Mid- and long-term effects of stock type on the growth and yield of spruce seedlings in a non-herbicide scenario

Nelson Thiffault[1]✉, Charles Ward[2]

[1]Canadian Wood Fibre Centre, Canadian Forest Service, Natural Resources Canada, Québec, Canada
[2]Direction de la recherche forestière, Ministère des Forêts, de la Faune et des Parcs du Québec, Québec, Canada

✉ nelson.thiffault@canada.ca

ARTICLE INFO

Citation:
Thiffault N, Ward C (2018) Mid- and long-term effects of stock type on the growth and yield of spruce seedlings in a non-herbicide scenario. Reforesta 6: 60-70. DOI: https://dx.doi.org/10.21750/REFOR.6.05.58.

Editor: Vladan Ivetić, Serbia
Received: 2018-11-20
Accepted: 2018-12-21
Published: 2018-12-28

CrossMark

This article was presented at the International Conference "**Reforestation Challenges 2018**" which was held in Belgrade, Serbia, June 20-22, 2018.

Abstract

Stock types used in reforestation projects can influence plantation success, as they determine the morphological attributes of the planted seedlings. They can also interact with silviculture treatments to influence early seedling survival and growth. As nurseries develop and produce new stock types in response to –and in interaction with– manager needs, research efforts must be pursued to validate early seedling performance and long-term growth and yields. In this context, we aimed to evaluate the main and interactive effects of mechanical site preparation and stock type on planted black (*Picea mariana* [Mill.] BSP) and white spruce (*P. glauca* [Moench.] Voss) seedling dimensions at 16-y, and estimate the long-term impact of stock type on the merchantable volume at rotation age for white spruce. We hence compared medium (200 cm^3 root plug) and large (350 cm^3 root plug) containerized seedlings, as well as large bare-root seedlings of both species, in a field experiment established in Quebec (Canada), where there is a ban on the use of chemical herbicides for vegetation management treatments. Our results confirm that there is a significant, although limited impact of stock type on the size of black and white spruce at the juvenile stage, when medium and large stock types are compared, but that these small differences have a negligible effect on the estimated merchantable volume produced at rotation age (60 years). Mechanical site preparation does not promote seedling growth on these rich sites with thin humus. Therefore, selection of a medium or larger stock type for reforestation projects and application of mechanical site preparation in ecosystems similar to the one studied here should be based on other considerations than growth and yield, such as seedling availability, production and planting costs, or operational constraints.

Keywords

Plantation; Alternatives to herbicide; Stock type; *Picea glauca*; *Picea mariana*; Quebec (Canada)

Contents

1 Introduction

The planting stock type used in reforestation projects can influence plantation success (Pinto et al. 2012). It determines the morphological attributes of the planted seedlings, which, in turn, influence seedling physiology, growth potential, and ability to compete with vegetation (Grossnickle 2000). Moreover, stock type can interact with silviculture treatments, such as site preparation (Thiffault et al. 2012) or vegetation management (Jobidon et al. 2003), to influence early seedling survival and growth.

Many authors have investigated or reviewed how stock types affect planted seedling growth and survival, either focussing on seedling initial size (e.g. South et al. 1993; South and Rakestraw 2004; Pinto et al. 2018), production approaches (e.g. Grossnickle and El-Kassaby 2016), or combinations of factors (e.g. Thiffault 2004). General trends have been identified, such as the positive link between seedlings' initial size and competitive potential (e.g. Grossnickle 2005, Jobidon et al. 2003). However, the longer term impact of stock type on plantation performances have rarely been reported.

Moreover, as nurseries develop and produce new stock types in response to – and in interaction with– manager needs (Dumroese et al. 2016), research efforts must be pursued to validate early seedling performance and long-term growth and yields. For example, the ban on the use of chemical herbicides in the public forests of Quebec (Canada) has triggered the development of production techniques to provide foresters with large seedling stock, so they can reduce the need for vegetation management treatments (Thiffault and Roy 2011). The vegetation management strategy in this province now relies on the use of a gradient of seedling sizes, ranging from very small (root plug volume = 25 cm^3), small (root plug volume = 50–110 cm^3), medium (root plug volume = 200 cm^3), to large (container root plug > 300 cm^3, or produced as bare-roots) seedling stock, based on the expected level of competition for light by competing species (Thiffault and Roy 2011).

Whereas the context of use and expected performances of very small and small seedling stock are generally well known (e.g. Thiffault et al. 2004; Hébert et al. 2014), those of the newer medium and large seedling stock remain to be documented. For example, early evidence suggest that medium-sized seedlings are well suited for reforestation projects in areas submitted to high browsing pressure by large cervids; their size offers the best compromise between competitive potential (being bigger, and hence, more tolerant to competition than small seedling stock) and vulnerability to browsing (being smaller, and hence, less visible than large seedling stock) (Beguin et al. 2016; Faure-Lacroix et al. 2013). Medium size seedlings have also shown adequate short-term survival and growth when planted in boreal mixedwood ecosystems, with limited interactions with site preparation (Thiffault et al. 2013). However, their longer-term performances and interactions with silviculture are still unknown, especially in comparison with those of large seedling stock.

In this context, our objective was to evaluate the main and interactive effects of mechanical site preparation and stock type on the 16th-y height, 16th-y diameter and 11th–16th-y height growth of black (*Picea mariana* [Mill.] BSP) and white spruce (*P. glauca* [Moench.] Voss) seedlings, two of the most planted species in Quebec (black and white spruce represented 73% of the 137 M seedlings planted annually in Quebec between 2010–2018; Salmon 2018). We also aimed at estimating the long-term impact of stock type on the merchantable volume at rotation age for white spruce (60 years), a planted species for which current growth and yield models allow long-term predictions (Prégent et al. 2010).

2 Materials and methods

2.1 Study site and region

We conducted our study in the eastern balsam fir—yellow birch (*Abies balsamea* [L.] Mill.—*Betula alleghaniensis* Britt.) bioclimatic domain of Quebec described by Saucier et al. (2009). The region is recognized for aggressive invasion of cutover sites by competing vegetation (Laflèche et al. 2000). It is characterized by a sub-humid continental climate, with a mean annual temperature of 2.5 °C and precipitation of 1000–1100 mm (Robitaille and Saucier 1998). More specifically, the study covers approximately 1 ha and is located near the town of Biencourt (47º52’10” N; 68º38’20” W). The soil is a humo-ferric podzol (Soil Classification Working Group 1998) with slow to medium drainage, developed from an undifferentiated till of loamy texture. It is covered by a mor humus 5–15 cm thick. The previous mature stand was dominated by balsam fir, white spruce and yellow birch, and was clearcut harvested during the summer of 1996. Slash were windrowed with minimal perturbation to the humus layer and the soil.

2.2 Experimental design and seedling measurement

In September 1996, we established a split-plot experimental design with 9 replicate blocks of ~19 m × 30 m, using mechanical site preparation as the main plot effect and stock type as the sub-plot factor. Each replicate was split in half along the long side, and half of it was randomly selected to receive either a mechanical site preparation treatment using a passive TTS disk trencher, or a control treatment (no trenching). In June 1997, following an early planting scenario (the year immediately after harvest), we planted black and white spruce seedlings produced as medium containerized stock (2+0; rigid wall containers; 25 cavities of 200 cm^3 each; further referred to as 25–200), large containerized stock (2+0; rigid wall containers with air slits; 25 cavities of 350 cm^3 each; further referred to as 25–350A), and large bare-root stock (2+2). Seedlings were produced in a governmental nursery from local seed sources. In each main plot, we distributed seedlings every 2 m along four 30-m long rows, each separated by 2 m. Within each main plot, the first two rows consisted in white spruce and the next two rows consisted in black spruce (no random distribution of species), hence preventing formal comparison between species. Each row comprised five seedlings of each stock type (25–200, 25–350A, bare-root), randomly distributed. The resulting planting density of the 2 m × 2 m planting grid was 2 500 seedlings ha^{-1}. Competing vegetation gradually established (Figure 1) and was rapidly dominated by red raspberry (*Rubus idaeus* L.), fireweed (*Chamaenerion angustifolium* [L.] Scopoli subsp. *angustifolium*), paper birch (*Betula papyrifera* Marsh.) and mountain maple (*Acer spicatum* Lam.).

Figure 1. Photo of a planted spruce seedling (lower left corner) and competing vegetation during the second growing season following planting.

In August 2000 (the 4th growing season since planting), we performed a mechanical release treatment of the entire experimental area using motor-manual brushsaws. We applied a second mechanical release in July 2007 (the 11th growing season since planting). These treatments and their timing correspond to the provincial silvicultural guidelines for similar sites (Thiffault and Hébert 2013; Gravel et al. 2016). Seedling were measured at the time of planting for their height (cm) and ground-level diameter (mm), (Table 1), and periodically afterwards. We reassessed seedling dimensions in 2007 (height) and 2012 (height and diameter at breast height (mm); 1.3 m). Height values from 2007 and 2012 were used to calculate the 5-y mean annual height growth (cm y^{-1}), as:

$$\text{Mean annual height growth} = \frac{height_{2012}(cm)\ - height_{2007}(cm)}{5\ years}$$

2.3 Statistical analyses

We submitted the height, dbh and mean annual height growth variables to mixed model analyses of variance (ANOVA) separately for each species, with respect to the split-plot experimental design and using blocks and interactions with blocks as random effects. We conducted the analyses using the *lmer* function from the *lme4* package in R v3.0.2 (Bates et al. 2015; R Core Team 2013). A threshold of α = 0.05 was defined for significance and the Sattherthwaite approximation was used for degrees of freedom computations (Bolker et al. 2009). In case of significant F-values from the ANOVAs, we compared treatment means using Tukey tests.

Table 1. Initial morphological characteristics of the three stock types used in the study (adapted from Thiffault and Jobidon 2005).

Species and stock type (n = 180 for each combination)	Height (cm)	Root-collar diameter (mm)
White spruce		
25–200	24.9 (3.1)	4.8 (1.0)
25–350A	27.9 (4.4)	6.5 (1.2)
Bare-root	35.3 (5.2)	8.4 (1.5)
Black spruce		
25–200	27.4 (3.2)	3.6 (0.5)
25–350A	36.3 (4.6)	5.1 (0.8)
Bare-root	36.7 (5.0)	7.0 (1.4)

Note. 25–200: 2+0; rigid wall containers; 25 cavities of 200 cm^3 each. 25–350A: 2+0; rigid wall containers with air slits; 25 cavities of 350 cm^3 each. Bare-root: 2+2 large bare-root stock

2.4 Estimated yield of white spruce at rotation age

We used the growth and yield models of Prégent et al. (2010) to evaluate treatment effects on long-term white spruce productivity. This growth model estimates the merchantable volume (m^3 ha^{-1}) over time, taking into account initial density and dominant height at age 25 y (site index at age 25, based on the 100 tallest trees). For each treatment combination, the tallest 100 trees were selected among the total number of individuals distributed over the entire experiment.

3 Results and discussion

3.1 Seedling size at age 16-y and mean annual height growth

For both species, we did not observe any significant effect of mechanical site preparation on 16^{th}-y height, 16^{th}-y diameter and mean annual height growth between the 11^{th} and 16^{th} growing seasons (Table 2). There was no significant interaction between mechanical site preparation and stock type influencing these variables either. These results confirm those observed after five growing seasons on the same site (Thiffault and Jobidon 2005). They support that mechanical site preparation is not necessary to the successful establishment and growth of white and black spruce in this ecological context, characterized by rich sites with thin humus layers (Thiffault et al. 2003). Indeed, little advantages should be expected from exposing the mineral soil through mechanical site preraration in such conditions, as thin humus have weak insulating properties, compared to boreal sites with thick organic layers (Prévost 1992; Prescott et al. 2000; Macdonald et al. 1998; Örlander et al. 1990). Hence, if used to create better access to reforestation sites for planting crews or subsequent release operation by managing coarse woody debris, mechanical site preparation in these conditions should not be expected to increase seedling survival, growth or affect competing vegetation cover (Thiffault et al. 2003).

Stock type, on the other hand, had a significant effect on tree height and diameter at age 16-y (Table 2). For white spruce, seedlings produced in 25–350A containers were significantly taller (Figure 2A) and had a significantly larger diameter (Figure 2B) than seedlings produced in 25–200 containers. White spruce seedlings produced as bare-root stock reached intermediate dimensions, being equivalent to both stock types in regards of their height and diameter (Figure 2A and 2B). For black spruce, seedling produced in 25–350A containers were significantly taller (Figure 2A) and had a significantly larger diameter (Figure 2B) than the other stock types, which reached similar dimensions. Stock type did not significantly influence tree growth in height between the 11th and 16th growing seasons, for both species (Table 2; Figure 2C).

Overall, stock type thus had a significant, although small effect on the size that the planted seedlings had reached after 16 years. For example, and as observed in other contexts (*e.g.* Faure-Lacroix et al. 2013), the medium seedling stock had remained significantly smaller than the large containerized stock for both species, a result likely related to their smaller initial size (South and Rakestraw 2004). The significant statistical differences that we observed, however, are not sufficient to have silviculture implications regarding, for example, the timing of a first commercial thinning treatment (Prégent 1998). Indeed, the biggest difference in height was observed between the 25–350A and 25–200 black spruce seedlings stock, and was of only 9% (55 cm). Differences in diameter were less than a centimeter for both species. As a result, the height-to-diameter ratio, a critical criterion to prescribe commercial thinning, only varied from 56 to 61 for white spruce and from 62 to 63 for black spruce.

Based on the similar height growth rate of the stock types between their 11th and 16th growing seasons, it appears that the initial (although small) growth differences that were observed in the short term (Thiffault and Jobidon 2005) have disappeared. Following planting, containerized seedlings can indeed present higher growth rates than bare-root seedlings, if they are of similar initial size (Thiffault et al. 2003). This can be due, among other things, to increased foliar nutrient concentrations because of cultural practices. But, once the seedlings become established (in equilibrium with site resources), differences in growth rates decrease for seedlings of similar sizes.

Table 2. ANOVA results for seedling height, diameter at breast height (dbh) and mean annual height growth between age 11-y and 16-y for white and black spruce seedlings produced in 25–350A containers, 25–200 containers or as bare-roots, with or without mechanical site preparation. Bold indicates significant effects at $P < 0.05$.

Source of variation (Fixed effects)	**Height**		**dbh**		**Height growth**	
	F-value	*P*-value	F-value	*P*-value	F-value	*P*-value
White spruce						
Mechanical site preparation (MSP)	0.236	0.630	0.252	0.618	0.008	0.933
Stock type (ST)	4.529	**0.017**	4.582	**0.016**	0.551	0.582
MSP × ST	1.859	0.169	0.635	0.535	1.443	0.252
Black spruce						
MSP	0.637	0.447	0.036	0.854	0.407	0.540
ST	8.304	**< 0.001**	6.090	**0.002**	2.040	0.148
MSP × ST	0.401	0.670	0.521	0.594	0.892	0.421

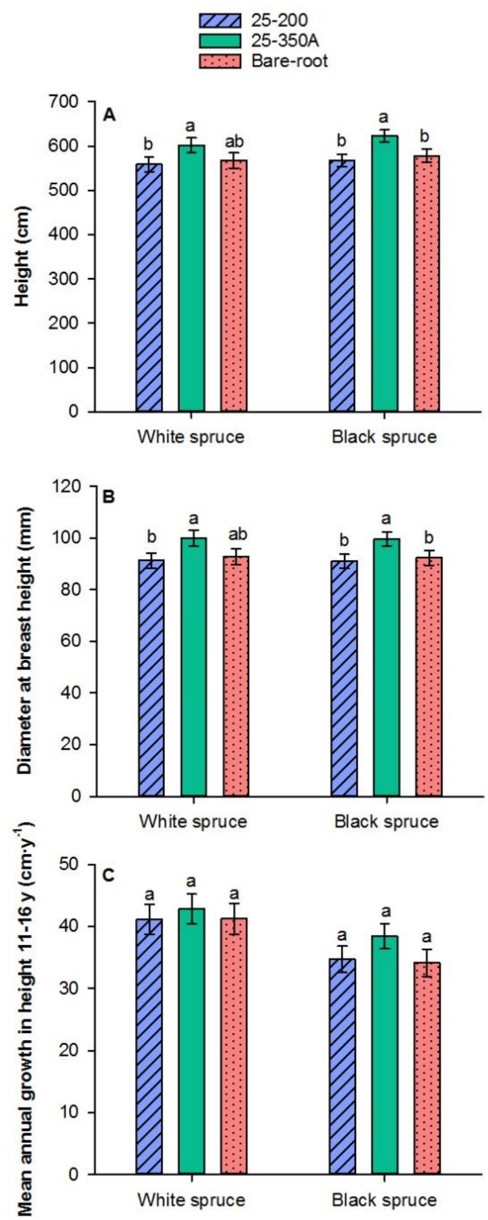

Figure 2. Height at age 16-y (A), diameter at breast height at age 16-y (dbh) (B) and mean annual height growth between age 11-y and 16-y (C) for white and black spruce seedlings produced in 25–350A containers, 25–200 containers or as bare-roots. Data presented as mean ± standard error. For a given species, bars with similar letters are not different at α = 0.05.

3.2 Estimated yield of white spruce at rotation age

Based on 16th-y results, which shown no significant effect of mechanical site preparation on seedling dimensions (Table 2), white spruce merchantable volume at rotation age was estimated according to the stock type effect only. Hence, 60 years following planting, the estimated volume for 25–350A containerized seedlings was 2.5% higher than for 25–200 containerize seedlings (+ 13.5 m^3 ha^{-1}), and 7.4% higher than for bare-root seedlings (+ 26.0 m^3 ha^{-1}), (Figure 3). In the worse case scenario (bare-root stock), the estimated merchantable volume was 520 m^3 ha^{-1} at age 60-y, making the differences between stock types negligible from a forest management perspective. Moreover, differences in volume (Fig. 3) and survival (higher than 80%; data not shown) would not affect the potential and timing for commercial thinning treatments.

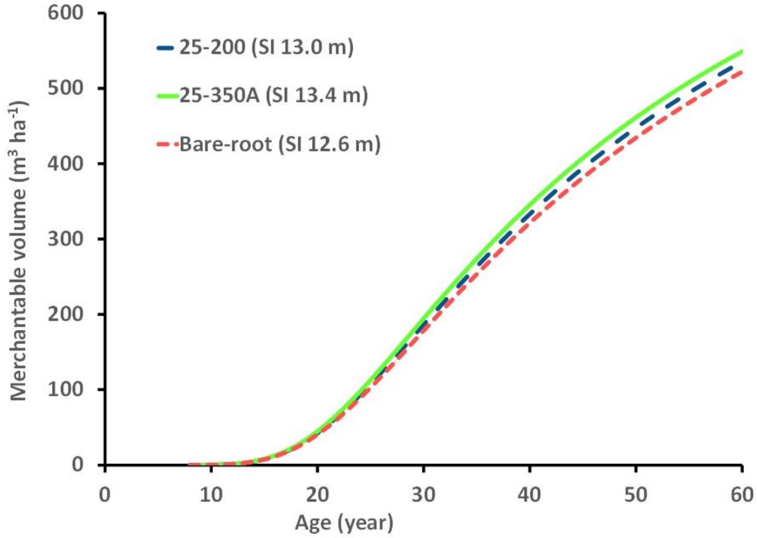

Figure 3. Evolution of planted white spruce merchantable volume, as a function of stock type. Curves are based on the growth model of Prégent et al. (2010), taking into account an initial density of 2 500 seedlings ha^{-1}. SI: site index (height at age 25-y).

4 Conclusion

Our results confirm that there is a significant, although limited impact of stock type on the size of black and white spruce at the juvenile stage, when medium and large stock types are compared, and that these small differences have a negligible effect on long term merchantable volume for white spruce. Therefore, selection of a medium or larger stock type for reforestation projects in ecosystems similar to the one studied here should be based on other considerations than growth and yield, such as seedling availability, production and planting costs, or operational constraints (Thiffault 2004). These results are, however, dependent upon the strict application of a vegetation management strategy that comprises early planting following harvesting and the timely application of release treatments (Thiffault and Roy 2011). Any delay between the harvesting and planting, or in the application of the release treatments would potentially exacerbate the differences between stock types (Jobidon et al. 2003). Stock type selection can also be made independently from mechanical site preparation prescriptions, as the two treatments do not interact. Mechanical site preparation in itself does not promote seedling growth in these rich sites with thin humus.

5 Acknowledgements

We thank Robert Jobidon, Jacques Carignan, Réjean Poliquin, Dominic Létourneau, Francis Cadoret, Steve Lemay, Alexandre Fortin-Pelletier, Evelyne Gaillard and Maïté Brémont for their contribution to the establishment and follow-up of this experiment. We are also indebted to Normand Gendron, Louis Labrecque and Serge Leclerc for their assistance in establishing the experimental design. Catherine

Larouche, Denise Tousignant and Nathalie Langlois provided constructive advice on an earlier version of this manuscript. This study was funded by the Ministère des Forêts, de la Faune et des Parcs du Québec.

6 References

Bates D, Mächler M, Bolker BM, Walker SC (2015) Fitting linear mixed-effects models using lme4. J Stat Soft 67: 1-48. https://doi.org/10.18637/jss.v067.i01

Beguin J, Tremblay JP, Thiffault N, Pothier D, Côté SD (2016) Management of forest regeneration in boreal and temperate deer–forest systems: challenges, guidelines, and research gaps. Ecosphere 7:e01488. https://doi.org/10.1002/ecs2.1488

Bolker BM, Brooks ME, Clark CJ, Geange SW, Poulsen JR, Stevens MHH, White JSS (2009) Generalized linear mixed models: a practical guide for ecology and evolution. Trends Ecol Evol 24: 127-135. https://doi.org/10.1016/j.tree.2008.10.008

Dumroese KR, Landis TD, Pinto JR, Haase DL, Wilkinson KW, Davis AS (2016) Meeting forest restoration challenges: Using the target plant concept. Reforesta 1:37-52. https://doi.org/10.21750/REFOR.1.03.3

Faure-Lacroix J, Tremblay JP, Thiffault N, Roy V (2013) Stock type performance in addressing top-down and bottom-up factors for the restoration of indigenous trees. For Ecol Manage 307: 333-340. https://doi.org/10.1016/j.foreco.2013.07.031

Gravel J, Beaupré P, Latrémouille I, Barrette M, Bédard S, Gauthier MM, Guillemette F, Hébert F, Larouche C, Prégent G, Prévost M, Raymond P, Thiffault N, Tremblay S (2016) Fiches d'aide à la décision pour les traitements sylvicoles au Québec. Ministère des Forêts, de la Faune et des Parcs, Direction de l'aménagement et de l'environnement forestiers and Direction de la recherche forestière. Document n° DAEF2-0088. Québec, QC. [https://www.mffp.gouv.qc.ca/publications/forets/entreprises/fiches-aide-decision-traitement_sylvicole.pdf]

Grossnickle SC (2000) Ecophysiology of Northern Spruce Species. The Performance of Planted Seedlings. NRC Research Press. Ottawa, ON.

Grossnickle SC (2005) Seedling size and reforestation success. How big is big enough? The Thin Green Line: A symposium on the state-of-the-art in reforestation. July 26–28 2005, Thunder Bay ON. Proceedings compiled by SJ Colombo. Ontario Ministry of Natural Resources, Ontario Forest Research Institute. Forest Research Information Paper n° 160.

Grossnickle SC, El-Kassaby YA (2016) Bareroot versus container stocktypes: a performance comparison. New Forest 47: 1-51. https://doi.org/10.1007/s11056-015-9476-6

Hébert F, Boucher JF, Walsh D, Tremblay P, Côté D, Lord D (2014) Black spruce growth and survival in boreal open woodlands 10 years following mechanical site preparation and planting. Forestry 87: 277-286. https://doi.org/10.1093/forestry/cpt052

Jobidon R, Roy V, Cyr G (2003) Net effect of competing vegetation on selected environmental conditions and performance of four spruce seedling stock sizes after eight years in Québec (Canada). Ann For Sci 60: 691-699. https://doi.org/10.1051/forest:2003063

Laflèche V, Ruel JC, Archambault L (2000) Évaluation de la coupe avec protection de la régénération et des sols comme méthode de régénération de peuplements mélangés du domaine bioclimatique de la sapinière à bouleau jaune de l'est du Québec, Canada. For Chron 76: 653-663. https://doi.org/10.5558/tfc76653-4

Macdonald SE, Schmidt MG, Rothwell RL (1998) Impacts of mechanical site preparation on foliar nutrients of planted white spruce seedlings on mixed-wood boreal forest sites in Alberta. For Ecol Manage 110: 35-48. https://doi.org/10.1016/S0378-1127(98)00272-2

Örlander G, Gemmel P, Hunt J (1990) Site Preparation: A Swedish Overview, FRDA Report 105, British Columbia Ministry of Forests, Victoria, BC.

Pinto JR, Marshall JD, Dumroese KR, Davis AS, Cobos DR (2012) Photosynthetic response, carbon isotopic composition, survival, and growth of three stock types under water stress enhanced by vegetative competition. Can J For Res 42: 333-344. https://doi.org/10.1139/x11-189

Pinto J, McNassar B, Kildisheva O, Davis AS (2018) Stocktype and vegetative competition influences on *Pseudotsuga menziesii* and *Larix occidentalis* seedling establishment. Forests 9 (5), 228. https://doi.org/10.3390/f9050228

Prégent G (1998) L'éclaircie des plantations. Direction de la recherche forestière, Ministère des Ressources naturelles. Mémoire de recherche forestière n° 133. Québec, QC. [http://www.mffp.gouv.qc.ca/publications/forets/connaissances/recherche/Pregent-Guy/Memoire133.pdf]

Prégent G, Picher G, Auger I (2010) Tarif de cubage, tables de rendement et modèles de croissance pour les plantations d'épinette blanche au Québec. Ministère des Ressources naturelles et de la Faune, Direction de la recherche forestière. Mémoire de recherche forestière n° 160. Québec, QC. [https://www.mffp.gouv.qc.ca/publications/forets/connaissances/recherche/Pregent-Guy/Memoire160.pdf]

Prescott CE, Maynard DG, Laiho R (2000) Humus in northern forests: friend or foe? For Ecol Manage 133: 23-36. https://doi.org/10.1016/S0378-1127(99)00295-9

Prévost M (1992) Effets du scarifiage sur les propriétés du sol, la croissance des semis et la compétition : revue des connaissances actuelles et perspectives de recherches au Québec. Ann Sci For 49: 277-296. https://doi.org/10.1051/forest:19920306

R Core Team (2013) R: A language and environment for statistical computing. Dans : R Foundation for Statistical Computing. Vienna, Austria [http://www.R-project.org/]

Robitaille A, Saucier JP (1998) Paysages régionaux du Québec méridional. Publications du Québec. Québec, QC.

Salmon D (2018) Ressources et industries forestières du Québec. Portrait statistique édition 2017. Ministère des Forêts, de la Faune et des Parcs. Québec, QC. [https://mffp.gouv.qc.ca/wp-content/uploads/portrait-statistique-2017.pdf]

Saucier JP, Robitaille A, Grondin P (2009) Cadre bioclimatique du Québec. Doucet R, Côté M (eds.) Manuel de foresterie, 2nd edition. Ordre des ingénieurs forestiers du Québec. Éditions Multimondes. Québec, QC.

Soil Classification Working Group (1998) The Canadian System of Soil Classification. 3rd edition. Agriculture and Agri-Food Canada. Publication n° 1646. Ottawa, ON. [http://sis.agr.gc.ca/cansis/publications/manuals/1998-cssc-ed3/cssc3_manual.pdf]

South DB, Rakestraw JL (2004) Large-diameter seedlings: A method of reducing chemical use in some pine plantations. J Sustain For 18: 47-58. https://doi.org/10.1300/J091v18n04_03

South DB, Zwolinski JB, Donald DGM (1993) Interactions among seedling diameter grade, weed control, and soil cultivation for *Pinus radiada* in South Africa. Can J For Res 23: 2078-2082. https://doi.org/10.1139/x93-259

Thiffault N (2004) Stock type in intensive silviculture: A (short) discussion about roots and size. For Chron 80: 463-468. https://doi.org/10.5558/tfc80463-4

Thiffault N, Cyr G, Prégent G, Jobidon R, Charrette L (2004) Régénération artificielle des pessières noires à éricacées : effets du scarifiage, de la fertilisation et du type de plants après 10 ans. For Chron 80: 141-149. http://dx.doi.org/10.5558/tfc80141-1

Thiffault N, Hébert F (2013) Chapitre 13 — Le dégagement et le nettoiement. Larouche C, Guillemette F, Raymond P, Saucier JP (eds). Le guide sylvicole du Québec, Tome 2 — Les concepts et l'application de la sylviculture. Les Publications du Québec. Québec, QC.

Thiffault N, Chalifour D, Bélanger L (2013) Enrichment planting of *Picea glauca* in boreal mixedwoods: can localized site preparation enhance early seedling survival and growth? New Forest 44: 533-546. http://dx.doi.org/10.1007/s11056-012-9361-5.

Thiffault N, Jobidon R (2005) Existe-t-il une interaction entre le type de plants et le scarifiage? Le cas des PMD et des PFD d'épinettes. Ministère des Ressources naturelles et de la Faune, Direction de la recherche forestière. Note de recherche forestière n° 129, Québec, QC. [http://www.mffp.gouv.qc.ca/publications/forets/connaissances/recherche/Thiffault-Nelson/Note129.pdf]

Thiffault N, Jobidon R, Munson AD (2003) Performance and physiology of large containerized and bare-root spruce seedlings in relation to scarification and competition in Québec (Canada). Ann For Sci 60: 645-655. http://dx.doi.org/10.1051/forest:2003057

Thiffault N, Roy V (2011) Living without herbicides in Québec (Canada): historical context, current strategy, research and challenges in forest vegetation management. Eur J For Res 130: 117-133. http://dx.doi.org/10.1007/s10342-010-0373-4

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 Fenn 46: 667-682. https://doi.org/10.14214/sf.918