboisement en mélangeant la matière organique (MO) aux couches superficielles de sol minéral. Toutefois, sur certaines stations boréales caractérisées par des humus épais et un couvert dominé par les plantes éricacées, la compétition semble limiter les avantages du scarifiage. Une solution pourrait être d'enlever complètement la MO par décapage. Notre objectif est de comparer, sur une telle station, les effets à court terme du scarifiage et du décapage sur la croissance de plants de *Picea mariana* et de *Pinus banksiana*. Après 3 saisons, nous avons exploré les relations entre la croissance des plants et les groupes d'espèces de végétation concurrente, la profondeur de mise en terre et la distance jusqu'à l'amas de MO le plus proche. Les deux traitements ont eu des effets semblables sur les variables mesurées. La croissance dans les parcelles décapées était indépendante de la distance à la MO. La profondeur de mise en terre a eu un effet nul ou positif sur la croissance des plants. Les plants de *Pinus* ont poussé beaucoup plus vite que ceux de *Picea*. L'absence de différence à court terme entre les traitements doit être interprétée avec prudence, compte tenu des effets potentiels à moyen et à long termes de l'exportation de la MO sur les processus nutritionnels et l'érosion.

Mots-clés : reboisement, plantation, préparation de terrain, *Picea mariana*, *Pinus banksiana*

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Introduction

Maintaining ecosystem productivity is an essential part of sustainable forest management and implies an adequate regeneration of harvested sites after disturbances (Lieffers *et al.* 2003). When natural regeneration is insufficient, site productivity may be restored by planting to compensate for a poor distribution or insufficient density of natural seedlings (Nyland 2002). The performance of planted seedlings, however, depends on interactions between the planted material (species, stock type and genotype) and environmental conditions (Grossnickle 2012), especially the microenvironment which directly influences resource availability (air and soil temperatures, nutrients, water and light). Low availability of resources causes stress and jeopardizes seedling establishment (Margolis and Brand 1990). To optimize the significant investments devoted to genetic improvement programs, seedling production and planting (Thiffault *et al.* 2013), reforestation microsites should provide resource levels with values as optimal as possible (Burdett 1990).

However, the specific characteristics of reforestation microsites that minimize planting stress are hard to identify (organic/mineral mix, Salonius 1983; planting depth, Sutton 1995; amount of woody debris, Devine and Harrington 2007). Several studies have documented the effects of scarification on plantation establishment in boreal forests

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(e.g., Prévost and Dumais 2003, Hébert *et al.* 2014, Henneb *et al.* 2015). Other studies have focused on the management of woody debris and their effects on seedling microenvironment (e.g., Trottier-Picard *et al.* 2014) or the effect of planting depth on growth (Paquette *et al.* 2011) and frost heaving (Sahlén and Goulet 2002). However, thick humus layers that accumulate over very long fire cycles (Bouchard *et al.* 2008, Ward *et al.* 2014) characterize many mesic sites in Northeastern Quebec (Canada). Moreover, mature boreal stands are characterized by understories dominated by ericaceous shrubs, including *Rhododendron groenlandicum* (Oeder) Kron and Judd and *Kalmia angustifolia* L. (Thiffault *et al.* 2015) that can increase in cover following forest harvesting (Thiffault and Grondin 2003). In such restrictive conditions, trenching scarification is sometimes not effective in creating adequate microsites. Indeed, ericaceous shrub litter is rich in phenolic compounds that hamper the growth of conifers, directly and indirectly (Bradley *et al.* 1997, Inderjit and Mallik 1999, LeBel *et al.* 2008). Although trenching results in warmer soil temperatures and increases organic matter decomposition (Prévost 1992), the properties of the forest humus associated with ericaceous shrubs could limit the benefits expected from mixing humus with the mineral soil through scarification. Also, considering that even a relatively low *Kalmia* cover can significantly hamper initial conifer growth (Thiffault *et al.* 2005), planting microsites should provide planted seedlings with the largest possible area free of the impact of this species (Thiffault *et al.* 2012). Therefore, the effectiveness of trenching in creating productive microsites can be limited when forest humus layers are thick (Henneb *et al.* 2015). More radical methods such as forest harrowing might be considered, but the regional availability of specialized equipment, the presence of thin soils or high levels of stoniness can restrict the use of this method (Gravel *et al.* 2015).

Scalping organic matter is generally not recommended as a silvicultural tool (Prévost and Thiffault 2013) since the entire removal of forest humus deprives microsites of a major nutrient capital (Munson *et al.* 1993, Prescott *et al.* 2000). Exposed mineral soil is also subjected to temperature variations greater than soil covered by a humus layer with insulating properties (Prévost 1992). Such variations can cause seedling frost heaving (Goulet 2000), particularly in soils with a high clay content. In addition, temperature increases in a soil exposed by scalping can reduce its water content and cause major hydric stress to seedlings. Such impacts have been observed on a recently harvested site in Northwestern Quebec, characterized by an 8 cm-thick humus and a *Kalmia*, *Vaccinium* spp. and *Cladonia* spp. cover (Thiffault *et al.* 2004). Nonetheless, some silviculturists argue that the complete removal of humus might sometimes yield benefits, for instance in areas characterized by abundant annual rainfall and fewer risks of water stress. The benefits of creating an environment free of the influence of ericaceous shrubs or their related humus could likely offset the adverse effects of the treatment. Few studies have addressed the effects of complete scalping of organic matter in such conditions, which differ from winter removal of woody debris on frozen soils where a certain thickness of organic matter is maintained above the mineral soil layer. Most research on this topic has been conducted in mixed or hardwood forest ecosystems (e.g., Frey *et al.* 2003, Newmaster *et al.* 2007, Gradowski *et al.* 2008, Lazaruk *et al.* 2008, Dumas 2012) with treatments limited to a few square meters. By eliminating the organic matter layer, scalping could actually reproduce the impact of high-intensity fires in the boreal forest and, to some extent, be part of an ecosystem-based management strategy (Gauthier *et al.* 2008). However, forest fires usually do not eliminate organic matter entirely; Greene *et al.* (2007) reported an average reduction of 60% after studying 14 forest fires across Canada.

The objective of our study was to determine the short-term effects of organic matter scalping down to the first mineral horizon on the nutrition and growth of conifer seedlings planted on a site located in the North Shore region of Quebec, dominated by *Kalmia* and characterized by a thick layer of organic matter. We verified the hypothesis that organic matter incorporated into mineral soil through standard disk scarification is a short-term source of nutrients for planted seedlings and that it imparts microsites with characteristics conducive to initial seedling growth, including reduced ericaceous coverage. Based on this hypothesis, we predicted that the complete removal of forest humus through mechanical scalping would create microsites more nutrient deficient than those created through disk scarification. Lower leaf nutrient concentrations and stunted planted seedling growth on scalped plots should reflect such a prediction. On the same plots, we also predicted that seedlings would grow more slowly if their distance from the nearest windrow (their main source of nutrients, McCavour *et al.* 2014) was greater and that planting depth would play a significant and positive role in growth. To verify these predictions, we established an operational-level experiment that included two site preparation treatments prior to planting black spruce (*Picea mariana* [Mill.] BSP) and jack pine (*Pinus banksiana* L.) seedlings. These two species are known for their distinct efficiency in absorbing and using nutrients (Reich *et al.* 1998a).

Materials and Methods

Experimental Site and Design

We established an experimental design (50° 10′ 7″ N; 68° 44′ 57″ W) in the black spruce-feather moss bioclimatic domain of Quebec (Saucier *et al.* 2009), about 120 km northwest of Baie-Comeau, Quebec. The site is located on a till deposit more than one metre thick, where a podzolic soil developed (Soil Classification Working Group 1998). The soil has a sandy loam texture (74% sand, 18% loam, 8% clay) and mesic-to-subhydric drainage. The original stand was mainly dominated by black spruce with an understory dominated by *Kalmia*. The stand was harvested in 2010 with protection of regeneration and soils.

In September 2011, we delimited four experimental blocks of 60 × 50 m, each divided into two main plots of 25 × 50 m separated by a 10-m buffer strip. In each block, two site preparation treatments were assigned randomly to the plots: (*i*) disk trenching scarification or (*ii*) complete scalping of the forest humus down to the first mineral horizon. Scarification was performed with a T26 scarifier (Bracke Forest AB, Bräcke, Sweden). It produced straight trenches, each 2-m apart, 67 cm ± 18 cm (mean ± standard deviation) wide, 39 cm ± 12 cm deep and lined with an organic matter heap mixed with mineral soil. Scalping used a D7H bulldozer (Caterpillar, Peoria, Illinois). Organic horizons were scalped and piled in windrows 1 m to 2 m high at the edge of the plots.

The experimental design did not include any control plots (not treated with site preparation) since many studies have shown the importance of site preparation to ensure the survival and initial growth of seedlings planted on boreal sites dominated by ericaceous shrubs (e.g., Prévost and Dumais 2003, Thiffault and Jobidon 2006).

In June 2012, we divided each main plot into two subplots of 25 × 25 m to which we assigned species for planting, black spruce or jack pine. Seedlings were from local seed sources and grown in containers of 45 cavities of 110 cm^3 each. A randomly selected sample of 50 seedlings of each species was set aside before planting for planting stock characterization. The height and biomass of jack pine were superior to those of black spruce (except for twigs), but foliar nutrient concentrations were higher in black spruce (Table 1).

In each subplot, seedlings were planted based on a spacing grid of about 2.5 × 2.0 m. In scarified plots, seedlings were planted between the shoulder and the bottom of trenches. At the centre of each subplot, an 8-m radius circular sampling plot was established to include an average of 35 seedlings to measure per experimental unit (563 seedlings for the entire experiment).

Table 1. Initial dimensions and foliar nutrient concentrations of seedlings planted in the experimental design

	Black Spruce	Jack Pine	*t*	*p*
Height (cm)	26.5 (2.3)	29.3 (3.8)	−4.50	<0.001
Root collar diameter (mm)	2.9 (0.5)	3.0 (0.4)	−0.88	0.380
Root biomass (g)	1.05 (0.3)	1.31 (0.5)	−3.09	0.003
Stem biomass (g)	0.44 (0.1)	0.70 (0.2)	−7.77	<0.001
Twig biomass (g)	0.24 (0.1)	0.17 (0.1)	3.63	<0.001
Foliar biomass (g)	1.11 (0.2)	1.56 (0.4)	−7.45	<0.001
Foliar N (g/kg)	23.9 (2.0)	17.7 (1.6)	17.22	<0.001
Foliar P (g/kg)	2.9 (0.4)	2.1 (0.3)	11.43	<0.001
Foliar K (g/kg)	8.5 (0.7)	7.7 (0.8)	5.74	<0.001

Note: Data presented in the form of means (standard deviations). Seedlings were grown in containers of 45 cavities of 110 cm^3 each, measurements were taken using a sample of 50 seedlings for each species harvested on site prior to planting. Biomass values were determined after drying seedlings for 48 hr at 65°C. Foliar nutrient concentrations were determined by spectrophotometry (FIA Quickchem, Lachat, Milwaukee, WI) and plasma atomic emission spectrometry (ICAP 61^E, Thermo Instruments, Franklin, MA). Means were compared using a Welch *t* test.

Seedling and Vegetation Measurement

After planting, seedlings located in the circular sampling plots were identified with a metal rod marker and a sequential number. Their initial height (cm), ground-level diameter (mm), distance from the nearest ericaceous shrub (up to 150 cm) and planting depth were measured. Planting depth was defined as the vertical distance between the top of the peat root plug and soil level. A negative value means that the plug was inserted under the surface of the soil, while a positive value means that the plug was not completely buried. For each numbered seedling planted in the scalped plots, the distance between its base and the nearest organic matter heap (in most cases, the windrow) was measured.

In July 2014 (third growing season after planting), we surveyed competing vegetation growing within a 50-cm radius from each seedling. We visually assessed the proportion of plant cover (by 5% classes) using the following functional groups: trees, grass, moss, ericaceous shrubs, broad-leaved plants, woody shrubs, sphagnum, ferns and alder. The distance between the planted seedlings and the nearest ericaceous shrub individual was recorded up to 150 cm. In October 2014, at the end of the third growing season, the height and ground-level diameter of all the planted trees were measured once more.

Chemical Analyses

In October 2014, we randomly selected three seedlings in each experimental unit. We harvested a foliar sample from the current year in the upper third of their crown and a soil sample within a 10-cm radius from their base. Soil samples were collected to represent the seedling root environment, i.e., at a depth corresponding to plug position. Samples were kept cool until further manipulation. Foliar samples were dried at 65 °C for 48 hours and ground for one minute (Pulverisette 0, Fritsch, Idar-Oberstein, Germany). Soil samples were dried at room temperature and then ground to 2 mm. C and N concentrations were determined through combustion at 1350 °C using a TruMac CN Elemental Analyzer (LECO Corporation, St-Joseph, MI, USA) on 300 mg samples of tissue and 500 mg of soil. P and K concentrations of leaf tissue were determined through plasma atomic emission spectrometry (ICAP 61^E, ThermoInstruments, Franklin, MA) following $H_2SO_4 + H_2O_2$ digestion of 100 mg samples (Walinga *et al.* 1995). Soil samples (3.0 g) were subjected to a Mehlich III extraction before plasma atomic emission spectrometry analysis (Carter 1993).

Statistical Analyses

Using June 2012 and October 2014 seedling dimensions, we calculated absolute growth (dimensions in October 2014 – dimensions in June 2012) and relative growth rate over three growing seasons:

$$RGR = \frac{lnX_{F2014} - lnX_{S2012}}{3}$$

Where *RGR* = Relative growth rate
X = Height or ground-level diameter
F2014 = Measure taken in October (fall) 2014
S2012 = Measure taken in June (spring) 2012

All analyses were performed using R v3.0.2 (R Core Team 2013). Height (fall 2014), diameter (fall 2014), absolute growth and relative growth data as well as foliar and soil nutrient concentration data (fall 2014) were submitted to analyses of variance (ANOVA) for mixed models using the *lme* function of the *lme4* package (Bates *et al.* 2015). Blocks and block interactions were considered as random effects; site preparation treatment, species and the site preparation × species interaction were included as fixed effects. The per-

Table 2. Results from analyses of variance (fixed effects) on black spruce and jack pine seedling dimensions and growth following two site preparation treatments (disk scarification or scalping of the organic matter)

	Site preparation		Species		Site preparation × species	
Variable	**F**	***p***	**F**	***p***	**F**	***p***
Height after 3 growing seasons	1.70	0.284	123.98	<0.001	0.55	0.486
Absolute height growth	1.14	0.364	209.10	<0.001	0.65	0.452
Relative height growth rate	0.13	0.742	576.03	<0.001	4.95	0.068
Diameter after 3 growing seasons	4.37	0.128	111.05	<0.001	2.85	0.142
Absolute diameter growth	4.15	0.134	117.09	<0.001	3.45	0.113
Relative diameter growth rate	2.09	0.244	158.47	<0.001	3.00	0.134

cent cover of various groups of species was transformed using the inverse sine of the square root before being submitted to mixed model ANOVAs, with site preparation as the sole fixed effect. Data on the distance between planted seedlings and the nearest ericaceous shrubs were analyzed with a simple linear model for truncated data (*Tobit* model) using the *vglm* function of the *VGAM* package (Yee 2008). We used the *lm* function of the *car* package (Fox and Weisberg 2011) to perform linear regressions between planting depth and relative growth rates based on height and diameter. For seedlings planted in scalped plots, we also produced regressions between the relative growth rate and distance between seedlings and the nearest windrow.

To explore correlations between variables describing microsite characteristics and seedling response in terms of nutrient and growth, we submitted foliar nutrient, vegetation percent cover, relative height growth and soil characteristic data to principal component analyses using the *PCA* function of the *FactoMineR* package using correlation matrix (Lê *et al.* 2008). Data on the two species were analyzed separately. For each analysis, we restricted our interpretation to axes showing *eigenvalues* > 1. In addition, we only included the percent cover data of vegetation groups showing > 0% values in at least one of the treatments.

Results

Height and Diameter Growth

Survival of planted seedlings was very high. Among the planted trees, only two died at the end of the three-year monitoring period, a jack pine in a scalped plot and a black spruce in a scarified plot. We did not identify any significant effect of site preparation on height, diameter, absolute growth rate and relative growth rate in seedlings of the two species ($p \geq 0.128$; Table 2). However, differences between the two species were significant for all these variables (all the $p < 0.001$), regardless of treatment (site preparation × species, $p \geq 0.068$; Table 2). After three growing seasons, jack pine showed an average height of 58.4 cm ± 1.5 cm (mean ± standard error) and an average diameter of 15 mm ± 0.5 mm. Black spruce reached an average height of 40.2 cm ± 1.5 cm and an average diameter of 8.7 mm ± 0.5 mm. These dimensions were the results of three years absolute height growth of 48.5 cm ± 1.5 cm for jack pine and 25.7 cm ± 1.5 cm for black spruce. During the same period, the absolute diameter growth was 11.6 mm ± 0.4 mm for jack pine and 5.7 mm ± 0.4 mm for black spruce. The relative growth rates reflected the same trend (data not presented).

Competing Vegetation

Among all the groups of plant species, only grass, moss, ericaceous shrubs and broad-leaved plants were present in the immediate environment of the seedlings. Grass and moss percent covers (average values of 2% and 15%, respectively) were equivalent in scalped and scarified plots ($F_{1,3} \leq 0.98$, $p \geq 0.395$). Scalping significantly reduced the proportion of ericaceous shrub cover from 12% to 1%, compared with disk scarification ($F_{1,3} = 118.8$, $p = 0.002$). Scalping also reduced the percent cover of broad-leaved plants compared with scarification ($F_{1,3} = 13.5$, $p = 0.035$), with respective values of 0% and 3% for the two treatments. On most scalped plot microsites, the ericaceous shrub nearest to the planted seedlings at the time of planting was located more than 150 cm away (Fig. 1a). Conversely, the distribution of seedling-ericaceous shrub distance in scarified plots was unimodal with an average of 56 cm (Fig. 1a). The *Tobit* model revealed that the predicted distance value at the time of planting was 120 cm shorter in scarified plots than in scalped plots ($Z = -24.6$, $p < 0.001$). Overall, the effect of site preparation on the distance was strongly significant ($p < 0.001$). After three growing seasons, we observed that the frequency of the "150-cm" truncating value in scalped plots remained much higher than expected compared with the rest of the distribution (Fig. 1b). An average of 31 cm in distance values was recorded in scarified plots, with no occurrences of the truncating value (Fig. 1b). The predicted distance value after three growing seasons was 64 cm shorter in the scarified plots than in the scalped plots ($Z = -17.5$, $p < 0.001$). After three growing seasons, the effect of site preparation on the distance between the planted seedlings and the nearest ericaceous shrubs was still highly significant ($p < 0.001$).

Soil and Foliar Nutrient Concentrations

In October 2014, soil nutrient concentrations did not differ significantly among the site preparation treatments ($F_{1,3} \leq 1.02$, $p \geq 0.386$) or the species ($F_{1,6} \leq 1.74$, $p \geq 0.235$). Similarly, we did not detect any significant differences in seedling foliar N, P and K concentrations measured in October 2014, whether in the scarified or scalped plots ($F_{1,3} \leq 8.23$, $p \geq 0.064$). However, the species significantly influenced foliar P ($F_{1,6} = 53.86$, $p < 0.001$) and K ($F_{1,6} = 14.27$, $p = 0.009$) concentrations, with black spruce with higher foliar P and K concentrations than jack pine (P: 2.2 ± 0.07 *vs.* 1.4 ± 0.07 g/kg; K: 6.3 ± 0.2 *vs.* 5.2 ± 0.2 g/kg).

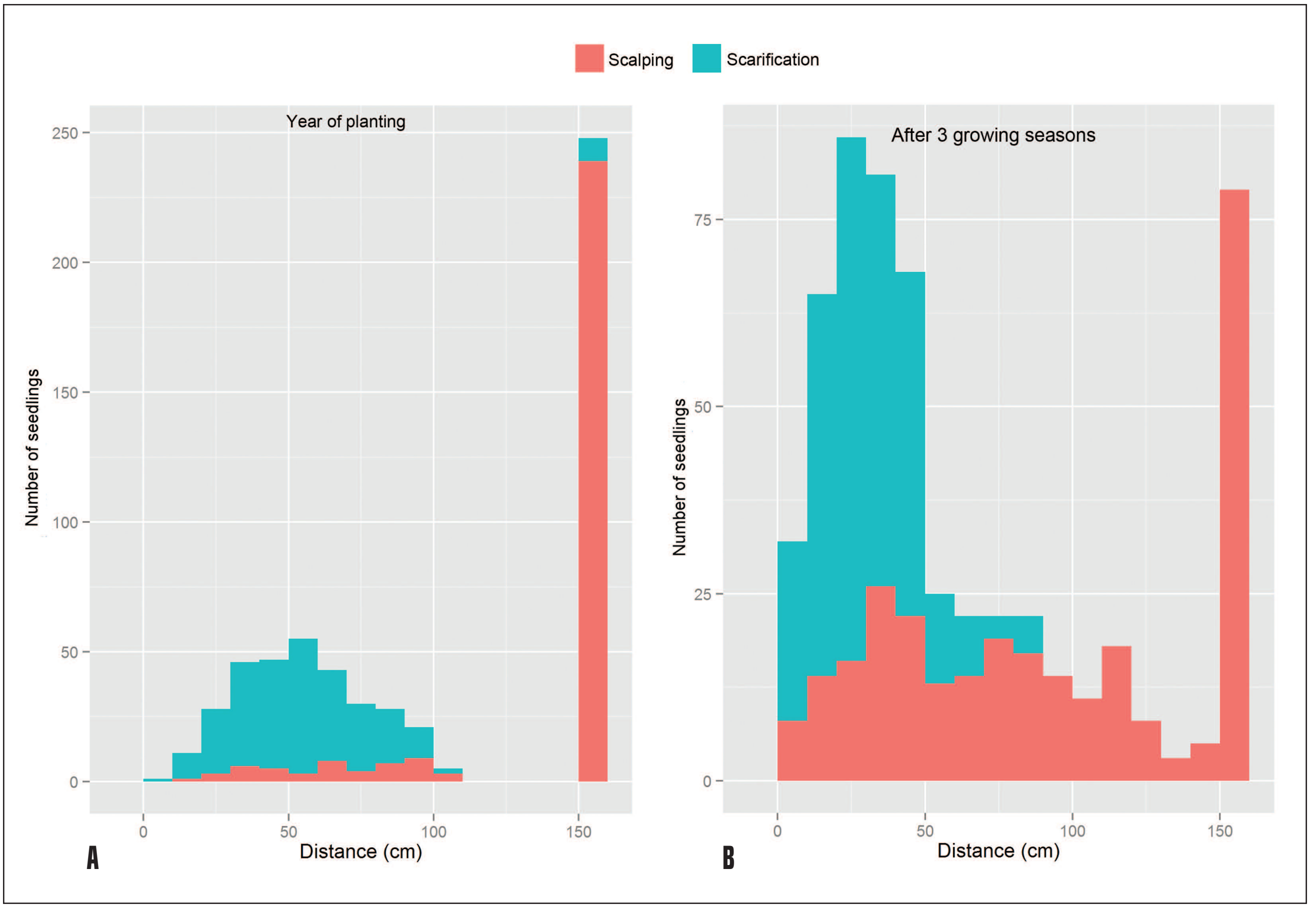

Fig. 1. Distribution of seedling number based on distance to nearest ericaceous shrub at planting **(A)** and after three growing seasons **(B)**.

Planting Depth and Distance from the Nearest Windrow

For black spruce, planting depth varied from −8 cm to 5 cm but did not have any significant effect on the relative height and diameter growth rates of seedlings in the scalped plots ($p \geq 0.098$; Fig. 2a and 2b). However, it had a significant ($p \leq 0.011$) yet low ($R^2 \leq 0.089$) effect for this species in plots prepared with disk scarification; relative height (Fig. 2a) and diameter (Fig. 2b) growth rates increased with planting depth. For jack pine, we observed a significant relationship ($p < 0.001$) between planting depth and the relative height growth rate in both scalped and scarified plots (Fig. 2c). The diameter growth of jack pine was not influenced by planting depth ($p \geq 0.123$; Fig. 2d).

For seedlings in scalped plots, we did not detect any significant effect ($p \geq 0.142$) of the distance between planting spot and nearest organic matter heap on relative height (Fig. 3a) and diameter (Fig. 3b) growth rates of both black spruce and jack pine.

Principal Component Analyses

For black spruce, the four first axes derived from the principal component analysis with *eigenvalues* >1 together accounted for 79.7% of the matrix variance. Soil C concentration (*Cos2* = 0.877; *CTR* = 27.11), with soil cation exchange capacity (*Cos2* = 0.817; *CTR* = 25.26) and soil N concentration (*Cos2* = 0.790; *CTR* = 24.42) were the variables best represented by the first axis (*eigenvalue* = 3.235; Fig. 4a). The second axis (*eigenvalue* = 2.364; Fig. 4a) appropriately represented the proportion of broad-leaved plant cover (*Cos2* = 0.442; *CTR* = 18.68), grass (*Cos2* = 0.393; *CTR* = 16.62) and ericaceous shrubs (*Cos2* = 0.385; *CTR* = 16.28) and soil P concentration (*Cos2* = 0.316; *CTR* = 16.36). The third axis (*eigenvalue* = 2.02; proportion of variance explained = 15.5; not presented) was primarily associated with foliar N concentration (*Cos2* = 0.664; *CTR* = 32.90; coordinate = −0.815), relative height growth rate (*Cos2* = 0.373; *CTR* = 18.47; coordinate = 0.611) and moss percent cover (*Cos2* = 0.346; *CTR* = 17.15; coordinate = 0.589). Lastly, the fourth axis (*eigenvalue* = 1.689; proportion of variance explained = 13.0; not presented) primarily represented soil P (*Cos2* = 0.456; *CTR* = 27.02; coordinate = 0.676) and K (*Cos2* = 0.370; *CTR* = 21.91; coordinate = 0.608) concentrations. When represented in the space formed by the two first axes (Fig. 4b), scarification and scalping observations presented an incomplete separation of the treatments with an overlapping of the 95% confidence ellipses. Scalped plot observations were associated with higher soil N and C concentrations and CEC values than those associated with scarified plot observations, whereas scarified plot observations were associated with higher soil base cation concentrations than those associated with scalped plot observations.

For jack pine, three axes with *eigenvalues* > 1 were identified through the principal component analysis of data.

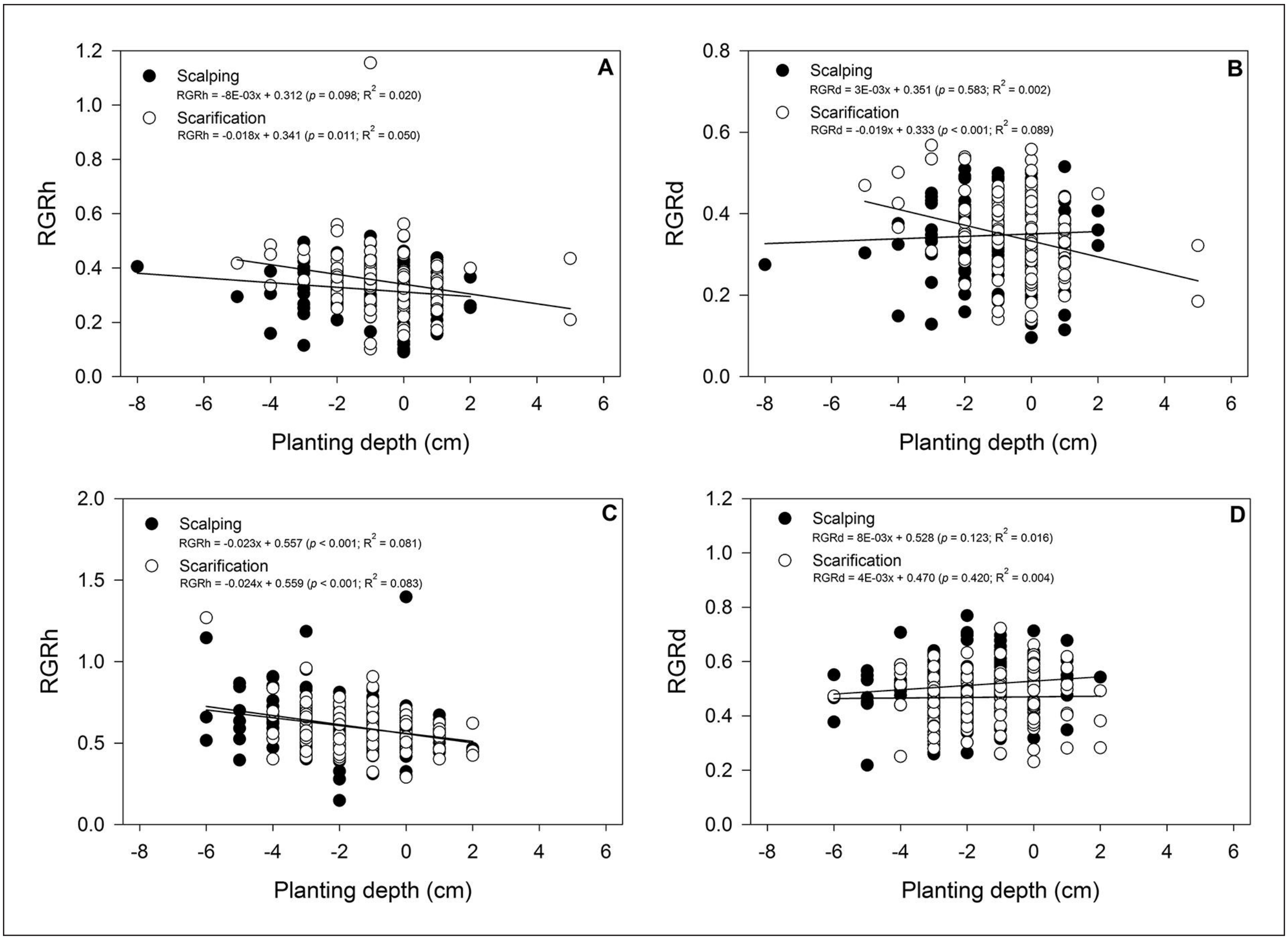

Fig. 2. Relationship between planting depth and relative height (RGRh; **A** and **C**) and diameter (RGRd; **B** and **D**) growth rates for black spruce (**A** and **B**) and jack pine (**C** and **D**). Depth is the distance between top of peat root plug and soil surface at planting. A negative value implies that the plug was planted below soil surface; a positive value implies that the plug was not entirely buried underground.

Together, the axes accounted for 71.6% of the matrix variance. The first axis (*eigenvalue* = 4.089; Fig. 5a) was strongly associated with soil C (*Cos2* = 0.653; *CTR* = 15.97) and N (*Cos2* = 0.583; *CTR* = 14.25) concentrations, the percent cover of ericaceous shrubs (*Cos2* = 0.536; *CTR* = 13.10) and cation exchange capacity (*Cos2* = 0.443; *CTR* = 10.83). The second axis (*eigenvalue* = 3.179; Fig. 5a) primarily captured the variance associated with foliar P (*Cos2* = 0.691; *CTR* = 21.75), N (*Cos2* = 0.609; *CTR* = 19.16) and K (*Cos2* = 0.526; *CTR* = 16.53) concentrations. Lastly, the third axis (*eigenvalue* = 2.04; proportion of variance explained = 15.7; not presented) appeared to be primarily associated with the percent cover of broad-leaved plant (*Cos2* = 0.395; *CTR* = 19.35; coordinate = 0.628) and ericaceous shrubs (*Cos2* = 0.285; *CTR* = 13.97; coordinate = 0.534) and the cation exchange capacity of soil (*Cos2* = 0.272; *CTR* = 13.35; coordinate = –0.522). The distribution of scalping and scarification observations in the space defined by the first two axes (Fig. 5b) showed significant overlapping. The averages of observation coordinates for each treatment were included in the 95% confidence interval of the other treatment.

Discussion

Overall, disk scarification and organic matter scalping treatments had similar short-term effects on soil and foliar nutrient concentrations. The same applied to black spruce and jack pine growth in spite of noteworthy differences between the treatments in terms of initial distance between the planted seedling and the nearest ericaceous shrubs and percent cover of these species. Ericaceous shrubs are known for their adverse effects on conifer nutrition and growth (de Montigny and Weetman 1990; Titus *et al.* 1995; Thiffault *et al.* 2004). Despite their higher cover in the scarified versus scalped plots, these species seemed to have influenced main resources very little. This finding was reflected by the almost nil (Fig. 4) or positive (Fig. 5) correlations between ericaceous cover and soil N concentrations and cation exchange capacity. In addition, the distribution of observations associated with the two treatments in the space defined by the first two principal components did not illustrate strong trends. Although the abundance of ericaceous shrubs was associated with low soil P concentrations as reported in other studies (e.g., Bloom and Mallik 2006), foliar P concentration in black spruce and jack pine remained relatively independent from the presence of

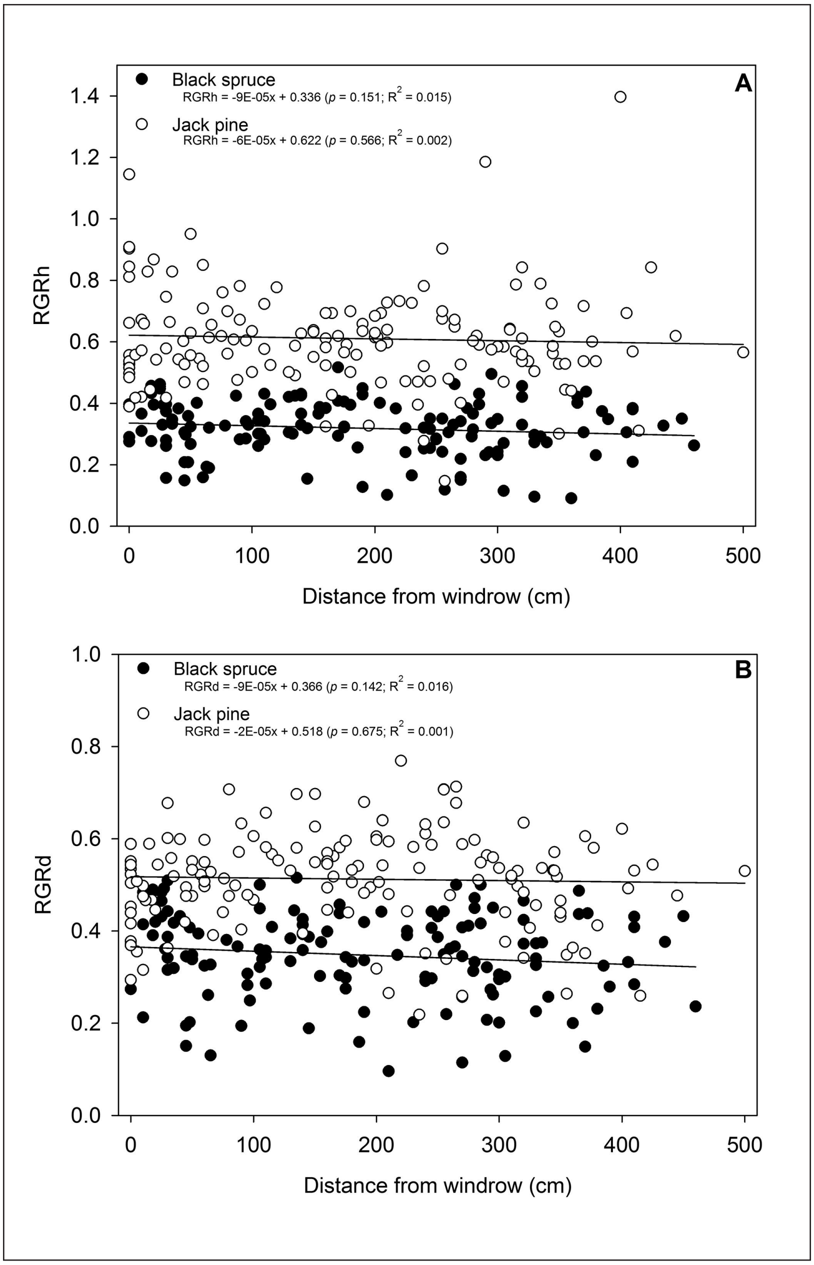

Fig. 3. Relationship between distance from nearest windrow and relative height (RGRh; **A**) and diameter (RGRd; **B**) growth rates for seedlings in plots subjected to scalping.

ericaceous shrubs. Trenching typically creates plantation microsites half comprised of exposed mineral soil (Prévost and Thiffault 2013). Such an environment is poorly suited to the vegetative reproduction of *Kalmia* (Mallik 1993). Therefore, seedlings planted on microsites created by scarification benefited from a growth environment partly free of the influence of ericaceous species, at least for the first three seasons following planting.

Contrary to our predictions, seedling growth in scalped plots did not vary significantly based on the distance from organic matter heaps. This absence of a significant relationship may be due to the relatively low nutritional requirements of conifers (Munson and Timmer 1989), compared with those of species such as *Prunus pensylvanica* L. (Jobidon 1995) for which such a relation was observed on sites subjected to conventional windrowing, without exporting organic matter (McCavour *et al.* 2014). In fact, the characteristics of the litter and the cold, humid climate of the boreal forest slow down organic matter mineralization (Van Cleve *et al.* 1981, Van Cleve *et al.* 1990, Scott and Binkley 1997, Pajuste and Frey 2003). Therefore, nutrients accumulated in windrows would certainly require several years to be re-circulated (Blumfield *et al.* 2004). Mid- and long-term monitoring of seedling growth and nutritional status will be required to verify this hypothesis. Over time, seedlings located at the centre of scalped plots (the farthest from the windrows) can be expected to show signs of nutrient deficiency, such as leaf chlorosis and stunted growth or even asymmetric root system development (in an attempt to reach the source of nutrients), compared with seedlings located at the edge of plots (next to the main piles of organic matter).

Deeper planting had a nil or positive effect on seedling growth, which varied based on the combinations of treatments and tree species. While we expected a marked positive effect of planting depth in scalped plots due to major temperature variations associated with humus removal (Heiskanen *et al.* 2013), this variable had the greatest effect in scarified plots for both black spruce and jack pine. Although significant, the relationship between planting depth and seedling growth was rather low, with a R^2 of 9% in the best of cases (Fig. 2b). This result is in line with those of Paquette *et al.* (2011), who reported that planting depth did not influence black spruce, white spruce (*Picea glauca* [Moench.] Voss.) and jack pine growth planted on boreal sites during the first 19 years of growth. Frost heaving issues are generally more prevalent in fine-textured soils because of the frost-defrost cycle (Rempel 2010). Therefore, the coarse textured soil of our study site could explain the low incidence of planting depth on growth.

As expected, jack pine largely outgrew black spruce. This difference probably reflects the intrinsic differences in carbon-fixing capacities between a shade-intolerant (jack pine) and tolerant (black spruce) species (Reich *et al.* 1998b). The principal component analyses highlighted these differences. Although the relative height growth rate was independent from soil N concentration and cation exchange capacity for black spruce (at a right angle, respectively along the two first axes; Fig. 4a), the same variables were negatively correlated

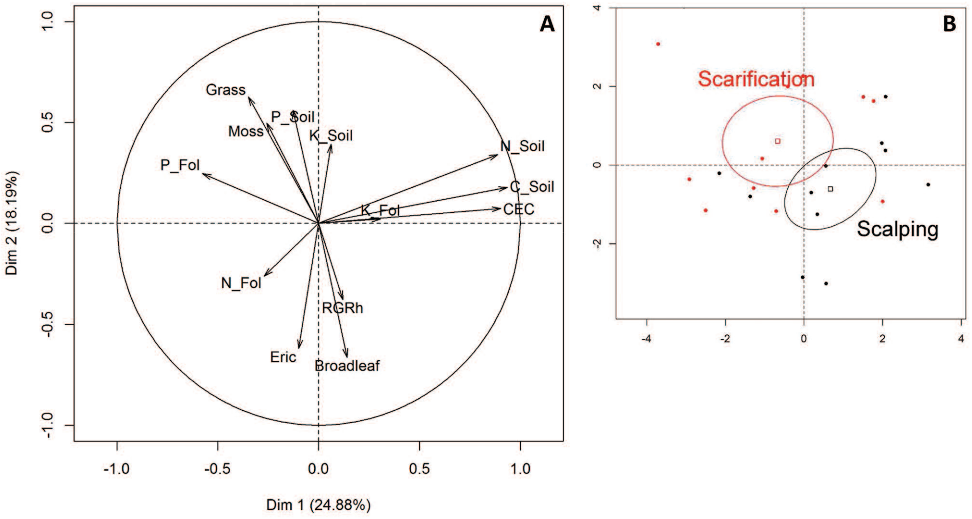

Fig. 4. Principal component analysis illustrating correlations between microsite characteristics, percent cover of main groups of species, and black spruce foliar nutrient concentration and growth **(A)**. N Fol = foliar nitrogen concentration; P Fol = foliar phosphorus concentration; K Fol = foliar potassium concentration; N Soil = soil nitrogen concentration; P Soil = soil phosphorus concentration; K Soil = soil potassium concentration; C Soil = soil carbon concentration; CEC = cation exchange capacity; RGRh = Relative growth rate in height over three growing seasons. **B** illustrates the distribution of observations associated with scalping and scarification in the space defined by the two first axes. The ellipses represent the 95% confidence intervals around the averages of the two treatments.

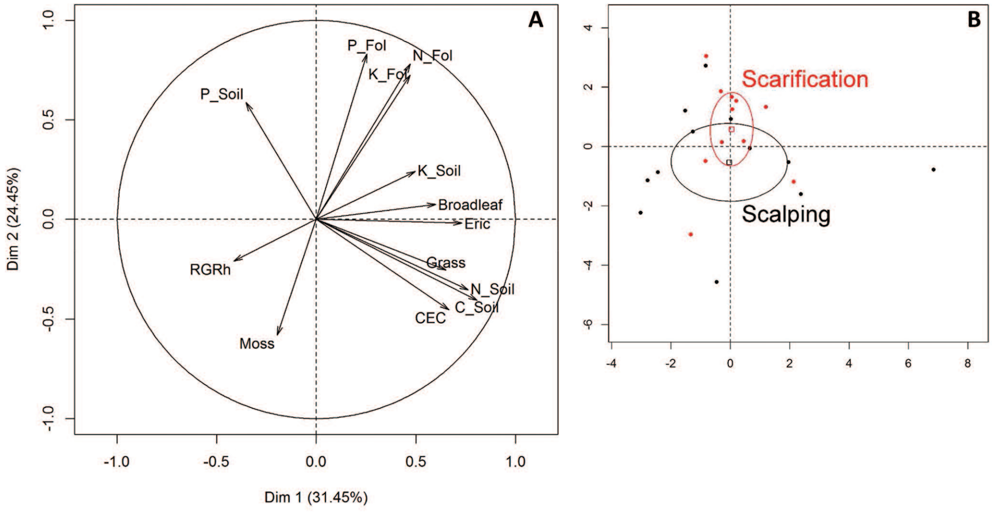

Fig. 5. Principal component analysis illustrating correlations between microsite characteristics, percent cover of main groups of species, and jack pine foliar nutrient concentration and growth **(A)**. N Fol = foliar nitrogen concentration; P Fol = foliar phosphorus concentration; K Fol = foliar potassium concentration; N Soil = soil nitrogen concentration; P Soil = soil phosphorus concentration; K Soil = soil potassium concentration; C Soil = soil carbon concentration; CEC = cation exchange capacity; RGRh = Relative growth rate in height over three growing seasons. **B** illustrates the distribution of observations associated with scalping and scarification in the space defined by the two first axes. The ellipses represent the 95% confidence intervals around the averages of the two treatments

for jack pine (in opposite directions along the first axis; Fig. 5b). In addition, the higher foliar nutrient concentrations in black spruce illustrate the ability of this species to adapt and store nutrients in depleted environments (Hom and Oechel 1983, Díaz *et al.* 2004). In contrast, jack pine is adapted to respond rapidly to the fluctuation of available resources (Díaz *et al.* 2004). However, foliar nutrient concentration does not completely shed light on the nutritional status of the seedlings because of a potential dilution effect (Timmer 1991). Considering leaf mass might have provided a more complete picture of seedling response in this regard.

For boreal sites with thick humus and dominated by ericaceous shrubs, the short-term results of our study show that the complete removal of organic matter through scalping supports the establishment and initial growth of conifer seedlings without significant differences from trenching. On the short term, the effects of scalping on seedling nutrition and growth can be however, masked by the residual effect of nutrients exported from the nursery in the peat root plug (Idris *et al.* 2004). The independence between measured soil and needle nutrient concentrations (Fig. 4a and Fig. 5a) illustrates decoupling between the nutritional resources availability and the nutritional status of the seedlings during the first years following planting. Therefore, these results after three years should be interpreted with caution, given the potential mid- and long-term effects of the exportation of organic matter associated with scalping. Indeed, forest humus is a major nutrient capital that should be maintained on sites to guarantee their long-term productivity (Prescott *et al.* 2000). Over the mid- and long-term, the accumulation of organic matter in the form of linear windrows located several metres away from seedlings may deprive trees located at the centre of plots from sufficient nutrient intake. In addition, the exposure of the mineral soil over large surfaces causes erosion (Merino and Edeso 1999, Merino *et al.* 2004) and creates a major source of sediments in watercourses (Olarieta *et al.* 1999), an aspect not measured in our study. Because of this risk, scalping that causes infertile mineral horizons to be exposed is subject to particular environmental monitoring in Quebec (Jetté 2004). However, ericaceous shrubs may invade trenches rapidly in scarified plots, as suggested by the rapidly shortening distance between planted trees and ericaceous shrubs in these plots (Figs. 1a and 1b). If the rate of *Rhododendron* and *Kalmia* invasion in scarified microsites remains significant, seedling nutrition and growth may be affected (Thiffault *et al.* 2005). Therefore, if organic matter scalping yields a significant benefit compared with conventional scarification in terms of plantation growth on sites with thick humus dominated by ericaceous shrubs, the use of this method should be regulated by conditions that restrict its environmental impact.

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