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Black spruce growth and survival in boreal open woodlands 10 years following mechanical site preparation and planting

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Since 1950, the creation of open woodlands has increased in Canada's northeastern continuous boreal forest and recent studies have demonstrated that the mechanisms underlying their creation are similar to those found in the lichen woodland zone. Since no natural re-densification of open woodlands has been observed to date, afforestation is necessary to counteract an increase of these types of stands in the continuous boreal forest. The aim of this study was to test the operational feasibility and success of afforestation efforts in open woodlands, 10 years after planting. The experimental design included different containerized seedling stocks and site preparation approaches, such as patch and disk scarification, and covered most of the geographical range of accessible continuous boreal forest in Québec. In open woodlands, regardless of black spruce stock size, disk scarification increased planted seedling survival and growth compared with patch scarification and direct planting, possibly due to a beneficial effect on seedling nutrition. However, even if seedling growth in open woodlands and feathermoss stands submitted to disk scarification was comparable, growth was higher in the latter stands. Nonetheless, we conclude that disk scarification followed by planting is an appropriate method to afforest boreal open woodlands.

Introduction

The northeastern North American continuous boreal forest is dominated by closed-crown black spruce (*Picea mariana* Mill. (B.S.P.))-feathermoss (FM) stands (Saucier *et al.*, 2009), where wildfire is considered to be the predominant regeneration driver (Payette, 1992; Girard *et al.*, 2008). Black spruce establishment following wildfire is generally relatively fast and abundant, thanks to its semi-serotinous cones and plentiful seedbeds (Rowe, 1984; Viereck and Johnston, 1990; St-Pierre *et al.*, 1992; DesRochers and Gagnon, 1997). A fire event that occurs when black spruce have reached sexual maturity, and where seeds and seedbeds are sufficient, will therefore normally lead to the re-establishment of the original tree density, i.e. the density before the fire event (Payette, 1992; St-Pierre *et al.*, 1992). However, the continuous boreal forest comprises a significant amount of open woodlands that occur near closed-crown stands, which are similar to open woodlands found in the more northern lichen woodland zone (Girard *et al.*, 2008). Previous studies revealed that the mechanisms creating these open woodlands are analogous in the continuous boreal forest zone and lichen woodland zone (Jasinski and Payette, 2005; Côté *et al.*, 2012). Open woodland creation results from compound disturbances such as successive wildfires, fire following a spruce budworm (*Choristoneura fumiferana*) outbreak or a fire after logging (Payette *et al.*, 2000; Payette and Delwaide, 2003; Girard *et al.*, 2011; Côté *et al.*, 2012). It could also result from low-intensity fires occurring early in the growing season (Girard *et al.*, 2009).

Previous studies report that open woodlands in the continuous boreal forest are alternative stable state ecosystems, more resilient than the original closed-crown stands, and could explain the anomalous presence of open woodlands scattered in a closed-crown forest matrix (Payette *et al.*, 2000; Payette and Delwaide, 2003; Jasinski and Payette, 2005; Girard *et al.*, 2008, 2009; Côté *et al.*, 2012; Gonzalez *et al.*, 2013). An alternative stable state is an ecosystem that can persist (i.e. pass through one or several turnovers) under the same environmental and climatic conditions as another ecosystem type (Lewontin, 1969). On a human-scale timeline, both palaeoecological and historical data have failed to demonstrate the effective natural shifting from open woodlands to closed-crown stands, which is theoretically possible but still uncommon (Jasinski and Payette, 2005; Girard *et al.*, 2008).

Between 1950 and 2002, the proportion of open woodlands within the continuous boreal forest increased by 9 per cent in northeastern North America, especially in the intact areas at the northern part of the zone (Girard *et al.*, 2008). A transition from a closed-crown stand to an open woodland is predictably accompanied by a loss of ecosystem productivity, through the encroachment of ground-dwelling lichens (*Cladonia* spp.) and ericad species, such as sheep laurel (*Kalmia angustifolia* L.), Labrador tea (*Rhododendron groenlandicum* (Oeder) Kron & Judd) and blueberries (*Vaccinium* spp.) (Gonzalez *et al.*, 2013). Encroachment of these species is associated with a decrease in tree productivity and site fertility in various boreal ecosystems around the world, through a multitude of direct and indirect competitive mechanisms, mainly for soil nutrients and water (Inderjit and Mallik, 1996; Yamasaki *et al.*, 2002; Bloom and Mallik, 2004; Nilsson and Wardle, 2005; Hébert *et al.*, 2006, 2010).

Anthropic conversion of an open woodland to a closed-crown black spruce-FM stand, where support capacity can be shown, could be achieved through silvicultural practices such as site preparation, followed by planting or natural seeding (Hébert *et al.*, 2006; Madec *et al.*, 2012; Veilleux-Nolin and Payette, 2012). This would contribute to restoring the historical tree density of the continuous boreal forest (Payette, 1992; Gagnon and Morin 2001; Jasinski and Payette, 2005; Girard *et al.*, 2008), as well as increasing the forest carbon sink to help mitigate climate change (Nabuurs *et al.*, 2007; Gaboury *et al.*, 2009; Boucher *et al.*, 2012; van Rooyen *et al.*, 2013). With ∼1.6 Mha of open woodlands in Québec's continuous boreal forest alone (MRNQ, third decennial forest inventory) – and probably up to several Mha in northern North America and Russia (Rowe, 1972; Shvidenko *et al.*, 1997) – such high latitude afforestation potential may correspond to a significant increase in forest productivity and carbon sink capacity (Boucher *et al.*, 2012). The idea of high latitude afforestation of open woodlands has to date only been tested in the field with small scale studies, and on the brief window of the establishment period. They also focussed on specific aspects related to water stress, natural seeding and early resilience to silvicultural disturbance (Hébert *et al.*, 2006; Madec *et al.*, 2012; Gonzalez *et al.*, 2013). A broader scaled study, both spatially and temporally, is required to enable a much needed generalization to various types of open woodlands in Québec's continuous boreal forest and with different silvicultural approaches (Girard *et al.*, 2008; Boucher *et al.*, 2012; Mansuy *et al.*, 2012).

The multiple benefits from site preparation techniques to planted trees' growth and survival are well known, especially in highly competitive environments such as open woodlands, or other encroached stand types with ericaceous shrubs (Yamasaki *et al.*, 2002; Thiffault *et al.*, 2003; Bloom and Mallik, 2004; Hébert *et al.*, 2006,2010; Thiffault *et al.*, 2010). A recurrent finding from those studies points towards the use of intensive site preparation techniques to better control shrubs and help planted trees survive the establishment window (Thiffault and Roy, 2011). Disk scarification is regularly elected as a minimal approach in this regard, but longer term investigations may be necessary to better evaluate lighter approaches, such as patch scarification (Hébert *et al.*, 2006).

Among the other relevant silvicultural approaches, choice of the planted seedling stock size depends primarily on the best possible compromise between regeneration success and resource availability. For example, large stock size for black spruce is widely used in the sub-boreal mixedwoods of Québec, where aggressive competition from non-commercial species hinders light availability (Thiffault *et al.*, 2004; Thiffault and Roy, 2011). However, large stock types are more expensive to produce and transport than conventional and smaller stock sizes (lower container density in the nursery and transport crates, and heavier weight). Smaller stock sizes can therefore be a smarter choice in remote areas, especially in open woodlands where light competition is not a limiting factor to seedling establishment (Hébert *et al.*, 2006). For this reason, a smaller stock type with only 25 cm^3 per root plug cavity – in comparison with 50 cm^3 for conventional small stock type – has recently been developed for Québec's boreal territory (MRNF, 2011). Similar stock sizes (∼25 cm^3) are currently used in ON for black spruce plantations on shallow soils (G. Racey, personal communication). We tested those smaller seedlings in productive stands following scarification and they showed a similar growth rate to conventional stock sizes (Walsh *et al.*, 2011). However, they have not so far been tested in terms of woody volume in unproductive stands, such as open woodlands, where the utility of less expensive containerized stock seedlings can be easily justified.

Hence, the objective of this study was to test the operational feasibility and success of afforestation of open woodlands, 10 years after plantation establishment, using different containerized seedling stocks and site preparation techniques. The experimental design used covered most of the geographical range of the accessible continuous boreal forest zone in Québec, and included a comparison with adjacent plantations in productive and managed black spruce-FM stands, to better ascertain the planted tree performance in open woodlands. The experimental design was laid out to test the following hypotheses: (1) planted black spruce survival and growth will increase with site preparation intensity in the open woodlands, (2) the initial (3 year) slower growth of planted black spruce observed in afforested open woodlands – compared with that in managed black spruce FM stands in a small subset of the same experimental design (Hébert *et al.*, 2006) – will be significantly less after 10 years of growth and (3) survival and growth rate will be similar between stock types.

Material and methods

Study sites

To achieve our research goals, the study sites needed to cover a wide latitudinal and longitudinal gradient. This resulted in identification of 18 experimental blocks distributed across six study sites, dominated by open lichen woodlands and located between latitudes 48–51° N and longitudes 71–76° W (Figure 1). The 18 blocks were accessible for site preparation machinery and planting. For each site, the open woodland was located near a black spruce-FM stand harvested or planned to be harvested not more than 2 years prior to the start of the experiment. Each of the 18 blocks chosen for this study included an open woodland that corresponded to the definition of open lichen woodlands in Girard *et al.* (2008), with a black spruce and/or a jack pine crown cover of <40 per cent, a shrub layer dominated by ericaceous species such as *K. angustifolia*, *R. groenlandicum*, *Vaccinium* spp., and ground layer dominated (ground cover >40 per cent) by lichens from the *Cladina* and *Cladonia* genera. Therefore, we selected (1) lichen woodlands with <25 per cent of crown cover, (2) lichen woodlands with a crown cover between 25 and 40 per cent, (3) recently burnt conifer stands showing clear signs of regeneration failure, and accompanied by abundant ericaceous shrubs and lichen mat. On two blocks, trees in the open woodlands were harvested prior to plantation. No available information indicated that the origin of the disturbance that led to the opening process (from a black-spruce FM to an open woodland) was other than natural.

All sites were located in the central part of the spruce–moss (15) or balsam fir (*Abies balsamea* L.)–white birch (*Betula papyrifera* Marsh.)

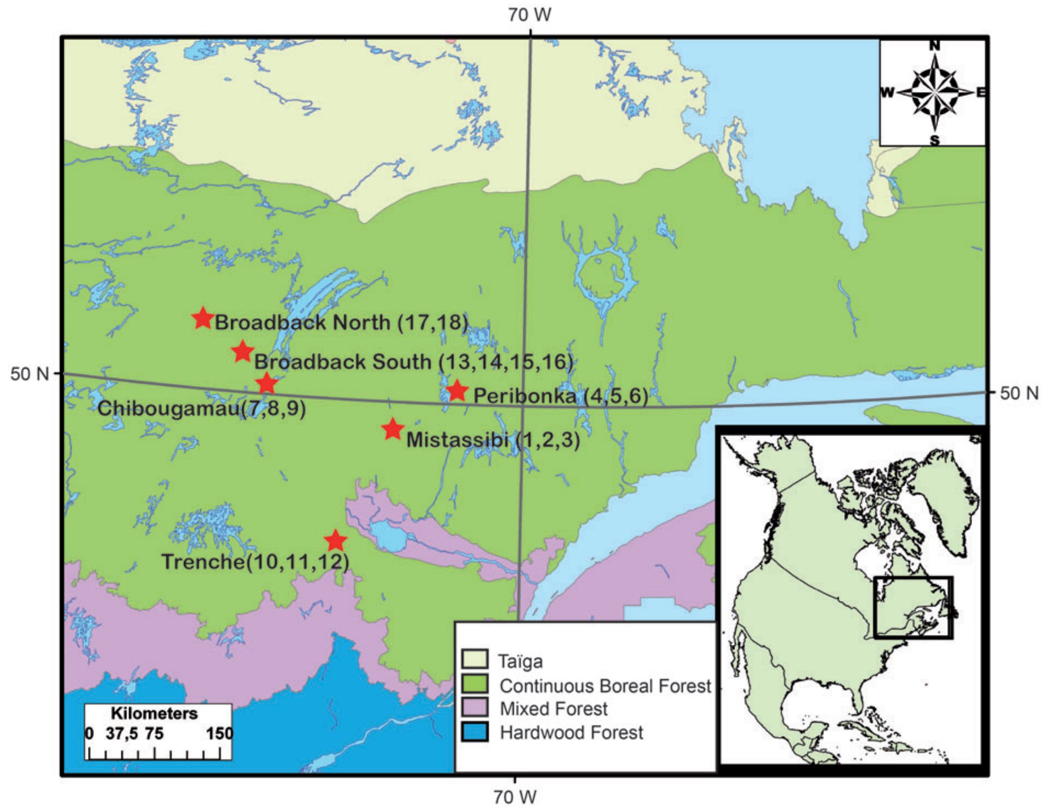

Figure 1 Geographical localisation of the experimental sites (and block numbers). This figure appears in colour in the online version of Forestry.

bioclimatic domains (3) of Québec's continuous boreal forest sub-zone (Saucier *et al.*, 2009). The climate is considered to be cool continental below and subarctic above 50° N. Mean annual temperature ranged from 1.2°C at the southern border of the study area (1971–2000 data from La Doré weather station, 48° 46′ N–72° 43′ W) down to −3.9°C at the northern border (1971–2000 data from Poste Montagnais weather station, 51° 53′ N–65° 44′ W) (Environment Canada, 2013). Mean total precipitation for the same period was similar throughout the latitudinal range (815.8 mm south *vs* 790.4 mm north). However, the percentage falling as snow was higher in the northern part of the study area (36 *vs* 25 per cent).

Experimental design

Each experimental block included an open woodland and a nearby black spruce-FM stand used as an operational control. The experimental design was an 18-complete block, 4 × 2 split-plot factorial design, with four site preparation/stand combinations (hereafter referred to as treatments), and two containerized stock types. Three treatment levels were randomly assigned to open woodlands, and were compared with a control treatment, i.e. a nearby and operationally managed black spruce-FM stand. The managed FM stands comprised a clearcut harvesting with the careful logging around advanced growth method (CLAAG), followed by a disk scarification. Treatments in the open woodlands were (1) no scarification (undisturbed open woodlands or OWno), (2) patch scarification (OWps) – which was performed with a modified brushsaw creating a 15-cm radius patch to reduce the humus layer thickness (without exposing the mineral soil) on a 2 × 2 m spacing, so that ~2 per cent of total stand area was disturbed – and (3) disk scarification (OWds) carried out with either a non-hydraulic (three blocks) or a hydraulic TTS disk trencher. There was, though, no observable difference in the intensity of the disturbance between these two disk trencher types. The furrows in OWds plots were 2 m apart and had a mean width of 67 cm and mean depth of 18 cm ($n = 24$), exposing the surface mineral soil or a mixture of organic matter and mineral soil. As a result of disk scarification, ~34 per cent of total stand area was disturbed.

Two black spruce containerized stock types were produced at the Université du Québec à Chicoutimi from a local seed lot (EPN-V8-025-K13-026-93; MRNQ) in 2000 and 2001, following cultivating recommendations from the MRNQ (MRNFQ, 2011). We used a conventional container of 67 cylindrical cavities with 50 cm^3 root plug volume per cavity (referred hereafter as 67-50) (IPL, Inc., Saint-Damien, QC, Canada), and a container of 126 rectangular cavities with a 25 cm^3 root plug volume per cavity (hereafter referred as 126-25) (IPL, Inc.). Both containers were of equivalent surface area, but the latter was 8.0 cm and the former 8.9 cm in height. Seedlings in all treatments were planted with a 2 × 2 m regular spacing (2500 plants ha^{-1}) in the summers of 2000 (Blocks 1–12) and 2001 (Blocks 13–18) (see Figure 1).

Sampling and morphological measurements

We randomly assigned an 80 × 40 m plot to each treatment, which was then split into two 1600 m^2 square sub-plots where one of the two seedling stock types was randomly assigned. In each sub-plot, 100 seedlings were identified at the time of planting for survival checks, and were visited 1, 2, 3, 5 and 10 years later. We considered a seedling as dead if <10 per cent of its foliage was green and turgescent. On the other 300 seedlings, we randomly selected five seedlings per sub-plot 1, 2, 3, 5 and 10 years following planting to measure total height and ground level diameter (GLD). Selected seedlings were also harvested at year 1, 2, 3 and 5 for aboveground dry mass determination (oven dried at 80°C until constant mass). No measurements were made at year 10 in Blocks 1, 2, 3 and 11 due to wildfire events that occurred in 2007 and 2010.

Foliar nutrients

Current year needles were collected on each seedling after dry mass determination for foliar nutrient concentration analyses after the first, third and fifth growing seasons. Total Kjeldahl nitrogen (TKN) was analyzed colorimetrically by spectrophotometry (Quickchem 8000, Zwellenger Instruments, USA), preceded by H_2SO_4–Se–K_2SO_4 digestion (Sen Tran and Simard, 1993). Phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) were extracted with a Mehlich III solution and measured by inductively coupled plasma analysis ICAP-61E (Inductively Coupled Argon Plasma-Optical Emission Spectrometry, Thermo Instruments, USA).

Statistical analyses

Analysis of variance for repeated measurements (ANOVAR) for a split-plot design was used for all variables, with the treatments (feathermoss disk scarification (FMds), OWds, OWps and OWno) as the main plot level and the stock type (67-50, 126-25) as the sub-plot level. The selection of the covariance structure, if sampling times were correlated, was based on the lower Akaike's information criterion (AIC). Sampling time effect was decomposed in its linear, quadratic and cubic components (von Ende *et al*., 1993). ANOVAR was performed with the MIXED procedure of SAS 9.2 (SAS Institute, Cary, NC, USA). *A priori* orthogonal contrasts were used to compare differences between treatments, stock types and their interaction with sampling time (Kirk, 1982).

Normality and homoscedasticity were verified for all data using visual distribution of data and by analysis of residues (Devore and Peck, 1994). Natural logarithmic or ArcSin(√) transformations were made when necessary; we present back-transformed means and confidence intervals with bias correction when appropriate (Ung and Végiard, 1988; Végiard and Ung, 1993; Devore and Peck, 1994). Statistical significance was fixed at $\alpha < 0.05$, and only significant results are presented in graphs.

Results

Survival

We found a significant triple interaction between site preparation treatments, time and stock type for seedling survival (Table 1). Regardless of the stock type, seedling survival was similar between the FMds and the OWds treatments and was above 80 per cent after 10 years (Figure 2a,b). The OWps 126-25 seedling survival was 23 per cent lower compared with the 67-50 seedlings in the OWps (Figure 2a,b). The temporal decline for survival was more pronounced for the 126-25 stock type in the OWno treatment (Figure 2a). Survival after 10 years in this treatment was only 15 per cent for the 126-25 and 39 per cent in the 67-50 (Figure 2a,b).

Total height and GLD

A significant interaction between sampling time × treatment and sampling time × stock type was found for total height (Table 1). The higher survival rate measured in the OWps compared with the OWno did not translate into a higher height growth (Figure 2c). Disk scarification was beneficial for seedlings in open woodlands, compared with the no treatment and patch scarification approaches. However, total height was significantly higher in the FMds treatment compared with all treatments in open woodlands. Ten years after planting, total height was 38 per cent higher in FMds than in OWds (Figure 2c). Total height was slightly higher for the 67-50 stock type compared with the 126-25 seedlings after 10 years, but this is likely due to the initial height difference at the time of planting (Figure 2d). Height growth was comparable between the two stock types for the first 10 years. Likewise, a significant interaction was found between treatments and time for the GLD (Table 1). As for total height, GLD after 10 years was higher in the FMds, followed by the OWds whose average was significantly higher than the two other treatments in open woodlands (Figure 2e). The difference in GLD of planted seedlings at 10 years between FMds and OWds was 9 per cent.

H : D *ratio and aboveground biomass*

We found slight differences in the seedling total height to GLD ($H:D$) ratio between treatments (Table 1). The highest $H:D$ ratio at year 10 was measured in the OWno treatment followed, in order, by the OWps, FMds and OWds treatments (Figure 2f). The ANOVAR revealed a significant triple interaction between treatment, sampling time and stock type for the aboveground dry mass (Table 1). The difference between the OWds and FMds after 5 years was higher for the 126-25 stock type where FMds seedlings had a 2.7 times higher aboveground biomass compared with OWds seedlings (Figure 2g). This difference is 50 per cent greater

Table 1 Summary of ANOVAR results for survival and morphological variables on planted black spruce seedlings

Source	Survival[1]			Total height			GLD			$H:D$			Aboveground dry mass[2]		
	ndf	F	$P>F$	ndf	F	$P>F$	ndf	F	$P>F$	ndf	F	$P>F$	ndf	F	$P>F$
Site preparation (SP)	3	51.39	<**0.0001**	3	99.89	<**0.0001**	3	98.02	<**0.0001**	3	46.51	<**0.0001**	3	97.85	<**0.0001**
Container size (C)	1	59.36	<**0.0001**	1	211.86	<**0.0001**	1	99.74	<**0.0001**	1	3.08	0.0961	1	150.96	<**0.0001**
SP × C	3	3.02	**0.0353**	3	9.90	<**0.0001**	3	2.32	**0.0884**	3	0.89	0.4516	3	9.84	<**0.0001**
Time (T)	3	188.00	<**0.0001**	5	279.51	<**0.0001**	4	327.46	<**0.0001**	4	79.71	<**0.0001**	3	266.49	<**0.0001**
SP × T	9	38.78	<**0.0001**	15	54.84	<**0.0001**	12	34.98	<**0.0001**	12	16.02	<**0.0001**	9	40.73	<**0.0001**
C × T	3	6.35	**0.0004**	5	16.17	<**0.0001**	4	1.12	0.3510	4	0.35	0.8417	3	5.45	**0.0028**
SP × C × T	9	2.24	**0.0210**	15	1.53	0.0938	12	1.07	0.3858	12	1.22	0.2635	9	2.86	**0.0038**

FMds = feathermoss disk scarification; OWds = open woodland disk scarification; OWps = open woodland patch scarification; OWno = undisturbed open woodland.
[1]ArcSin(√) transformed data. Bold indicates significance ($P < 0.05$).
[2]Five year results.

than that between the same two treatments with the 67-50 seedlings (Figure 2h). Scanty levels of aboveground dry mass were measured in the OWps and OWno treatments during the first 5 years of growth, regardless of the stock type (Figure 1g,h).

Foliar nutrients

We found a significant relationship between sampling time and treatments in foliar concentrations of major nutrients, except Mg (Table 2). Nitrogen (N), P and K concentrations decreased over time for all treatments. Seedlings in the OWds and FMds had significantly higher N, P and K foliar concentrations after the first growing season compared with the other treatments, but declined to the same level as found in the OWps and OWno treatments after 5 years (Figure 3a,c,e). This was not the case for Ca foliar concentration (Figure 3f). The interaction between stock type and sampling time was only significant for N and Ca foliar concentrations (Table 2). For N, foliar concentration increased at a faster rate for the 126-25 stock type in the early establishment phase, but after 5 years the concentration was similar to the 67-50 stock type (Figure 3b). The opposite situation occurred for Ca where the concentration increased in the early establishment phase, but this time for the 67-50 seedlings (Figure 3d).

Discussion

Planted black spruce response to site preparation intensity in open woodlands

This study shows the positive effect of increasing site preparation intensity on survival and growth of black spruce in 10-year-old afforested open woodlands. Planting following mechanical scarification has been identified as an efficient approach in different environments and silvicultural contexts, such as forest restoration or reforestation (Thiffault *et al.*, 2010; Löf *et al.*, 2012). As mentioned in other studies, soil scarification, owing to higher soil temperatures and lower interception of water by competing vegetation, can increase soil water availability and favour root growth, which can result in improved water relations and nutrient uptake, especially during the establishment phase (Boucher *et al.*, 1998; Hébert *et al.*, 2006; Thiffault and Roy, 2011). As found in similar habitats, the effect of disk scarification, regardless of the stock size, significantly increased survival and growth over that with the two other lighter treatments (no preparation and patch scarification) even after 10 years, a positive impact that was maintained up to 18 years after treatment in other comparable studies (Thiffault *et al.*, 2004,2010; Johansson *et al.*, 2013; Wallertz and Malmqvist, 2013).

Among important growth drivers, the higher foliar nutrient concentrations, especially N, P and K, observed in seedlings during the first 5 years of this study in the disk scarified open woodlands, over that in the two other treatments in open woodlands, indicates a positive short-term effect of scarification on seedling growth. This impact is possibly the result of a lower influence of competition on nutrient availability, mycorrhizal interference and allelopathy from ericaceous shrubs and lichens (Yamasaki *et al.*, 2002; Hébert *et al.*, 2010; Grossnickle, 2012). Even though it was not measured in this study, soil temperature was probably another key driver explaining the higher seedling growth after 10 years in scarified open woodlands, by exposing the mineral soil and decreasing the high albedo of the lichen mat, causing improved root growth and permeability, hence, better water and nutrient uptake (Boucher *et al.*, 2001; Bernier *et al.*, 2011).

Even if patch scarification (OWps) increased seedling survival rate compared with untreated open woodlands, the growth of planted seedlings was clearly insufficient to qualify this treatment as an efficient approach for the afforestation of open woodlands. Furthermore, morphological and growth variables of seedlings in OWps plots, 10 years after planting, are similar to seedlings planted in untreated open woodlands, which are roughly similar in size to the initial values 10 years before. Due to a possible lack of root development, seedlings in the lighter approach treatments – untreated and patch scarification – suffered from nutritional and water deficiencies, as found in Hébert *et al.* (2006) during the early establishment phase, and were not able to recover afterwards. Field observations often revealed signs of chlorosis, necrosis and premature senescence in these two approaches. Furthermore, foliar nutrient concentrations during the early establishment were less than optimal for spruce growth, probably due to a stagnation or even a decrease in root growth after 3 years in the untreated and

Table 2 Summary of ANOVAR results for foliar nutrient concentration in planted spruce seedlings

Source	Foliar N conc.			Foliar P conc.		Foliar K conc.		Foliar Ca conc.		Foliar Mg conc.	
	ndf	*F*	*P* > *F*	*F*	*P* > *F*	*F*	*P* > *F*	*F*	*P* > *F*	*F*	*P* > *F*
Site preparation (SP)	3	56.51	**<0.0001**	13.42	**<0.0001**	54.83	**<0.0001**	5.64	**0.0019**	0.29	0.8300
Container size (C)	1	8.60	**0.0053**	<0.01	0.9524	2.35	0.1420	46.11	**<0.0001**	2.74	0.1155
SP × C	3	1.57	0.1991	0.59	0.6255	0.37	0.7715	1.07	0.3659	0.93	0.4356
Time (*T*)	2	97.24	**<0.0001**	93.61	**<0.0001**	60.10	**<0.0001**	52.07	**<0.0001**	65.94	**<0.0001**
SP × *T*	6	26.23	**<0.0001**	9.28	**<0.0001**	7.95	**<0.0001**	4.10	**0.0010**	0.72	0.6344
C × *T*	2	4.27	**0.0200**	1.98	0.1459	1.20	0.3061	10.24	**0.0003**	0.62	0.5416
SP × C × *T*	6	1.61	0.1493	0.80	0.5761	1.78	0.1077	0.23	0.9661	0.42	0.8646

FMds = feathermoss disk scarification; OWds = open woodland disk scarification; OWps = open woodland patch scarification; OWno = undisturbed open woodland.
Bold indicates significance ($P < 0.05$).

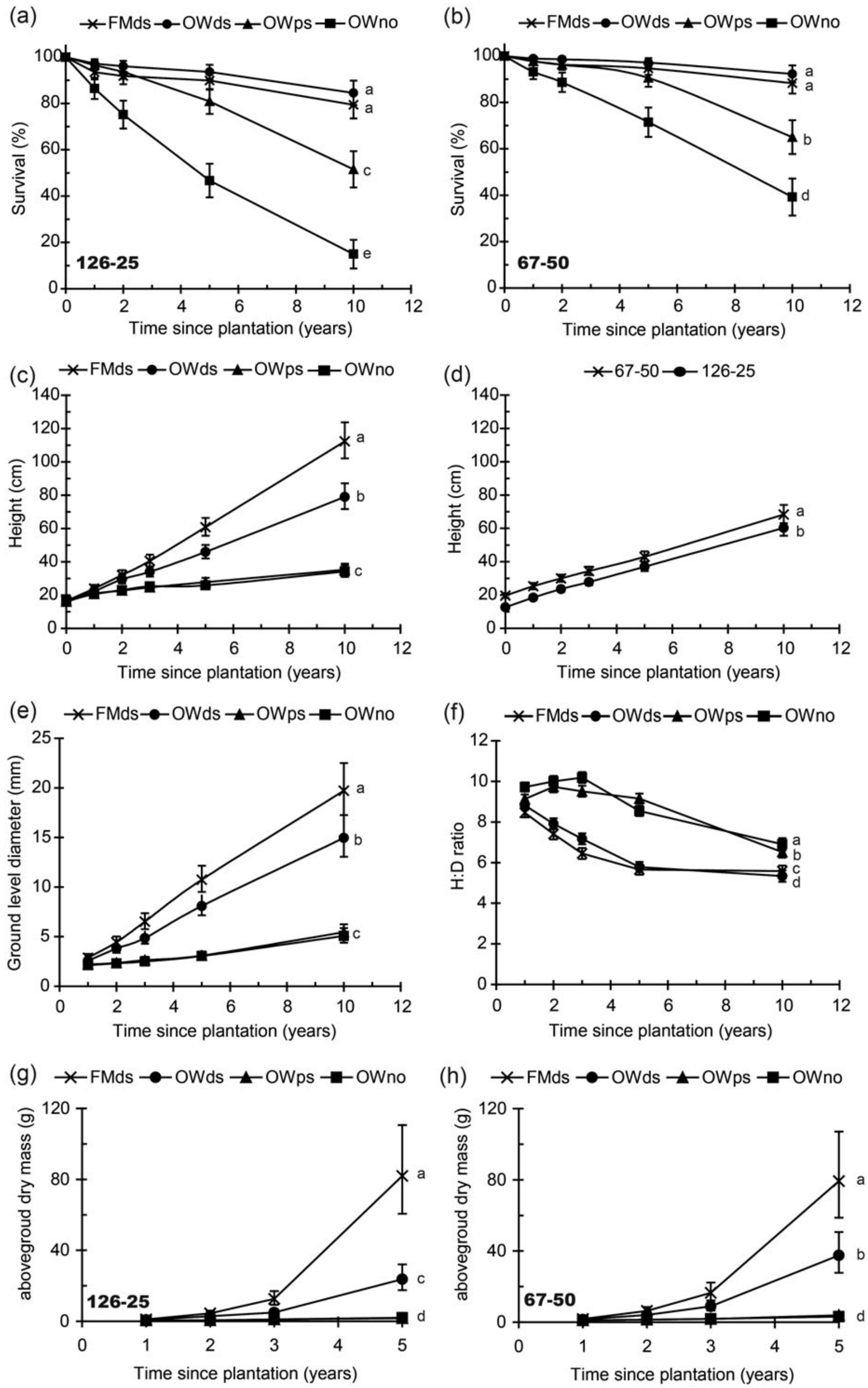

Figure 2 Site preparation × stock type × time (a,b,g,h), site preparation × time (c,e,f), and stock type × time (d) effects on per cent survival (a,b), total height (c, d), GLD (e), height to diameter ratio (f), and aboveground dry mass (g,h). FMds = feathermoss disk scarification, OWds = open woodland disk scarification, OWps = open woodland patch scarification, OWno = undisturbed open woodland.

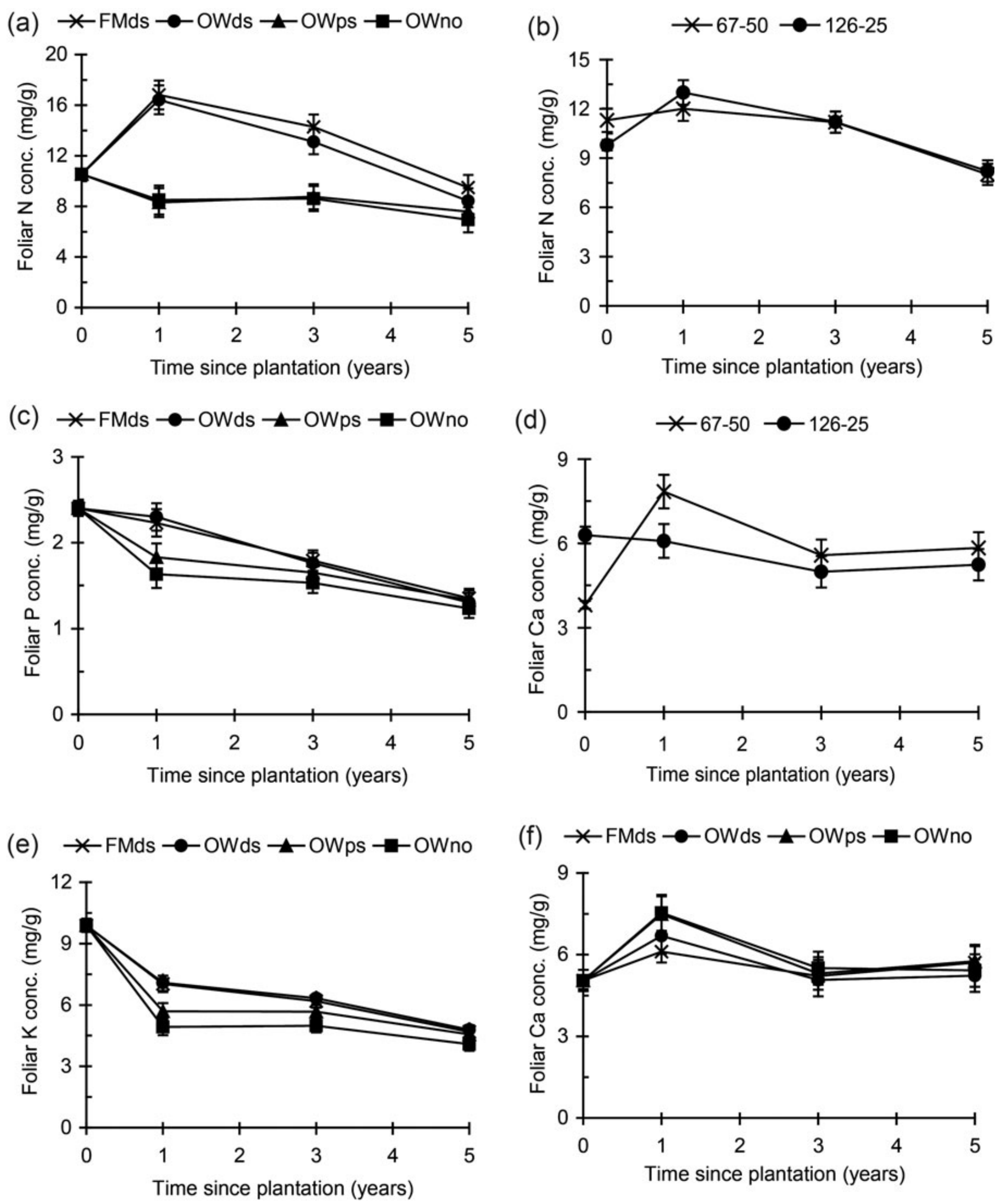

Figure 3 Site preparation × time (a,c,e,f) and stock type × time (b,d) effects on nutrient foliar concentration. Refer to Figure 2 for abbreviations.

patch scarified treatments (results not shown). The modest effects of patch scarification can result from a less intense and durable disturbance on the competing shrubs and organic layer (Thiffault *et al*., 2004; Hébert *et al*., 2006). Clearly, our results indicate that disk scarification should be preferred over lighter approaches for the afforestation of open woodlands.

Planted black spruce growth and survival comparison between stand types

Even if seedling survival in the disk scarified open woodlands are comparable to those in the managed FM stands, planted trees performed better in the latter in terms of growth. Hébert *et al*. (2006) suggested that this effect is probably due to nutritional limitations in afforested open woodlands. However, we did not detect any nutritional differences between planted trees in scarified open woodlands and those in managed FM stands. The same authors also found that the growth difference during the early establishment phase between planted seedlings in disk scarified open woodlands and those in managed FM stands was not related to a higher water stress in open woodlands, since seedlings' water relation was similar in both stand types.

The seedling growth difference between stand types in this study could in part result from a more favourable temperature in the FM stands compared with open woodlands, especially in the spring. The albedo caused by the lichen mat in the open woodlands may result in lower energy absorption by the soil that, as well as more frequent early summer frost events in the open woodlands, would contribute to lower planted tree growth in the scarified open woodlands (Lamontagne *et al*., 1998; Boucher *et al*., 2001; Lajzerowicz *et al*., 2004), especially at northern latitudes where early summer temperature is a limiting factor (Vaganov *et al*., 1999; Löfvenius *et al*., 2003). Most of the growth limitations in open woodlands explained in this study may potentially be reversed with the longer term development of a dense tree cover in afforested open woodlands, which would decrease the impact of competing brush species and the lichen mat. Clearly, this hypothesis deserves further research efforts.

Furthermore, the extent of the geographical range of sites in this study revealed a non-negligible variability in terms of disk scarification response between FM and open woodlands and showed that seedlings in some open woodlands responded better than others to this treatment. For more than a quarter of the experimental blocks, black spruce total height after 10 years was higher in the OWds than the FMds (result not shown). However, future research projects are needed to find indicators that would allow selecting open woodlands with the most growth potential.

Seedling stock-type performance

The slightly lower survival rates measured in the open woodlands, compared with managed FM stands, resulted mainly from a lower survival of the 126-25 seedlings in the untreated and patch scarified open woodlands. However, the survival rate of 126-25 seedlings was comparable to that of Thiffault *et al.* (2012) with seedlings planted under similar growth conditions. Johansson *et al.* (2007) attributed the higher mortality of smaller Norway spruce stock size to frost heaving, but we did not observe, or measure, this phenomenon in open woodlands.

The difference in seedling total height after 10 years in favour of the 67-50 seedlings resulted from the initial height difference prior to planting, and not from a higher growth rate. On the other hand, the lower 126-25 seedling aboveground dry mass after 5 years found in disk scarified open woodlands, compared with the 67-50 seedlings, could result from an initial higher root growth with the 126-25. This response may have been necessary for nutrient absorption, since the 126-25 root plugs are possibly less efficient in providing enough nutrients to sustain a similar height and diameter growth rate to that found in the 67-50 seedlings. However, foliar N concentration increased slightly 1 year following planting for the 126-25 stock type, and was similar to the concentration encountered afterwards in the 67-50.

Conclusion

Silvicultural considerations

Our results suggest that disk scarification provides a minimal level of disturbance to afforest open woodlands. Survival rates for the two lightest treatments (untreated open woodlands and patch scarification) were too low, the few seedlings that survived did not show any significant growth. Planted black spruce growth is still lower after 10 years in open woodlands compared with managed FM stands, indicating that growth limitations in afforested open woodlands persist longer than hypothesized. Other site preparation treatments with different levels of disturbance intensity, for example, inverting or mounding (Johansson *et al*., 2013; Wallertz and Malmqvist, 2013), could also be tested to help alleviate these initial limitations in open woodlands. With regard to the main objective of this study, the results after 10 years indicate that by performing disk scarification and planting, it seems possible to at least durably increase the stand density, and eventually restore the tree volume found in those stands prior to the shift from FM stands to open woodlands. However, longer term investigations are needed to fully validate this hypothesis. Site preparation and planting in remote areas such as the spruce–moss bioclimatic domain, where road access is limited, can be expensive. The results of this study suggest that a smaller containerized stock size than the conventional one can achieve similar growth rates during the first 10 years after establishment, thanks to the lack of significant competition for light from the ericaceous shrubs and lichen mat in this environment (Hébert *et al*., 2006, 2010). Therefore, using 126-25 seedlings could be an efficient way to reduce open woodlands afforestation costs, since those seedlings are at least four times less expensive to produce than the conventional 67-50 stock type, and twice as cheap to carry. Another way to reduce costs for the afforestation of open woodlands could be by only performing disk scarification without tree harvest prior to site preparation. Exposing the mineral soil could also favour black spruce natural regeneration by natural seeding, since most of the residual trees left after site preparation are sexually mature (Madec *et al*., 2012). The cost effectiveness of approaches for the afforestation of open woodlands is an important argument when one considers the potential it represents in terms of carbon offset opportunity, especially in the growing carbon markets (Boucher *et al*., 2012).

Finally, the importance of the open woodlands for the maintenance of the caribou population in the spruce–moss domain should be addressed before the implementation of a large afforestation programme based on these results. The open woodlands are one of the numerous types of habitats used by caribou, but more research is needed before significant afforestation programmes in open woodlands can be planned, in which all environmental services (biodiversity, carbon, etc.) are fully considered (Courtois *et al*., 2003).

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Conflict of interest statement

None declared.

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