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Growth and wood quality of black spruce and balsam fir following careful logging around small merchantable stems (CLASS) in the boreal forest of Quebec, Canada

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Careful logging around small merchantable stems (CLASS) is a partial cutting treatment in which 70–90 per cent of the merchantable volume of uneven-aged, irregular or multi-layered conifer stands is harvested. The decrease in stand density by means of partial cutting is known to induce an increase in residual stem growth, which could also influence wood properties. This research aims to evaluate the effect of CLASS on the growth and some wood quality parameters of black spruce (*Picea mariana* (Mill.) B.S.P.) and balsam fir (*Abies balsamea* (L.) Mill.) in the boreal forest of Quebec, Canada. Four uneven-aged black spruce-balsam fir stands were selected for the study and 15 black spruce and 15 balsam fir trees were sampled in each stand, distributed between a treated and a control area. Radial growth, latewood proportion, ring density, tracheid length and the moduli of elasticity and rupture were measured in each tree. A high proportion of residual stems significantly increased their radial growth after CLASS. No significant change was obtained for latewood proportion, average ring density, tracheid length or mechanical properties for black spruce. However, latewood proportion and ring density were significantly reduced in balsam fir after treatment, with no effect on modulus of elasticity or modulus of rupture. When looking at the wood properties comprehensively, a canonical discriminant analysis did not detect any significant difference between the wood properties before and after treatment for either species. This suggests that CLASS can stimulate the radial growth of residual stems with limited short-term effects on wood quality.

Introduction

New silvicultural practices are increasingly being proposed in the boreal forest to pursue different aims, including a higher volume growth of individual trees, favouring the establishment of natural regeneration or emulating natural disturbances (Thorpe and Thomas, 2007; Bose *et al.*, 2013). Careful logging around small merchantable stems (CLASS, known as CPPTM in Québec) is a partial cutting treatment in which a large proportion of the forest cover (70–90 per cent of the merchantable volume of a stand) is harvested (Riopel et al., 2010). The residual stand consists of a minimum of 900 stems per hectare within a diameter range from 2 to 14 cm at breast height (1.3 m), including at least 125 small merchantable stems of 10–14 cm in diameter (Ministère des Ressources Naturelles, 2002; MRNFP, 2003). Harvesting trees with a diameter below 14 cm is generally unprofitable and generates less yield due to the small dimensions and greater handling required (Auty *et al.*, 2014). CLASS therefore allows these small stems more time to grow so that they can eventually constitute the dominant stratum of the future stand, which could decrease rotation length by about 10 years before the next scheduled harvest, i.e. when the new stand will have reached maturity (Pothier *et al.*, 1995; Ministère des Ressources Naturelles, 2002; Riopel *et al.*, 2010). Currently, the CLASS treatment is not necessarily viewed as system of recurring interventions over several rotations, and may thus only be applied as punctual intervention in time (MRNFP, 2003). This type of partial harvesting is suitable for uneven-aged, irregular or multi-layered softwood stands (Ministère des Ressources Naturelles, 2002; Riopel *et al.*, 2010) and aims to perpetuate the internal structure of a forest stand by maintaining some of its structural attributes (Groot, 2002).

The decrease in stand density by means of partial cutting is known to induce an increase in individual stem growth (Youngblood, 1991; Latham and Tappeiner, 2002; Thorpe *et al.*, 2007). An accelerated growth is reflected in the ring by an increased number of earlywood cells, with little change in the latewood width, resulting in a lower mean ring density (Barbour *et al.*, 1994; Koga *et al.*, 2002; Mäkinen *et al.*, 2002b; Jaakkola *et al.*, 2005a). Koga and Zhang (2002) explained that the average ring density is determined by its components, i.e. the earlywood and latewood density, and by the proportion of latewood. Therefore, changes in the intra-ring density, and thus in the uniformity of the wood after treatment, are likely to cause undesirable changes in wood properties (Peltola *et al.*, 2007).

Average ring density at breast height is also a good predictor of mechanical properties (Zink-Sharp, 2003) and bending strength has been shown to increase linearly with increasing wood density (Bowyer *et al.*, 2007; Todaro and Macchioni, 2011). The relationship between wood density and tracheid length has rarely been considered (Dutilleul *et al.*, 1998), but an accelerated growth caused by intensive silvicultural treatments can result in the production of shorter tracheids (Mäkinen *et al.*, 2002a; Jaakkola *et al.*, 2005b). Since longer tracheids lead to better bonding by increasing cell to cell contact (Via *et al.*, 2004), a reduced tracheid length might also lead to a decrease in mechanical properties.

Because CLASS is still a relatively new silvicultural treatment, only a limited number of studies have investigated its effects on the tree- and stand-level responses (Liu *et al.*, 2007; Yelle *et al.*, 2008; Cimon-Morin *et al.*, 2010; Riopel *et al.*, 2010; Légaré *et al.*, 2011; Riopel *et al.*, 2011; Ruel *et al.*, 2013). A few studies have focused on the growth response of residual trees after treatment (Thorpe *et al.*, 2007; Pamerleau-Couture *et al.*, 2015), but little attention has been given to understanding the effects of the treatment on the wood quality of black spruce (*Picea mariana* (Mill.) B.S.P.) or balsam fir (*Abies balsamea* (L.) Mill.). Black spruce is a slow-growing species, well adapted to life in the understory (Viereck and Johnston, 1990) while balsam fir can survive for many years under cover (Frank, 1990). Balsam fir is known to react vigorously after canopy opening as it adapts more rapidly than black spruce to new environmental conditions (Sullivan and Peterson, 1994; Ministère des ressources naturelles, 2013). Both species are known to increase their growth after canopy removal (Solomon and Frank, 1983; Ministère des ressources naturelles, 2013), but acclimation to the new environmental condition requires a few years because the majority of resources are first allocated to root growth (Kneeshaw *et al.*, 2002; Ruel *et al.*, 2003), which causes a delay in the response to the treatment in other parts of the tree. Once the acclimation period is over, the growth response can differ between the two species given that balsam fir has a higher capacity for horizontal crown expansion (Messier *et al.*, 1999; Claveau *et al.*, 2002), a better capacity for morphological adjustments (like a reduced specific leaf area after canopy removal) and physiological characteristics (such as lower transpirational losses) better adapted to canopy opening (Dumais and Prévost, 2008). These two species are important commercial species in the eastern boreal forest of Canada. It is thus important to verify and quantify their growth response following CLASS, and ensure that any consequence on the wood properties of residual stems will not affect the suitability for the most important end-uses (i.e. construction lumber and pulp).

This study aims to evaluate the effect of CLASS on the radial growth of individual trees, as well as on several wood quality parameters (latewood proportion, ring density, tracheid length, moduli of elasticity and rupture) of black spruce and balsam fir in the boreal forest of Quebec, Canada. We compared growth and wood quality parameters of treated and control trees over a period of 30 years, i.e. the 20 years prior to the partial cutting treatment and the 10 years that followed. The hypotheses were that: (1) a significant radial growth increase would occur 3–4 years after CLASS for black spruce, but the increase would occur faster (after 2–3 years) and be greater in balsam fir; (2) the increased radial growth of the stem following treatment would occur in the earlywood part of the annual ring, thus causing a decrease in latewood proportion and ring density; (3) mechanical properties would decrease following CLASS since they are highly correlated with wood density.

Material and methods

Experiment design and sampling

Four uneven-aged black spruce-balsam fir stands were sampled in the Saguenay-Lac-Saint-Jean and Côte-Nord regions, Quebec, Canada, between 48° 41′ and 50° 30′ N and 68° 47′ and 70° 22′ W. These stands are part of a project for which permanent plots were established between 1997 and 2002 in 27 experimental blocks in the balsam fir-yellow birch, balsam fir-white birch and spruce moss bioclimatic zones (Riopel *et al.*, 2010, 2011). In each selected block, one part of the stand was treated with a CLASS at least 10 years prior to sampling and another part of the stand was left untreated to be used as a control. All four blocks presented similar characteristics in terms of composition, density, diameter and age of the stands (Table 1).

Three 150 m² plots were established in each treated stand and two plots of the same dimensions in each control stand to characterize the variability inside each treated and control stand. A higher number of plots were used in treated stands to obtain a better representation of the variability induced by the treatment. Three black spruce and three balsam fir trees were sampled in each plot, for a total of 120 trees. Sample trees were chosen randomly from the dominant or codominant stems in the control plots and from the dominant and codominant residual stems in the treated plots, with a diameter at breast height (DBH) between 8 and 15 cm, free of visible injuries or defects and located at least 2 m from a logging trail. DBH, height, age and slenderness coefficient (calculated as H (m)/DBH (m)) were recorded for each sample tree (Table 2). Due to the nature of the CLASS treatment, where all stems with a DBH over 14 cm were harvested, the selected treated trees were slightly smaller and younger than the controls. Our general approach was to compare the resource being currently harvested (the control trees), to the trees that will eventually dominate the stands at the end of the rotation that will follow the CLASS treatment (treated trees). It was impossible to select mature trees in the latter case because the CLASS treatment has only been applied for about a decade in the province of Quebec.

Growth and wood quality analyses

Discs were collected at every metre along the stem and at breast height. Tree-ring widths and latewood proportion were measured to the nearest 0.01 mm along four radii (up to a height of 2 m) or two radii (3 m to the top of the tree), using the WinDENDRO software (Guay *et al.*, 1992) (Régent Instruments, Inc., 2009). The data were visually cross-dated (Stokes and Smiley, 1968; Fritts, 1976) and statistically verified by the COFECHA program (Holmes, 1983).

To assess the response to treatment, a radial growth percentage was calculated for each stem at breast height. The mean increase was calculated as the ratio of the average annual ring width of the 10 years following the CLASS to the average annual ring width of the 20 years preceding the treatment (Vincent *et al.*, 2009):

Table 1 Description of sampling sites.

Stand	Merchantable volume before CLASS (m³ ha^{-1})	GPS coordinates	Treatment	Treatment year	Merchantable volume harvested (%)	Residual basal area (m² ha^{-1})
B3	145	N 48° 41′ 00.7″ W 70° 21′ 50.9″	CLASS	1997	79.0	10.6
		N 48° 41′ 10.0″ W 70° 21′ 50.0″	Control	–	–	–
B4	157	N 50° 30′ 03.7″ W 68° 47′ 41.0″	CLASS	1997	84.5	8.2
		N 50° 29′ 59.2″ W 68° 48′ 10.0″	Control	–	–	–
B10	147	N 48° 41′ 33.3″ W 70° 21′ 32.1″	CLASS	1999	80.0	13.0
		N 48° 41′ 36.3″ W 70° 22′ 07.6″	Control	–	–	–
B20	132	N 48° 42′ 58.1″ W 70° 13′ 15.1″	CLASS	2000	72.0	16.6
		N 48° 43′ 02.3″ W 70° 13′ 27.4″	Control	–	–	–

Table 2 Characteristics of sampled trees.

Stand	Treatment	Black spruce				Balsam fir			
		Mean age (years)	Mean DBH (cm)	Mean height (m)	Slenderness coefficient	Mean age (years)	Mean DBH (cm)	Mean height (m)	Slenderness coefficient
B3	CLASS	85.0	12.7	9.5	75.8	104.7	12.3	7.8	62.8
	Control	122.3	17.5	13.8	78.8	141.7	15.4	12.3	80.2
B4	CLASS	171.8	13.7	10.2	74.1	116.4	14.3	8.7	62.2
	Control	183.5	15.0	12.4	83.1	130.8	13.6	10.3	75.3
B10	CLASS	87.2	12.9	9.0	71.3	97.9	13.3	9.5	72.0
	Control	99.8	16.1	11.7	74.7	108.0	13.6	10.6	78.9
B20	CLASS	126.2	13.6	10.4	77.0	123.3	11.8	8.1	69.0
	Control	133.3	15.1	11.4	75.6	109.0	13.5	10.7	80.6
Mean	CLASS	117.6	13.2	9.8	74.6	110.6	12.9	8.5	66.6
	Control	134.7	15.9	12.3	78.0	122.1	14.0	11.0	78.8

$$\gamma = \frac{\left(\sum_{t=\mathrm{TY}+1}^{t=\mathrm{TY}+10} \alpha_t\right)/10}{\left(\sum_{t=\mathrm{TY}-20}^{t=\mathrm{TY}-1} \alpha_t\right)/20} \times 100 \qquad (1)$$

where γ = radial growth increment (per cent), TY = treatment year, t = time (year) and α = ring width (mm).

Wood density profile measurements were taken on radial segments from a stem sample collected at breast height. Strips 1.63 mm thick (longitudinal) and 25 mm wide (tangential) were dried under restraint to 12 per cent moisture content in a conditioning room at 20°C and 65 per cent relative humidity (Alteyrac *et al.*, 2006). Measurements were taken from bark to pith on unextracted samples at intervals of 4 µm, using a QTRS-01X Tree Ring Scanner and X-ray densitometer (Quintek Measurement System, Knoxville, TN, USA). Working from the raw data from the wood density profiles and using an algorithm developed by Genet *et al.* (2013) using the *tcltk* library in the R statistical software (R Development Core Team, 2014), the boundary between consecutive growth rings and the transition from earlywood to latewood within a ring were defined as the point where the maximum change in density was reached (Mothe *et al.*, 1998). Earlywood, latewood and average ring density were measured for every annual ring of each sample. Only the data from the 20 years prior to the CLASS until 10 years after were kept for further analyses.

A 20 mm thick (longitudinal) and 15 mm wide (tangential) piece of wood from the breast height disc was used to determine tracheid length of the six growth rings prior to CLASS and of years 3–8 after treatment. Because the process of separating each growth ring is very time consuming, the 2 years after treatment were not taken into account to reflect the results of several studies reporting a delay in response to the treatment (Youngblood, 1991; Latham and Tappeiner, 2002; Bebber *et al.*, 2004; Thorpe *et al.*, 2007; Vincent *et al.*, 2009). In this way, only the years when the most important response was expected were used (Thorpe *et al.*, 2007; Pamerleau-Couture *et al.*, 2015). Earlywood and latewood portions of each ring were separated manually using a razor blade. All samples were macerated in a solution of glacial acetic acid and hydrogen peroxide (1:1, v/v) at 75°C for 15 h (Franklin, 1945). The macerated samples were carefully rinsed with distilled water and gently shaken to obtain a uniform suspension to be measured with a L&W FiberTester (Lorentzen & Wettre, Kista, Sweden). For each sample, a length-weighted mean tracheid length (TL_W) was calculated from the measurements of 5000 tracheids:

$$TL_W = \frac{\sum n_i L_i^2}{\sum n_i L_i} \quad (2)$$

where $i = 1, 2, 3,\ldots, n$ are categories, n is the fibre count in the «i^{th}» category and L is the contour length. Using this method, the bias caused by the large number of fines generated during preparation is reduced (Herman *et al.*, 1998; Mäkinen and Hynynen, 2014; Mäkinen *et al.*, 2015). An average tracheid length for the whole ring was computed by weighting the tracheid length for each wood zone by the relative width of each zone (Mvolo *et al.*, 2015).

Small clear specimens of 10 mm × 10 mm × 150 mm (R × T × L) were prepared from a 50 cm stem bolt collected between 0.5 and 1.0 m from the ground to measure bending strength and stiffness in static bending. Because wood is a non-homogenous material and its mechanical properties can differ from one sample to another, two samples were used from wood formed in the years prior to the CLASS and two samples from wood formed in the years after treatment (Figure 1). Specimens were dried to 12 per cent moisture content in a conditioning room. Three-point bending tests were performed with an MTS Alliance RT/100 machine (TestResources, Inc., Shakopee, MN, USA) according to the ASTM D-143 standard for small clear specimens (ASTM, 2010). The specimens were placed pith side up with a span of 110 mm (L) and speed of 1.3 mm min^{-1}. The modulus of elasticity (MOE) and modulus of rupture (MOR) (in N mm^{-2}) were then calculated as follows:

$$MOE = \frac{P_1 L^3}{4bd^3 y_1} \quad (3)$$

$$MOR = \frac{3PL}{2bd^2} \quad (4)$$

where b and d are the width and thickness (mm) of the specimen, P_1 and y_1 represent the load (N) and the deflection (mm) at the limit of the range of elasticity and P is the maximum load (N) before rupture (Poncsák *et al.*, 2006; Bowyer *et al.*, 2007). For each specimen, cambial age, distance from pith and number of rings in the sample were also noted. An average of the MOE and MOR of the two samples tested both prior to and after treatment was used for further analyses.

Statistical analyses

Growth and wood quality parameters of treated and control trees were compared after treatment using a covariance analysis for repeated measurements and a nested data structure. The MIXED procedure in SAS was used, with the estimation of the restricted maximum likelihood, and an autoregressive covariance structure AR(1) was applied to model the autocorrelation of individual measurements within trees (SAS Institute, Inc., 2013). A covariate was used to account for differences between the selected trees. The covariate was calculated as the mean of the growth or wood quality parameter for the 20 years prior to the CLASS treatment. For tracheid length, the mean of the 6 years prior to treatment was used as covariate and for MOE and MOR, the covariate was the mean of the two samples containing wood formed before treatment. The SLICE option of the LSMEANS statement was used when the interaction term Treatment × Year was found to be significant to identify which years differed between the control and treated trees (Littell *et al.*, 2006).

In the end, the study produced a multivariate data set that was analysed with a canonical discriminant analysis using proc CANDISC in SAS. This type of analysis finds linear combinations of the quantitative variables that provide maximal separation between classes or groups (SAS Institute, Inc., 2013). The pre- and post-treatment periods were used as the classification variable and the measured wood quality parameters were used to perform the canonical discriminant analysis to derive canonical variables. For this analysis, only the treated trees were used to see if we could find a distinct separation in the wood properties before and after the application of the CLASS.

Data were log-transformed when necessary to meet the normality and homoscedasticity assumptions (Quinn and Keough, 2002). Differences between mean values were considered significant when P was <0.05. Statistical analyses were performed using SAS 9.1 software (SAS Institute Inc., 2013) and R 3.1.2 (R Development Core Team, 2014).

Results

There was a clear positive growth effect on the residual trees after the CLASS. Two-thirds of the treated black spruce trees showed a radial growth increase at breast height after treatment, whereas nearly 95 per cent of balsam fir trees showed a growth increase. In the trees treated with CLASS, black spruces had a mean radial growth increment of 145 per cent on average (maximum 290 per cent increase) while balsam firs had an average of 360 per cent (maximum 1120 per cent increase). Ring width at breast height was similar between the two species

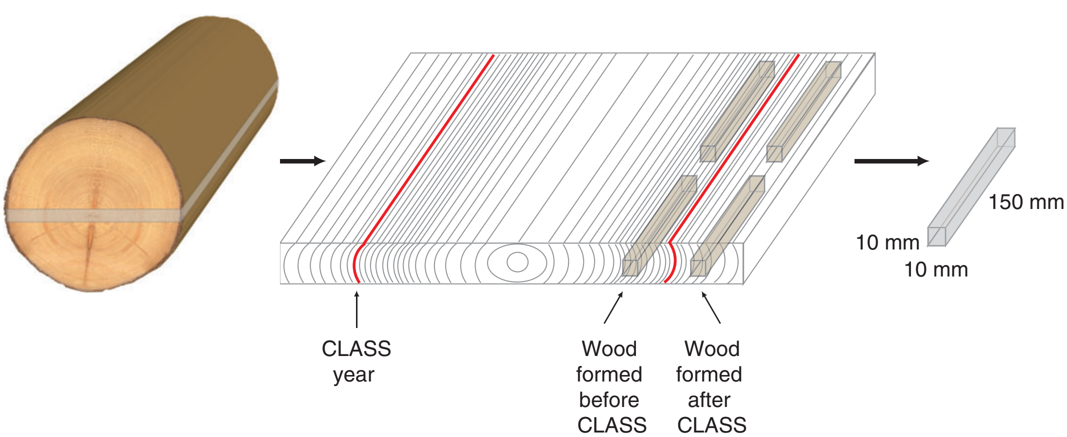

Figure 1 Schematic representation of sample preparation for bending strength and stiffness testing.

before CLASS but was higher for balsam fir after treatment, the mean values for the latter species having more than tripled (Figure 2A). A significant difference between treated and control trees appeared in the fourth year after treatment for black spruce and the third year for balsam fir (Table 3A, Figure 2A). By the 10th year after CLASS, ring width values tended to decrease for both species, but remained higher than pre-treatment values. The standard error was higher after treatment for the two species, indicating that the CLASS induced more variability in the data.

There was no significant difference in latewood proportion between treated and control trees for black spruce (Table 3B,

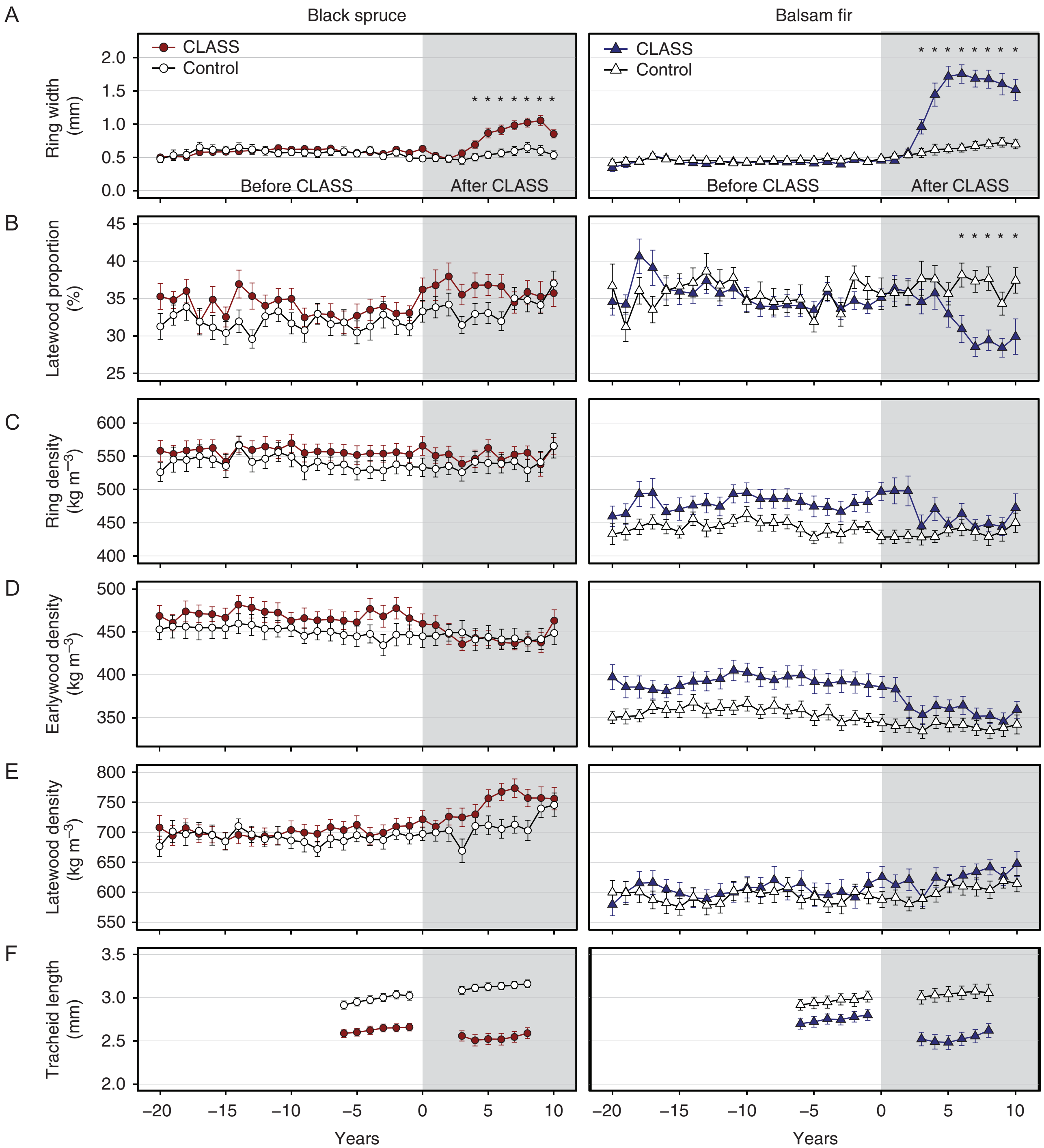

Figure 2 Radial growth, latewood proportion, average ring density, earlywood density, latewood density and tracheid length of residual black spruce and balsam fir stems before and after CLASS. The shaded area represents the years after treatment, with year 0 being the treatment year. Asterisks indicate a significant difference between treated and control trees for a given year, as determined by a slice test.

Table 3 Repeated measures ANOVA results of the measured growth and wood quality parameters for black spruce and balsam fir.

Parameter		Effect	Black spruce			Balsam fir		
			DF	*F*	Pr > *F*	DF	*F*	Pr > *F*
(A)	Ring width	Treatment	1	15.06	**0.0015**	1	29.80	**0.0098**
		Year	9	32.12	**<0.0001**	9	64.61	**<0.0001**
		Treatment × year	9	8.61	**<0.0001**	9	29.55	**<0.0001**
		Covariate	1	48.19	**<0.0001**	1	35.70	**<0.0001**
(B)	Latewood %	Treatment	1	0.18	0.7007	1	13.76	**0.0015**
		Year	9	0.84	0.5791	9	1.78	0.0693
		Treatment × year	9	1.49	0.1498	9	3.60	**0.0002**
		Covariate	1	54.58	**<0.0001**	1	25.94	**<0.0001**
(C)	Ring density	Treatment	1	<0.01	0.9612	1	0.42	0.5307
		Year	9	1.73	0.0800	9	1.83	0.0612
		Treatment × year	9	0.79	0.6214	9	2.30	**0.0164**
		Covariate	1	113.92	**<0.0001**	1	94.59	**<0.0001**
(D)	Earlywood density	Treatment	1	6.16	**0.0250**	1	3.04	0.1086
		Year	9	1.22	0.2796	9	4.63	**<0.0001**
		Treatment × year	9	0.92	0.5040	9	1.37	0.2007
		Covariate	1	250.82	**<0.0001**	1	164.26	**<0.0001**
(E)	Latewood density	Treatment	1	7.13	**0.0487**	1	1.38	0.2624
		Year	9	4.54	**<0.0001**	9	3.73	**0.0002**
		Treatment × year	9	1.30	0.2335	9	1.46	0.1622
		Covariate	1	71.80	**<0.0001**	1	87.24	**<0.0001**
(F)	Tracheid length	Treatment	1	6.08	**0.0183**	1	5.74	**0.0281**
		Year	5	1.36	0.2418	5	0.38	0.8626
		Treatment × year	5	0.19	0.9661	5	0.90	0.4807
		Covariate	1	78.23	**<0.0001**	1	75.81	**<0.0001**
(G)	MOE	Treatment	1	0.36	0.5706	1	<0.01	0.9778
		Covariate	1	14.61	**0.0005**	1	1.46	0.2349
(H)	MOR	Treatment	1	0.82	0.4250	1	1.06	0.4066
		Covariate	1	4.90	**0.0331**	1	8.85	**0.0067**

The covariate represents the mean of the 20 years prior to CLASS for each parameter, or the mean of the preceding 6 years in the case of tracheid length. Significant results are presented in bold.

Figure 2B). The latewood percentage for balsam fir was similar before and for the first 5 years after treatment but then became significantly lower in the treated than in control trees in years 6–10 after CLASS. Average ring density at breast height showed a similar pattern to latewood proportion, as there was no difference between treated and controls trees for black spruce (Table 3C, Figure 2C). For balsam fir, statistical analyses detected a change in the slope of the treated trees as opposed to control trees, but could not pinpoint a single year where treatments were different. For both species, earlywood density tended to decline after treatment (Figure 2D) and latewood density tended to increase (Figure 2E), but those changes were not significant (Table 3D,E). While the latewood proportion values were similar for both species, ring density values were on average 15–20 per cent lower for balsam fir than black spruce.

Tracheid length at breast height tended to be lower after treatment (3.5 and 8 per cent for black spruce and balsam fir, respectively, compared with pre-treatment values) but this decline over time was not significant in either species (Table 3F, Figure 2F). Tracheid length did differ between treated and control trees but that difference was already present before CLASS.

The MOE in bending did not differ significantly between treated and control trees (Table 3G, Figure 3). Black spruce had higher MOE values compared with balsam fir. MOR exhibited exactly the same pattern as MOE (Table 3H, Figure not shown).

The canonical discriminant analysis showed that for both species, there was no significant difference in the wood properties of treated trees between the periods before and after treatment (Wilks' Lambda statistic: $P = 0.0820$ for black spruce and $P = 0.4233$ for balsam fir). We can observe that there is more variability in the canonical variables representing the wood quality parameters in the period after CLASS, but both groups are relatively close to each other (Figure 4) and could not be statistically separated. The same was observed for control trees (results not shown).

Discussion

Growth response

Results confirmed that CLASS increases the growth of residual stems in the years after harvest. A large proportion of

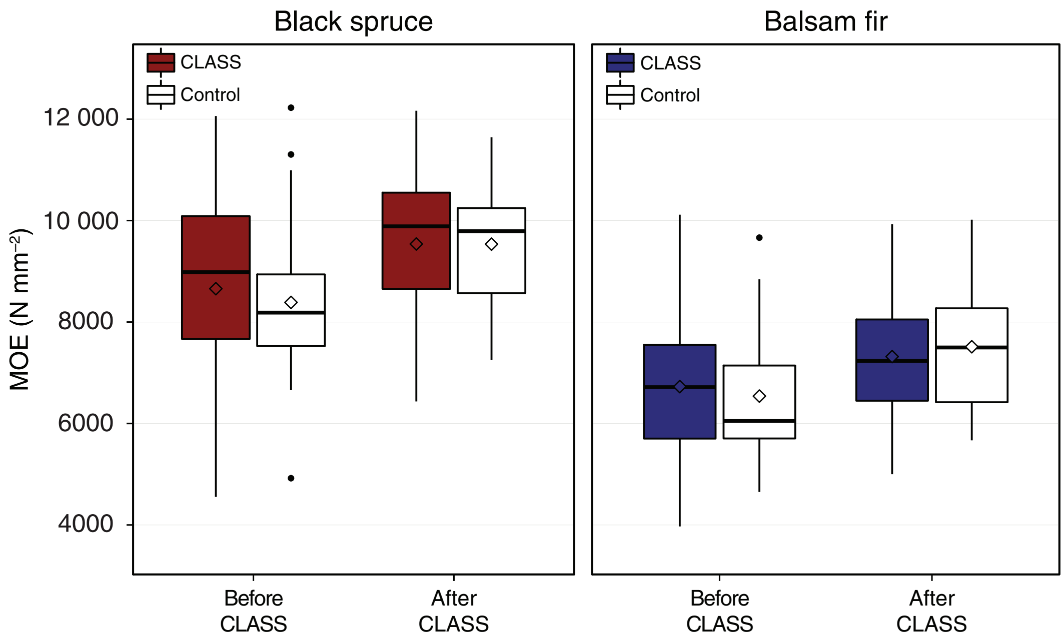

Figure 3 MOE values before and after CLASS for black spruce and balsam fir. The black horizontal line represents the median and the diamond is the mean.

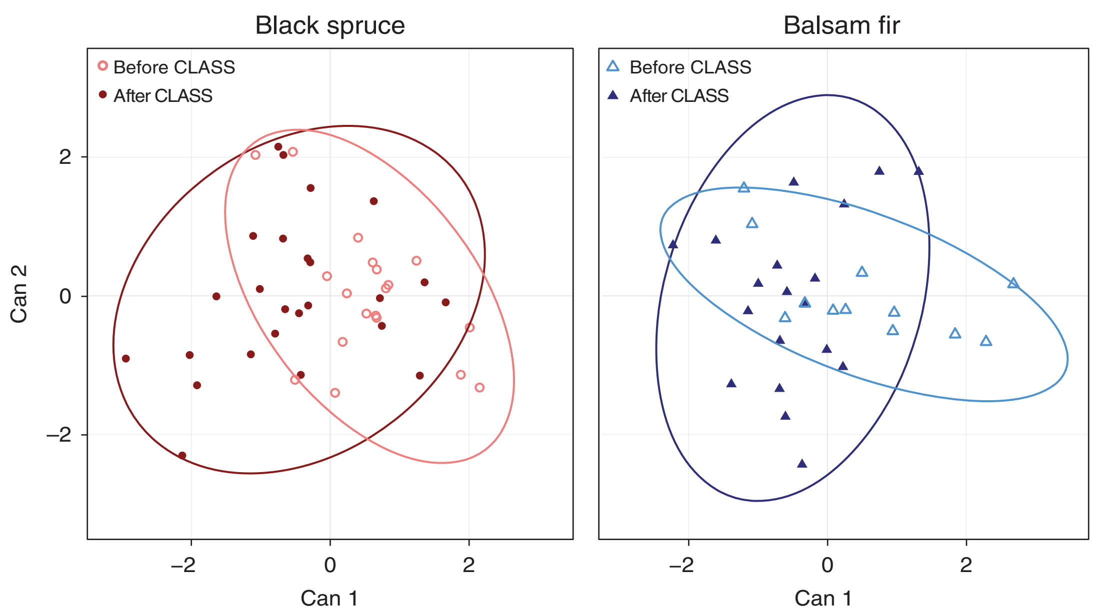

Figure 4 Canonical representation of the wood quality parameters in the periods before and after CLASS for black spruce and balsam fir. Ellipses represent 95 per cent of the data.

individuals showed an increase in radial growth at breast height following the treatment, both when compared with untreated controls and pre-treatment growth. Several studies have already shown a positive radial growth response of residual stems following a release from their neighbours, either through a commercial thinning (Mäkinen and Isomäki, 2004; Vincent *et al.*, 2009; Pamerleau-Couture *et al.*, 2015) or with other types of partial cuts (Bebber *et al.*, 2004; Thorpe *et al.*, 2007; Deal *et al.*, 2010; Pamerleau-Couture *et al.*, 2015).

In black spruce, a significant radial growth increase following CLASS was only observed 4 years after treatment. This delay in the treatment response was also observed by Vincent *et al.* (2009) and Thorpe *et al.* (2007) for black spruce and Bebber *et al.* (2004), Latham and Tappeiner (2002) and Youngblood (1991) for other species. It is likely that in the first 3 years, the additional resources are allocated to root growth as a priority rather than shoot growth (Kneeshaw *et al.*, 2002; Ruel *et al.*, 2003; Vincent *et al.*, 2009), which can improve tree stability (Krause *et al.*, 2014). In addition, such a response may increase the uptake and transport capacities for water and nutrients so that trees can cope with the greater wind penetration in the stand (Ruel, 1995) and the associated higher evapotranspiration (Kneeshaw *et al.*, 2002).

As was the case for black spruce, a radial growth increase was observed after treatment in balsam fir stems. However, at 3 years, the response delay was shorter, which is similar to what has been observed in other studies on the same species (Solomon and Frank, 1983; Doucet and Blais, 2000). The growth increase was also greater in balsam fir, which is also in line with previous results by Doucet and Blais (2000). True firs (*Abies* genus) usually show a faster response to release than spruce species (McCaughey and Ferguson, 1988) since they tend to show more plasticity in their shoot and crown morphology in relation to light availability (Kohyama, 1980; O'Connell and Kelty, 1994). Hence, balsam fir is better adapted to react rapidly to the environmental changes following the CLASS.

Our study addressed short-term response to CLASS treatment; however, over a longer period of time, balsam fir may eventually lose the advantage it had first acquired over black spruce. Even though the response of black spruce occurred later and its growth rate was lower than that of fir in the first few years, the species is known to have a more 'conservative' growth pattern as it can maintain its growth over a longer period of time and ultimately surpass fir (Doucet and Boily, 1995; Doucet and Blais, 2000).

Wood properties

For black spruce, the latewood proportion did not change after CLASS and stayed similar to controls in the years after cutting. Likewise, no significant effect of the treatment was detected on average ring density for this species. After thinning in conifer stands, it is generally considered that the growth response of the earlywood part of the ring is proportionally greater than that of the latewood, possibly as a result of the increased need to transport water in the sapwood (Barbour *et al.*, 1994; Kneeshaw *et al.*, 2002). The resulting decrease in the proportion of high-density latewood also leads to a decrease in the overall ring density (Zhang, 1995; Koga *et al.*, 2002; Jaakkola *et al.*, 2005a; Franceschini *et al.*, 2013). However, in this study, even if the CLASS had a significant positive effect on the radial growth, this growth increase comprised an increase in the width of both earlywood and latewood. Peltola *et al.* (2007) and Tasissa and Burkhart (1998) also noted that a thinning operation did not alter the proportion of the ring in earlywood or latewood and as a result had no effect on wood density. Furthermore, a high intensity thinning tends to decrease the density of earlywood and increase the density of latewood, which results in no change in the average ring density (Moschler *et al.*, 1989; Peltola *et al.*, 2007). This is exactly what was observed here after CLASS (Figure 2D,E), which could explain the results obtained with average ring density.

Black spruce trees showed an increasing trend in tracheid length in the period preceding the treatment, and this trend was only maintained in the control trees after treatment. This might be explained by the fusiform initials of the cambium, which tend to grow in length with cambial age as a result of the declining ratio of anticlinal to periclinal divisions (Lachenbruch *et al.*, 2011). Hence, with increasing cambial age, longer tracheids tend to be formed from these initials (Dinwoodie, 1961; Bowyer *et al.*, 2007). This might also explain the difference that was present even before treatment between treated and control trees, as treated trees were generally of lower cambial age than control trees.

For many conifer species, an increase in radial increment following thinning is linked to a decrease in mechanical properties, such as the moduli of elasticity and rupture (Jozsa and Middleton, 1994; Zhang, 1995; Bowyer *et al.*, 2007). In our study, MOE and MOR values were unaffected by the CLASS treatment in both black spruce and balsam fir. Thus, the accelerated growth in the years after the CLASS had no effect on the bending strength and stiffness, as was reported in studies by Gagné *et al.* (2012), Guller (2007) and Vincent *et al.* (2011), which examined wood properties in conifers following thinning treatments.

Aside from the results for tracheid length and mechanical properties, balsam fir showed a somewhat different trend than black spruce with regards to wood properties. Contrary to the results for black spruce, a significant decrease in the latewood proportion is noticeable in balsam fir from years 6–10 after CLASS (Figure 2B), in years when the ring was on average more than three times wider than it was before treatment. Average ring density also decreased in the years following treatment. Jaakkola *et al.* (2005a) noted that large increases in tree growth, higher than those achieved by conventional thinning treatments, are required to create substantial reductions in wood density. This could be the case here with balsam fir, where a decrease in the average ring density is visible when the radial growth increase is at its strongest. Lindström (1997) asserted that wood density depends on latewood proportion and radial diameter of earlywood tracheids. Indeed, it appears that the latewood proportion is not the only factor determining ring density since, after the CLASS treatment, the observed ring density decrease in balsam fir occurs from the third year after treatment (Figure 2 C) while the decrease in latewood proportion occurs only from the sixth year after the partial cutting (Figure 2B). The ring density reduction could be interpreted as a result of a decrease in the width of the earlywood cell walls after CLASS (Pamerleau-Couture, 2011), albeit not sufficiently important to cause a statistically significant reduction in earlywood density, combined with the change in latewood proportion that was observed.

Balsam fir is known for the low quality of its wood (Zhang and Koubaa, 2009), especially in terms of mechanical properties (Mullins and McKnight, 1981). This was confirmed in our study, with an average ring density 17 per cent lower and with MOE and MOR values around 23 per cent lower than black spruce. However, latewood proportion is similar for both species. Given this result, the difference in average ring density is likely due to anatomical differences between the two species. Tracheids of both species are the same length on average, but the balsam fir tracheid diameter is slightly larger (30–40 μm) than black spruce (25–30 μm) (Zhang and Koubaa, 2009). With cell walls of similar size in earlywood and a little thinner in latewood (Krause *et al.*, 2010), balsam fir is left with a smaller cell wall–lumen ratio than black spruce, which could explain the lower density, given that the density of cell walls shows little variation across species (Butterfield, 2003). These inferior wood density values combined with a higher lignin content in balsam fir than black spruce (Zhang and Koubaa, 2009) could also induce a lower mechanical resistance since the tension strength and resistance to rupture decreases as the amount of lignin increases (Zobel and Van Buijtenen, 1989).

Growth vs *wood quality*

The CLASS treatment led to a significant growth response of the residual stems of both species without major changes in the wood properties observed. However, pre-treatment comparisons of wood properties from treated *vs* control trees contrasted with those of radial growth for both species. Whereas the mean ring width and, to a lesser extent, latewood percentage profiles over time were very similar before treatment, those of ring density and tracheid length tended to show some differences. These add complexity to the interpretation of the treatment effect. In our specific case, differences were to be expected because of the stand structure changes due to the treatment. Indeed, the CLASS harvest implies that all stems with a DBH over 14 cm are harvested in a stand with an irregular structure. Residual stems will therefore unavoidably be smaller than the pre-harvest stand average. They are also likely to have developed in the shade prior to the CLASS treatment, and in this study results showed that they tended to be younger on average than the control stems. The higher density and shorter tracheids of treated trees prior to the year of treatment are characteristics of wood found near the pith. Telewski (1989) referred to this as 'flexure wood', and explained that such wood forms under the influence of flexural stresses and has the function of resisting the complex loading patterns to which small stems are submitted. Therefore, a potential unexpected outcome of the application of the CLASS treatment is that the stems harvested at the end of the next rotation may contain more flexure wood than stems that have regenerated after a clear-cut or other major disturbance. A similar pattern could explain the observation of Torquato *et al.* (2014) that wood from irregular stands has lower stiffness than wood from even-aged stands.

Despite this, the comprehensive examination of the wood properties of the treated trees contained in the canonical discriminant analysis (Figure 4) did not reveal any significant differences between the periods before and after treatment for either black spruce or balsam fir. This means that overall, wood properties in treated trees were not significantly affected by the CLASS in the 10 years following treatment, although some wood quality parameters taken individually were affected, mainly in the case of balsam fir. It could be argued that in such a situation wood quality could still be adversely affected by the treatment due to a change in the uniformity of growth rings (Moschler *et al.*, 1989). However, the benefits of the gain in volume per stem are very likely to surpass the limited negative effects that could be linked to the treatment (Bendtsen, 1978).

Conclusion

In light of the results obtained, CLASS appears to be a good silvicultural option to preserve greater structural variability in uneven-aged stands while stimulating the radial growth of residual black spruce and balsam fir stems, which supports our first hypothesis regarding the effect of the treatment on stem growth. As for the quality of the wood produced in the years following CLASS, we had hypothesized that the increased radial growth would cause a decrease in latewood proportion and ring density. This was not the case for black spruce, but was confirmed for balsam fir. However, our third hypothesis regarding a decrease in mechanical properties was refuted, as we did not observe any measurable consequence of the increased growth and lower wood density on the MOE and MOR values. A canonical discriminant analysis revealed that in general, the wood properties compared before and after treatment did not differ, which leads us to believe that the changes observed on the individual wood properties would not reduce the value or change the suitability of the wood for a given end-use. A study over a longer period of time remains necessary to assess the extent of the treatment effect on ring width and wood properties. Additional studies on other parameters such as stem taper, branch diameter, proportion of compression wood, wall thickness and lumen diameter could also provide further information concerning the wood quality of the stems after CLASS.

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Conflict of interest statement

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