

Article

White Spruce Growth and Wood Properties over Multiple Time Periods in Relation to Current Tree and Stand Attributes

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Academic Editor: Timothy A. Martin

Received: 18 January 2016; Accepted: 17 February 2016; Published: 24 February 2016

Abstract: The relationships between white spruce radial increment and wood properties were investigated in relation to tree and stand attributes using data from mature white spruce stands in the boreal forest of western Canada that experienced a range of shelterwood treatments. The model with the highest predictive ability was radial increment ($\text{adj-}R^2 = 67\%$) and included crown attributes, diameter at breast height (DBH), average height of competitors, and a climate index. Radial growth was positively related to live crown ratio, whereas wood density and modulus of elasticity were negatively correlated to the crown attribute. Tree slenderness had a significant negative effect on wood density and modulus of elasticity, as it reflects the mechanical stability requirement of the tree. The models consistently improved when using annual averages calculated over longer periods of time. However, when the annual averages were calculated using time periods of 5–10 and 10–20 years prior to sampling, the predictive ability of the models decreased, which indicated that the current tree and stand conditions were the best predictors of growth and wood properties up to five years prior to sampling. This study suggests that crown length equal to 2/3 of the tree height might represent an optimal balance between radial growth and wood quality.

Keywords: white spruce; radial growth; wood density; microfibril angle; modulus of elasticity

1. Introduction

White spruce (*Picea glauca* (Moench) Voss) has high ecological and economic value and is a key component of the boreal forests of North America. Radial growth rates and wood and fibre characteristics have important effects on the mechanical properties of wood and fibre products (e.g., [1–3]), therefore, accurate tree level estimates of these factors can improve planning of wood flow to industrial plants and can add value to wood products [4].

Shelterwood systems affect total stand density and therefore the resources available for tree growth by partially removing the overstory canopy while protecting the advanced regeneration in the understory [5]. These treatments also have a strong influence on tree crown characteristics which in turn have direct effects on wood formation and fibre properties [6]. Several studies have also shown that site characteristics [7], climate [8] and genotype [9] are important factors to be considered when investigating wood and fibre properties.

Several models have already indicated a strong link between white spruce radial growth and: 1—competition levels [10], and 2—climate [11]. Likewise, wood properties have been successfully

modeled in relation to crown attributes and climate [6]. While climate information can be easily obtained [12], collecting crown and competition information is costly and time consuming, thus only one measurement per plot is often available. In this regard, this study investigated the challenges related to modeling past growth rates and wood characteristics in relation to current crown attributes and competition levels.

This study developed predictive models of radial growth, wood density, microfibril angle, and modulus of elasticity using white spruce data from eight mature stands that underwent a wide range of shelterwood treatments in the boreal forests of western Canada. The base models were built using the three most recently produced annual rings to: 1—assess the influence of current crown and stand characteristics, and 2—test the predictive ability of the base models using time periods of different length and age.

2. Materials and Methods

Data for this study came from eight mature white spruce stands in the boreal forest of western Canada that experienced a wide range of shelterwood treatments (for more details, please refer to Table 1 and Figure 1).

Table 1. Study information and treatment description. Coordinates are expressed in decimal degrees and elevation in meters. AW, Trembling aspen; SW, White spruce; FB, Balsam fir; and SB, Black spruce. The provinces (Prov.) represented are Alberta (AB), Saskatchewan (SK) and Manitoba (MB). Lat., latitude; Long., longitude; Elev., elevation; Trt.Yr., year of treatment; Age@Trt., stand age at the time of treatment.

Study	Prov.	Lat.	Long.	Elev. (m)	Species	Trt. Yr.	Age @Trt.	Sampling Yr.	Treatment Description
EMEND	AB	56.7	−118.3	732	AW, SW, FB	1999	70	2010	50% Removal Mixedwood Control/Untreated 50% Removal Conifer-Dominant Control/Untreated Buffer
Hotchkiss	AB	57.1	−118.1	677	AW, SW	1993	80	2009	Control/Untreated Understory Protection
Drayton Valley	AB	53.2	−115.6	964	AW, SW	1988	110	2009	Control/Untreated Understory Protection
Calling Lake	AB	55.1	−113.0	633	AW, SW	1998	75	2010	Control/Untreated Understory Protection
Alcott Creek	SK	53.7	−108.4	674	AW, SW, SB, FB	2000	49	2010	Control/Untreated Modified Shelterwood
Candle Lake	SK	53.7	−105.2	497	AW, SW	1952	70	2010	Control/Untreated All aspen removed
Riding Mountain	MB	50.7	−99.9	662	AW, SW	1954	40	2010	Control/Untreated All aspen removed
Black River	MB	50.8	−96.3	230	AW, SW, FB	1995	80	2010	Control/Untreated Shelterwood

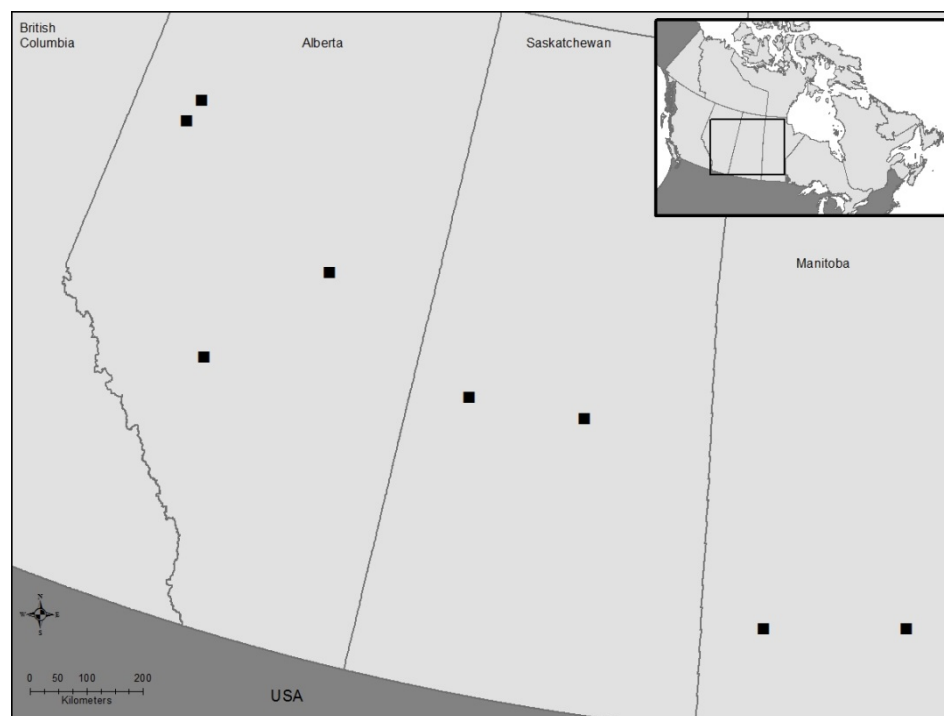


Figure 1. Location of the eight long-term studies.

Treatments had been completed by Canadian Forest Service staff between 1952 and 2000 on the various study sites. Soils are predominantly luvisolic with medium to fine texture. Crown information (e.g., crown radius, crown length) was collected on the white spruce trees that were either destructively sampled (*i.e.*, four trees per treatment at each site) or cored (*i.e.*, seven trees per treatment at each site). The trees were randomly selected based on the average tree size in the plot in order to be representative of the range of diameter size classes of each site. Cores or tree cookies were taken at breast height. The cored trees were sampled at breast height only, whereas the disked trees had disks taken at five heights along the tree, for more in-depth analysis (not included in this study). Destructive sampling was restricted, as the trees were sampled from long-term Permanent Sample Plots, thus the cored trees were added to obtain a larger sample size. On both the cored and destructively sampled trees, the same height and crown attributes were measured, and the same methodology was followed on non- and destructively sampled trees.

The total number of white spruce trees selected was 218. For the sampled trees age ranged between 29 and 153 years (average = 69 years), diameter at breast height (DBH) ranged between 14.4 cm and 35.9 cm (average = 21.7 cm) and height ranged between 9.9 m and 32.1 m (average = 18.2 m). The crown attributes of each measured tree included: crown radii and crown length in four cardinal directions, while competition measurements included: diameter (*i.e.*, DBH), height and distance from the subject tree for every tree within a 6 m radius. The height to the base of the live crown ranges from 0.8 to 18.8 m (average = 8.5 m) and the crown extended below breast height (1.3 m) for only two of the sampled trees (0.9% of total). This information suggests that the dataset is likely composed exclusively by mature wood.

The disks and cores collected were analyzed at the FPInnovations laboratory in Vancouver, British Columbia, Canada using the SilviScan™ system [13]. SilviScan™ combines image analysis, X-ray densitometry, and X-ray diffractometry to provide multiple wood and fibre properties including pith-to-bark profiles of wood density (WD), microfibril angle (MFA), and modulus of elasticity (MOE).

Several preliminary tests explored the correlation between average current tree and stand variables available at the time of sampling and annual: (1) radial area increment; (2) wood density (WD);

(3) microfibril angle (MFA); and (4) modulus of elasticity (MOE). The base model was built using the most current information on growth and wood properties represented by the three-year annual averages similar to [14].

Linear and non-linear mixed effect models were tested to account for the hierarchical structure of the dataset (*i.e.*, treatments nested within sites and sites nested within the study). The base model was built by testing and retaining only those explanatory variables that were significant at $\alpha = 0.05$ and that improved the overall predictive ability of the model. The models were compared using several criteria including: (1) Akaike's information criterion (AIC, [15]); (2) the coefficient of determination (Adjusted- R^2 , [16]); and, (3) residual plots. Parameter estimation for the mixed effects model was completed using the NLME statistical package in R (version 3.1.2) [17].

Variables related to the crown attributes of the subject tree were tested first (*i.e.*, crown radius, crown length, live crown ratio, crown volume, crown projected base area, crown lateral surface area) followed by the remaining tree variables related to the subject tree (*i.e.*, tree age, DBH, height, and tree slenderness). The estimates of competition within 6 m of the subject trees were then added to the model (*i.e.*, DBH sum, BA sum, basal area of larger trees within the plot (BALT), average height of the competitors, average distance of the closest competitor per quadrant, average height of the competitors divided by the average distance and number of competitors). Finally, several climate variables were calculated for each site using the software ClimateNA (version 5.10) [12], including: mean annual temperature (MAT), mean warmest month temperature, mean coldest month temperature, mean annual precipitation (MAP), mean summer precipitation (MSP), precipitation as snow (PAS), annual heat-moisture index (*i.e.*, $AHM = (MAT + 10)/(MAP/1000)$), growing degree-days above 5 °C and 18 °C. These variables were averaged over the five-year period (2005–2009) prior to the field measurements and added to the model (Table 2).

Table 2. List of climate variables by study location together with the average value over the 5-year period (2005–2009): mean annual temperature (MAT, °C), mean warmest month temperature (MWMT, °C), mean coldest month temperature (WCMT, °C), mean annual precipitation (MAP, mm), mean summer precipitation (MSP, mm), annual heat-moisture index (*i.e.*, $AHM = (MAT + 10)/(MAP/1000)$), growing degree-days above 5 °C and 18 °C (DD5 and DD18, respectively), and precipitation as snow (PAS, mm).

Study	MAT	MWMT	MCMT	MAP	MSP	AHM	DD5	DD18	PAS
EMEND	0.84	15.66	−16.5	459.8	300	23.76	1213.6	32.4	137
Hotchkiss	0.42	15.64	−17.68	453.8	294.6	23.12	1196.2	31.8	139
Drayton Valley	2.62	15.56	−11.72	593.8	454.6	21.26	1194.4	31	109.8
Calling Lake	1.62	16.58	−15.54	486.4	342.6	23.92	1309.8	47.2	117
Alcott Creek	0.86	16.84	−16.7	466.4	315	23.76	1303.4	51.4	128.8
Candle Lake	0.62	17.56	−17.58	497.8	327.6	21.8	1362.6	66.8	140.6
Riding Mountain	0.9	17.12	−17.6	556.6	348	19.98	1366.6	61.2	150.6
Black River	2.2	18.82	−17.26	563.6	341.2	22.08	1644.4	122.4	136.2

The base models selected for radial growth and wood properties were then tested using the annual averages over longer periods of time (*i.e.*, five, ten and 20 years), and for older time periods including average values for the 5–10 and 10–20 years prior to sampling.

3. Results

The site level random effect was removed from the final equations because it did not improve the overall predictive ability of the model. This outcome is likely related to the inclusion of stand and climate variables that already capture most of the variability between sites.

3.1. Radial Area Increment

The results for the average annual radial area increment over three years indicated that the model improved (lower AIC and higher adjusted R -square) when more variables were added to the model up to a total of five variables (Table 3). The final model Equation (1) included: live crown ratio, crown radius, DBH, average height of the competitors, and AHM.

$$Y_{ijz} = a_0 + (a_1 + au_1) \times LCR_{jz}^2 + a_2 \times CrRad_{jz}^2 + a_3 \times DBH_{jz} + a_4 \times HtCAv_{jz} + a_5 \times AHM_i + \varepsilon_{ijz} \quad (1)$$

where Y_{ijz} is average annual radial area increment over three years (cm^2/year) of tree z , in treatment j , in site i ; LCR_{jz} , Live crown ratio of the subject tree; $CrRad_{jz}$, Crown Radius (m) of the subject tree; DBH_{jz} , Diameter at Breast Height of the subject tree (cm); $HtCAv_{jz}$, average height of competitors (m) for each subject tree; AHM_i , Annual Heat-Moisture index for each site; a_n ($n = 0, 1, 2, 3, 4$, and 5) are the fixed effects parameters; au_1 is the random effect (normally distributed with mean zero and an unknown variance component) relative to LCR_{jz} for tree z , in treatment j ; the ε_{ijz} term represents the unexplained error.

Table 3. Average annual radial area increment over three years: parameter estimates reported with standard error and goodness-of-fit for Equation (1). Akaike's information criterion (AIC) and adjusted- R^2 values for the fixed effects and treatment-level mixed effects models are included for comparison.

	Number of Variables	1	2	3	4	5
		Intercept	Intercept	Intercept	Intercept	Intercept
Parameters	Estimate	9.92136	1.760033	−2.962901 *	0.985296 *	−22.943880
	Std. Error	2.034	0.810	2.107	2.472	8.068
		LCR ²	LCR ²	LCR ²	LCR ²	LCR ²
	Estimate	44.49982	10.960747	11.725360	11.820046	11.166332
	Std. Error	10.004	3.488	3.248	3.162	2.917
	σ_μ	21.665	10.156	8.970	8.639	7.375
			CrRad ²	CrRad ²	CrRad ²	CrRad ²
	Estimate		0.897244	0.751498	0.658454	0.651599
	Std. Error		0.266	0.271	0.269	0.265
				DBH	DBH	DBH
	Estimate			0.229425	0.363225	0.344003
	Std. Error			0.096	0.104	0.100
					HtCAv	HtCAv
	Estimate				−0.341102	−0.431336
	Std. Error				0.116	0.117
						AHM
	Estimate					1.164386
	Std. Error					0.379
AIC	Mixed	1301.2	1292.0	1288.6	1282.1	1275.0
Adj- R^2	Fixed	0.331	0.355	0.403	0.474	0.492
	Mixed (Treatment)	0.635	0.653	0.653	0.663	0.668

* Not significantly different from zero ($\alpha = 0.05$).

Adjusted R -square values for the final model were: 49% for the fixed effect model (*i.e.*, $au_1 = 0$), and 67% for the mixed effect model with treatment as the random effect (RMSE = 10.7%) (Table 3 and Figure 2). The coefficient values of Equation (1) indicated that radial area increment: (1) increased as live crown ratio (LCR) ($a_1 = 11.166332$) (Figure 3), crown radius ($a_2 = 0.651599$), and DBH ($a_3 = 0.344003$) of

the subject tree increased; (2) decreased as the average height values of the competitors ($a_4 = -0.431336$) increased; and, (3) increased as the climate variable AHM ($a_5 = 1.164386$) increased (Table 3).

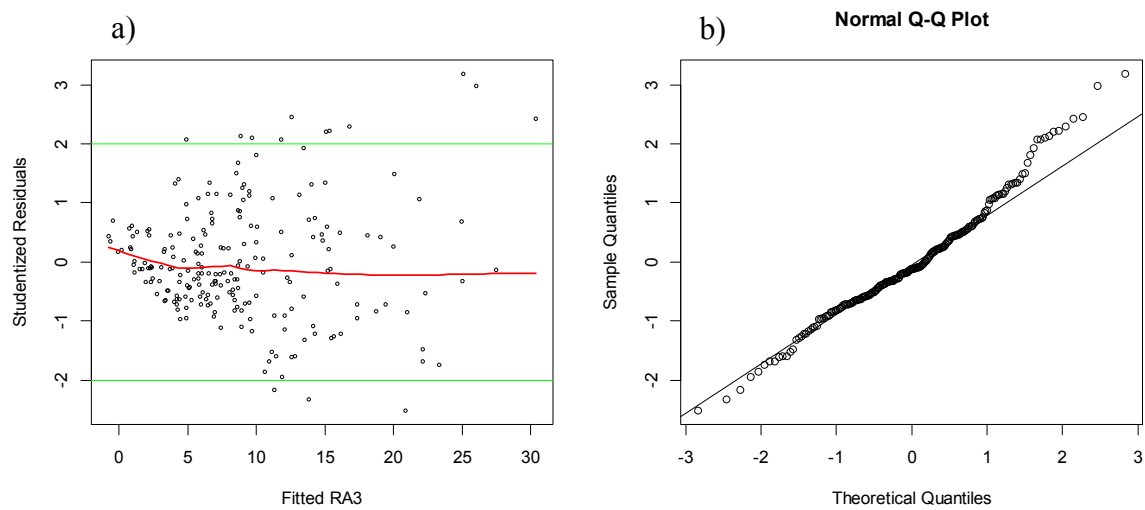


Figure 2. Plots representing the goodness-of-fit for Equation (1): (a) scatter plots of studentized residuals against predicted together with the fitted Lowess line and (b) normal Q-Q plot.

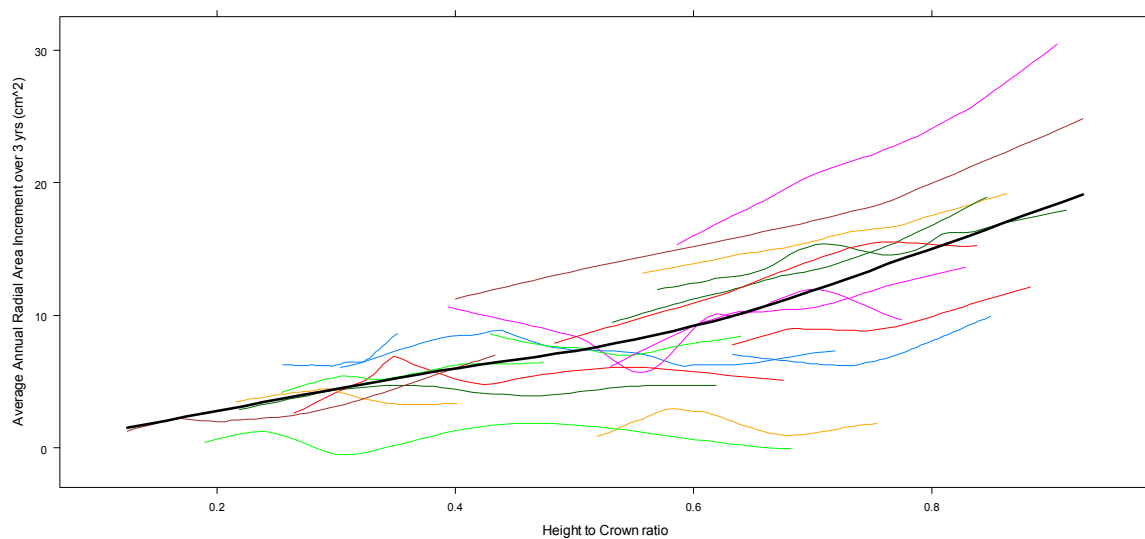


Figure 3. Predicted values of average annual three-year radial area increment Equation (1) by treatment (thin lines) in relation to LCR of the subject tree. The thicker black line represents the fitted values at the study level (*i.e.*, fixed effects).

The overall predictive ability of the model improved as the annual average of basal area increment was calculated over increasingly longer periods of time (*i.e.*, 5, 10, and 20 years) (Table 4). The climate variable AHM was not significantly different from zero for the two longer time periods (*i.e.*, 10 and 20 years). However, the predictive ability of the model decreased (*i.e.*, higher AIC) when radial area annual increment over the 5–10 and 10–20 year periods (prior to sampling) were tested.

Table 4. Average annual radial area increment, parameter estimates reported with standard error and goodness-of-fit for Equation (1) using time periods of 3, 5, 10, and 20 years. AIC and the adjusted *R*-square values for the fixed effects and treatment-level mixed effects models are included for comparison.

Annual Radial Area Increment		Intercept	LCR ²	CrRad ²	DBH	HtCAv	AHM	AIC	Adj-Rsq	
3 Years	Est.	−22.94388	11.166332	0.651599	0.344003	−0.431336	1.164386	1275.0	0.492	0.668
	Std.Er.	8.068	2.917	0.265	0.100	0.117	0.380			
	σ_{μ}		7.376							
5 Years	Est.	−16.558041	10.865740	0.646478	0.353730	−0.358835	0.805285	1242.9	0.502	0.691
	Std.Er.	7.635	2.805	0.245	0.094	0.109	0.358			
	σ_{μ}		7.346							
10 Years	Est.	−6.503536 *	10.576541	0.665314	0.305187	−0.344630	0.37347 *	1152.5	0.587	0.708
	Std.Er.	5.836	2.048	0.201	0.073	0.087	0.275			
	σ_{μ}		4.769							
20 Years	Est.	4.991468 *	7.338765	0.579518	0.388236	−0.339377	−0.1667 *	1047.1	0.636	0.687
	Std.Er.	4.289	1.451	0.158	0.054	0.067	0.203			
	σ_{μ}		2.876							
5–10 Years	Est.	17.71571 *	48.33033	3.57944	1.27351	−1.67308	−0.252 *	1836.8	0.588	0.664
	Std.Er.	27.218	9.353	0.972	0.345	0.417	1.289			
	σ_{μ}		20.091							
10–20 Years	Est.	180.09832	50.59283	4.36070	4.20109	−2.11672	−8.32214	2074.6	0.471	0.626
	Std.Er.	54.352	20.916	1.661	0.665	0.749	2.542			
	σ_{μ}		59.407							

* Not significantly different from zero ($\alpha = 0.05$).

3.2. Wood Density

The results for average annual wood density over three years indicated that the model improved (lower AIC and higher adjusted *R*-square) when more variables were added to the model up to a total of three variables (Table 5). The final model Equation (2) included: live crown ratio, tree slenderness; and the climate variable DD18 (*i.e.*, growing degree days above 18 °C).

$$Y_{ijz} = a_0 + (a_1 + au_1) \times LCR_{jz} + a_2 \times HD_{jz} + a_3 \times DD18_i + \varepsilon_{ijz} \quad (2)$$

where Y_{ijz} is average annual wood density over three years ($\text{g}/\text{cm}^2 \cdot \text{year}^{-1}$) of tree z , in treatment j , in site i ; LCR_{jz} , Live Crown ratio of the subject tree; HD_{jz} , Height to Diameter ratio of the subject tree; $DD18_i$, Growing Degree Days above 18 °C of each site; a_n ($n = 0, 1, 2$, and 3) are the fixed effects parameters; au_1 is the random effect (normally distributed with mean zero and an unknown variance component) relative to LCR_{jz} for tree z , in treatment j ; the ε_{ijz} term represents the unexplained error.

Table 5. Average annual wood density over three years: parameter estimates reported with standard error and goodness-of-fit for Equation (2). AIC and adjusted R -square values for the fixed effects and treatment-level mixed effects models are included for comparison.

Number of Variables		1	2	3
Parameters		Intercept	Intercept	Intercept
	Estimate	0.5198779	0.6013871	0.5710909
	Std. Error	0.011	0.021	0.023
		LCR	LCR	LCR
	Estimate	−0.1465140	−0.0941405	−0.0661430
	Std. Error	0.022	0.025	0.027
	σ_μ	0.029	0.033	0.028
			HD	HD
	Estimate		−0.0904490	−0.0978845
	Std. Error		0.020	0.019
				DD >18
	Estimate			0.0004606
	Std. Error			0.001
AIC	Mixed	−665.7	−683.2	−687.5
Adj- R^2	Fixed	0.269	0.310	0.336
	Mixed (Treatment)	0.310	0.382	0.382

The adjusted R -square values of the final model were: 34% for the fixed effect model (*i.e.*, $au_1 = 0$), and 38% for the mixed effect model with treatment as the random effect (RMSE = 10.3%) (Table 5 and Figure 4). The coefficient values of Equation (2) indicated that wood density: (1) decreased as LCR ($a_1 = -0.0661430$) (Figure 5) and slenderness ($a_2 = -0.0978845$) of the subject tree increased; and, (2) increased as the climate variable DD >18 ($a_3 = 0.0004606$) increased (Table 5).

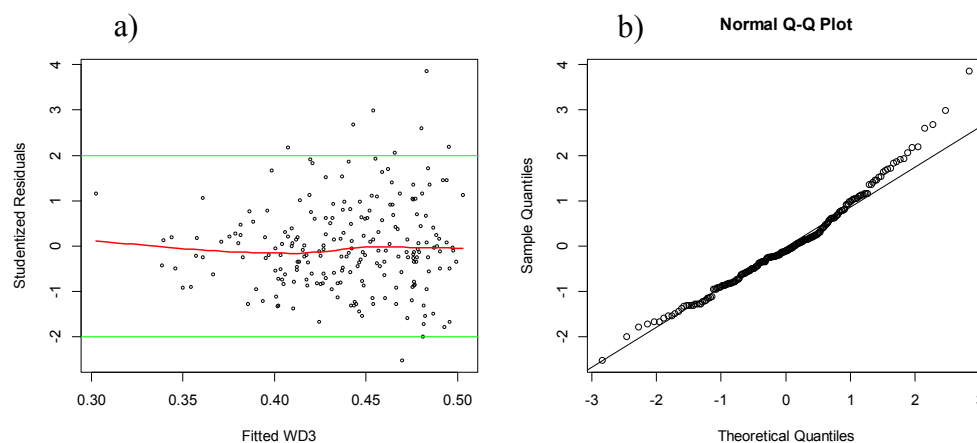


Figure 4. Plots representing the goodness-of-fit for Equation (2): (a) scatter plots of studentized residuals against predicted together with the fitted Lowess line and (b) normal Q-Q plot.

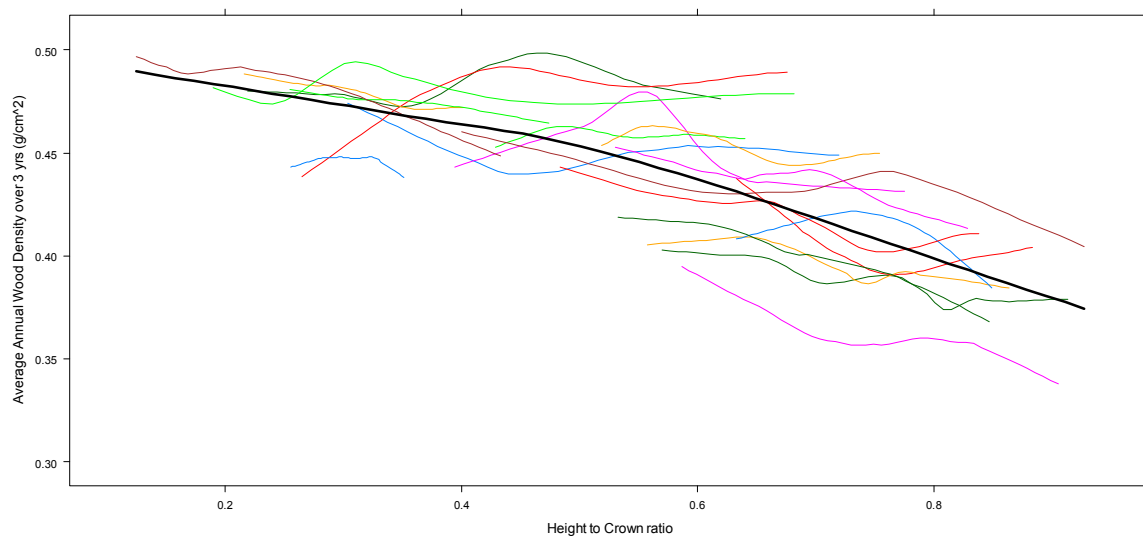


Figure 5. Predicted values of average annual three-year wood density Equation (2) by treatment (thin lines) in relation to LCR of the subject tree. The thicker black line represents the fitted values at the study level (*i.e.*, fixed effects).

The overall predictive ability of the model improved (*i.e.*, lower AIC) as the annual average of wood density was calculated over increasingly longer periods of time (*i.e.*, five, ten, and 20 years) (Table 6). Live crown ratio and the climate variable DD >18 were not significantly different from zero for the five and ten-year time periods, respectively. However, the predictive ability of the model decreased (*i.e.*, lower adjusted *R*-square) when annual wood density over the 5–10 and 10–20 year periods (prior to sampling) were tested.

Table 6. Average annual wood density, parameter estimates reported with standard error and goodness-of-fit for Equation (2) using time periods of 3, 5, 10, and 20 years. AIC and the adjusted *R*-square values for the fixed effects and treatment-level mixed effects versions are included for comparison.

Annual Wood Density		Intercept	LCR	HD	DD >18	AIC	Adj-Rsq Fixed	Mixed
3 Years	Est.	0.5710909	−0.0661430	−0.0978845	0.0004606	−687.5	0.336	0.382
	Std.Er.	0.023	0.026	0.019	0.001			
	σ_{μ}		0.028					
5 Years	Est.	0.5884310	−0.0410275 *	−0.1156817	0.0004217	−728.8	0.349	0.422
	Std.Er.	0.022	0.025	0.018	0.001			
	σ_{μ}		0.029					
10 Years	Est.	0.6195852	−0.0439326	−0.1162893	0.0000066 *	−766.4	0.338	0.484
	Std.Er.	0.021	0.024	0.201	0.001			
	σ_{μ}		0.034					
20 Years	Est.	0.6192953	−0.0555787	−0.0964703	−0.0003135	−791.1	0.323	0.477
	Std.Er.	0.020	0.023	0.016	0.001			
	σ_{μ}		0.033					
5–10 Years	Est.	0.6446777	−0.0460028 *	−0.1116542	−0.0004171	−724.9	0.291	0.498
	Std.Er.	0.024	0.027	0.019	0.001			
	σ_{μ}		0.043					
10–20 Years	Est.	0.6198269	−0.0710513	−0.0757283	−0.000636	−744.3	0.277	0.408
	Std.Er.	0.021	0.025	0.018	0.001			
	σ_{μ}							

* Not significantly different from zero ($\alpha = 0.05$).

3.3. Microfibril Angle (MFA)

The results for average annual MFA over three years indicated that the model improved (lower AIC and higher adjusted *R*-square) when more variables were added to the model up to a total of three variables (Table 7). The final model Equation (3) included: live crown ratio of the subject tree, average height of the competitors, and the climate variable PAS (*i.e.*, precipitation as snow).

$$Y_{ijz} = a_0 + (a_1 + au_1) \times LCR_{jz} + a_2 \times HtCAv_{jz}^2 + a_3 \times PAS_i + \varepsilon_{ijz} \quad (3)$$

where Y_{ijz} , average annual MFA over three years ($^{\circ}\text{C}/\text{year}$) of tree z , in treatment j , in site i ; LCR_{jz} , Live crown ratio of the subject tree; $HtCAv_{jz}$, Average Height of the Competitors of the subject tree; PAS_i , Precipitation as Snow of each site; a_n ($n = 0, 1, 2$, and 3) are the fixed effects parameters; au_1 is the random effect (normally distributed with mean zero and an unknown variance component) relative to LCR_{jz} for tree z ; in treatment j , the ε_{ijz} term represents the unexplained error.

Table 7. Average annual microfibril angle (MFA) over three years: parameter estimates reported with standard error and goodness-of-fit for Equation (3). AIC and adjusted *R*-square values for the fixed effects and treatment-level mixed effects models are included for comparison.

		Number of Variables	1	2	3
Parameters			Intercept	Intercept	Intercept
	Estimate		0.5198779	12.072171	20.307119
	Std. Error		0.011	1.165	3.915
			LCR	LCR	LCR
	Estimate		−0.1465140	4.238867	3.925477
	Std. Error		0.022	1.546	1.463
	σ_{μ}		0.029	1.946	1.567
				HtCAv ²	HtCAv ²
	Estimate			−0.003920	−0.004247
	Std. Error			0.002	0.002
AIC					PAS
	Estimate				−0.059424
	Std. Error				0.027
AIC	Mixed		1185.9	1184.3	1181.9
Adj- <i>R</i> ²	Fixed		0.046	0.075	0.104
	Mixed (Treatment)		0.127	0.123	0.113

The adjusted *R*-square values of the final model were: 10% for the fixed effect model (*i.e.*, $au_1 = 0$), and 11% for the mixed effect model with treatment as the random effect (RMSE = 7.6%) (Table 7). The plots representing the goodness-of-fit suggested that the residuals for the base model of MFA are relatively skewed (Figure 6). The coefficient values of Equation (3) indicated that MFA increased as LCR ($a_1 = 3.925477$) of the subject tree increased (Figure 7), decreased as the average height of the competitors increased ($a_2 = -0.004247$), and decreased as the climate variable PAS (precipitation as snow) ($a_3 = -0.059424$) increased (Table 7).

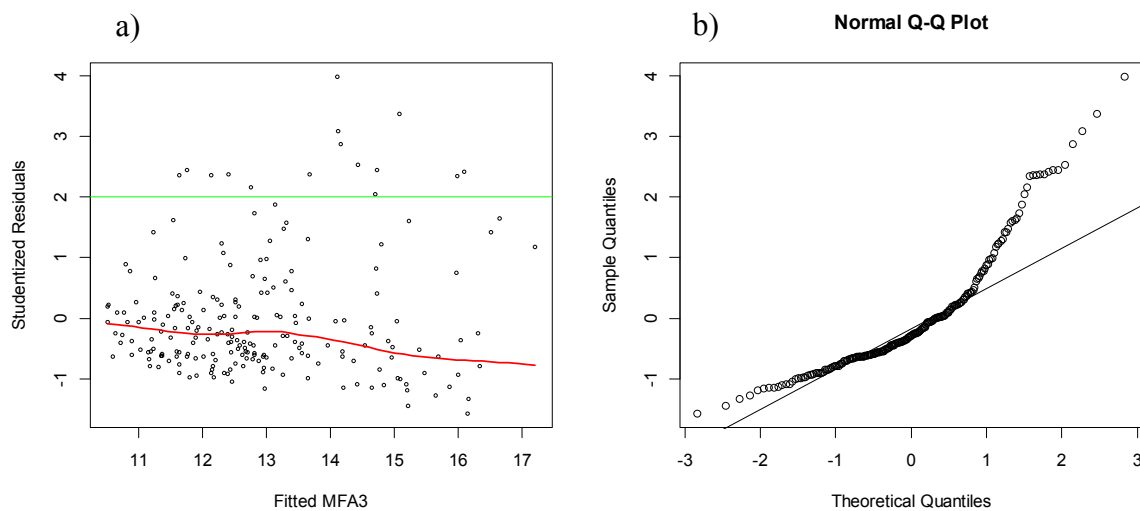


Figure 6. Plots representing the goodness-of-fit for Equation (3): (a) scatter plots of studentized residuals against predicted together with the fitted Lowess line and (b) normal Q-Q plot.

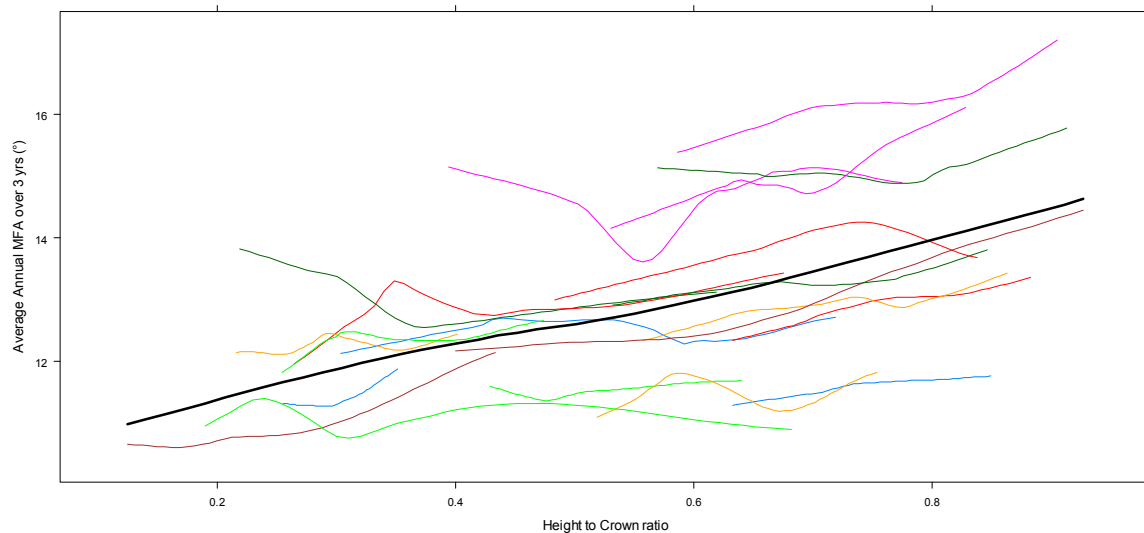


Figure 7. Predicted values of average annual three-year MFA Equation (3) by treatment (thin lines) in relation to LCR of the subject tree. The thicker black line represents the fitted values at the study level (*i.e.*, fixed effects).

The overall predictive ability of the model improved (*i.e.*, lower AIC) as the annual average of MFA was calculated over increasingly longer periods of time (*i.e.*, 5, 10, and 20 years) (Table 8). The adjusted R -square values for fixed and mixed effect models suggested that, for the time periods longer than three years, the random effect represented by treatment did not improve the overall predictive ability of the model. However, the predictive ability of the model decreased (*i.e.*, higher AIC) when annual MFA over the 5–10 and 10–20 year periods (prior to sampling) were tested.

Table 8. Average annual MFA, parameter estimates reported with standard error and goodness-of-fit for Equation (3) using time periods of three, five, ten and 20 years. AIC and the adjusted *R*-square values for the fixed effects and treatment-level mixed effects versions are included for comparison.

Annual MFA		Intercept	LCR	HtCAv ²	PAS	AIC	Adj-Rsq	
							Fixed	Mixed
3 Years	Est.	20.307119	3.925477	−0.004247	−0.059424	1181.9	0.104	0.113
	Std.Er.	3.915	1.463	0.002	0.027			
	σ_{μ}		1.567					
5 Years	Est.	20.577460	4.051355	−0.004564	−0.061617	1169.4	0.125	0.120
	Std.Er.	3.687	1.391	0.002	0.026			
	σ_{μ}		1.376					
10 Years	Est.	21.667055	4.389949	−0.005575	−0.068027	1158.1	0.172	0.159
	Std.Er.	3.524	1.337	0.002	0.024			
	σ_{μ}		1.251					
20 Years	Est.	22.903691	4.530841	−0.006739	−0.073882	1156.6	0.215	0.213
	Std.Er.	3.625	1.362	0.002	0.025			
	σ_{μ}		1.393					
5–10 Years	Est.	22.667668	4.741829	−0.006551	−0.073923	1174.2	0.201	0.189
	Std.Er.	3.668	1.390	0.001	0.025			
	σ_{μ}		1.312					
10–20 Years	Est.	21.924366	4.976295	−0.007163	−0.066365	1206.9	0.202	0.272
	Std.Er.	4.801	1.720	0.002	0.033			
	σ_{μ}		2.428					

3.4. Modulus of Elasticity (MOE)

The results for average annual MOE over three years indicated that the model improved (lower AIC and higher adjusted *R*-square) when more variables were added to the model up to a total of four variables (Table 9). The final model Equation (4) included: live crown ratio; height to diameter ratio of the subject tree; average height of the competitors; and, the climate variable AHM.

$$Y_{ijz} = a_0 + (a_1 + au_1) \times LCR_{jz} + a_2 \times HD_{jz} + a_3 \times HtCAv_{jz}^2 + a_4 \times AHM_i + \varepsilon_{ijz}, \quad (4)$$

where Y_{ijz} , average annual MOE over three years (GPa/year) of tree z , in treatment j ; in site i , LCR_{jz} , live crown ratio of the subject tree; HD_{jz} , Height to Diameter ratio of the subject tree; $HtCAv_{jz}$, average height of the competitors; AHM_i , Annual Heat-Moisture index of each site; a_n ($n = 0, 1, 2, 3$, and 4) are the fixed effects parameters; au_1 is the random effect (normally distributed with mean zero and an unknown variance component) relative to LCR_{jz} for tree z , in treatment j ; the ε_{ijz} term represents the unexplained error.

Table 9. Average annual modulus of elasticity (MOE) over three years: parameter estimates reported with standard error and goodness-of-fit for Equation (4). AIC and adjusted R -square values for the fixed effects and treatment-level mixed effects models are included for comparison.

		Number of Variables	1	2	3	4
Parameters		Intercept	Intercept	Intercept	Intercept	
	Estimate	16.350420	19.520644	18.123647	27.103851	
	Std. Error	0.523	0.931	1.206	3.555	
		LCR	LCR	LCR	LCR	
	Estimate	−5.784725	−4.012604	−4.236899	−3.633662	
	Std. Error	1.062	1.081	1.031	0.995	
	σ_μ	1.728	1.400	1.170	0.891	
			HD	HD	HD	
	Estimate		−3.411718	−2.866999	−3.162503	
	Std. Error		0.868	0.8891843	0.848	
				HtCAv ²	HtCAv ²	
	Estimate			0.002239	0.003660	
	Std. Error			0.0012672	0.001	
					AHM	
	Estimate				−0.419140	
	Std. Error				0.155	
AIC	Mixed		968.9	956.3	955.6	950.7
Adj- R^2	Fixed		0.226	0.302	0.325	0.353
	Mixed (Treatment)		0.351	0.372	0.361	0.357

The adjusted R -square values of the final model were: 35% for the fixed effect model (*i.e.*, $au_1 = 0$), and 36% for the mixed effect model with treatment as the random effect (RMSE = 7.5%) (Table 9 and Figure 8). The coefficient values of Equation (4) indicated that three-year radial area increment: 1—decreased as LCR ($a_1 = -3.633662$) (Figure 9) and HD ($a_2 = -3.162503$) of the subject tree increased, 2—increased as the average height of the competitors increased ($a_3 = 0.003660$), and 3—decreased as the climate variable AHM (Annual Heat-Moisture index) ($a_4 = -0.419140$) increased (Table 9).

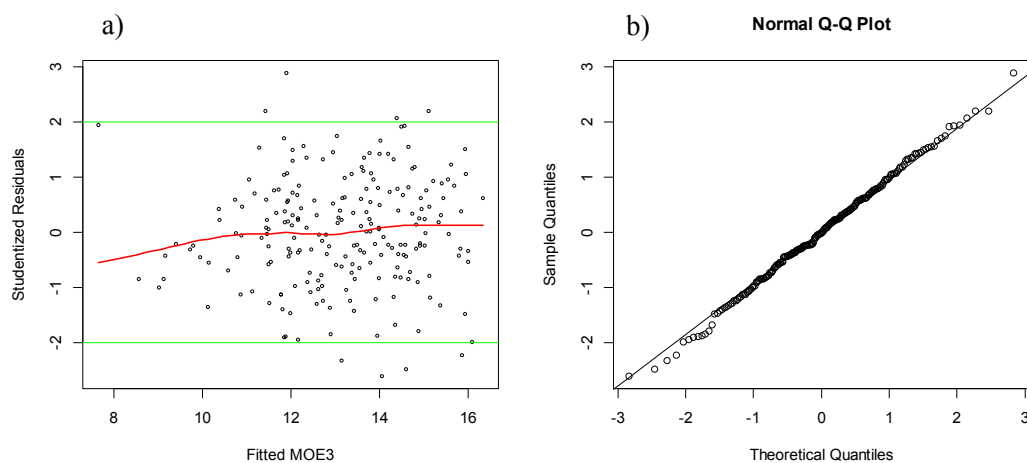


Figure 8. Plots representing the goodness-of-fit for Equation (4) 1—scatter plots of studentized residuals against predicted together with the fitted Lowess line, and 2—Normal Q-Q plot.

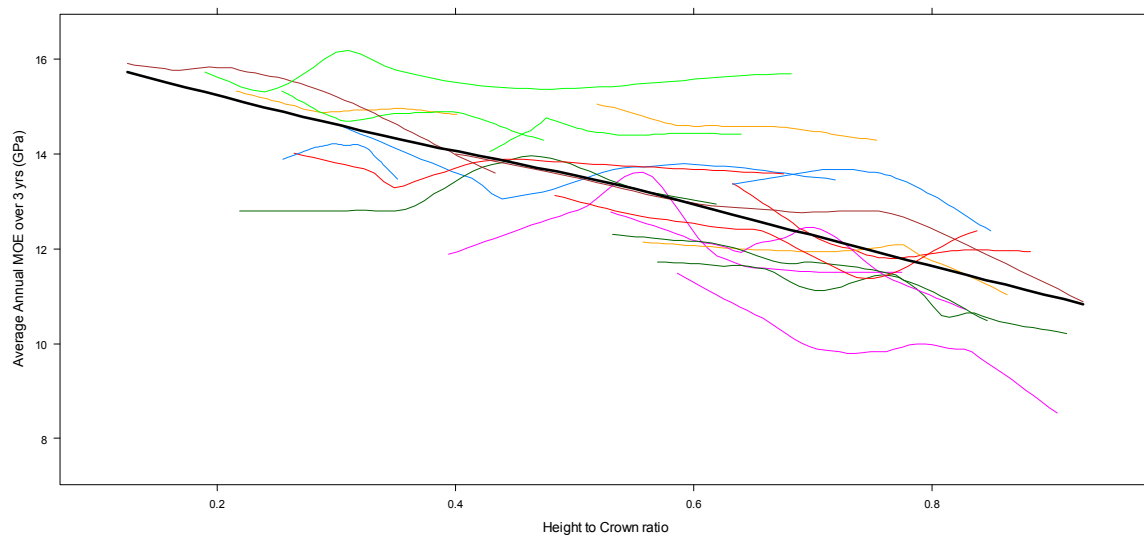


Figure 9. Predicted values of average annual three-year MOE Equation (4) by treatment (thin lines) in relation to LCR of the subject tree. The thicker black line represents the fitted values at the study level (*i.e.*, fixed effects).

The overall predictive ability of the model improved (*i.e.*, lower AIC) as the annual average of MOE was calculated over increasingly longer periods of time (*i.e.*, five, ten, and 20 years) (Table 10). The adjusted R -square values for fixed and mixed effect models suggests that for the five and ten-year time periods the random effect represented by treatment does not improve the overall predictive ability of the model. Moreover, the climate variable AHM was not significant for the MOE annual average over the ten-year period. However, the predictive ability of the model decreased (*i.e.*, higher AIC) when annual MOE over the 5–10 and 10–20 year periods (prior to sampling) were tested.

Table 10. Average annual MOE, parameter estimates reported with standard error and goodness-of-fit for Equation (4) using time periods of 3, 5, 10, and 20 years. AIC and the adjusted R-square values for the fixed effects and treatment-level mixed effects versions are included for comparison.

Annual MOE		Intercept	LCR	HD	HtCAv ²	AHM	AIC	Adj-Rsq Fixed	Adj-Rsq Mixed
3 Years	Est.	27.103851	−3.633662	−3.162503	0.003660	−0.41914	950.7	0.353	0.357
	Std.Er.	3.556	0.995	0.848	0.001	0.155			
	σ_{μ}		0.891						
5 Years	Est.	26.460672	−3.639036	−3.383339	0.003657	−0.376473	943.2	0.373	0.365
	Std.Er.	3.412	0.960	0.819	0.001	0.148			
	σ_{μ}		0.787						
10 Years	Est.	23.781897	−3.452631	−3.520098	0.003696	−0.255223 *	939.8	0.379	0.379
	Std.Er.	3.439	0.964	0.822	0.001	0.149			
	σ_{μ}								
20 Years	Est.	19.909238	−3.247938	−3.305205	0.003831	−0.104610	932.8	0.379	0.426
	Std.Er.	3.779	1.033	0.866	0.001	0.165			
	σ_{μ}								
5–10 Years	Est.	20.978195	−3.288288	−3.49492	0.003476	−0.132001 *	965.8	0.350	0.398
	Std.Er.	4.030	1.105	0.928	0.001	0.176			
	σ_{μ}		1.266						
10–20 Years	Est.	15.51042	−3.26696	−2.69103	0.00369	0.058197	980.4	0.312	0.453
	Std.Er.	5.085	1.327	1.047	0.001	0.224			
	σ_{μ}		2.161						

* Not significantly different from zero ($\alpha = 0.05$).

4. Discussion

This study indicated that live crown ratio (the ratio of crown length to tree height) was overall the best predictor of radial area growth and wood properties of white spruce. [14] also found a strong relationship between ring area and crown length when investigating Pressler's law. Likewise, several recent studies have indicated that wood density and other wood properties are strongly related to crown architecture [6,18,19]. Reference [20] also found that wood density of *Pinus resinosa* decreased as the live crown ratio increased. This study confirms that the predictive ability of radial growth and wood and fibre attribute models greatly benefit when information on crown characteristics is taken into account [21,22].

This study also confirmed that, for the genus *Picea*, ring width is often negatively correlated with wood density [23], as indicated by the decrease in wood density as radial area increased for trees with proportionally longer crowns. Moreover, height to diameter ratio had a significant effect on wood density and MOE, as other recent studies suggest, with tree slenderness reflecting the mechanical stability requirement of the tree [24,25].

Competition (*i.e.*, average height of the competitors within the plot) significantly affected radial annual increment (*i.e.*, negative effect), MFA (*i.e.*, negative effect) and MOE (*i.e.*, positive effect). Many studies have indicated that white spruce growth is reduced by competition in mixed boreal forests [26], and wood characteristics are similarly affected by competition levels [27]. The annual heat-moisture index was the more reoccurring climate variable among the candidates selected, which confirmed that both temperature and precipitation play an important role in white spruce development [28–30]. The annual heat-moisture index had a positive effect on radial annual increment but a negative effect on MOE, which indicated that a warmer and relatively drier climate enhances growth but reduces wood stiffness.

The models consistently improved when using annual averages calculated over longer periods of time, which indicated that current tree and stand attributes could explain a significant portion of

the variability related to past radial growth and wood properties up to 20 years prior to sampling. This outcome is likely related to the relatively low between-ring variability for the most current increments [31]. However, when the annual averages were calculated using time periods of 5–10 and 10–20 years prior to sampling the predictive ability of the models decreased, which indicated that the current tree and stand conditions (*i.e.*, up to five years prior to sampling) were the best predictors of radial growth and wood properties, and should be preferred over longer period of times. Moreover, at five out of the eight study sites investigated the treatment was applied less than 20 years prior to sampling and, therefore, the current tree and stand conditions do not reflect pre-treatment conditions.

This study suggests that forest management treatments that aim at maximizing growth should allow for relatively longer crowns (e.g., thinning), while crown lift should be facilitated if higher wood quality is the only management goal (e.g., higher stand density, pruning). Crown length equal to 2/3 of the tree height might represent an optimal balance between radial growth and wood quality.

Acknowledgments: Special thanks go to Laura Chittick (Natural Resources Canada, Canadian Wood Fibre Centre) and to FPInnovations (Vancouver) for supplying the data. The map presented in this manuscript was created by Mr. Gurp Thandi (Natural Resources Canada, Canadian Forest Service). Funding of this research was provided by the Canadian Wood Fibre Centre (Natural Resources Canada).

Author Contributions: Francesco Cortini led the statistical analysis and drafted the manuscript. Dan MacIsaac and Philip Comeau provided substantial input planning the study and drafting the manuscript. Dan MacIsaac funded the tree analysis and provided supervision in providing the data.

Conflicts of Interest: The authors declare no conflict of interest.

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