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ORIGINAL ARTICLE

Silvicultural options to promote seedling establishment on *Kalmia–Vaccinium*-dominated sites

NELSON THIFFAULT[1], BRIAN D. TITUS[2] & ALISON D. MUNSON[3]

[1]*Ministère des Ressources naturelles et de la Faune, Direction de la recherche forestière, Sainte-Foy, Canada,* [2]*Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, Canada, and* [3]*Centre de recherche en biologie forestière, Faculté de foresterie et de géomatique, Université Laval, Sainte-Foy, Canada*

Abstract

Seedling growth is often hampered on sites dominated by *Kalmia angustifolia*. In June 2000, a trial was established on a clear-cut site in Quebec, Canada, with a high cover of *Kalmia* and *Vaccinium* species. The objectives were to evaluate how soil scarification and fertilization at the time of planting influence early growth and establishment of black spruce [*Picea mariana* (Mill.) BSP] and jack pine (*Pinus banksiana* Lamb.) seedlings. During the first 2 years, scarification reduced *Kalmia* cover three-fold and doubled the distance from seedlings to the nearest *Kalmia* stem. Scarification did not increase soil-extractable NH_4-N concentration, and reduced soil potassium, calcium and magnesium. Scarification had no effect on seedling water stress. Seedling growth improved and foliar nutrient concentrations were generally higher in scarified plots than in unscarified control plots. No differences were observed between single- and double-pass scarification for any variables except for ground-level stem diameter of seedlings, which was greater with double-pass scarification (12.1 vs 13.1 mm). Spot fertilization increased seedling growth and foliar nitrogen concentrations. Jack pine growth was greater than black spruce growth, an effect enhanced when seedlings were fertilized.

Keywords: *Fertilization, growth, Kalmia angustifolia, nutrition, Picea mariana, Pinus banksiana, Quebec, scarification, water stress.*

Introduction

Ericaceous shrubs previously present as understorey species have the potential to rapidly dominate burned or clear-cut sites through vegetative regeneration (Messier & Kimmins, 1991; Mallik, 1993, 1995; Titus, Sidhu, & Mallik, 1995). They can be associated with reduced growth of naturally regenerated and planted conifer seedlings (Anon., 1972; English & Hackett, 1994; Fraser, Chanway, & Turkington, 1995; Titus et al., 1995; Zackrisson, Nilsson, Dahlberg, & Jäderlund, 1997). The shrub *Kalmia angustifolia* L. (sheep laurel, lambkill; hereafter referred to as *Kalmia*), which is found in eastern Canada and the north-eastern USA (Ebinger, 1997), interferes with conifer seedling establishment on some sites. Mechanisms that have been proposed to explain this interference include allelopathy (Mallik, 1992), nutrient competition (Yamasaki, Fyles, & Titus, 2002), hindering of mycorrhizal associations (Titus et al., 1995; Yamasaki, Fyles, Egger, & Titus, 1998) and nutrient sequestration in recalcitrant humus (Damman, 1971; Bradley, Titus, & Preston, 2000). Regardless of the mechanism, conifer seedling growth on *Kalmia*-dominated sites is often "checked" and foliage appears chlorotic, which can indicate nutrient deficiencies (Chapman, 1966).

Control of *Kalmia* with herbicides (e.g. glyphosate plus surfactant) is effective and promotes early seedling growth (English & Titus, 2000), but silvicultural alternatives must be considered because of increasing public concern about use of herbicides (Wagner, Flynn, & Gregory, 1998). Soil scarification (Richardson, 1981; Mallik, 1994; Titus et al., 1995), conifer seedling fertilization (Taylor & Tabbush, 1990) and species choice (Blevins & Prescott,

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Correspondence: N. Thiffault, Ministère des Ressources naturelles et de la Faune, Direction de la recherche forestière, 2700 rue Einstein, Sainte-Foy, QC, G1P 3W8, Canada. E-mail: nelson.thiffault@mrnfp.gouv.qc.ca

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2002) are the three main silvicultural options that forest managers can consider for ensuring plantation success on sites dominated by ericaceous vegetation.

In the first few years after treatment, soil scarification can increase nutrient mineralization through changes in soil temperature and moisture regimen, and by mixing organic material with mineral horizons (Örlander, Gemmel, & Hunt, 1990). Trench scarification may also limit *Kalmia* expansion by creating barriers to rhizome extension because *Kalmia* roots and rhizomes proliferate in humus rather than in bare mineral soil on some sites (Titus et al., 1995). This may partially explain the significant negative impact of scarification on ericaceous shrub cover [*Kalmia*, *Rhododendron groenlandicum* (Oeder) Kron & Judd, *Vaccinium* sp.] on boreal sites in Quebec (Prévost, 1996, 1997). However, the effect of operational scarification on early growth, physiology and nutrition of planted seedlings on *Kalmia*-dominated sites remains largely unknown, although some studies have been carried out on non-operational field trials (Thiffault, Titus, & Munson, 2004).

Fertilization can be used to overcome plantation establishment problems on sites dominated by the ericaceous shrubs *Calluna vulgaris* (L.) Hull (Taylor & Tabbush, 1990) and *Gaultheria shallon* Pursh (Prescott, Weetman, & Barker, 1996; Blevins & Prescott, 2002). Although *Kalmia* and *Vaccinium* spp. can dominate nutrient uptake processes after broadcast fertilization, spot fertilization can double black spruce [*Picea mariana* (Mill.) BSP] seedling height and diameter growth over 2 years (Thiffault, Titus, & Munson, 2004). However, it is not known whether the effectiveness of spot fertilization at planting is increased when combined with scarification.

Different conifer species growing on sites dominated by ericaceous shrubs can respond differently to scarification and fertilization when these treatments are applied either singly or in combination (Blevins & Prescott, 2002). Choice of planting species will therefore also have an impact on tree crop response to treatment, but little is known about this response for sites dominated by *Kalmia*, which are usually planted with black spruce or jack pine (*Pinus banksiana* Lamb.).

In some stands, *Kalmia* is associated with the build-up of a thick forest floor (Krause, 1998), and *Kalmia*-derived humus can have very low nitrogen (N) mineralization rates (Damman, 1971; Titus et al., 1995). In considering the above three silvicultural options, the long-term forest management objective is therefore to achieve canopy closure so that *Kalmia* is shaded out (Titus et al., 1995; Mallik, 1998). The expectation is that site productivity will then be maintained. In other ecosystems where accelerated canopy closure and a concomitant reduction in ericaceous shrubs were achieved through silvicultural treatments, improvements in soil properties 10 years after treatment (Bradley, Titus, Preston, & Bennett, 2000) suggest that increased stand productivity (Bennett, Blevins, Barker, Blevins, & Prescott, 2003) will persist in the long term. Improved conifer growth after scarification has been measured on *Kalmia* and *Kalmia–Rhododendron groenlandicum* sites in Quebec (Prévost & Dumais, 2003; Thiffault, Cyr, Prégent, Jobidon, & Charette, 2004), but no silvicultural trial has yet been conducted on sites where *Kalmia* is associated with a dense cover of *Vaccinium*. The main differences between these and *Kalmia–Rhododendron groenlandicum* sites is that humus thickness is less and soil moisture regimens are drier on *Kalmia–Vaccinium* sites.

The objectives of this study were to evaluate how soil scarification intensity and fertilization at the time of planting, both independently and in combination, influence early growth and foliar nutrient concentrations of black spruce and jack pine seedlings planted on a clear-cut dominated by *Kalmia* and *Vaccinium* spp., and how these treatments affect especially *Kalmia* cover, as *Kalmia* is considered the most problematic species. The effect of scarification intensity on black spruce water stress and on soil nutrient availability was also studied. It was hypothesized that for each of the two conifer species: (1) scarification has a positive effect on seedling growth, foliar nutrient concentrations and soil nutrient availability; (2) scarification reduces black spruce seedling water stress; (3) scarification reduces *Kalmia* cover; (4) fertilization at the time of planting leads to improved seedling nutrient status and growth; and (5) fertilization effects on conifer seedlings are enhanced when seedlings are planted in scarified soil. This trial was established adjacent to a non-operational trial that examined the effects of *Kalmia* control (with herbicides) and humus removal (by mechanical and manual scalping) on early seedling growth and physiology (Thiffault, Titus, & Munson, 2004).

Materials and methods

Study site

The trial was established in the Abitibi region of northwestern Quebec (48°29′37″ N, 76°55′40″ W), within the balsam fir [*Abies balsamea* (L.) Mill.]–white birch (*Betula papyrifera* Marsh.) bioclimatic region (Saucier, Bergeron, Grondin, & Robitaille, 1998). The regional climate is subpolar subhumid continental (mean annual temperature 2.5°C, growing season 150–160 days, mean annual precipitation 950 mm, 30% of which falls as snow). The previous 70-year-old stand (dominant and co-dominant trees 12–17 m tall, 61–80% canopy cover, 100 m^3 ha^{-1} merchantable wood) originated after wildfire, was composed of black spruce and jack pine, and was clear-cut in summer 1999. The humo-ferric podzol soil (Soil Classification Working Group, 1998) is characterized by an 8-cm deep mor humus, and developed on a moderately well-drained fluvioglacial deposit with a loamy-sand texture (74% sand, 22% silt, 4% clay) in surface mineral horizons (0–15 cm). *Kalmia*, *Vaccinium angustifolium* Ait., *V. myrtilloides* Michx. and ground lichens (mainly *Cladina* spp.) formed an evenly distributed cover across the site at the time of planting in early June 2000, 1 year after harvesting. Although 59% of the ericaceous biomass 2 years after planting was *Vaccinium* spp. (Thiffault, Titus, & Munson, 2004), this study initially focused on *Kalmia* because, before these studies, seedling check had not been associated with *Vaccinium* in eastern Canada, unlike *V. myrtillus* L. in some parts of Europe (e.g. Jäderlund, Zackrisson, Dahlberg, & Nilsson, 1997). Subsequently, ^{15}N studies demonstrated the importance of N uptake by *Vaccinium* (Thiffault, Titus, & Munson, 2004).

Experimental design and treatments

A split-plot factorially designed field trial was established, with treatments randomly applied within 10 replicate blocks (total of ~2.4 ha, including buffer zones). First, one of three scarification treatments was applied (October 1999) to each of three main plots (18 × 30 m, separated by 6-m buffers) within each block (30 × 66 m): (1) no scarification (S0); (2) single-pass scarification with a TTS passive disk trencher (S1; Figure 1A); and (3) double-pass scarification, with the second pass perpendicular to the first (S2; Figure 1B). Then 72 black spruce seedlings and 72 jack pine seedlings were planted in the hinge position (trench–berm interface; Figure 1C) in each main plot in early June 2000. Seedlings (black spruce seed origin 48°51′ N 78°01′ W, jack pine seed origin 48°37′ N 77°48′ W) were grown over 2 years in 45–110 containers (45 cells of 110 cm^3 each per container) at the provincial nursery at Trécessons using standard nursery practices for production of 2+0 stock in Quebec (Tétreault, Brouillette, & Lortie, 1990). For each species, seedlings were planted 1 m apart in three rows of 24 seedlings each, with 2 m between rows. Main plots were split longitudinally into two subplots; one subplot was chosen at random as a control (F0) and the other for fertilization (F1) at the time of planting using a slow-release fertilizer package (Silva Pak; Reforestation Technologies International, Salinas, CA, USA). For each fertilization subplot, Silva Paks were buried 5 cm deep about 2 cm away from each seedling. Each Silva Pak contained 9 g of fertilizer [26.3% total N, 12.0% available phosphoric acid, 6.0% soluble potash; equivalent to 2.4, 0.5 and 0.5 g elemental N, phosphorus (P) and potassium (K), respectively; N, P and K polymer-coated to provide 24.9% slow-release N, 5.3% slow-release available P, 5.1% slowly-available potash and 6.0% sulfur (S)]. Within each subplot and for each species (i.e. 36 seedlings), one seedling out of two was tagged (alternate seedlings) for future identification and long-term growth measurements (i.e. 18 seedlings). Untagged seedlings were used for destructive sampling for determination of biomass, xylem water potential and foliar nutrient concentrations.

Conifer seedling and Kalmia measurements

Height (cm) and ground-level stem diameter (mm) of tagged seedlings (18 per subplot) were measured immediately after planting [black spruce: 28.5 ± 4.6 cm tall (mean ± SD), 3.2 ± 0.5 mm diameter; jack pine: 31.5 ± 5.6 cm tall, 4.3 ± 0.6 mm diameter] and again at the end of the third growing season. Mortality was assessed after 3 years. In October 2001 (after two growing seasons), three seedlings were harvested in each scarification × fertilization × species combination of every block (total of 360 seedlings). Seedlings were dried at 65°C for 48 h, partitioned into needles, twigs and stem, and weighed. *Kalmia* cover was estimated visually (by 5% cover class) within a 0.5-m radius circle centred on each tagged seedling at the time of planting and again after two growing seasons. The distance between each tagged seedling and the nearest *Kalmia* stem > 0.1 m in height was measured on two occasions: at the time of planting and after two growing seasons.

Xylem water potential

In the second growing season (2001), the predawn (03.00 h) and midday (13.00 h) xylem water potential of unfertilized black spruce seedlings was measured in all main plots (S0, S1, S2) of all blocks by taking predawn measurements on 26 July, 28 July and 10 August, and midday measurements on 25 July, 27 July and 9 August. (Logistical constraints precluded measurement of fertilized seedlings.) Xylem water potential was measured in 1-year-old shoots (one shoot per seedling, one seedling per main plot, total of 30 measurements at each measurement time) using a portable pressure chamber

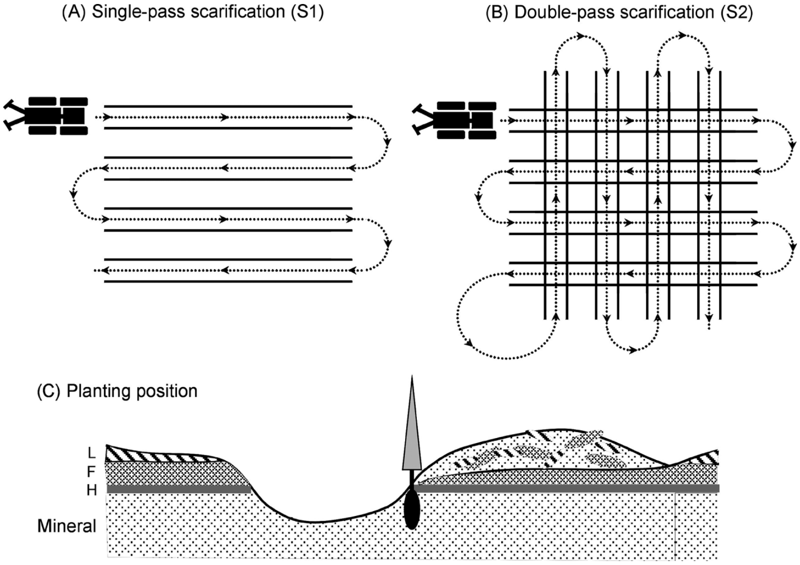

Figure 1. Schematic representation of (A, B) the scarification treatments (solid lines = scarified trenches; dotted lines = the path of the scarifier), and (C) the planting position in scarified plots (adapted from Sutherland & Foreman, 1995, with the authors' permission).

(PMS Instruments, Corvallis, OR, USA), following the recommendations of Ritchie and Hinkley (1975). Cut shoots were kept in paper bags until they were measured (within 20 min of excision). Different spruce seedlings were sampled for water potential on each measurement date.

Foliar nutrient concentrations

Current-year shoots from black spruce and jack pine seedlings were sampled in October of the second growing season (2001) to determine foliar nutrient concentrations. For both species, at least two composite samples were collected from three seedlings in each subplot in all blocks. Samples were stored frozen, oven-dried at 65°C for 48 h and ground to pass through a 40-mesh screen. Using standard techniques (digestion with $H_2SO_4/H_2O_2/Se$; Walinga, van der Lee, Houba, van Vark, & Novozamsky, 1995), Kjeldahl N was measured colorimetrically by spectrophotometry (FIA Quickchem; Lachat, Milwaukee, WI, USA) and P, K, calcium (Ca) and magnesium (Mg) by inductively coupled plasma analysis (ICAP-9000; Thermo Instruments, Franklin, MA, USA).

Available soil nutrients

Mixed bed ion-exchange resin (IER, IONAC NM-60 $H^+/OH-$; JT Baker, Phillipsburg, NJ, USA) was used to assess soil nutrient availability during the first (2000) and second (2001) growing seasons. Resin was washed with 2 M NaCl, deionized water and 0.1 M NaOH (after Thiffault, Jobidon, De Blois, & Munson, 2000), and 15 ml (at 50% weight-based humidity; = 4.05 g dry weight) of resin was sealed into a nylon polyester fabric bag (8 × 8 cm). Resin bags were then rinsed in deionized water and stored at ~5°C until used. Ten resin bags were buried (horizontally, 10 cm below soil surface) in each of the three main plots (S0, S1, S2) of seven replicate blocks in early June 2000 and 2001, and retrieved in late October after one growing season. Placement sites were distributed and flagged evenly within each main plot, regardless of species and fertilization treatments. Adsorbed ions were extracted with 2 M NaCl, and concentrations of NH_4-N, NO_3-N and PO_4-P determined using colorimetric methods and spectrophotometry (FIA Quickchem), and K, Ca and Mg using plasma atomic emission spectrometry (ICAP-9000).

Extractable soil nutrients

Nine random surface mineral horizon samples (to 10 cm depth) were collected in main plots (S0, S1, S2) of all blocks at the end of the first (2000) and second (2001) growing seasons. (Soil samples in scarified plots were taken from the hinge planting position.) A gardening shovel was used and samples were composited by threes to give three samples per main plot for chemical analysis. Before analysis, soil samples were air-dried (to $<5\%$ weight-based humidity at $<30°C$) and ground (2-mm mesh screen). Mineral N (NH_4-N and NO_3-N) was extracted with a 2 M KCl solution, and extractable P, K, Ca and Mg were extracted with Mehlich-3 solution (Sen

Tran & Simard, 1993). Chemical analyses were performed using the techniques described above.

Statistical analyses

Anova for a split-split-plot design was used, with the three scarification treatments (S0, S1, S2) as main plots, the two fertilization treatments (F0, F1) as subplots, and the two species (black spruce, jack pine) as sub-subplots to test for treatment effects on third year total height and diameter, second year foliar nutrient concentrations, and *Kalmia* cover and distance to the nearest *Kalmia* stem (10 blocks) at planting and after 2 years. Scarification effects on nutrient adsorption by resins (7 blocks) and extractable soil nutrient concentrations (10 blocks) were evaluated by anova for a completely randomized block design; given the period of the study (3 years), species and spot fertilization were not expected to influence these variables. The effect of scarification on black spruce water potential was determined using anova for a split-plot in time design, with scarification as main plots and time as subplots (10 blocks).

Statistical analyses were performed with the MIXED procedure of SAS 8.02 (SAS Institute, Cary, NC, USA) (Littell, Milliken, Stroup, & Wolfinger, 1996). Fisher's protected LSD test (Steel, Torrie, & Dickey, 1997) was used to separate treatment means when anovas showed significant effects ($p < 0.05$). To evaluate scarification effects, orthogonal contrasts were constructed *a priori* to answer the following questions, using one-tailed tests of significance: (1) is there an advantage to scarification, regardless of method? and (2) if scarification is done, is double-pass better than single-pass scarification? Data were first tested for anova prerequisites. Data that were not normally distributed or that had heterogeneous variances were transformed before analysis. When transformed data gave results comparable to those of anovas performed on untransformed data, the latter were retained, because the F test is robust even when variances are not homogeneous if sample sizes are nearly equal (Milliken & Johnson, 1984; Montgomery, 1991). Above-ground biomass, soil nutrient data and distance to nearest *Kalmia* stems were natural-log transformed before analysis. Back-transformed means and 95% confidence intervals are presented for these variables, which were calculated following the method proposed by Ung and Végiard (1988) for bias correction. As *Kalmia* cover data were proportional (i.e. between 0 and 1), they were arcsin transformed (Steel et al., 1997). Back-transformed means and approximates of 95% confidence intervals are presented.

Results

Seedling height, diameter and survival

Soil scarification had similar and significant effects on third-year height of spruce and pine seedlings (Table I), increasing seedling height by 12 cm. For both species, single- and double-pass scarification gave comparable height results (Table II). Scarification increased the seedling diameter of both species (Table I), and this response was greater for jack pine than for black spruce (Tables I and II). For both species, double-pass scarification was significantly more effective than single-pass scarification in increasing third-year diameter (Table II). Fertilization increased black spruce seedling height (by 9.9 cm, or 22%) and diameter (by 2.6 mm, or 34%) (Table I). The response of jack pine to fertilization was greater than that for black spruce for both height (an increase of 21.4 cm, or 37%) and diameter (an increase of 5.1 mm, or 48%) (Table I). No scarification × fertilization interaction for seedling dimensions was found (Table I). Seedling mortality was not affected by the treatments and overall was $<2\%$ at the end of the third growing season.

Seedling biomass

In October 2001, seedlings in scarified plots had a mean above-ground biomass of 12.7 g, whereas seedlings in control plots had a mean above-ground biomass of 8.6 g, a difference that was highly significant ($p < 0.001$). Single- and double-pass scarification did not significantly differ from each other ($p = 0.397$). Fertilization increased above-ground biomass threefold for both species ($p < 0.001$). Although always significant, the difference in above-ground biomass between jack pine and black spruce was more pronounced for fertilized (25.2 g vs 14.1 g) than for unfertilized (7.9 g vs 5.5 g) seedlings (fertilization × species, $p = 0.018$). Similar patterns were observed for needle biomass, except that black spruce and jack pine were equivalent in unscarified, unfertilized subplots ($p = 0.271$).

Kalmia response

At the time of planting (8 months after the scarification treatments), mean *Kalmia* cover in the control treatment was 6% (Figure 2A), and mean distance from planted seedlings to the nearest *Kalmia* stems was 23 cm (Figure 2B). Single-pass scarification reduced mean *Kalmia* cover to 1% at the time of planting (Figure 2A), and mean distance from planted seedlings to nearest *Kalmia* stems increased to 46 cm (Figure 2B). Double-pass was more

Table I. Scarification, fertilization, species and interaction effects on third year seedling dimensions (total height and ground-level diameter) and nutrient concentrations in current foliage 2 years after planting.

Effect and statistical parameter		dfn	dfd	Total height (cm)	GLD (mm)	Nutrient concentration in current foliage (g kg^{-1})				
						N	P	K	Ca	Mg
S	p-Value	2	45.1	**<0.001**	<0.001	<0.001	<0.001	<0.001	**0.156**	**0.002**
S0	Mean			**50.8**	8.8	13.0	1.6	5.1	**2.7**	**1.0**
S1	Mean			**62.4**	12.1	17.1	1.9	5.9	**3.1**	**0.9**
S2	Mean			**63.3**	13.1	17.3	1.9	6.1	**2.9**	**0.9**
	SE			**1.3**	0.4	0.4	0.03	0.1	**0.1**	**0.02**
F	p-Value	1	45.1	<0.001	<0.001	<0.001	0.003	0.022	**0.002**	0.861
F0	Mean			51.0	9.3	14.5	1.8	5.8	**3.1**	0.9
F1	Mean			66.7	13.3	17.2	1.7	5.5	**2.7**	0.9
	SE			1.2	0.3	0.4	0.03	0.1	**0.1**	0.02
SP	p-Value	1	54.3	<0.001	<0.001	0.013	<0.001	<0.001	**<0.001**	0.534
bS	Mean			49.5	8.9	15.3	1.9	6.2	**3.8**	0.9
jP	Mean			68.2	13.8	16.3	1.6	5.2	**2.0**	0.9
	SE			1.2	0.3	0.3	0.03	0.1	**0.1**	0.02
S × F	p-Value	2	45.1	0.952	0.445	0.065	0.907	**0.012**	0.078	0.178
S0F0	Mean			43.2	7.0	11.1	1.6	**5.0**	2.8	1.0
S0F1	Mean			58.4	10.5	15.0	1.5	**5.2**	2.7	1.0
S1F0	Mean			54.5	10.1	15.7	1.9	**6.2**	3.4	0.9
S1F1	Mean			70.4	14.2	18.4	1.8	**5.6**	2.7	0.9
S2F0	Mean			55.3	10.9	16.6	1.9	**6.3**	3.2	0.9
S2F1	Mean			71.3	15.3	18.1	1.8	**5.9**	2.7	0.9
	SE			1.6	0.5	0.5	0.04	**0.1**	0.2	0.03
S × SP	p-Value	2	54.3	0.731	**0.011**	**0.002**	**0.008**	0.131	0.784	0.896
S0bS	Mean			42.0	**6.9**	**11.5**	**1.7**	5.7	3.6	1.0
S0jP	Mean			59.7	**10.7**	**14.5**	**1.5**	4.4	1.9	1.0
S1bS	Mean			52.9	**9.6**	**17.5**	**2.1**	6.4	4.0	0.9
S1jP	Mean			71.9	**14.7**	**16.7**	**1.6**	5.4	2.1	0.9
S2bS	Mean			53.5	**10.2**	**16.8**	**2.0**	6.4	3.8	0.9
S2jP	Mean			73.0	**16.0**	**17.8**	**1.7**	5.7	2.1	0.9
	SE			1.6	**0.4**	**0.6**	**0.04**	0.2	0.2	0.03
F × SP	p-Value	1	54.3	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.116	**0.001**
F0bS	Mean			**44.5**	**7.6**	**13.2**	**2.0**	**6.5**	4.1	**1.0**
F0jP	Mean			**57.5**	**11.1**	**15.7**	**1.6**	**5.1**	2.1	**0.9**
F1bS	Mean			**54.4**	**10.2**	**17.3**	**1.8**	**5.8**	3.5	**0.9**
F1jP	Mean			**78.9**	**16.4**	**17.0**	**1.6**	**5.3**	1.9	**0.9**
	SE			**1.4**	**0.4**	**0.5**	**0.04**	**0.1**	0.2	**0.03**
S × F × SP	p-Value	2	54.3	0.622	0.735	0.310	0.057	0.273	0.380	0.510

Note: Mean values in bold are for interpretation, according to anova results; other mean values are included for completeness only. Refer to Table II for orthogonal contrasts related to scarification effects.

GLD = ground-level diameter; S = scarification (S0, unscarified; S1, single-pass scarification; S2, double-pass scarification); F = fertilization at the time of planting (F0, unfertilized; F1, fertilized); SP = species (bS, black spruce; jP, jack pine); SE = standard error of the means; dfn = numerator degrees of freedom for all variables, calculated using Satterhwaite's formula (Littell et al., 1996); dfd = denominator degrees of freedom for height, calculated using Satterhwaite's formula. dfd for GLD vary from 18.0 to 54.2, dfd for N are 90.6 for all effects, dfd for P vary from 18.9 to 80.2, dfd for K vary from 18.8 to 90.5, dfd for Ca are 96.3 for all effects, dfd for Mg are 277 for all effects.

effective in controlling *Kalmia* than single-pass scarification ($p < 0.024$), with a mean *Kalmia* cover < 1% (Figure 2A), and distance to nearest *Kalmia* stem of 59 cm (Figure 2B). After two growing seasons, *Kalmia* cover in control plots had increased to 15% (Figure 2A). Distance from planted seedlings to nearest *Kalmia* stems decreased to 7 cm (Figure 2B). *Kalmia* cover at the end of the second growing season was similar in S1 and S2 plots (5%, $p = 0.058$, Figure 2A). Distances to nearest *Kalmia* stems decreased in S1 and S2 plots, and were comparable after 2 years (17 cm, $p = 0.078$,

Table II. Orthogonal contrasts for third-year seedling dimensions and nutrient concentrations in current foliage 2 years after planting.

	Total height		GLD		Foliar N		Foliar P		Foliar K	
Contrast	df	p-Value[a]	df	p-Value[a]	df	p-Value[a]	df	p-Value[a]	df	p-Value[a]
S0 vs S1 and S2	45.2	<0.001	18.0	<0.001	90.5	<0.001	18.9	<0.001	18.8	<0.001
(S0 vs S1 and S2) × Fertilization	45.2	0.378	27.1	0.111	90.4	0.021	79.9	0.446	90.3	0.002
(S0 vs S1 and S2) × Species	54.5	0.224	54.4	0.003	90.5	<0.001	80.0	0.005	90.4	0.044
S2 vs S1	44.9	0.262	17.9	0.014	90.7	0.326	18.9	0.469	18.8	0.092
(S2 vs S1) × Fertilization	44.9	0.492	26.9	0.375	90.7	0.121	80.4	0.337	90.6	0.207
(S2 vs S1) × Species	54.0	0.417	54.0	0.121	90.7	0.052	80.4	0.007	90.6	0.138

Note: S0 = unscarified; S1 = single-pass scarification; S2 = double-pass scarification; GLD = ground-level diameter; df = degrees of freedom, calculated using Satterhwaite's formula (Littell et al., 1996).

[a] For one-tailed tests of significance.

Figure 2B). Species, fertilization and interaction effects on *Kalmia* cover and distance to nearest *Kalmia* stems were not significant (data not shown).

Xylem water potential

Scarification did not influence spruce seedling water stress throughout the second growing season at either predawn or midday ($p > 0.480$). Seedlings in S0, S1 and S2 plots had mean predawn and midday water potentials of -1.2 and -2.8 MPa, respectively.

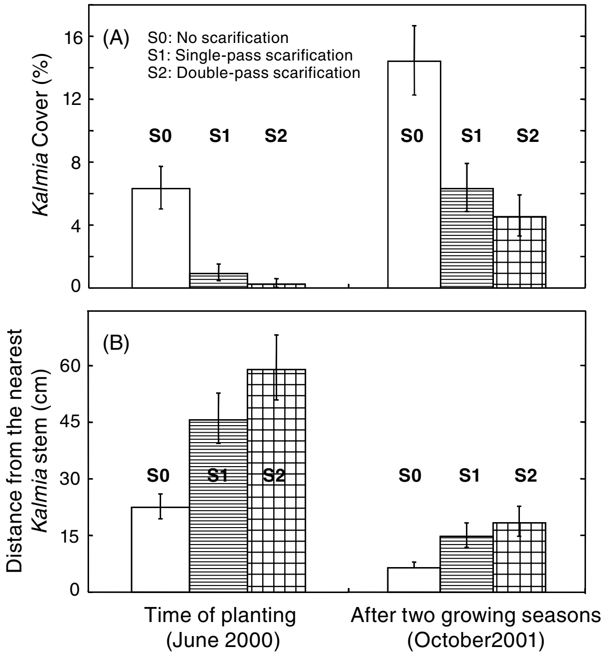

Figure 2. Scarification effect on (A) *Kalmia* cover at the time of planting ($p < 0.001$ for S0 vs S1–S2 contrast, $p = 0.024$ for S2 vs S1 contrast) and after two growing seasons ($p < 0.001$ for S0 vs S1–S2 contrast, $p = 0.058$ for S2 vs S1 contrast), and (B) distance from seedlings to the nearest *Kalmia* stem (cm) at the time of planting ($p < 0.001$ for S0 vs S1–S2 contrast, $p = 0.006$ for S2 vs S1 contrast) and after two growing seasons ($p < 0.001$ for S0 vs S1–S2 contrast, $p = 0.078$ for S2 vs S1 contrast). All scarification treatments were performed in October 1999. p-Values for overall scarification effects are <0.001. In (A), statistical results are for arcsin-transformed data; back-transformed means and approximates of 95% confidence intervals are presented. In (B), statistical results are for ln-transformed data; back-transformed means and 95% confidence intervals (Ung & Végiard, 1988) are presented.

Foliar nutrient concentration

Second year foliar N concentration increased significantly with scarification (Table I) and was greater for black spruce (an increase of 6 g kg^{-1}) than for jack pine (an increase of 3 g kg^{-1}) (Tables I and II). No difference between single- and double-pass scarification was observed (Table II). As for N, foliar concentration of P in black spruce and jack pine needles was positively influenced by scarification (Table I) and the increase was greater for black spruce (0.4 g kg^{-1}) than for jack pine (0.2 g kg^{-1}) (Tables I and II). Spot fertilization at planting enhanced foliar N concentration of black spruce (an increase of 4.1 g kg^{-1}) and jack pine (an increase of 1.3 g kg^{-1}), but had no effect on foliar P concentration in jack pine, and reduced P concentration in black spruce (a decrease of 0.2 g kg^{-1}) (Table I). For both species, scarification enhanced foliar K concentration by 1.3 g kg^{-1} when seedlings were not fertilized and by 0.6 g kg^{-1} when seedlings were fertilized (Tables I and II). There was no difference between S1 and S2 plots. Fertilization significantly reduced black spruce foliar K concentration, but had no impact on jack pine.

Soil nutrients

Both single- and double-pass scarification reduced K (Table III), Ca and Mg (data not shown) availability as estimated using resin bags in the first and second growing seasons. There was no difference between S1 and S2 for these variables. Nitrate, NH_4-N and PO_4-P adsorption by resins was below detection limits (0.2, 1.0 and 0.2 mg bag^{-1} for NH_4-N, NO_3-N and PO_4-P, respectively). Extractable NH_4-N,

Table III. Scarification effects on soil nutrient availability (ion-exchange resins) and extractable soil nutrient concentrations during the first and second growing seasons.

Effect and statistical parameter		dfn	dfd	Soil nutrient availability (mg bag^{-1})	Extractable soil nutrient concentration (mg kg^{-1})		
				K	NH_4-N	PO_4-P	K
Year 1 (2000)							
S	*p*-Value	2	27	<0.001	0.099	0.152	<0.001
S0	Mean			4.8 (3.8, 6.2)	3.5 (2.7, 4.5)	12.7 (10.6, 15.1)	18.7 (16.9, 20.6)
S1	Mean			1.9 (1.4, 2.4)	2.4 (1.8, 3.0)	11.9 (10.0, 14.2)	13.6 (12.3, 15.0)
S2	Mean			1.9 (1.4, 2.4)	2.9 (2.2, 3.7)	10.0 (8.4, 12.0)	12.9 (11.7, 14.3)
Year 2 (2001)							
S	*p*-Value	2	27	<0.001	0.893	0.664	<0.001
S0	Mean			6.7 (5.2, 8.6)	9.7 (8.5, 11.1)	12.0 (9.0, 15.9)	15.7 (13.5, 18.3)
S1	Mean			2.0 (1.5, 2.6)	9.6 (8.4, 10.9)	10.3 (7.7, 13.6)	11.7 (10.1, 13.7)
S2	Mean			1.7 (1.3, 2.2)	9.3 (8.1, 10.6)	10.5 (7.9, 13.9)	11.3 (9.7, 13.2)

Note: S = scarification (S0, unscarified; S1, single-pass scarification; S2, double-pass scarification); dfn = numerator degrees of freedom, calculated using Satterhwaite's formula (Littell et al., 1996); dfd = denominator degrees of freedom, calculated using Satterhwaite's formula. dfd = 11.4 for K availability in 2000, 18.7 for K availability in 2001, and 18.0 for P and K concentrations in 2001.
Analyses performed on ln-transformed data. Back-transformed means and 95% confidence intervals (in parentheses) are shown here.

PO_4-P (Table III) and Ca (data not shown) concentrations in the mineral soil were not affected by scarification, whereas the treatment reduced extractable K (Table III) and Mg (data not shown) concentrations during the first growing season, and extractable K (Table III), Ca, and Mg (data not shown) concentrations during the second season. Extractable NO_3-N concentration was below the detection limit (1 mg kg^{-1}). Again, no significant difference in extractable mineral soil nutrient concentrations was observed between S1 and S2 treatments.

Discussion

Scarification effects

Scarification treatments resulted in enhanced seedling growth over the first three growing seasons. No scarification effect on xylem water potential was found, even though this treatment can increase soil water availability to seedlings. Scarification reduced *Kalmia* cover, an effect that persisted over two seasons. This is consistent with results for ericaceous shrub cover 3 (Prévost, 1996) and 5 years (Prévost, 1997) after scarification of two different black spruce–moss sites in Quebec. Moreover, scarification significantly increased the distance between planted seedlings and the nearest *Kalmia* plants, which could explain the enhanced seedling foliar nutrient concentrations measured in this treatment. This latter effect was also observed by Yamasaki et al. (1998) for distance-dependent relationships on *Kalmia*-dominated sites. Soil temperature was not measured in this study, but results from an adjacent experiment on the same site suggest positive effects of scarification, as humus plus *Kalmia* removal by scalping significantly increased mean daily soil temperature by up to 7°C (Thiffault, Titus, & Munson, 2004).

Seedlings usually respond positively to scarification in the short-term but, depending on the site, increased growth may (e.g. Mattsson & Bergsten, 2003) or may not (e.g. Bedford, Sutton, Stordeur, & Grismer, 2000) persist in the long-term. The authors predict that scarification will benefit seedlings on this site in the long-term, as black spruce seedlings in scarified plots were twice the height of those in control plots on *Kalmia–Rhododendron groenlandicum*-dominated sites in northeastern Quebec after 10 years (Thiffault, Cyr, et al., 2004).

Scarification did not increase N adsorption by resins to detectable levels, and extractable NH_4-N concentration in mineral soil did not increase with scarification. Moreover, scarification reduced soil K, Ca and Mg availability and concentration. This observation is consistent with previous studies in sub-boreal forests that demonstrated the important contribution of the organic forest floor to nutrient availability in surface mineral soil (Munson, Margolis, & Brand, 1993; Thiffault, Jobidon, & Munson, 2003). However, seedling growth improved and foliar nutrient concentrations were generally higher in scarified plots than in unscarified control plots, as also observed by Prévost and Dumais (2003). It may be concluded that scarification favoured seedling nutrient uptake either by reducing below-ground competition from *Kalmia* (Thiffault, Titus, &

Munson, 2004), or by reducing direct (Zhu & Mallik, 1994) or indirect (Yamasaki et al., 2002) allelopathic effects, or some combination of these mechanisms.

No significant differences between single- and double-pass scarification were found for *Kalmia* cover, distance to the nearest *Kalmia* plant, seedling height and biomass, foliar nutrient concentrations or soil nutrient availability. However, ground-level stem diameter was about 10% greater for the double-pass than for the single-pass treatment (12.1 vs 13.1 mm). This may indicate a growth advantage, as conifer stem diameter is a sensitive predictor of vegetation competition (Thiffault, Jobidon, & Munson, 2003). It was originally hypothesized that this treatment might be effective in limiting the rhizomatous spread of *Kalmia* (Titus et al., 1995). However, based on the present results and those of Prévost (1996), it may be concluded that there is no important short-term gain in using a second perpendicular pass of disk trench scarifiers on *Kalmia*-dominated sites. It remains to be seen whether there are long-term advantages in using double-pass scarification, especially on sites where *Kalmia* is not evenly distributed across a site, and scarification can therefore isolate *Kalmia*-free patches of the site. Future monitoring of this site will be used to test this hypothesis further.

Fertilization effects

This study, along with results from a concomitant study on the same site (Thiffault, Titus, & Munson, 2004), demonstrates that spot fertilization with slow-release fertilizer at the time of planting can be used to increase early conifer growth without inducing mortality, even in the absence of scarification. Burying fertilizer is an efficient method of delivering nutrients in close proximity (~ 2 cm) to seedling root systems while avoiding stimulation of *Kalmia* growth (Mallik, 1996), as ericaceous shrubs can take up a large proportion of broadcast N fertilizer (Thiffault, Titus, & Munson, 2004). Similar results were found in experiments on salal-invaded sites on northern Vancouver Island, where the greatest height response of *Thuja plicata* to fertilizer was found when fertilizer in a small bag was placed adjacent to seedling root plugs (Blevins & Prescott, 2002).

Species effects

The difference between jack pine and spruce seedlings at the time of planting (3.1 cm height and 1.1 mm diameter) increased over the 3 years of the study. After three growing seasons, differences between jack pine and black spruce dimensions were compounded when seedlings were fertilized, compared with unfertilized seedlings. The superior growth of planted jack pine compared with black spruce is well documented (e.g. Wagner, Mohammed, & Noland, 1999), although the present study is the first to confirm this trend on a *Kalmia–Vaccinium* site. Jack pine is a more nutrient-efficient species than black spruce. Krause (1998) calculated that a 75–80-year-old stand of jack pine accumulates 849 kg of above-ground biomass for 1 kg of N; this value is 466 kg of above-ground biomass for 1 kg of N for a black spruce stand. Spruce apparently adapts to a nutrient-limiting environment by conserving nutrients (Hom & Oechel, 1983) and slowing growth rate, demonstrating attributes that are related to a "conservative type" of plant (Diaz et al., 2004). In contrast, pine reacts more strongly to increased resources, showing characteristics of an "acquisitive type" of plant (Munson, Margolis, & Brand, 1995; Diaz et al., 2004). Given that nutritional processes are important in the observed conifer check on these types of sites (Yamasaki et al., 2002; Thiffault, Titus, & Munson, 2004), species that are less vulnerable to soil nutrient deficiencies should grow better. However, *Kalmia* may not be as shaded out under a pine canopy as under a spruce canopy, which may be important for maintaining site productivity (Titus et al., 1995).

Treatment combinations

Although site preparation treatments were expected to enhance the impact of fertilizer on seedling growth, this was not the case. For black spruce and jack pine, most treatment responses were additive and about the same magnitude for scarification and fertilization. Thiffault, Cyr, et al. (2004) also found that scarification and fertilization effects on jack pine growth were additive on a *Kalmia–Rhododendron groenlandicum*-dominated site in north-eastern Quebec. However, while jack pine height doubles in 10 years with mechanical scarification, it only increases by $<30\%$ with fertilization (Thiffault, Cyr, et al., 2004). Results are different for black spruce, and fertilization effects diminish over time for seedlings planted in unscarified soil (Thiffault, Cyr, et al., 2004).

In the present study, either fertilization or scarification was needed for seedling foliar N concentrations to increase above critical thresholds (15 g kg^{-1} oven-dry weight; Morrison, 1974). Scarification and fertilization independently led to increased above-ground biomass and needle biomass for both species, as well as increased foliar N concentrations. Such responses suggest that the treatments have alleviated, at least partially, limiting available nutrient conditions (Salifu & Timmer, 2001).

Management implications

The long-term strategy for management of *Kalmia*-dominated sites is to achieve canopy closure as soon as possible so that *Kalmia* is shaded out (Titus et al., 1995; Mallik, 1998). Silvicultural treatments that maximize early growth of seedlings should therefore be applied as soon after harvesting as possible, before *Kalmia* spreads and dominates the site (Titus et al., 1995). Scarification alone increased early growth of black spruce seedlings from 38 to 47 cm, and early growth of jack pine seedlings from 49 to 62 cm. There was no further increase in seedling growth of either conifer species when double-pass instead of single-pass scarification was used. The longer term potential of the double-pass scarification alternative on these sites needs to be examined to evaluate its potential to hinder the spatial expansion of ericaceous shrubs.

Combining scarification with spot fertilization resulted in the greatest conifer growth response. For example, fertilized black spruce seedlings in either single- or double-pass scarified plots were 55% taller (59 cm) than unfertilized seedlings planted without scarification (38 cm) after 3 years. Scarification is therefore recommended before planting and, if funding permits, spot fertilization at planting. However, the length of time over which spot fertilizer applications confer a growth advantage is usually limited (e.g. English, 1997), and it is not known how long this will persist in these systems.

Species choice also has an impact on regeneration success on *Kalmia*-dominated sites. In the absence of either scarification or fertilization, jack pine (49 cm) grew 30% taller than black spruce (38 cm) over three growing seasons. This species difference increased to 40% when seedlings were fertilized and planted in scarified plots (83 cm vs. 59 cm). Species choice will also depend on forest management objectives for projected industrial demands in Quebec (Thiffault, Roy, Prégent, Cyr, Jobidon, Ménétrier, 2003). In addition, differences in canopy density need to be taken into account, as canopy closure and shading out of ericaceous vegetation is a key objective, which may be more difficult to achieve with jack pine than with spruce.

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