Canadian Journal of
Forest Research

OPEN ACCESS | Article

Translocating seed sources to new geoclimatic environments has limited effect on lumber quality of eastern Canadian white spruce

Isabelle Duchesne[a], **Patrick R.N. Lenz**[a], **Martin P. Girardin**[b], **and Nathalie Isabel**[b]

[a]Natural Resources Canada, Canadian Forest Service, Canadian Wood Fibre Centre, 1055 du P.E.P.S., P.O. Box 10380, Stn. Sainte-Foy, Québec, QC G1V 4C7, Canada; [b]Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, 1055 du P.E.P.S., P.O. Box 10380, Stn. Sainte-Foy, Québec, QC G1V 4C7, Canada

Corresponding author: **Isabelle Duchesne** (email: isabelle.duchesne@nrcan-rncan.gc.ca)

Abstract

Assisted gene flow according to expected climate gradients is considered as a forest management strategy to mitigate impacts of environmental change on forest growth. However, the effects of seed translocation on wood properties and lumber quality remain unknown. This study evaluated the effect of provenance origin on lumber production and quality at rotation age in two white spruce provenance trials established in contrasting environments in eastern Canada. Based on 108 sample trees, which resulted in 943 pieces of lumber, average volume production per tree at the southernmost site was twice that of the production at the northern site. Provenance had a significant influence on growth and lumber strength in the first sawlog but had no effect on lumber stiffness and wood density. Although visual grade yields of No. 2 and better were high in both trials (over 86%), the machine stress rated (MSR) grade potential and percentage of lumber that met the bending stiffness design values of the visual grades were generally low (12%–26%). Hence, plantation-grown lumber should preferably be machine stress rated to ensure its fitness for structural applications in buildings. Management strategies aiming to efficiently sequester carbon should primarily maximize volume productivity in northern sites, as moving seed sources north still reduces provenance productivity, while breeding programs should aim to prevent decrease in lumber stiffness due to augmented productivity and shortened rotation cycles.

Key words: assisted migration, lumber visual grade, provenance trial, MOE (stiffness), MOR (strength), wood density, tree breeding

Résumé

Le flux génétique assisté, selon les gradients climatiques prévus, est considéré comme une stratégie de gestion des forêts visant à atténuer les impacts des changements environnementaux sur la croissance des forêts. Toutefois, les effets de la translocation des graines sur les propriétés du bois et la qualité des sciages demeurent inconnus. La présente étude a évalué l'effet de l'origine de la provenance sur la production et la qualité du bois d'œuvre à un âge de rotation dans deux essais de provenance d'épinettes blanches établis dans des environnements contrastés dans l'Est du Canada. Fondé sur 108 arbres échantillons qui ont produit 943 pièces de bois d'œuvre, la production moyenne en volume par arbre sur le site le plus au sud était le double de la production du site au nord. La provenance a eu une influence significative sur la croissance et la résistance du bois d'œuvre dans la première bille de sciage, mais n'a pas eu d'effet sur la rigidité des sciages et la densité du bois. Même si les rendements en grades visuels No. 2 et meilleur étaient élevés dans les deux essais (plus de 86 %), le potentiel de classer les sciages dans les catégories de bois MSR (bois évalués par contrainte mécanique) et le pourcentage de bois d'œuvre qui respectait les valeurs de conception de la rigidité en flexion des grades visuels étaient généralement faibles (12 % à 26 %). Par conséquent, le bois d'œuvre qui a poussé en plantation devrait de préférence être classé par contrainte mécanique afin d'assurer sa conformité à des applications structurales dans des bâtiments. Les stratégies de gestion visant à séquestrer efficacement le carbone devraient avant tout maximiser la productivité en volume dans les sites du nord, puisque le déplacement des sources de graines au nord réduit toujours la productivité de la provenance, alors que les programmes de sélection devraient viser à prévenir la diminution de la rigidité du bois d'œuvre en raison de l'augmentation de la productivité et de la diminution des cycles de rotation. [Traduit par la Rédaction]

Mots-clés : migration assistée, qualité visuelle du bois d'œuvre, essai de provenance, MOE (rigidité), MOR (résistance), densité du bois, amélioration des arbres

Introduction

Canada's forest economy has largely developed around the utilization of abundant, high-quality, but largely unmanaged softwood resource (Barbour and Kellogg 1990). However, the increasing pressure on fibre resources from natural disturbances such as fire and pests (Stinson et al. 2011), drought (Girardin et al. 2014), and other land uses urges stakeholders to intensify forest management practices that accelerate growth rates, and shorten harvest rotation to prevent fibre shortage in the near future (Kennedy 1995). As a result, the quality of the fibre supply is changing rapidly within an unprecedented context of climate change that may further exacerbate fibre shortage if trees cannot cope with extreme and more frequent climatic events, e.g., due to deficient adaptation (Chaste et al. 2019).

Boreal forest tree populations already show a significant adaptation lag behind their optimal climate niche (Gray and Hamann 2013) and optimal growing conditions tend to move northward with projected climate warming (Périe and de Blois 2016). Supporting assisted gene flow, i.e., moving southern seedlots within a species' distribution northbound, has been advocated as an adaptive forest management measure (Pedlar et al. 2012; Gray and Haman 2013). Still, breeding programs have been established for most Canadian commercial conifers since the 1960 and have achieved considerable gain for growth and adaptive traits (Mullin et al. 2011). Transplant experiments and provenance trials from the breeding programs' early days are currently reaching rotation age and offer unique opportunities for studying wood properties as lumber quality and economic value remain poorly documented in genetic selection programs. So far, only very few studies have looked at sawn wood properties from genetic trials in northern conifers (Beaulieu et al. 2001, 2002, 2006).

White spruce (*Picea glauca* (Moench) Voss) is an important species of the spruce–pine–fir (S–P–F) lumber basket and is valued for its superior wood quality (Zhang and Koubaa 2008). It has a transcontinental range in North America, growing from the northeastern US to the northern treeline from the Atlantic Ocean to the Pacific Ocean. It grows under a wider range of ecological conditions including extreme sites (Nienstaedt and Teich 1972), indicating that the species harbours significant amounts of genetic variation (Hornoy et al. 2015). In its eastern range, especially in the Great Lakes–St. Lawrence forest region, it is among the most productive species with remarkable increment and economic value.

Provenance trials for eastern Canadian white spruce were established in the 1960 and 1970 to identify best growing seed sources and to start breeding for enhanced growth and volume production (Corriveau and Boudoux 1971; Beaulieu 1996) mining the important intra-specific variation (Li et al. 1997). Early studies on wood density had reported important differentiation in eastern Canadian white spruce provenances (Corriveau et al. 1991). Later, it was shown that wood traits are under moderate to high genetic control in spruces leading to important expected genetic gain when considering wood quality in breeding (Yanchuk and Kiss 1993; Ivcovich et al. 2002; Duchesne and Zhang 2004; Lenz et al. 2013). Nevertheless, wood traits that are key for mechanical applications of wood, such as density, modulus of elasticity (MOE), and modulus of rupture (MOR), are adversely correlated with growth (Corriveau et al. 1991; Hylen 1997; Duchesne and Swift 2008; Lenz et al. 2010; Duchesne and Tanguay 2011; Chen et al. 2014), which needs particular attention in tree improvement. Given that lumber represents the most important end-use application and an important economic incentive for breeding efforts (Hassegawa et al. 2020), and to better inform future silvicultural investments in a context of changing climate, there is a need to study rotation-age lumber quality in breeding populations and to evaluate lumber properties of plantation-grown genetic material moved to a new geoclimatic environment.

Therefore, the objective of the study was to evaluate, at a rotation age of 55–56 years, the effect of genetic origin on white spruce growth performance, lumber product yields, and lumber quality, defined as structural lumber visual grades, lumber MOE, MOR, and wood density. To achieve this objective, two legacy white spruce provenance trials planted in two contrasting geoclimatic environments in eastern Canadian forests were compared, and the results are discussed in a context of assisted gene flow and climate change mitigation through the translocation of seed sources.

Materials and methods

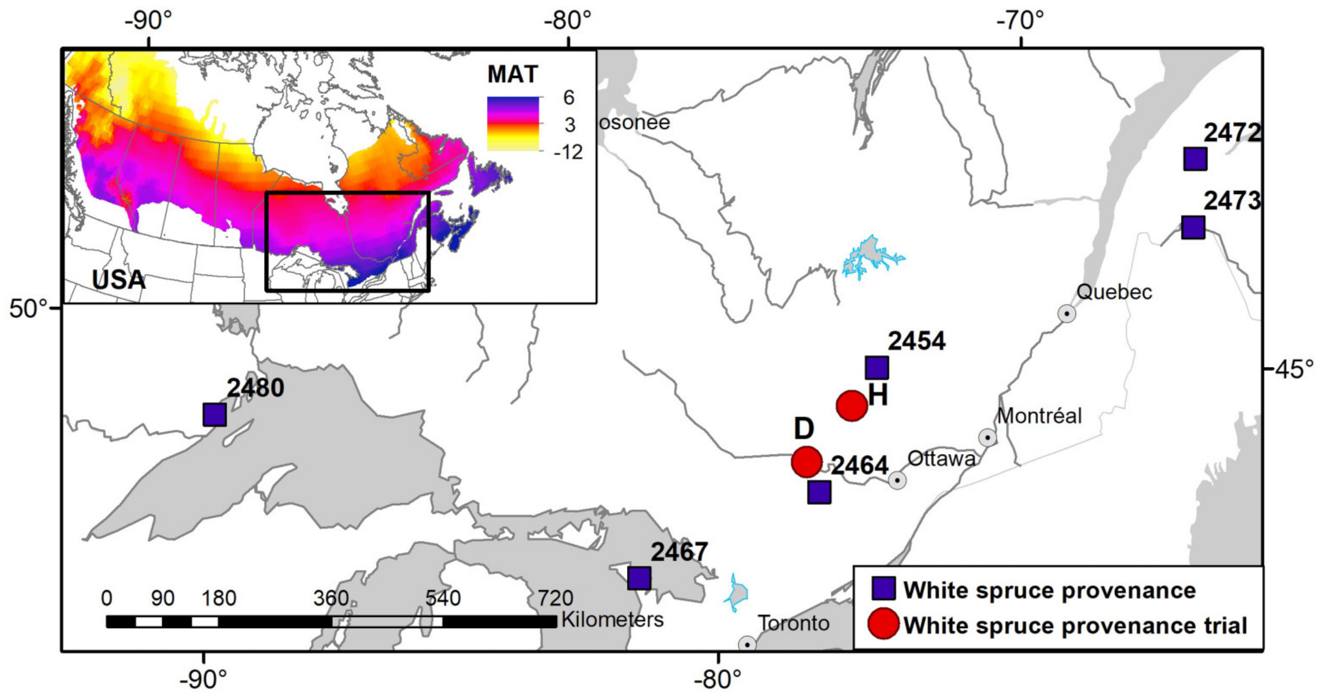
Site description

Measurements and sample trees were collected from a legacy provenance trial spanning the eastern Canadian range of white spruce. The trial had been replicated in different locations across eastern Canadian provinces with varying numbers of provenances planted in each site during the mid-1960s (Corriveau and Boudoux 1971; Morgenstern et al. 2006). As many sites have been abandoned or logged since, we identified two well-maintained and contrasting sites for this wood quality study. The Baskatong trial (E-194 H) was established in 1964 in the boreal forest surrounding Lac Baskatong, about 100 km north of Mont-Laurier in the province of Quebec. The experimental design consisted of a randomized complete block design where each provenance was planted in square plots with 6 rows of 6 trees each and a 1.8 m × 1.8 m spacing between trees (Corriveau and Boudoux 1971). The experiment was never thinned or pruned since its establishment. For the current study, trees from three replications with the best survival out of the six planted repetitions were chosen.

The trial at the Petawawa Research Forest (E-194 D1) near Chalk River, Ontario, is located in the Great Lakes–St. Lawrence forest region and was established in spring 1963. The experimental design consisted of 0.04 ha square plots with 12 rows of 12 trees each planted at 1.8 m × 1.8 m spacing with three replications (Morgenstern et al. 2006). Trees were pruned in 1979. The experiment was commercially thinned by removing every second row in 1986 at age 26 years from seed (Morgenstern and Copis 1999; Morgenstern et al. 2006).

The northern trial at Baskatong has a mean annual temperature (MAT) of 2.8 °C, whereas the southern Petawawa trial has a MAT of 4.6 °C. The difference in MAT at both sites represents the minimum expected temperature increase by

Fig. 1. White spruce provenances included in the lumber quality study (blue squares) and location of the studied trials Baskatong (H) and Petawawa (D) (red circles). In inset, the study area is marked with black box, with mean annual temperature (MAT, °C) averaged over 1950–1980 superimposed on the range-wide distribution of white spruce in Canada (see Supplementary Table S1 for MAT values specific to each provenance and trial). Maps were created using ArcGIS v10.5.1 for Windows and ESRI spatial data (ESRI 2017).



mid-century (Price et al. 2013). Supplementary Table S1 gives the coordinates and climate data of the two trials evaluated in this study. Figure 1 presents the geographical distribution of the six provenances used for destructive sampling. Provenance original locations were distributed from Thunder Bay, in western Ontario, to Edmundston, New Brunswick. The MAT of the selected provenances ranged from 1.8 to 6.0 °C (Table S1).

Tree selection for lumber quality evaluation

In September 2016, a subsample of six provenances planted in both sites was selected to represent the geoclimatic range of eastern white spruce (Fig. 1) and to investigate growth and lumber quality (Fig. 2) when moving seed sources into different climatic and environmental conditions. Among the retained provenances were the local provenance of each trial, i.e., Lac Baskatong and Chalk River (Table S1). In total, nine trees per provenance per site were randomly selected (i.e., 6 provenances × 3 trees per provenance × 3 blocks). Hence, we harvested 54 trees at each site for a total of 108 trees in this study. Each tree had to have a minimum diameter at breast height (DBH) class of 12 cm to ensure sufficient piece size for subsequent log conversion. In the rare cases where conditions were not met, we selected another tree within the same block. To minimize potential growth interference/heterogeneity due to tree mortality, each sample tree had to have at least six live neighbours, out of eight possible neighbours.

Prior to felling, tree DBH and height were recorded using a diameter tape and a laser (Vertex Häglöf), respectively. Acoustic velocity (AV; km·s^{-1}), which is a good indicator of wood stiffness, was measured on the north and the south face of each standing tree using the ST300 tool (Fiber-gen, Christchurch, New Zealand). Probes were placed approximately 1 m apart around breast height. An average of six AV readings were recorded per tree (three per face). AV measurements were conducted within the period of early September to end of October 2014. AV had been found to be under moderate genetic control (Lenz et al. 2013; Desponts et al. 2017) and offers a cost-efficient opportunity for integrating end product quality, in addition to growth into multitrait improvement strategies (Hassegawa et al. 2020; Lenz et al. 2020).

After manual felling with a chain saw, total stem length, log length below live crown, and the diameter of the five largest branches in the live crown were recorded. The live crown base was defined as the height of the lowest branch that presented green foliage and above which all whorls included at least one living branch. Thereafter, stems were topped at approximately 9.1 cm diameter and skidded with an all-terrain vehicle (Baskatong) or tractor (Petawawa) to road side. Stems were delivered by truck to the Duchesnay sawmill near the city of Québec, where they were manually measured at every meter to calculate volume and taper, and bucked to maximize the production of 3.6 m (12 ft) logs. The 108 sample trees produced 384 logs (161 for Baskatong and 223 for Petawawa) that were carefully numbered to keep track of their origin. The

Fig. 2. (*a*) Baskatong site in September 2016, (*b*) Petawawa site in September 2014, (*c*) stem measurements, (*d*) log conversion using a portable sawmill, (*e*) structural lumber produced, and (*f*) edgewise three-point static bending test.

first butt log of each tree was identified with A, and the second, third, and fourth sawlogs were identified with B, C, and D, respectively. The diameter inside bark was measured at the large and small ends of each log in two orthogonal directions. Log volumes were estimated using Smalian's formula. Tree merchantable stem volume was defined as the sum of the volume of all 1 m log segments up to the 9.1 cm stem top diameter. Stem taper was defined as the rate of decrease in stem diameter with increasing height from ground level to the tree tip (Burkhart and Tomé 2012).

Log conversion and lumber quality assessment

The 384 sawlogs were converted into 943 pieces of lumber of actual sizes 38 mm × 64 mm, 38 mm × 89 mm, and 38 mm × 140 mm, or nominal sizes 2 in. × 3 in., 2 in. × 4 in., and 2 in. × 6 in.) using a Gilbert portable sawmill (SGM Scierie Mobile Gilbert, Quebec, Canada). Trials in Baskatong and Petawawa produced 331 and 612 pieces of lumber, respectively. The lumber was then kiln dried and planed at the Duchesnay sawmill and shipped to FPInnovations in the city of Québec for quality evaluation. Each piece of lumber was visually graded by a qualified inspector according to paragraph No. 124 "Structural Light Framing, Joists and Planks" of the National Lumber Grades Authority (NLGA 2017), which comprises the following quality classes: Select Structural (Premium, best grade), No. 1, No. 2, No. 3, and Economy. Reasons for downgrading or rejecting each piece were recorded (e.g., wane, knots, grain deviation, decay, etc.). Lumber width and thickness were measured on each piece of lumber to determine its actual (as opposed to nominal) lumber volume. Dried and dressed lumber volume and grade recoveries were expressed on a volume basis, based on the actual lumber volume produced (i.e., nominal dimensions were not used to calculate volumes). Lumber volume recovery was expressed as the ratio between the dried and dressed actual lumber volume produced by a log and the green volume of the same log.

Prior to mechanical testing in static bending, the lumber was conditioned at 20 °C and 78% relative humidity to achieve a target equilibrium moisture content (MC) of 15%. An edgewise bending machine with a three-point loading configuration and a span-to-depth ratio of 21 was used to determine the MOE and MOR. The bending test was performed at the FPInnovations facilities in Québec and followed ASTM D 4761-05 (ASTM International 2009*a*). Following ASTM D 1990-14 (ASTM International 2014), MOE and MOR values were normalized to 15% MC, and MOR was adjusted to the characteristic size of 38 mm by 89 mm (1.5 in. by 3.5 in.). After the test, a 38-mm-thick block was cut to determine the actual MC and relative density of each lumber piece. Relative basic density and MC for each board were determined according to section 5.1 in ASTM D4442-07 (ASTM International 2009*b*) and section 8.2.2.3 in ASTM D2395-07a (ASTM International 2009*c*), respectively.

Design values and machine stress rated (MSR) grades

In Canada and the United States, most of the lumber sold on the market is visually graded and each visual grade has their specific design values for different properties. For the Canadian S–P–F species group, the current bending stiffness lumber design values (mean MOE) assigned to the visual grades Select Structural, No. 1, No. 2, and 3 No. are 10.5, 9.5, and 9.0 GPa, respectively (Table 4; Barrett and Lau 1994).

 Can. J. For. Res. **52:** 1–13 (2022) | dx.doi.org/10.1139/cjfr-2022-0075

These design values have been determined on lumber produced from unmanaged, mature or old-growth forests.

In this study, the lumber pieces visually graded as No. 2 and better were further graded for MSR yield following the NLGA SPS 2 (NLGA 2010), i.e., they had to meet the lower limits (5th percentile) for stiffness and strength (MOE and MOR) for a given MSR grade. We considered three commonly produced MSR grades on the wood construction market: MSR 2100f-1.8E, 1650f-1.5E, and 1450f-1.3E.

In contrast with visual grading, MSR lumber is evaluated by a stress-rating equipment to measure its true MOE, which is an important trait for value-added structural/engineering applications.

Statistical analysis

General linear models with fixed and random effects were used to evaluate the effect of genetic origin on white spruce growth performance, wood quality, lumber volume, and grade. Analyses were conducted using SAS 9.4 and the MIXED procedure according to a complete randomized block design.

$$(1) \quad Y_{ijkl} = S_i + B_{j(i)} + P_k + P_k \times S_i + \mathrm{CI} + \varepsilon_{ijkl}$$

where Y_{ijkl} is the observation on the lth tree or the mean lumber trait of a log or entire tree depending on the analysis, S_i is the fixed site, P_k is the fixed provenance effect, $P_k \times S_i$ is the interaction term, and $B_{j(i)}$ is the random block effect nested in each site. To account for competition, the DBH (1.3 m) of neighbour trees was measured and considered in a competitionindex according to Hegyi (1974):

$$(2) \quad \mathrm{CI} = \sum_{i=1}^{n} \left(\frac{\mathrm{DBH\_comp}}{\mathrm{DBH}} \times \frac{1}{L} \right)$$

where DBH_comp is the diameter of the competitor, DBH is the diameter of the focus tree, and L is the distance between the competitor and the focus tree. The competition effect CI standardised by site was added as a covariate with one degree of freedom into the analyses to account for competition and irregular mortality of surrounding trees. We verified assumptions of residuals' normality and homoscedasticity for all models using standard graphical approaches.

Results

Growth and wood quality traits

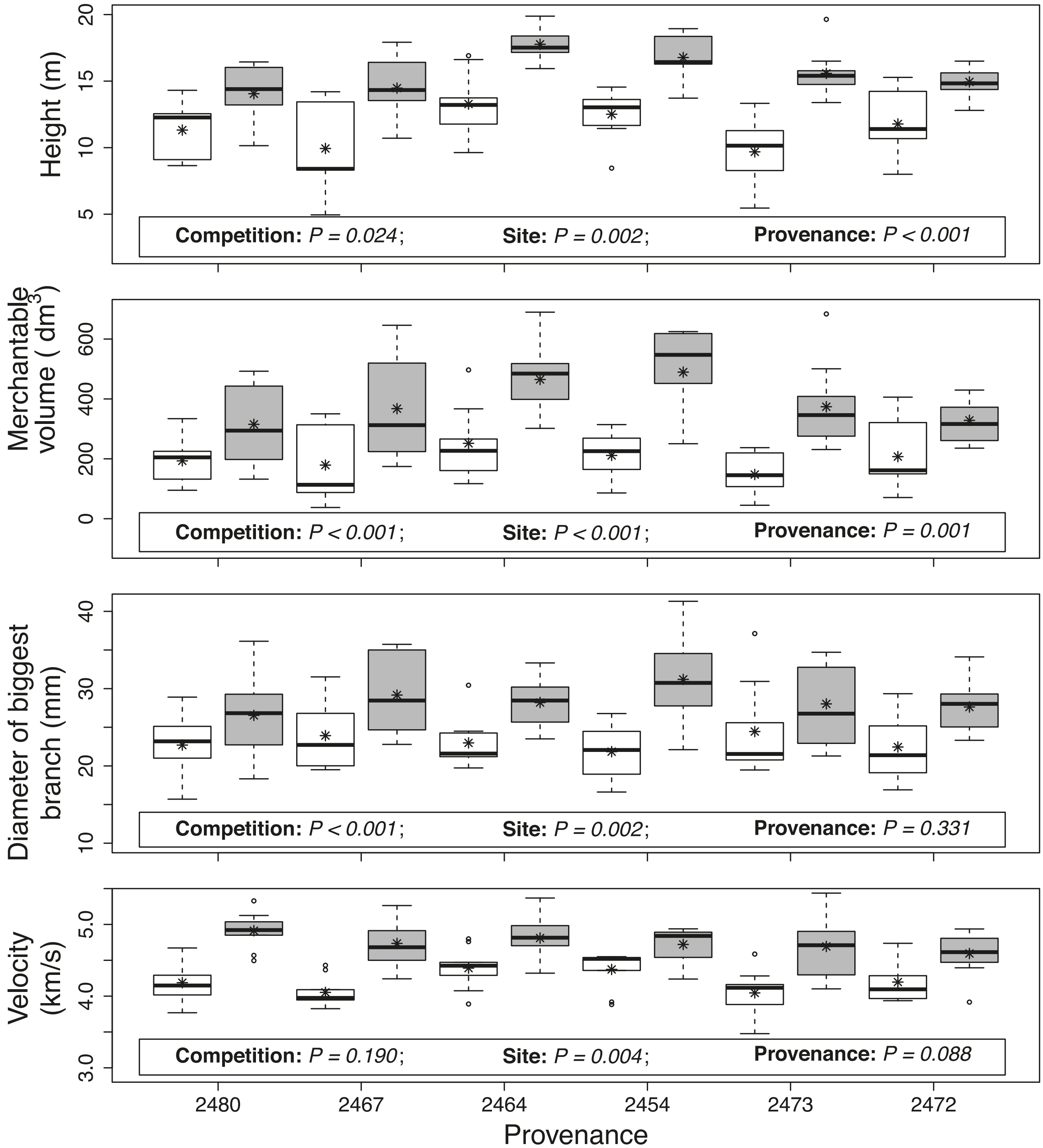
Dendrometric measurements and wood traits were evaluated on 108 standing trees from six provenance origins spanning the latitudinal range of eastern Canadian white spruce. Expectedly, trees at the southernmost site (Petawawa) showed higher height and diameter growth (Table 1), being over 3 m taller and 46 mm bigger at breast height than trees from northernmost site (Baskatong). This led to significant more volume accumulation in the Petawawa trial, compared with the Baskatong site. When pooling the six provenances together, the average volume per tree in the Petawawa and Baskatong trials in 2016 was 390 and 200 dm^3, respectively. These volumes correspond to a stand productivity of approximately 612 $\mathrm{m}^3{\cdot}\mathrm{ha}^{-1}$ for the never-thinned Baskatong trial, and 602 $\mathrm{m}^3{\cdot}\mathrm{ha}^{-1}$ for the heavily thinned Petawawa trial where 50% of the trees, or every other row, were removed in 1986. Within 30 years after the thinning intervention (i.e., 1986–2016), the standing volume at Petawawa caught up with the volume grown at Baskatong since its establishment. This highlights the superior site productivity in the southernmost trial. The enhanced growth together with thinning of the Petawawa trial also led to significant larger branch diameter in that site compared with Baskatong (Table 1). Significant differences in branch size were, however, not observed on the provenance level (Fig. 3). All three effects, competition, site, and provenance, had a significant influence on tree height and volume (Fig. 3). Site had also a significant effect on standing tree AV ($P = 0.004$), which is a prior for mechanical wood stiffness. AV as measured around breast height was more than 10% higher in the Petawawa trial compared with Baskatong. Nevertheless, basic density of wood did not vary much between sites and provenances. Compared with growth, we found a rather weak provenance effect for wood quality traits while within provenance varia-

Table 1. Summary statistics obtained on 108 trees from six provenances.

	E-194 provenance trials	
Trait	Baskatong	Petawawa
Tree characteristics*		
Height (m)	15.14 (14.20)	18.56 (11.53)
	[9.80–19.30]	[13.20–22.20]
DBH (mm)	175.50 (18.45)	221.69 (13.30)
	[109.00–248.00]	[176.00–285.00]
Crown diameter (m)	3.34 (20.84)	2.75 (19.54)
	[1.80–5.00]	[1.70–3.90]
Mean branch diameter (mm)	23.06 (17.91)	28.46 (16.97)
	[15.70–37.13]	[18.33–41.30]
Height to live crown (m)	9.41 (21.54)	12.89 (10.98)
	[4.77–12.68]	[8.50–15.18]
Velocity ($\mathrm{km{\cdot}s^{-1}}$)	4.21 (7.21)	4.75 (6.85)
	[3.48–4.80]	[3.92–5.44]
Taper ($\mathrm{cm{\cdot}m^{-1}}$)	1.24 (16.62)	1.25 (13.96)
	[0.73–1.72]	[0.90–1.64]
Total volume (dm^3)	200.00 (50.32)	390.00 (36.98)
	[40.00–500.00]	[130.00–690.00]
Lumber traits†		
MOE (GPa)	8.55 (13.36)	8.85 (15.35)
	[4.77–11.85]	[5.40–13.18]
MOR (MPa)	35.27 (17.86)	34.88 (21.59)
	[21.80–55.77]	[19.19–64.76]
Basic density ($\mathrm{kg{\cdot}m^{-3}}$)	357.15 (6.33)	353.46 (5.73)
	[297.55–421.52]	[296.27–418.49]

Note: Coefficient of variation in round brackets; trait range in square brackets.
*Tree characteristics were obtained in 2016, except for acoustic velocity, which was recorded in fall 2014.
†Average lumber quality traits.

Fig. 3. Dendrometric variables at the tree level ($n = 108$) as a function of provenance and site for tree height, tree merchantable volume, mean diameter of the five biggest branches, and acoustic velocity. Provenances are ordered from west to east. P values are shown at the bottom of each panel. White box: Baskatong site; gray box: Petawawa site. The thick line in each box represents the median and the asterisk (∗) the mean value. See Fig. 1 and Supplementary Table S1 for the geographic distribution of provenances.



tion was high for all wood and growth traits (Figs. 3 and 5). No significant interaction between provenance and site was detected for none of the investigated growth and quality traits.

Lumber volume, size, and grade recoveries

Lumber volume per tree was significantly dependent on site and provenance effects that jointly influenced tree growth (Table 2). The average lumber volume of trees grown

Can. J. For. Res. 52: 1–13 (2022) | dx.doi.org/10.1139/cjfr-2022-0075

Table 2. Fixed effects (*P* value) for total lumber (actual) volume produced per tree in m^3 and for lumber volume recovery (percentage of tree merchantable volume transformed into lumber), as a function of site, provenances, and sample units (whole tree, 1st log).

	Lumber volume per tree (m^3)				Lumber volume recovery (%)			
Source of variation	numDF/denDF	Tree *P* value	numDF/denDF	1st log *P* value	numDF/denDF	Tree *P* value	numDF/denDF	1st log *P* value
Competition	1/90	0.3976	1/89	**<0.0001**	1/90	0.5428	1/89	0.4378
Site	1/4	**0.0017**	1/4	**0.0012**	1/4	**<0.0001**	1/4	**0.0003**
Provenance	5/90	**0.0076**	5/89	**0.0250**	5/90	0.4491	5/89	0.3666
Site × Provenance	5/90	0.2169	5/89	0.1826	5/90	0.1473	5/89	0.2714

Note: numDF, numerator degree of freedom; denDF, denominator degree of freedom. Bold values denote statistical significance at the 5% level ($P < 0.05$).

Table 3. Fixed effects (*P* value) for the actual lumber volume (m^3) as a function of competition, site, and provenance, and piece size (2 × 3, 2 × 4, and 2 × 6 in.) and NLGA lumber quality grades for structural light framing.

	Actual lumber volume (m^3)					
Source of variation	numDF/denDF	2 × 3 *P* value	2 × 4 *P* value	2 × 6 *P* value	No. 2 and better *P* value	No. 3 and Economy *P* value
Competition	1/90	0.0549	0.3187	**<0.0001**	**<0.0001**	0.3759
Site	1/4	0.0926	**0.0036**	**0.0071**	**0.0023**	0.0561
Provenance	5/90	0.8800	0.4259	**0.0076**	**0.0028**	0.3510
Site × Provenance	5/90	0.9116	0.6855	0.0874	0.1059	0.6910

Note: No. 2 and better combines three lumber visual grades: Select Structural, No. 1, and No. 2. numDF, numerator degree of freedom; denDF, denominator degree of freedom.

in Petawawa outperformed the average lumber volume of trees grown in Baskatong by 117% (150 dm^3·tree^{-1} against 70 dm^3·tree^{-1}; Supplementary Fig. S1). At the Baskatong site, populations 2464 (Chalk River) and 2454 (Lac Baskatong, i.e., the local provenance) produced the largest volumes of lumber per tree (90 vs. 78 dm^3·tree^{-1}, respectively), while provenance 2473 (Edmundston) produced the least (50 dm^3·tree^{-1}). In Petawawa, the most productive provenances were the same at those in Baskatong, but in the reversed order, first 2454 (Lac Baskatong) produced 194 dm^3·tree^{-1} and 2464 (Chalk River, i.e., the local provenance) produced 188 dm^3·tree^{-1}. The least productive provenance was 2480 (Kakabeka Falls) with 120 dm^3·tree^{-1}. On the other hand, lumber recovery was only dependant on site and about 7% higher in Petawawa than in Baskatong (43.3% and 40.5%, respectively). Provenances alone or in interaction with site had no detectable effect on average lumber volume recoveries at tree and first-log levels (Table 2).

The influence of site and provenance on lumber volume was more present in larger dimensional classes. This is especially true for 2 × 6 lumber, where competition was also highly significant in addition to site and provenance effects (Table 3, Supplementary Table S2). The 54 trees grown in Petawawa produced 68.5% of the total lumber volume sawn in this study (i.e., produced by the 108 trees), reflecting the better growth conditions of this site. We observed a significant shift in lumber size proportions between trees from Baskatong that predominantly produced 2 × 4s (57.2%) and trees from Petawawa that predominantly produced 2 × 6s (52.3%) (Supplementary Fig. S2, Table S2).

Visual lumber grades were exceptionally high for trees from both sites: the volume yields of high-quality grades (No. 2 and better) ranging from 83.3% (provenance 2480) to 93.1% (provenance 2454) in Petawawa (mean = 88.0%), and from 78.4% (provenance 2467) to 96.3% (provenance 2480) in Baskatong (mean = 86.2%) (Fig. 4). Statistical analyses showed that competition, site, and provenance significantly influenced the production of No. 2 and better grades but not the production of low-quality lumber grades (No. 3 and Economy) (Table 3). A clear differentiation in the quantity of No. 2 and better grades produced per tree is observed between the two trials, where Petawawa trees were the most productive (Supplementary Fig. S3). The differentiation at the provenance level was, however, less contrasted and showed an important within-provenance variation (Fig. S3).

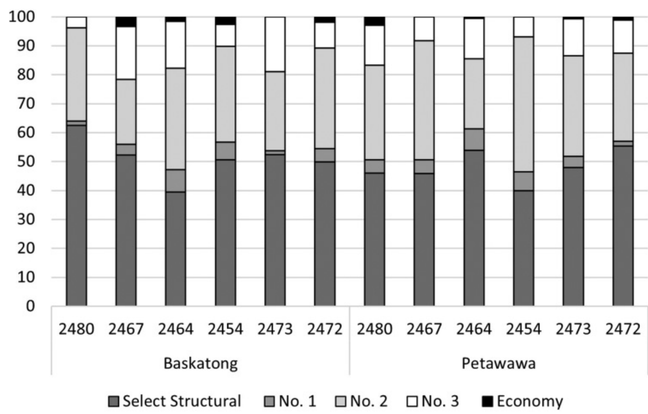
The most important reason for lumber downgrade was wane, i.e., the lack of wood fibre along the edge of a piece of lumber, at both sites (Petawawa = 40.3% and Baskatong = 37.8%, Supplementary Table S3). Lumber volume downgrades due to knots were more prominent in Petawawa (23.9%) than Baskatong (13.2%). Surprisingly, nearly 23% of the lumber volume produced in Baskatong was downgraded due to warp, whereas it was only 12% in Petawawa. Downgrades due to grain deviation, decay, and compression wood were similar for both trials. Except for wane that was superior in Petawawa, the percentage of lumber downgraded to low-quality grades (No. 3 and Economy; Table S3, right) followed a similar trend as that observed when considering any lumber downgrade.

Table 4. Percentage of lumber pieces that met the current grade requirements for bending stiffness design values and MSR grade yield for the Baskatong and Petawawa trials.

		Design values for S–P–F species group*	% of lumber pieces that met the bending stiffness design values		
NLGA visual grade	Sample size	Mean MOE (GPa)	Baskatong	Petawawa	Two sites combined
Select Structural	457	10.5	4.2	22.0	15.5
No. 1 and No. 2	348	9.5	16.8	28.1	24.4
No. 3	104	9.0	29.7	38.8	35.6
Total	909		11.7	26.3	21.2
MSR grade		Mean MOE (GPa)	Yield (%)		
2100f-1.8E	—	12.4 (1.8 Mpsi)	0.0	0.0	0.0
1650f-1.5E	—	10.3 (1.5 Mpsi)	0.0	0.0	0.0
1450f-1.3E	—	9.0 (1.3 Mpsi)	51.3	60.5	57.3

*CSA O86-14 (Canadian Standards Association 2014). Design values at 15% moisture content.

Fig. 4. NLGA lumber grade distribution (%) as a function of site and provenances.



Lumber mechanical properties

Despite faster growth in Petawawa, lumber stiffness (MOE) and lumber strength (MOR) were very similar at both sites (Table 1). There was no obvious geoclimatic gradient between the six contrasted provenances for these structural properties, although within-provenance variation was high (Fig. 5). Competition had a significant impact on lumber MOE at the tree level, whereas both competition and site significantly influenced lumber MOE at the first-log level (Supplementary Table S4). Tree-level lumber MOR was only significantly influenced by competition, whereas first-log lumber MOR was somewhat influenced by provenance ($P = 0.04$). Finally, only competition had a significant effect on lumber density in this study, at both tree and first-log levels.

For the two plantations of this study (tree age 55–56 years), the percentage of lumber pieces complying with the MOE design values assigned to the visual grade was only 21.2% (Table 4). Notably, the lumber produced from the Baskatong trial had a much lower percentage of pieces that met the expected bending stiffness design value (mean MOE 11.7%) compared to the Petawawa trial (26.3%). Overall, the low percentage of compliance observed in these plantations indicates that visual grading of lumber poorly reflected the measured mechanical properties of lumber close to rotation age.

In this study, the Baskatong and Petawawa sites yielded 86.2% and 88.0% No. 2 and better grade lumber, respectively. However, none of this lumber could classify for the MSR 1650f-1.5E or for the MSR 2100f-1.8E category (Table 4). Only 51.3% (Baskatong) and 60.5% (Petawawa) of the lumber pieces could classify for the MSR 1450f-1.3E category, which ranks among the lowest strength categories available on the market for stress-rated lumber. Hence, these results highlight the low MSR grade potential of these two plantations.

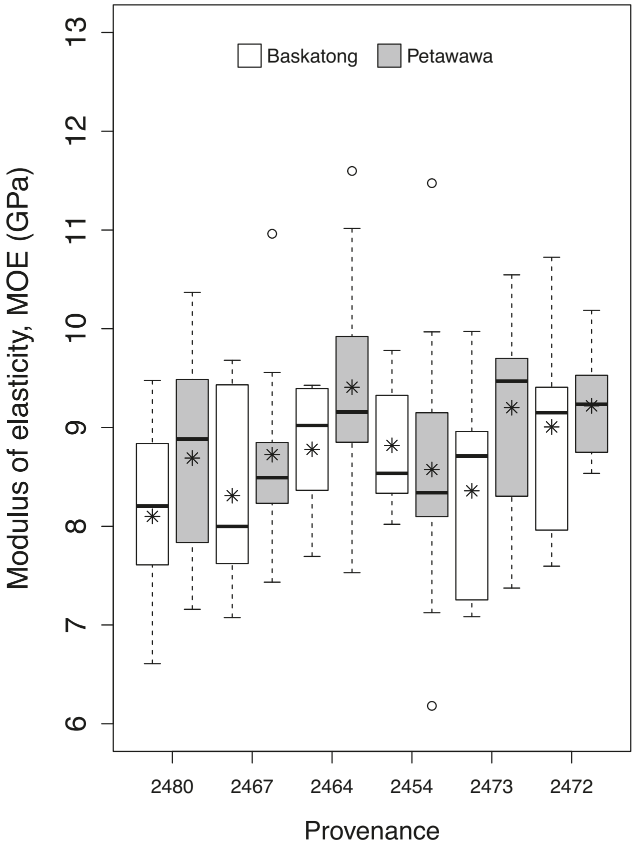
We observe that the higher lumber grades (No. 2 and better) had similar 5th percentile MOR, mean MOR, and mean MOE values (Supplementary Table S5). The expected performance differentiation among grades No. 1, No. 2, and No. 3 was not observed in our data. Still, the Economy grade had the lowest mechanical performance (Table S5). The behavior of lumber mechanical property values in relation to visual grades was very similar among the two plantations, confirming that lumber visual and mechanical quality did not vary much in the different environments.

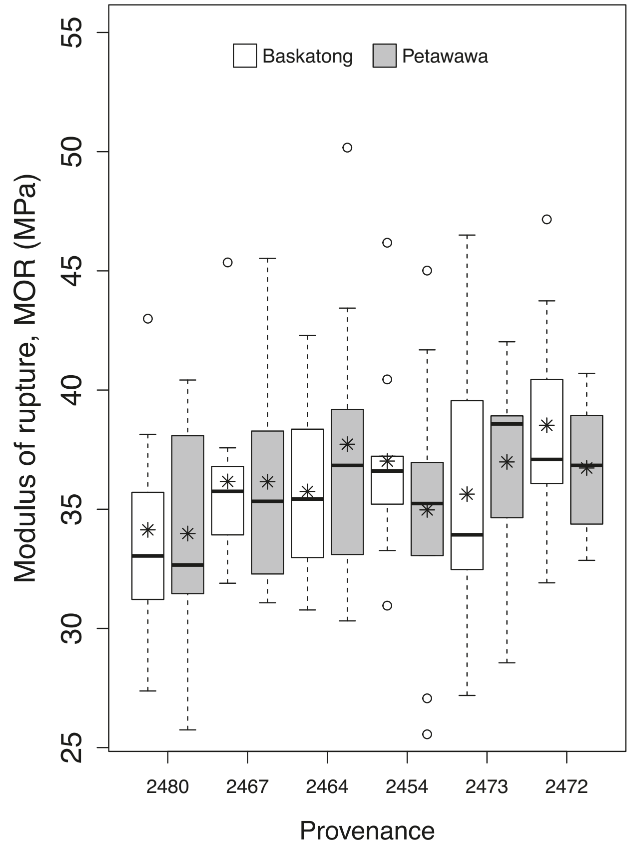
Discussion

Site and provenance origin effects on tree productivity and quality

Rotation-age growth and lumber properties were analysed from six provenances planted in two contrasting environments. Planting site was the most important differentiator for all growth traits analysed, whereas provenance origin only affected height and volume. The six common provenances planted at the Petawawa site (the drier, but warmer site), located in the southern hardwood forest zone, had a much faster growth than the same provenances planted at the Baskatong site, located at the fringe of the northern boreal forest. Silvicultural treatments may even have enhanced growth in Petawawa compared with Baskatong. The heavy thinning (50% tree removal) performed at Petawawa in 1986 (23 years after plantation establishment) is a clear indica-

Fig. 5. Lumber MOE and MOR of mature white spruce per provenance and site. Provenances are ordered from west to east. The thick line in each box represents the median and the asterisk (∗) the mean value.





tor that juvenile growth was so good that thinning had to be applied to prevent tree mortality, proving its superior growth. Trees in Baskatong were never thinned nor pruned and overall mortality was still relatively low at the time of harvest in 2016. The positive impact of pruning on wood stiffness was supported by the AV values that were superior in Petawawa (Table 1). Together with higher height increments, pruning most likely promoted the early formation of mature wood in the first log of trees in this site. Pruning of lower branches has been observed to increase diameter growth in the upper stem, thus reducing overall stem taper (Larson 1965; Larson 1969). Conversely, thinning is known to increase stem taper (Karlsson 2000; Duchesne and Swift 2008). In this study, the fact that stem taper values were similar between the two sites (Table 1) suggests that pruning improved stem form by favouring diameter growth in the upper stem, and thus counterbalanced the thinning effect on taper.

The absence of silvicultural treatments in Baskatong does not allow for exact separation of site and geoclimatic effects in this study. Nevertheless, our results underline that productivity level and planting site conditions are essential drivers for growth performance. Results also show that translocating a provenance to a site with similar climate mean characteristics during the growing period of a plantation, such as the Edmundston provenance at Baskatong, does not guarantee optimal performance if neither the adaptation lag at the seed source origin (Gray and Hamann 2013) nor the genetic differentiation of populations (Girardin et al. 2021) is captured. In a recent study on black spruce, Girardin et al. (2021) showed that genetic structure was an important component for modelling growth and biomass accumulation of different provenances. The same authors concluded that moving provenances solely considering climatic gradients is not a promising avenue for maintaining optimal biomass production until the mature age of a plantation. Indeed, the present study underlines that performance and adaptation of seed sources follow much complex patterns demanding for genetic testing in comparative plantations to identify best-performing planting stock.

Superior growth and adaptation of white spruce provenances from the Ottawa valley and adjacent regions in the provinces of Quebec and Ontario have been reported earlier for the juvenile age (Niensteadt and Teich 1972). Reforestation and breeding programs have consequently included selections from those provenances (Beaulieu 1996) with important genetic gain (Mullin et al. 2011). Still, it is interesting to see that enhanced height growth and volume of local provenances are maintained at both sites until rotation age, i.e., 53 years after plantation establishment.

Lumber volume and size recoveries

The relationships between crown development, branch and knot size, and sawn wood product yields and quality are complex as they are simultaneously influenced by intrinsic growth, site conditions, individual tree responses to climate through time, and forest management practices. Expectedly, the larger individual tree sizes found in Petawawa had a positive effect on lumber volume recovery. The slower tree growth moving north produced smaller logs and piece sizes that reduced lumber recovery. Considering those results, it remains questionable that translocating seed sources northbound will fully compensate for the volume productivity loss expected in the southern temperate forest regions due to climate change, because boreal forest regions (i.e., Canadian Shield) often have poorer acidic soils leading to lower site productivity (Bickerstaff et al. 1981). As a result, more intensive forest management strategies including thinning and fertilization may also be needed to fulfill fibre supply demand when climate change will impact growth in meridional forest regions.

Lumber visual grading

In North America, classification of lumber by a qualified inspector through visual grading relies exclusively on visual indicators, such as knots, wane, and rot (NLGA 2017). Using established correlations between appearance and strength, lumber graders are trained to assign a strength grade to dimensional lumber based on the presence or absence of certain natural characteristics (Canadian Wood Council 2022;Canadian Standards Association 2014). For example, when grading for Structural Light Framing, Joists, and Planks (NLGA Article 124), knots are considered as defects because of the strength-reducing effect caused by grain deviation around them (Jozsa and Middleton 1994). Therefore, a maximum allowable knot size is attributed to each visual grade to ensure strength performance. This maximum knot size will depend on the width of the lumber piece (ratio of clear wood face to knot diameter) and the position of the knots (knot positioned on the wide face or on the edge). In this study, both trials had a very high lumber visual grade yield of No. 2 and better (over 86%). The fact that trees grew significantly larger branches in Petawawa (mean of five biggest branches = 28.5 mm; Fig. 3) compared to Baskatong (23.1 mm) did not translate into major lumber downgrades because larger lumber pieces (2 × 6) were dominantly produced (i.e., knot size tolerance increases with increased lumber dimensions for each visual grade). This piece size factor combined with the formation of clear wood following pruning of the first sawlog that reduced branch/knot size jointly contributed to maintain or slightly improve lumber visual quality in Petawawa compared to Baskatong.

Lumber mechanical properties

In this work, the large differences in tree growth observed between the two sites at a harvest age of 55–56 years did not translate into large differences in lumber mechanical properties. Competition was the main significant effect for lumber stiffness (MOE), strength (MOR), and basic density. We observed a slight effect of site and a limited effect of provenance (only for lumber MOR in the first log; see Table S4). However, a high within-provenance variation for wood traits was detected that can be exploited in breeding programs. As previously reported, wood quality traits are under moderate to strong genetic control and their inclusion into selection criteria could lead to significant improvement of wood quality in future seedling stock (Beaulieu et al. 2006; Lenz et al. 2010, 2013; Chen et al. 2014).

Our results are comforting because the overall wood quality was relatively similar for the two test sites, with only a slightly superior MOE of +3.4% obtained in Petawawa. Translocating provenances or seed sources to a colder or a warmer climate did not markedly affect lumber quality. Surprisingly, the heavy commercial thinning treatment applied to the Petawawa trial in 1986 (age 26 years from seed) to prevent tree mortality and promote growth of residual trees did not reduce the mechanical properties of lumber. The analysis at first-log level aimed to evaluate the potential influence of tree pruning on mechanical properties (Table S4): in Petawawa, approximately 60% of the first log length was pruned (2.32 m on average or 12% of the total tree height), whereas trees were never pruned in Baskatong. The pruning treatment in Petawawa very likely contributed to maintain good lumber mechanical properties (despite faster growth rates) by allowing the growth of knot-free wood above pruned branches (overgrown knots) on the first log of the trunk. Along with larger piece size (more 2 × 6), pruning in Petawawa most likely counterbalanced the negative impact of knot size on lumber mechanical properties by preventing first-log branches to grow further. In contrast, trees in Baskatong were never pruned nor thinned. Tree crowns had to compete for light and nutrients, which resulted in significantly smaller branch diameters. The lower site index (poorer soil conditions) combined with cooler temperatures led to reduced tree growth, but wood density remained similar to that of trees grown in Petawawa, which is supported by findings of an earlier study in Norway spruce (Wilhemsson et al. 2002). The lower growth performance of the Baskatong site suggests that the planting site was not optimal for white spruce, presumably due to poorer availability of soil nutrients, combined with the high competition between trees in this unthinned plantation. Lumber stiffness was slightly lower (3.4%) in the northern, colder, and more humid site Baskatong, while lumber MOR was similar at both sites. Of more concern is the average stiffness of lumber from the two plantations as it was lower than the expected stiffness (design value) associated to No. 2 and better grades.

Compliance of lumber stiffness values to visual grade requirements

This study shows that the percentages of acceptance to visual grade requirements for mean MOE were generally low in both trials (Baskatong: 11.7%; Petawawa: 26.3%, Table 4). Despite the fact that over 86% of the lumber produced in this study visually qualified for No. 2 and better grades, the measured average lumber MOE values of both plantations (Baskatong: 8.55 GPa; Petawawa: 8.85 GPa) were below the bending stiffness design values expected for a piece of S–P–F lumber graded as No. 3 (i.e., 9.0 GPa; Table 4). Indeed, the expected mean MOE of the No. 2 and better lumber produced should have been of at least 9.5 GPa or above (Table 4). Hence, the NLGA grades assigned by visual inspection in this study overestimated the true stiffness of the lumber produced at both sites. The MSR potential of this plantation-grown lumber was also low. As far as knot characteristics are concerned, visual grading is considered efficient (Zhang et al. 2002), but besides knot characteristics, other wood characteristics such as juvenile wood also have an effect on both lumber stiffness and strength, although they are difficult to consider in visual grading (Barrett and Kellogg 1991; Zhou and Smith 1991). Consequently, to better meet end users' needs and specifications, the relationships between visual grades and associated stiffness/strength design values, which are currently based on old-growth unmanaged forests, should be revised downwards to take into account the higher content of juvenile wood of lumber grown in plantations or in more intensively managed forests. This approach was recently applied in the case of intensively managed southern yellow pine plantations in the United States (França et al. 2018).

It is well known that shorter rotation time in plantation stands generally leads to lower lumber stiffness values compared to unmanaged old-growth forest stands on which design values are based (Biblis et al. 1993; Zhang et al. 2002; Duchesne and Tanguay 2011; Canadian Standards Association 2014). The low competition between young trees (initial spacing was 1.8 m) in the initial growth phase of the plantation favored crown development and thus the formation of juvenile wood. As trees reach harvestable size sooner in plantations, the proportion of juvenile wood increases and negatively affects wood strength compared to unmanaged, longer rotation or old-growth trees. The percentage of compliance to grade requirements is known to increases with tree age (Biblis et al. 1993; Duchesne 2006), but considering that one of the major objectives of intensive forest management is to produce sawlogs in shorter rotation cycles, plantation-grown lumber should either be machine stress rated to ensure its fitness for structural end-uses or used in non-structural applications. As the proportion of plantation-grown wood is expected to increase in coming decades (to protect native forests for ecological values), lumber stiffness (MOE) design values should be revised to better reflect its intrinsic properties. Breeding trees for superior growth remains a highly relevant strategy from an economic viewpoint, but other traits should be considered to maintain/improve wood quality (e.g., trees with smaller branches, juvenile wood with improved strength properties). In any case, a suite of appropriate silvicultural treatments should be applied throughout the life of the plantation to maintain homogenous annual growth rates and wood properties and ensure a good return on investment. More research is needed to find the best trade-off between current intensive forest management objectives promoting fast growth and shorter rotations (increasing juvenile wood content) and wood quality for the range of stand conditions found in Canada. Future selection strategies could focus on increasing the mechanical properties of juvenile wood to better control the general impact of intensive forest management practices on lumber quality, in conjunction with the many other tree productivity challenges, such as seedling survival and adaptation that are encountered in a context of climate change.

Conclusions

The objective of this study was to evaluate the effects of tree provenance and growth site conditions on lumber quality traits in merchantable size white spruce plantations established in Quebec and Ontario. While both sites proportionally produced very high yields of good-quality lumber (i.e., No. 2 and better grades), the site productivity and hence quantity of lumber were much greater in Petawawa compared with Baskatong. Results show that translocation of provenances within the eastern Canadian range of the species had relatively limited impact on lumber quality, expressed in terms of visual grading and mechanical properties of full-size lumber near the end of the rotation. Planting seed sources in more northern sites may slightly reduce MOE as seen in the Baskatong site. Although provenance effects were marginally significant for first-log MOR in this study, it is possible that a bigger dataset considering additional provenances and trees may detect more significant differences. Overall, the percentage of compliance to visual grade design values and the MSR potential were generally low in the investigated plantations. Although compliance is expected to increase with tree age, design values associated to visual grades would need to be revised to better reflect lumber properties of more intensively managed forests. In the meantime, machine stress grading should be preconized to ascertain lumber product mechanical performance for structural end-uses. Given that the provenance had almost no impact on lumber quality in this study, assisted gene flow and forest management strategies should primarily aim at efficient carbon sequestration and focus on maximizing productivity for mitigating climate change impacts. The selection of productive sites and plantation of well-adapted trees that are tolerant to drought and resilient to climate extremes are important tools to reduce risks of mortality and ensure efficient carbon uptake. Still, the evaluation of seed sources over geoclimatic gradients and consideration of the standing genetic variation as done in breeding programs present the best way to produce optimally adapted planting stock and to enhance growth and wood quality in future plantations.

Acknowledgements

The authors are grateful to Jean Beaulieu for initial project ideas and discussions, and Marie Deslauriers, Eric Dussault, Philippe Labrie, Jean-François Légaré, Daniel Plourde, Peter Arbour, Steve D'Eon, Melissa Vekeman, and Sébastien Clément for field and laboratory work, help with data acquisition and planning. The authors thank Luc Bédard and Francis Tanguay, FPInnovations, for their support to field and sawmilling operations and mechanical testing of lumber, and Johann Housset for initial preparation of Supplementary Table S1. We acknowledge all the people who were involved in seed collection, curation, plantation establishment during the 1950s and 1960s as well as colleagues involved in maintenance of sites over the decades.

Article information

History dates

Received: 19 March 2022
Accepted: 23 August 2022
Accepted manuscript online: 31 August 2022
Version of record online: 9 November 2022

Copyright

Data availability

Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

Author information

Author ORCIDs

Isabelle Duchesne https://orcid.org/0000-0003-4472-1646
Patrick R.N. Lenz https://orcid.org/0000-0002-0184-9247
Martin P. Girardin https://orcid.org/0000-0003-0436-7486
Nathalie Isabel https://orcid.org/0000-0001-8621-9801

Author notes

Isabelle Duchesne served as an Associate Editor at the time of manuscript review and acceptance; peer review and editorial decisions regarding this manuscript were handled by Pekka Saranpää.

Author contributions

ID: Conceptualization, methodology, statistical analysis, writing, editing, and funding.
PL: Conceptualization, methodology, statistical analysis, writing, and editing.
MG: Conceptualization, statistical analysis, reviewing.
NI: Conceptualization, reviewing.

Competing interests

The authors declare there are no competing interests.

Funding information

This research was funded by the Canadian Wood Fibre Centre of Natural Resources Canada through the Fibre Solutions Research Program.

Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/cjfr-2022-0075.

References

American Society of Testing and Materials (ASTM International). 2009a. Standard Test Methods for Specific Gravity of Wood and Wood-Based Materials (ASTM D 2395-07). ASTM, Philadelphia, PA.

American Society of Testing and Materials (ASTM International). 2009b. Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Based Materials (ASTM D 4442-07). ASTM, Philadelphia, PA.

American Society of Testing and Materials (ASTM International). 2009c. Standard Test Methods for Mechanical Properties of Lumber and Wood-Base Structural Material (ASTM D 4761-05). ASTM, Philadelphia, PA.

American Society of Testing and Materials (ASTM International). 2014. Standard Practice for Establishing Allowable Properties for Visually-Graded Dimension Lumber from In-Grade Tests of Full-Size Specimens (ASTM D 1990-14). ASTM, Philadelphia, PA.

Barbour, R.J., and Kellogg, R.M. 1990. Forest management and end-product quality: a Canadian perspective. Can. J. For. Res. **20**: 405–414. doi:10.1139/x90-058.

Barrett, J.D., and Kellogg, R.M. 1991. Bending strength and stiffness of second-growth Douglas-fir dimension lumber. For. Prod. J. **41**(10): 35–43.

Barrett, J.D., and Lau, W. 1994. Canadian lumber properties. Canadian Wood Council, Ottawa, Canada. 346pp.

Beaulieu, J. 1996. Breeding program and strategy for white spruce in Quebec. Information report LAU-X-117E. Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, Sainte-Foy, QC. 25pp.

Beaulieu, J., Girard, B., and Fortin, Y. 2001. Study of geographical variation in kiln-drying behavior of plantation-grown white spruce. Wood Fiber Sci. **35**(1): 56–67.

Beaulieu, J., Girard, B., and Fortin, Y. 2002. Effect of drying treatments on warping of 36-year-old white spruce seed sources tested in a provenance trial. Ann. For. Sci. **59**: 503–509. doi:10.1051/forest:2002034.

Beaulieu, J., Zhang, S.Y., Yu, Q., and Rainville, A. 2006. Comparison between genetic and environmental influences on lumber bending properties in young white spruce. Wood Fiber Sci. **38**(3): 553–564.

Biblis, E.J., Brinker, R., Carino, H.F., and McKee, C.W. 1993. Effect of stand age on flexural properties and grade compliance of lumber from loblolly pine plantation timber. For. Prod. J. **43**(2): 23–28.

Bickerstaff, A., Wallace, W.L., and Evert, F. 1981. Growth of forests in Canada. Part 2: a quantitative description of the land base and the mean annual increment. Information report PI-X-1. Environment Canada, Canadian Forestry Service, Ottawa, ON.

Burkhart, H.E., and Tomé, M. 2012. Tree form and stem taper. In Modeling forest trees and stands. Springer, Dordrecht. doi:10.1007/978-90-481-3170-9_2.

Canadian Standards Association. 2014. Engineering design in wood. CSA O86-14. Canadian Standards Association, Toronto, Canada.

Canadian Wood Council. 2022. Lumber grades. Available from https://cwc.ca/how-to-build-with-wood/wood-products/lumber/grades/.

Chaste, E., Girardin, M.P., Kaplan, J.O., Bergeron, Y., and Hély, C. 2019. Increases in heat-induced tree mortality could drive reductions of biomass resources in Canada's managed boreal forest. Landscape Ecol. **34**(2): 403–426. doi:10.1007/s10980-019-00780-4.

Chen, Z.Q., Gil, M.R.G., Karlsson, B., Lundqvist, S.O., Olsson, L., and Wu, H. 2014. Inheritance of growth and solid wood quality traits in a large Norway spruce population tested at two locations in southern Sweden. Tree Genet. Genomes, **10**: 1291–1303. doi:10.1007/s11295-014-0761-x.

Corriveau, A., and Boudoux, M.S.N. 1971. Le développement des provenances d'épinette blanche de la région forestière des Grands Lacs et du St-Laurent au Québec. Rapport d'information Q-F-X-15. Service canadien des forêts, Ste-Foy, QC. 38pp.

Corriveau, A., Beaulieu, J., and Daoust, G. 1991. Heritability and genetic correlations of wood characters of Upper Ottawa Valley white spruce populations grown in Quebec. For. Chron. **67**: 698–705. doi:10.5558/tfc67698-6.

Desponts, M., Perron, M., and DeBlois, J. 2017. Rapid assessment of wood traits for large-scale breeding selection in *Picea mariana* [Mill.] B.S.P. Ann. For. Sci. **74**: 53. doi:10.1007/s13595-017-0646-x.

Duchesne, I. 2006. Effect of rotation age on lumber grade yield, bending strength and stiffness in jack pine (*Pinus banksiana* Lamb.) natural stands. Wood Fiber Sci. **38**: 84–94.

Duchesne, I., and Swift, D.E. 2008. Impact of intensive silviculture on wood product quality and value in a jack pine stand—long-term impact of late commercial thinning at wide spacing. FPInnovations—Forintek report No. 5767. FPInnovations, Québec, QC. 49pp.

Duchesne, I., and Tanguay, F. 2011. Effects of initial spacing on tree and wood attributes on lumber quality and value in white spruce—the Stanley spacing trial case study. FPInnovations report. FPInnovations, Québec, QC. 34pp.

Duchesne, I., and Zhang, S.Y. 2004. Variation in tree growth, wood density and pulp fibre properties of 35 white spruce (*Picea glauca* (Moench) Voss) families grown in Quebec. Wood Fiber Sci. **36**: 467–475.

ESRI. 2017. ArcGIS Desktop: ArcMap Release 10.5.1. Environmental Systems Research Institute, Redlands, CA.

França, T.S.F.A., França, F.J.N., Seale, R.D., and Shmulsky, R. 2018. Bending strength and stiffness of no. 2 grade southern pine lumber. Wood Fiber Sci. **50**(2): 205–219. doi:10.22382/wfs-2018-021.

Girardin, M.P., Guo, X.J., de Jong, R., Kinnard, C., Bernier, P.Y., and Raulier, F. 2014. Unusual forest-growth decline in boreal north America covarying with the retreat of Arctic Sea ice. Global Change Biol. **20**(3): 851–866. doi:10.1111/gcb.12400.

Girardin, M.P., Isabel, N., Guo, X.J., Lamothe, M., Duchesne, I., and Lenz, P. 2021. Annual aboveground carbon uptake enhancements from assisted gene flow in boreal black spruce forests are not long-lasting. Nat. Commun. **12**(1): 1–15. doi:10.1038/s41467-021-21222-3.

Gray, L.K., and Hamann, A. 2013. Tracking suitable habitat for tree populations under climate change in western north America. Clim. Change, **117**: 289–303. doi:10.1007/s10584-012-0548-8.

Hassegawa, M., Savard, M., Lenz, P.R., Duchateau, E., Gélinas, N., Bousquet, J., and Achim, A. 2020. White spruce wood quality for lumber products: priority traits and their enhancement through tree improvement. For.: Int. J. For. Res. **93**(1): 16–37. doi:10.1093/forestry/cpz050

Hegyi, F. 1974. A simulation model' for managing jack-pine stands. In Growth models for tree and stand simulation. Edited by J. Fries. Royal College of Forestry, Stockholm, Sweden. pp. 74–90.

Hornoy, B., Pavy, N., Gérardi, S., Beaulieu, J., and Bousquet, J. 2015. Genetic adaptation to climate in white spruce involves small to moderate allele frequency shifts in functionally diverse genes. Genome Biol. Evol. **7**(12): 3269–3285. doi:10.1093/gbe/evv218.

Hylen, G. 1997. Genetic variation of wood density and its relationship with growth traits in young Norway spruce. Silvae Genet. **46**(1): 55–56.

Ivkovich, M., Namkoong, G., and Koshy, M. 2002. Genetic variation in wood properties of interior spruce. I. Growth, latewood percentage, and wood density. Can. J. For. Res. **32**(12): 2116–2127. doi:10.1139/x02-138.

Jozsa, L.A., and Middleton, G.R. 1994. A discussion of wood quality attributes and their practical implications. Special publication no. SP-34. Canada–British Columbia Partnership Agreement on Forest Resource Development: FRDA II. Forintek Canada Corporation, Vancouver, BC. 42p.

Karlsson, K. 2000. Stem form and taper changes after thinning and nitrogen fertilization in *Picea abies* and *Pinus sylvestris* stands. Scand. J. For. Res. **15**(6): 621–632. doi:10.1080/02827580050216879.

Kennedy, R.W. 1995. Coniferous wood quality in the future: concerns and strategies. Wood Sci. Technol. **29**(5): 321–338. doi:10.1007/BF00202581.

Larson, P.R. 1965. Stem form of young larix as influenced by wind and pruning. For. Sci. **11**(4): 412–424.

Larson, P.R. 1969. Wood formation and the concept of wood quality. Bulletin no. 74. Yale University, School of Forestry, New Haven, CT. 54p.

Lenz, P., Cloutier, A., MacKay, J., and Beaulieu, J. 2010. Genetic control of wood properties in *Picea glauca*—an analysis of trends with cambial age. Can. J. For. Res. **40**: 703–715. doi:10.1139/X10-014.

Lenz, P., Auty, D., Achim, A., Beaulieu, J., and MacKay, J. 2013. Genetic improvement of white spruce mechanical wood traits—early screening by means of acoustic velocity. Forests, **4**: 575–594. doi:10.3390/f4030575.

Lenz, P.R.N., Nadeau, S., Azaiez, A., Gérardi, S., Deslauriers, M., Perron, M., et al. 2020. Genomic prediction for hastening and improving efficiency of forward selection in conifer polycross mating designs: an example from white spruce. Heredity, **124**: 562–578. doi:10.1038/s41437-019-0290-3.

Li, P., Beaulieu, J., and Bousquet, J. 1997. Genetic structure and patterns of genetic variation among populations in eastern white spruce (*Picea glauca*). Can. J. For. Res. **27**: 189–198. doi:10.1139/x96-159.

Morgenstern, E.K., and Copis, P. 1999. Best white spruce provenances in Ontario. (Les meilleures provenances d'épinette blanche en Ontario). Information Report ST-X-16.Natural Resources Canada, Can. For. Serv., Headquarters, Science Branch, Ottawa, ON. 34pp.

Morgenstern, K., D'Eon, S., and Penner, M. 2006. White spruce growth to age 44 in a provenance test at the Petawawa research forest. For. Chron. **82**: 572–578. doi:10.5558/tfc82572-4.

Mullin, T.J., Andersson, B., Bastien, J.C., Beaulieu, J., Burdon, R.D., Dvorak, W.S., et al. 2011. Economic importance, breeding objectives and achievements. In Genetics, genomics and breeding of conifers. Science Publishers, Inc., New Hampshire. pp. 40–127. doi:10.1201/b11075-3.

Nienstaedt, H., and Teich, A. 1972. The genetics of white spruce. USDA For. Serv. Res. Pap. Wo-15. Pacific Southwest Forest and Range Experiment Station, Berkeley, CA, USA.

NLGA. 2010. SPS2. Special Products Standard for Machine Graded Lumber. National Lumber Grades Authority, New Westminster, BC.

NLGA. 2017. Standard grading rules for Canadian lumber. National Lumber Grades Authority, Vancouver, BC.

Pedlar, J.H., McKenney, D.W., Aubin, I., Beardmore, T., Beaulieu, J., Iverson, L., et al. 2012. Placing forestry in the assisted migration debate. BioScience, **62**(9): 835–842. doi:10.1525/bio.2012.62.9.10.

Périé, C., and de Blois, S. 2016. Dominant forest tree species are potentially vulnerable to climate change over large portions of their range even at high latitudes. Peer J. **4**: e2218. doi:10.7717/peerj.2218.

Price, D.T., Alfaro, R.I., Brown, K.J., Flannigan, M.D., Fleming, R.A., Hogg, E.H., et al. 2013. Anticipating the consequences of climate change for Canada's boreal forest ecosystems. Environ. Rev. **21**: 322–365. doi:10.1139/er-2013-0042.

Stinson, G., Kurz, W.A., Smyth, C.E., Neilson, E.T., Dymond, C.C., Metsaranta, J.M., et al. 2011. An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008. Global Change Biol. **17**(6): 2227–2244. doi:10.1111/j.1365-2486.2010.02369.x.

Wilhelmsson, L., Arlinger, J., Spångberg, K., Lundqvist, S.-O., Grahn, T., Hedenberg, O., and Olsson, L. 2002. Models for predicting wood properties in stems of *Picea abies* and *Pinus sylvestris* in Sweden. Scand. J. For. Res. **17**: 330–350. doi:10.1080/02827580260138080.

Yanchuk, A.D., and Kiss, G.K. 1993. Genetic variation in growth and wood specific gravity and its utility in the improvement of interior spruce in British Columbia. Silvae Genet. **42**: 141.

Zhang, S.Y., and Koubaa, A. 2008. Softwoods of Eastern Canada: their silvics, characteristics, manufacturing and end-uses. SP-526E: 653. FPInnovations, Vancouver, BC.

Zhang, S.Y., Chauret, G., Ren, Q.H., and Desjardins, R. 2002. Impact of initial spacing on plantation black spruce lumber grade yield, bending properties, and MSR yield. Wood Fiber Sci. **34**: 460–475.

Zhou, H., and Smith, I. 1991. Factors influencing bending properties of white spruce lumber. Wood Fiber Sci. **23**(4): 483–500.