SILVA FENNICA
Silva Fennica 46(5) research articles
www.metla.fi/silvafennica · ISSN 0037-5330
The Finnish Society of Forest Science · The Finnish Forest Research Institute

Planted *Picea mariana* Growth and Nutrition As Influenced by Silviculture × Nursery Interactions on an Ericaceous-Dominated Site

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Thiffault, N., Hébert, F. & Jobidon, R. 2012. Planted *Picea mariana* growth and nutrition as influenced by silviculture × nursery interactions on an ericaceous-dominated site. Silva Fennica 46(5): 667–682.

We aimed at evaluating the interacting effects of silvicultural and nursery practices on planted black spruce (*Picea mariana* (Mill.) BSP) dimensions, growth, survival and nutrition, 8 years following planting on a carefully logged boreal stand heavily invaded by *Kalmia angustifolia* L. and *Rhododendron groenlandicum* (Oeder) Kron & Judd. We also evaluated functional traits related to light and nutrient acquisition and key environmental resource availability to interpret treatment impacts on spruce seedling leaf traits and growth. An experimental black spruce plantation, consisting in a randomized block split-split-split plot design with 13 replicates was established in northeastern Quebec (Canada). Scarification (single-pass, double-pass), fertilization at the time of planting (control; macronutrients only; macro + micronutrients), stock type (container-grown; bare-root), and initial foliar N concentration (4 increasing levels) treatments were applied, and measurements were performed 5 and 8 years following planting. Double-pass scarification significantly increased soil temperature and reduced the competition cover, compared to the single-pass treatment. As a result, double-pass scarification promoted seedling growth over the single-pass treatment, and influenced the expression of other treatment effects. However, the relative gains associated with the second scarification pass have to be balanced against the supplemental investment involved by the treatment before being recommended. Our results point to variable effects of fertilization at planting to stimulate seedling initial growth. In this ecosystem, it appears that the silvicultural gains of this treatment depend on the variable of interest. Bare-root seedlings grew faster than containerized seedlings in the most intense site preparation treatment, but the differences have limited silvicultural impacts.

Keywords black spruce, *Kalmia angustifolia, Rhododendron groenlandicum,* scarification, fertilization, stock type
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Received 24 July 2012 **Revised** 8 October 2012 **Accepted** 9 October 2012
Available at http://www.metla.fi/silvafennica/full/sf46/sf465667.pdf

1 Introduction

There is a worldwide trend in the development of harvesting techniques aimed at maintaining the structure and functions of forest stands and reducing logging impacts on the ecosystems (e.g. Schwartz et al. 2012). In that regard, careful logging around advance growth (CLAAG) is a modified clearcut harvesting technique used to preserve established regeneration through restricted circulation of machinery on cutover sites (Harvey and Brais 2002). For the past 15–20 years, CLAAG has been the main logging practice used in Quebec (Canada); it is applied on more than 141 000 ha every year, mainly in boreal ecosystems (Parent et al. 2012).

However, CLAAG increases light availability to the shrub layer without disturbing the soil (Lorente et al. 2012), which may stimulate the rhizomatous growth of ericaceous shrub species such as *Kalmia angustifolia* L. and *Rhododendron groenlandicum* (Oeder) Kron & Judd on some sites (Titus et al. 1995). Past research has evidenced the adverse effects of ericaceous shrubs on tree regeneration and growth in various ecosystems, including in western Canada (Prescott et al. 1996), Fennoscandia (Nilsson and Wardle 2005) and northern Turkey (Eşen et al. 2004). *Kalmia* and *Rhododendron* mainly affect black spruce (*Picea mariana* (Mill.) BSP) regeneration growth through competition for soil nutrients (Thiffault et al. 2004b, Hébert et al. 2010a) and by reducing microbial activity and hence, soil N mineralization (Joanisse et al. 2007). Moreover, these ericaceous shrubs can rapidly acclimate to changing site conditions following logging (Inderjit and Mallik 1996, Hébert et al. 2010b). Overall, direct and indirect hindering of nutritional processes appears as the key driver of planted and natural conifer growth check on *Kalmia–Rhododendron* dominated sites following harvesting (Yamasaki et al. 2002).

CLAAG can also favour the development of very thick forest floors composed of poorly decomposed litter (Fenton et al. 2005), which are associated with poor conifer growth (Lavoie et al. 2007). In Quebec, sites harvested through CLAAG that are deficient in terms of conifer regeneration abundance are usually planted following regeneration surveys to ensure good stocking, but a conifer "growth check" is observed when ericaceous shrubs are present and organic matter accumulates (Thiffault and Jobidon 2006). Such impact can impair the sustained productivity of these ecosystems (de Montigny and Weetman 1990).

Common silvicultural options to promote planted conifer growth in these ecosystems include mechanical site preparation and fertilization (Thiffault et al. 2005). Field trials have demonstrated that scarification can improve conifer seedling growth, notably through improved soil temperature (e.g. Thiffault et al. 2012), and seedling responses appear to be related to treatment intensity (Prévost and Dumais 2003). Fertilization at the time of planting using slow release fertilizers with macronutrients can enhance early seedling growth, but the effect is short-term (LeBel et al. 2008). The addition of micronutrients could potentially enhance seedling response to fertilizer in this context (Thiffault and Jobidon 2006, Johansson et al. 2012).

Nursery practices, such as increased foliar nutrient concentrations (Timmer 1997, Villar-Salvador et al. 2012) or tree seedling types (i.e. bare-root *vs.* containerized) can also affect seedling performance on planting sites. Thiffault and Jobidon (2006) reported a significant, although short-term impact of initial foliar N on growth for black spruce seedlings outplanted in northeastern Quebec. Container seedlings generally outperform bare-root stock in the field (e.g. McDonald 1991), and site preparation intensity has a greater effect on small containerized seedlings than on bare-root seedlings (Johansson et al. 2007). However, in some cases, bare-root seedlings exhibit a better root-to-soil contact, a deeper root-depth and better anchorage, better water relations, a greater resistance to frost and herbivory and reduced root spiralling, compared to containerized seedlings (Mohammed et al. 2001).

Although many silvicultural options that could be used on these sites have been studied (e.g. Prévost and Dumais 2003, Thiffault and Jobidon 2006), their potential interactions have yet to be fully documented, within a single factorial experiment, in the context of boreal sites invaded by ericaceous species. Hence, our objective was to evaluate the effects of silvicultural and nursery practices on planted black spruce seedling dimensions, survival and nutrition, 8 growing seasons following planting on a carefully logged stand heavily invaded by *Kalmia* and *Rhododendron*. We also investigated key functional trait responses, to better understand treatment effects on growth. We hypothesized that: i) seedling growth increases with scarification intensity; ii) containerized seedlings offer better performances than bare-root seedlings, an effect that is dependant of scarification intensity; iii) the use of a fertilizer containing micronutrients increases growth, as compared to the sole addition of macronutrients, and its effect increases with scarification intensity; and iv) the use of seedlings with increased initial foliar N concentrations promotes growth, an effect that is dependant of scarification intensity. Functional traits related to light and nutrient acquisition were expected to reflect treatment impacts on key environmental resource availability (soil temperature and nutrient availability).

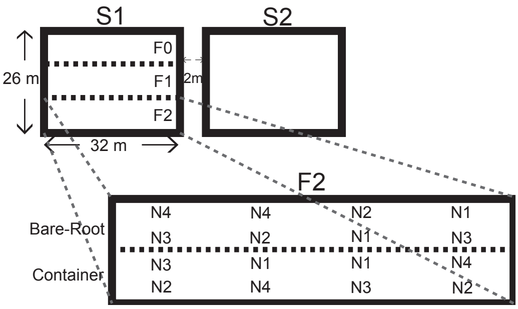

Fig. 1. Graphic representation of one complete experimental block with details of one subplot. S1 = single-pass scarification, S2 = double-pass scarification, F0 = no fertilization, F1 = fertilization with micronutrients (Forest Packs), F2 = fertilization without micronutrients (Silva Packs). Refer to Table 1 for initial foliar N concentrations (N1, N2, N3, N4). Each "N" represents 4 seedlings.

2 Materials and Methods

2.1 Site Description

The experimental site is located in northeastern Quebec (Canada), within the black spruce–feathermoss bioclimatic domain described by Saucier et al. (2009), approximately 125 km north of Baie-Comeau (49°47´36˝N, 69°21´10˝W). This region has a cool climate with a mean annual temperature of 1.5 °C and a mean total precipitation of 1014 mm, with 32.5% falling as snow (1971–2000 data from Baie-Comeau weather station [49°7´N, 68°12´W]; Environment Canada 2010). The study site supported a 120 year-old black spruce stand with a site index (height at age 50) of 15 m. Careful logging around advanced growth was performed in 1993, producing 176 m^3 ha^{-1} of timber wood. Soils are moderately-well drained humo-ferric podzols (Humods Spodosols) formed from a deep (>1 m) coarse till glacial deposit with a mor humus (18 cm) and a loamy-sand texture (first 15 cm). After CLAAG, ericaceous species (*Kalmia angustifolia, Rhododendron groenlandicum*) formed a dense shrub layer associated with black spruce advance regeneration.

2.2 Experimental Design and Treatments

The experimental layout, implemented in October 2000, was a randomized block split-split-split plot, with 13 replicates (26×66 m; Fig. 1). Each block was separated into 2 main plots of 26×32 m, with 2 m buffers. One of the following mechanical site preparation treatments was randomly assigned to each plot: simple-pass Waddell cone scarification (S1) or double-pass Waddell cone scarification (S2). For S2, the second pass was perpendicular to the first (as illustrated in Thiffault et al. 2005). Unscarified plots were not included in the design as many studies have already demonstrated how spruce seedling establishment is seriously compromised on such sites without proper humus management (Prévost and Dumais 2003, Thiffault et al. 2004a, Thiffault et al. 2005, Hébert et al. 2006, Thiffault and Jobidon 2006, Thiffault et al. 2012).

In June 2001, we split main plots in 3 subplots, to which one of 3 fertilization treatments was randomly assigned: no fertilization (F0), fertilization at the time of planting with a slow-release fertilizer tea-bag containing macro- and micronutrients (F1; Forest Packs, Reforestation Technologies International, Salinas, CA) and fertilization at the time of planting with a slow-release fertilizer tea-bag containing only macronutrients (F2; Silva Packs, Reforestation Technologies International). Each Forest Pack (F1) contained 10 g of fertilizer with 15% total N; 15% P (P_2O_5) available as phosphoric acid; 8% K (K_2O) available as soluble potash; 8.20% S; 0.20% Zn; 0.41% Fe; 0.98% Mg; 0.10% Cu; 0.012% B; 0.22% Mn; and 0.09% Mo. Nitrogen, P, and K sources were polymer-coated to supply 14.73% N, 6.64% P, and 5.49% K in a slow release form. Each Silva Pack (F2) contained 10 g of fertilizer with 26.3% total N; 12% P (P_2O_5) available as phosphoric acid; and 6% K (K_2O available as soluble potash). Nitrogen, P, and K sources were polymer-coated to supply 24.9% N; 5.3% P, and 5.1% K in a slow release form. We buried fertilizer bags at approximately 2 cm from planting holes and 4 cm deep at the time of planting (June 2001).

Each subplot was divided into 2 sub-subplots, and one of 2 stock types of black spruce seedlings was randomly assigned to each one. The stock types were either seedlings (2+0) grown in containers of 45 cells of 110 cm^3 each (IPL 45–110, IPL, Saint-Damien-de-Buckland, Quebec, Canada), or seedlings (1+1) seeded in Jiffy pots (Jiffy Products Lte, Shippegan, NB, Canada), transplanted in containers of 25 cells of 310 cm^3 each (IPL 25–310, IPL, Saint-Damien-de-Buckland, Quebec, Canada), and transplanted in open field beds for their second growing season at the nursery (this stock type is hereafter referred to as bare-root). The seedlings were grown from the same seed source in governmental nurseries between 1999 and 2001.

We randomly distributed seedlings representing one of 4 qualitative treatments of initial foliar N concentration (N1 = low, N2 = normal, N3 = high, N4 = very high) in each sub-subplot, as a sub-sub-subplot treatment. The desired foliar N concentrations (Table 1) were obtained through exponential nutrient loading at the nursery, using the PLANTEC software (Girard et al. 2001). This software calculates the weekly fertilizer doses required to attain specified foliar nutrient level and seedling size in the nursery by integrating the evolution, over time, of seedling dry biomass, foliar N, P, and K concentrations, and substrate fertility. Nitrogen concentrations were determined colorimetrically by spectrophotometry, preceded by H_2SO_4–Se–K_2SO_4 digestion, immediately prior seedling shipment to the experimental site. The N2 treatment corresponded to the standard N foliar concentration for seedling production in Quebec. Seedlings were planted in June 2001 at 1×2 m spacing and one seedling out of two (2×2 m) was tagged for long term growth measurements.

2.3 Soil Temperature and Nutrient Availability

We monitored mineral soil temperature at a 10 cm depth, in each main plot (S1 and S2) of 6 blocks, from June to October 2008 (8th growing season post-planting). Temperature was measured using thermistors (model 107 BAM, Campbell Scientific Inc., Logan, UT, USA) and a CR-10 data logger (Campbell Scientific Inc.). Temperature was recorded every 15 min and averaged hourly.

Nutrient concentrations in the surface mineral soil (0–10 cm) were measured from composite samples (each composed of 3 sub-samples) collected 5 and 8 growing seasons after planting (October 2005 and 2008) in all main plots of every block. Composite samples were dried to 5% mass-based humidity at ambient temperature, and grounded to pass a 2 mm mesh screen. Extraction of inorganic N was made with a 2 mol L^{-1} KCl solution and measured colorimetrically by spectrophotometry (Lachat Quickchem 8000, method No. 13-107-06-2-C; Zwellenger Instruments, Milwaukee, WI, USA). Extractable P, K, Ca, and Mg were extracted with a Mehlich-III solution (Sen Tran and Simard 1993) and were measured by inductively coupled argon plasma – optical emission spectrometry analysis (Optima 4300 DV; Perkin-Elmer, Norwalk, CT, USA). The pH was determined following mixing of a 10 g sub-sample with demineralized water (Fisher Scientific accumet 50, Denver Instrument, Bohemia, NY).

2.4 Ericaceous Cover

We visually estimated the percent cover (%) of ericaceous species (*Kalmia angustifolia, Rhododendron groenlandicum*) in 2 m^2 circular plots, centered on the seedling, for 2 randomly selected seedlings in each scarification × fertilization × stock type × initial N combination of each block. Measurements were performed in mid-July of growing seasons 5 and 8 following plantation.

2.5 Seedling Measurements

Prior planting, we collected 25 seedlings of each initial N × stock type combination (200 total), for initial aboveground biomass measurements (Table 1). Needles, twigs, and stems were weighted separately. Seedlings harvested for biomass measurements were kept frozen until drying at 65° C for 48 hours. We measured height (cm), ground-level diameter (GLD) (mm), and calculated height to diameter ratio (H/D) on 8 seedlings per sub-sub-subplot (scarification × fertilization × stock type × initial N) in all blocks (4992 seedlings total) at the time of planting (June 2001), and 5 and 8 growing seasons after planting. We estimated 3-year relative growth rates in height (RGR_H) and GLD (RGR_{GDL}) using the difference of the natural logarithmic of height (or GLD) between year 5 and 8 following plantation.

Foliar nutrient concentrations were evaluated on 2 seedlings per sub-sub-sub-subplot in 12 blocks, 8 growing seasons following planting (late October 2008). A sub-sample of dry needles (~3.5 g) was ground to pass a 0.5 mm mesh. We analyzed total Kjeldahl N colorimetrically by spectrophotometry, preceded by H_2SO_4–Se–K_2SO_4 digestion; and measured P, K, Ca, Mg concentrations by inductively coupled plasma analysis.

In 2011, 2 seedlings of each scarification × fertilization × stock type combination (N2 seedlings only) were harvested in 3 blocks for root:shoot biomass ratio and leaf mass per area (LMA) measurements. Seedlings were kept in a freezer until analyses and dried at 65 °C until constant mass. The root:shoot ratio was calculated by dividing the root dry mass by the total shoot dry mass. We used a fresh sub-sample of ~50–100 needles for LMA calculations. Total needle area was determined by image analysis using the WinSEEDLE system (Regent Instruments Inc. Québec, QC, Canada). Samples were dried at 65 °C for 48 h and weighted to calculate LMA.

Table 1. Mean (SD) foliar N concentration and morphological traits of bare-root and containerized black spruce seedlings submitted to various N loading treatments in the nursery. N2 represents the standard N foliar concentration for seedling production in Quebec (Canada). Foliar N concentrations were measured at the nursery, prior shipping to the field (n = 30 for each stock type × initial N combination). Morphological data were collected prior planting (n = 25 for each stock type × initial N combination).

	Bare-root				Container			
	N1	N2	N3	N4	N1	N2	N3	N4
Foliar N concentration (%)[a)]	1.72	2.05	2.17	2.28	1.17	1.57	2.00	2.33
Dimensions								
Height (cm)	19.71 (3.97)	20.83 (4.41)	20.78 (4.52)	20.56 (4.05)	23.66 (2.87)	22.70 (30.7)	23.29 (3.21)	23.63 (3.30)
Ground-level diameter (mm)	3.51 (0.61)	3.64 (0.69)	3.88 (0.74)	3.87 (0.69)	2.96 (0.53)	3.04 (0.58)	3.21 (0.62)	3.29 (0.68)
Dry biomass								
Needles (g)	1.94 (0.64)	1.84 (0.55)	1.95 (0.55)	1.88 (0.65)	1.42 (0.26)	1.28 (0.29)	1.44 (0.25)	1.18 (0.16)
Twigs (g)	0.48 (0.23)	0.45 (0.15)	0.52 (0.20)	0.60 (0.29)	0.24 (0.06)	0.22 (0.06)	0.28 (0.09)	0.21 (0.05)
Stem (g)	0.85 (0.25)	0.80 (0.20)	1.07 (0.29)	1.04 (0.32)	0.75 (0.10)	0.63 (0.15)	0.77 (0.15)	0.70 (0.16)
Total aboveground (g)	3.27 (1.08)	3.08 (0.83)	3.53 (0.99)	3.53 (1.19)	2.42 (0.38)	2.12 (0.45)	2.49 (0.43)	2.09 (0.29)

[a)] SD values were not available for this variable.

2.6 Statistical Analyses

Analyses of variance for a split-split-split-plot design were used to assess treatment effects on height (H) and GLD (8 growing seasons following plantation), RGR_H and RGR_{GLD}, survival (5 and 8 growing seasons following plantation), ericaceous cover (5 and 8 growing seasons following plantation), and foliar nutrient concentrations (8 growing seasons following plantation). Scarification intensity (S1, S2) was considered as the main plot treatment, fertilization (F0, F1, F2) was the subplot level, stock type (bare-root, container) was the sub-subplot level, and the initial foliar N concentration category (N1, N2, N3, N4) was the sub-sub-subplot factor. Analysis of variance with repeated measurements was conducted to compare scarification treatment effects on soil temperature, during the 8th growing season after plantation; a power spatial covariance structure (sp(pow)) was selected (Littell et al. 2006). Soil nutrient differences between scarification treatments, 5 and 8 growing seasons after planting, were assessed by a one-way ANOVA. We analysed treatment impact on LMA and root:shoot ratio with ANOVAs for a split-split plot design, with scarification as the main plot treatment, fertilization at the sub-plot level and stock type at the sub-sub-plot factor.

We performed all analyses with the MIXED procedure of SAS 9.2 (SAS Institute, Cary, NC, USA). Fisher's protected LSD tests were used to compare differences between treatments ($\alpha = 0.05$). Normality and homoscedasticity were verified for all data using visual distribution of data and by analysis of residues. Natural logarithmic transformations were made when necessary; we present back transformed means and 95% confidence intervals with bias correction when appropriate (Ung and Végiard 1988).

3 Results

3.1 Soil Temperature and Nutrient Availability

Soil temperature profiles, during the 8th growing season following plantation, differed significantly between single (S1) and double-pass (S2) scarified plots for most of the sampled period ($p = 0.002$) (Fig. 2). The maximum difference was observed on June 8 (Julian Day 160), with a 1.21 °C higher soil temperature measured in the S2 plots compared to the S1 treatment. We did not detect significant difference for soil nutrient concentrations between the scarification treatments at growing seasons 5 (data not shown) and

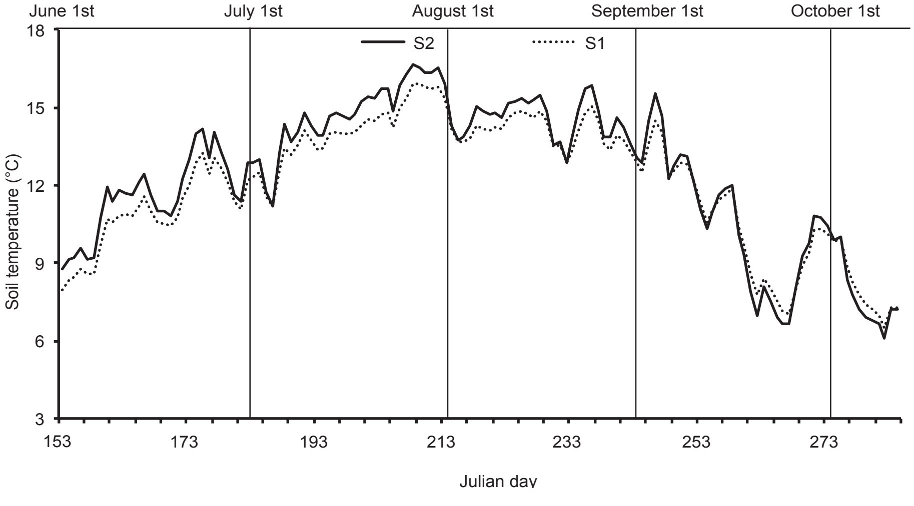

Fig. 2. Soil temperature profile for the 2008 growing season (8th growing season post-planting). S1 = single-pass scarification, S2 = double-pass scarification.

Table 2. Summary of ANOVA results and treatment means with (SE) or [95% CI] for the scarification effect on selected soil variables measure for the upper mineral horizon (0–10 cm) 8 growing seasons after plantation

	ndf	*P*	Single-pass scarification (S1)	Double-pass scarification (S2)	SE
C [a)] (g/kg)	1	0.119	21.0 [16.7; 26.3]	26.5 [21.2; 32.8]	-
C/N [a)]	1	0.517	25.4 [23.7; 27.2]	26.2 [24.4; 28.0]	-
Organic matter (g/kg)	1	0.409	46.8	52.1	4.4
pH	1	**0.032**	4.74	4.88	0.04
NH_4 concentration (mg/kg)	1	0.112	3.3	3.7	0.2
P concentration (mg/kg)	1	0.990	14.4	14.5	2.3
K [a)] concentration (mg/kg)	1	0.475	17.4 [14.7; 20.4]	18.7 [15.9; 21.9]	-
Ca [a)] concentration (mg/kg)	1	0.476	29.8 [21.4; 40.9]	33.7 [24.3; 45.9]	-
Mg [a)] concentration (mg/kg)	1	0.562	4.5 [2.9; 6.5]	4.0 [2.4; 5.8]	

Bold indicates significant effects ($\alpha = 0.05$).

[a)] Analyses performed on ln-transformed data. We present back-transformed means and 95% CI with bias correction (Ung and Végiard 1988).

8 following plantation, except for pH, which was slightly higher in the S2 plots 8 growing seasons following plantation (Table 2).

3.2 Ericaceous Cover

Percent ericaceous cover differed significantly across scarification treatments (Table 3). In October of the 5th growing season, ericaceous cover was 1.5 higher in S1 plots, compared to S2 plots. Eight years after plantation, the percent ericaceous cover remained higher in S1 plots compared to S2 plots, but the difference had decreased. Ericaceous cover differed between fertilized (F1 and F2) and non-fertilized (F0) plots at year 5 and 8 following plantation, but no significant difference was found between F1 and F2 (Table 3). Percent cover was 1.20 – 1.24 higher in the F0 plots, compared to fertilized conditions. However, the higher percent cover measured in the F0 plots, compared to the fertilized plots, was only detectable in the S2 treatment (Fig. 3).

3.3 Survival and Growth

We detected a significant stock type × fertilization interaction for seedling survival 5 (results not shown) and 8 growing seasons following plantation (Table 3). The highest survival at year 8 was observed in the non-fertilized plots and was similar across stock types (Fig. 4). The lowest survival was observed for seedlings established in F2 plots. Containerized and bare-root seedlings planted in F0 plots had approximately two times higher survival than seedlings of the corresponding stock types planted in F2 plots (Fig. 4). Compared to non-fertilized conditions, seedlings planted in F1 plots exhibited reduced survival as well; the effect was more pronounced for bare-root than for containerized seedlings (Fig. 4).

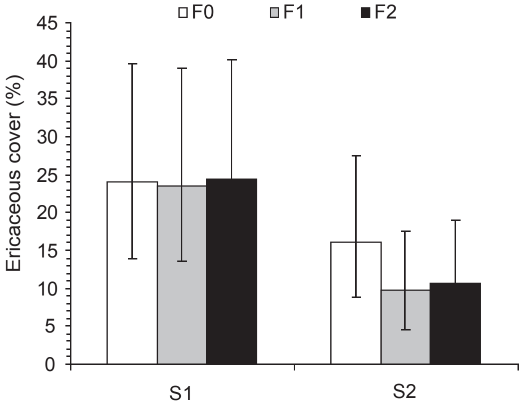

Fig. 3. Scarification × fertilization effects on ericaceous cover 8 growing seasons following plantation. Refer to Fig. 1 for treatment abbreviations.

Stock type and scarification interacted to influence height and GLD measured 8 growing seasons after plantation (Table 3). The tallest seedlings were measured in the S2 plots; bare-root seedlings were 14% (19.4 cm) taller than containerized seedlings. Height was similar across

Table 3. Summary of ANOVA results for selected traits measured on planted black spruce seedlings.

Source of variation	ndf	H_t 2008	GLD [a] 2008	Survival 2008	RGR_H 2008	RGR_{GLD} 2008	Eri. Cover 2005 [a]	Eri. Cover 2008 [a]	LMA [a] 2008	Root:shoot [a] 2008	H/D 2008 [a]
Scarification (S)	1	**<0.001**	**<0.001**	0.285	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.007**	0.272	**<0.001**
Fertilization (F)	2	**<0.001**	**<0.001**	**<0.001**	**0.001**	**<0.001**	**0.005**	**0.034**	**0.005**	0.794	**<0.001**
S×F	2	0.085	**0.001**	0.322	0.027	**0.001**	0.262	**0.040**	0.908	0.300	**<0.001**
Stock type (ST)	1	**<0.001**	**0.002**	0.728	**<0.001**	**0.003**	0.945	0.097	0.883	**0.020**	**<0.001**
S×ST	1	**<0.001**	**0.001**	0.945	0.966	**0.033**	0.325	0.923	0.251	0.597	0.552
ST×F	2	0.088	**0.011**	**0.002**	0.058	0.128	0.902	0.480	0.683	0.367	**0.010**
S×ST×F	2	0.625	0.929	0.721	0.466	0.435	0.862	0.898	0.203	0.937	0.453
Foliar N conc. (N)	3	**0.010**	**0.001**	0.572	0.797	0.347	0.544	0.448			**0.014**
S×N	3	0.481	0.245	0.144	0.954	0.224	0.984	0.910			0.350
ST×N	3	0.233	0.878	0.637	0.221	0.475	0.499	0.934			0.129
N×F	6	0.060	**0.001**	0.572	0.683	0.313	0.825	0.835			0.610
S×ST×N	3	0.066	0.081	0.583	0.900	0.366	0.618	0.378			0.755
S×N×F	6	0.955	0.948	0.780	0.624	0.624	0.555	0.642			0.923
ST×N×F	6	**0.023**	0.256	0.945	0.720	0.130	0.834	0.901			0.307
S×ST×N×F	6	0.081	0.729	0.802	0.466	0.977	0.732	0.606			0.859

H_t = height, GLD = ground level diameter, RGR_H = relative growth rate (height), RGR_{GLD} = relative growth rate (ground level diameter), Eri Cover = Ericaceous cover, LMA = Leaf mass per area, Root:shoot: root:shoot ratio (biomass), H/D = height to diameter ratio.
Bold indicates significant effects ($\alpha = 0.05$).
[a] Analyses performed on ln-transformed data.

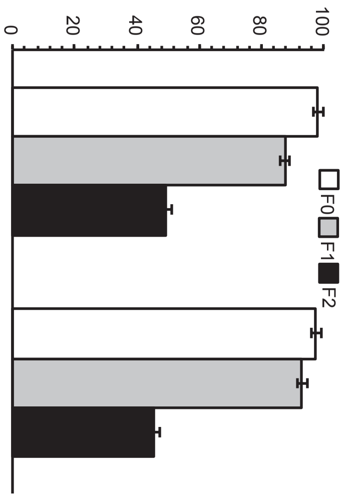

Fig. 4. Stock type × fertilization effects on seedling survival, 8 growing seasons following plantation. Refer to Fig. 1 for treatment abbreviations.

stock types in the S1 treatment (Fig. 5a). Similar trends were noted for GLD (Fig. 6a). Fertilized containerized seedlings had larger GLD than non-fertilized containerized seedlings (Fig. 6b). For bare-root seedlings, the F1 treatment favoured larger GLD, compared to F2 conditions, which was still significantly better than non-fertilized (F0) conditions (Fig. 6b).

There was a triple interaction between initial foliar N, stock type and fertilization influencing seedling height at age 8 (Table 3). F1 and F2 seedlings were taller than F0 seedlings, and bare-root seedlings were slightly taller than containerized seedlings (Fig. 5b). The analysis revealed a significant interaction between initial foliar N and fertilization (Table 3); overall, GLD was larger for F1 seedlings, compared to F2 and F0 seedlings (Fig. 6c). But overall, the effect of initial foliar N on seedling growth was no longer detectable 8 growing seasons following planting.

Relative growth rate in height (RGR_H) differed significantly between scarification treatments (S2 > S1), stock types (bare-root > containerized), and fertilization treatments (F2 > F1 and F0) (Table 3; Fig. 7a,b,c). Scarification interacted with stock type as well as fertilization to influence RGR_{GLD} (Table 3): the scarification effect on RGR_{GLD} was only significant for bare-root seedlings, and in F2 plots (Fig. 7d,e). In both cases, seedling planted in S2 plots outperformed seedlings planted in S1 plots.

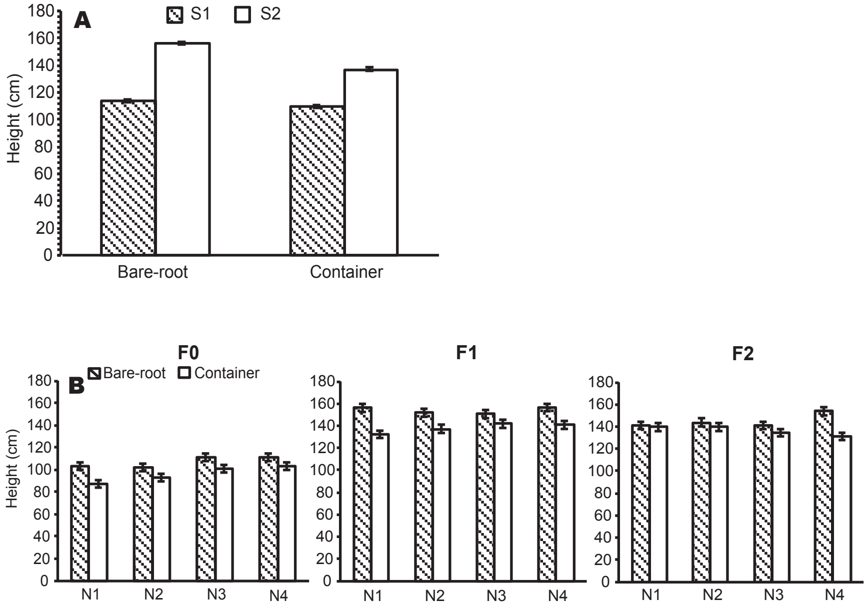

Fig. 5. Stock type × scarification (a), and stock type × fertilization × initial N (b) effects on seedling height, 8 growing seasons following plantation. Refer to Fig. 1 for treatment abbreviations.

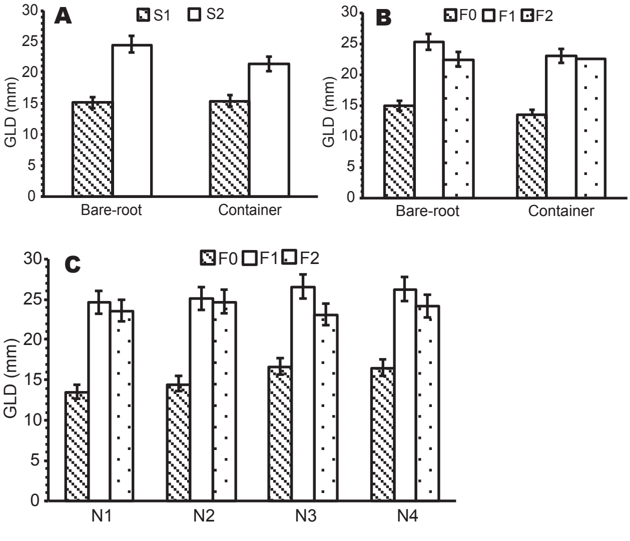

Fig. 6. Stock type × scarification (a), stock type × fertilization (b), and fertilization × initial N (c) effects on ground-level diameter (GLD), 8 growing seasons following plantation. Refer to Fig. 1 for treatment abbreviations.

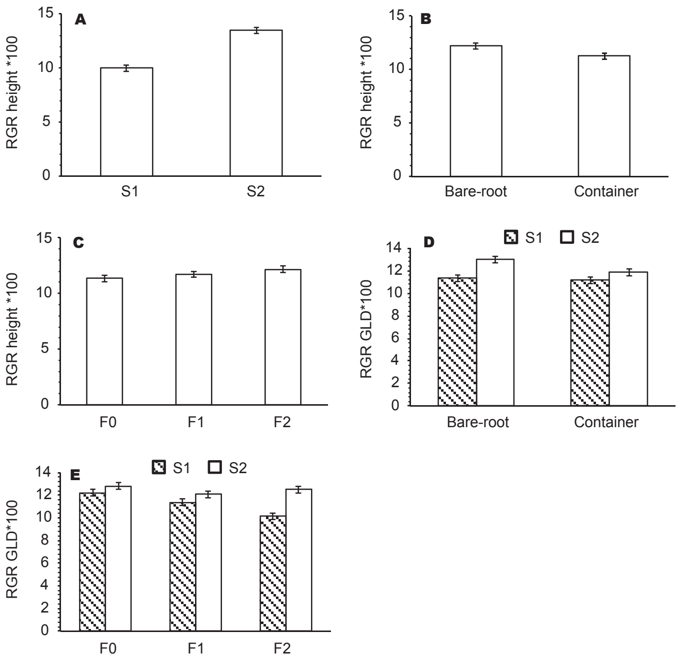

Fig. 7. Scarification (a), stock type (b), fertilization (c), stock type × scarification (d), and scarification × fertilization (e) effects on relative growth rate in height and ground-level diameter, 8 growing seasons following plantation. Refer to Fig. 1 for treatment abbreviations.

3.4 LMA, Root:shoot and H/D Ratios

Leaf mass per unit of area (LMA) was 14% higher for seedlings planted in S2 plots compared to seedlings planted in S1 plots (Table 3, Fig. 8a), and in fertilized compared to non-fertilized conditions (Table 3, Fig. 8b). A significant interaction between fertilization and stock type, as well as between fertilization and scarification, was detected for the H/D ratio (Table 3). The H/D ratio was slightly higher for F0 seedlings, compared to F1 and F2 seedlings (Fig. 8c,d) and for S1 seedlings compared to S2 seedlings, but only in the F0 and F2 treatments (Fig. 8d). Scarification intensity and fertilization significantly influenced root biomass in 2011 ($p<0.001$). Seedlings planted in S2 plots increased their root biomass by a factor of 1.7, compared to seedlings planted in S1 plots ; fertilized seedlings (F1 and F2) had a root biomass 1.4 larger than F0 seedlings. We detected a significant difference between stock types for the root:shoot ratio (Table 3); the ratio was higher for bare-root compared to containerized seedlings (Fig. 8e).

3.5 Foliar Nutrient Concentrations

Fertilization influenced foliar N and K concentrations 8 years after plantation, and we found a significant scarification × fertilization interaction for P. Fertilization had a modest but significant effect on N concentration; F1 and F2 seedlings (1.03%) presented higher concentrations than F0 seedlings (1%) ($p=0.013$). Results for K were similar; F2 seedlings (0.59%) presented higher concentrations than F1 seedlings (0.57%), which were higher than F0 (0.56%) ($p<0.001$). Phosphorus concentration was higher for seedlings planted in S2 plots, except for the F1 treatment, for which the concentrations were similar across scarification treatments (0.15%). Double-pass scarification lead to a modest increase in P concentration for the F0 (1.6%) and F2 (1.7%) seed-

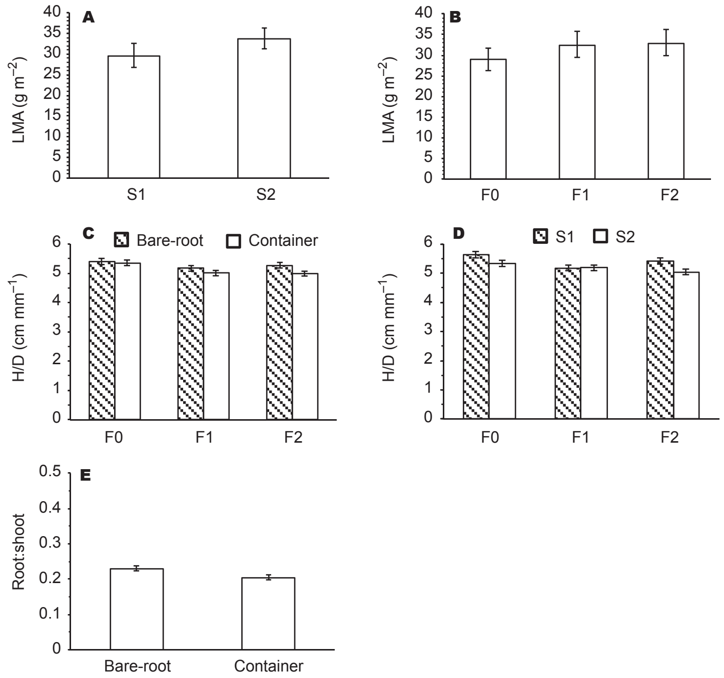

Fig. 8. Scarification (a), fertilization (b), fertilization × stock type (c), fertilization × scarification (d), and stock type (e) effects on leaf mass per unit of area (LMA), height to diameter ratio (H/D), and root:shoot ratio, 8 growing seasons following plantation. Refer to Fig. 1 for treatment abbreviations.

lings ($p = 0.001$), compared to the F1 seedlings (1.5%).

Stock type significantly influenced N, P and Mg foliar concentrations 8 growing seasons after plantation, containerized seedlings presenting slightly higher concentrations for N and P compared to bare-root seedlings (for N: $p < 0.001$, 1.1% *vs* 1.0%; for P: $p = 0.030$, 0.16% *vs* 0.15%). Magnesium concentration was slightly higher in bare-root seedlings (0.11%) compared to containerized seedlings (0.10%) ($p = 0.010$). Calcium foliar concentrations differed between scarification treatments ($p = 0.020$); higher values were measured for seedlings planted in S1 plots (0.52%), compared to seedlings planted in S2 plots (0.49%).

4 Discussion

Our results support previous findings regarding the beneficial impact of S2 on early seedling growth in the presence of thick humus layers and significant competition by ericaceous shrubs (Prévost and Dumais 2003, Thiffault and Jobidon 2006). Height and diameter growth were significantly higher in the double-pass scarification plots compared to the single pass treatment (by 8–9%) between year 5 and 8. We mainly attribute this increased growth in the intensive treatment, compared to the one-pass treatment, to its effects on soil temperature (Grossnickle 2000, Thiffault and Jobidon 2006). Higher soil temperature favours root growth (Kaspar and Bland 1992). It also improves water and nutrient absorption by decreasing soil water viscosity and increasing root permeability and hydraulic conductivity (Boucher et al. 2001). The increased soil temperature we measured in the S2 plots, compared to the S1 plots, is most probably a combined effect of many factors including differences in humus layer disruption and distinct impacts on competing vegetation dynamics. The similar root:shoot ratio for seedling planted in S1 and S2 treatments suggests that the increase in height and diameter remained correlated to root growth despite these different above- and belowground constraints.

Also, the reduced ericaceous cover around the planted seedlings likely decreased interspecific competition for water and nutrients, and favoured black spruce height growth in S2 plots, compared to S1 conditions (Yamasaki et al. 1998, Hébert et al. 2006, Thiffault et al. 2012). The higher leaf N concentration and higher LMA we measured on seedlings established in the double-pass treated plots, compared to seedlings planted in the single-pass treatment, support this interpretation. These traits generally favour higher photosynthetic rates, which are positively related to growth for black spruce (Tjoelker et al. 1998).

Few studies have compared the growth of containerized and bare-root seedlings in boreal conditions (Menes et al. 1996, Johansson et al. 2007). We hypothesized that container seedlings would outperform bare-root seedlings, and that differences between stock types would be exacerbated with increased scarification intensity. However, we observed that both stock types performed equally following S2, and that bare-root seedlings slightly outperformed containerized seedlings in the double-pass treatment. When it is observed, better growth of bare-root over containerized seedlings is typically attributed to their larger initial size (Mohammed et al. 2001). Indeed, most studies have compared stock types with important size differences (Menes et al. 1996, Pinto et al. 2011). In the present experiment, although statistically different ($p<0.001$), initial seedling dimensions were similar across stock types by silvicultural standards (difference in height <3 cm; difference in GLD <0.6 mm); initial aboveground size effects must thus be discarded. We hypothesize that the higher root:shoot ratio and the better root–soil contact of the bare-root stock may have enabled the seedlings to take advantage of the enhanced growing conditions found in the S2 plots (Grossnickle 2005). Also, the initial lower H/D of the bare-root seedlings compared to the container seedlings (5.5 *vs.* 7.5, as calculated from Table 1) may have led to a lower resistance to water transport during the establishment phase, with respect to fluid dynamics (Taiz and Zeiger 2010). However, the H/D ratio of container seedlings decreased to similar levels 8 growing seasons following plantation. This suggests that growth differences between the stock types will continue to decrease over time.

Fertilization still had an effect on height growth between year 5 and 8, as demonstrated by the significant increase in RGR compared to control conditions. This result is concomitant with increased leaf N and LMA in fertilized plots compared to control conditions at year 8. But although statistically significant, the small differences in foliar N are not expected to have biological consequences; all values remain low and within the typical range observed for seedlings planted in these ecosystems (Thiffault and Jobidon 2006). LeBel et al. (2008) observed a short-term effect (<7 years) of fertilization on black spruce seedling growth on a site dominated by *Kalmia* and *Vaccinium angustifolium* Ait. These contrasting results indicate that seedling response to fertilization is site-specific. Although authors have reported strong correlation between micronutrients such as Fe and Zn and leader increment for some conifers (Kranabetter et al. 2003), there was no marked effect of micronutrient fertilization on seedling growth and nutrition in this ecosystem.

Survival of the N-P-K treated seedlings was low (<50%), compared to the seedlings fertilized with N-P-K + micronutrients (>88%). The F2 treatment contained two times the N available in the F1 treatment. The higher N concentration supplied to the F2 seedlings, coupled with the fertilization method we used may have limited the expansion of the root system and induced mortality through water stress (Jacobs et al. 2004), which is the main cause of initial seedling mortality following planting (Grossnickle 2012). Moreover, we observed that radial growth decreased with fertilization (especially F2) in the single-pass treatment, compared to F0 conditions (Fig. 7e). This further support the hypothesis that in this particular ecosystem, the F2 treatment created stressful conditions that were exacerbated by the competitive environment found in the S1 plots, compared to the S2 plots.

We evaluated the potential of using seedling with increased initial foliar N concentration to promote survival and growth on these low-fertility sites. Our hypothesis was infirmed; the effect of initial foliar N on seedling growth was no longer detectable 8 growing seasons following planting, even in the most intensively scarified plots. The differences that were still apparent at year 8 were carried-on effects of the early initial N concentration impacts on seedling growth (Munson and Bernier 1993, Thiffault and Jobidon 2006). Heiskanen et al. (2009) have also evidenced that foliar N loading effects can be short-lived following plantation and cannot fully compensate for low soil nutrient availability. Significant growth responses to increased initial nutrient status are expected to be higher on fertile sites, compared to sites where other factors (such as soil temperature) become limiting (Salifu and Timmer 2001).

5 Conclusion

Care must be taken in interpreting the results of this study, as it was conducted on only one site. However, the experimental design comprised a large number of experimental units, replicated over many experimental blocks. Moreover, 8th-year containerized seedling height in S1F0 plots –which represents the common silvicultural scenario in this region– was representative of the average regional values for planted black spruce seedlings at age 8-years (98 cm ± 35; Guy Prégent, pers. comm.). Double-pass scarification promoted seedling growth over a single-pass treatment on this thick-humus, *Kalmia*-dominated site of northeastern Quebec. However, the relative gains associated with the second-pass have to be balanced against the supplemental investments involved by the treatment. Longer-term growth assessments, combined with appropriate financial analyses are necessary to conclude on the profitability of the more intensive treatment (Hawkins et al. 2006). These results although indicate that regeneration success of these sites is positively related to forest floor disturbance intensity. Despite the fact that CLAAG might ensure higher stocking of natural regeneration, traditional clearcut approaches that disrupt the forest floor could benefit both natural and planted conifer growth in these ecosystems and limit the need to proceed with S2 treatments prior planting. Our results point to variable effects of fertilization at planting to stimulate seedling initial growth. In this ecosystem, it appears that the silvicultural gains of this treatment depend on the variable of interest (e.g. diameter *vs.* height growth). On the other hand, initial foliar N had marginal effects on seedling size, relative to the other treatments. Both containerized and bare-root seedlings can successfully be used for resforestating similar boreal sites covered by thick humus and dominated by *Kalmia* and associated species (given that stock types are of similar initial size). Bare-root seedlings indeed grew faster in the most intense site preparation treatment, but the differences we measured have limited silvicultural impacts.

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