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Effect of Tree Spacing on Tree Level Volume Growth, Morphology, and Wood Properties in a 25-Year-Old *Pinus banksiana* Plantation in the Boreal Forest of Quebec

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Abstract: The number of planted trees per hectare influences individual volume growth, which in turn can affect wood properties. The objective of this study was to assess the effect of six different plantation spacings of jack pine (*Pinus banksiana* Lamb.) 25 years following planting on tree growth, morphology, and wood properties. Stem analyses were performed to calculate annual and cumulative diameter, height, and volume growth. For morphological and wood property measurements several parameters were analyzed: diameter of the largest branch, live crown ratio, wood density, and the moduli of elasticity and rupture on small clear samples. The highest volume growth for individual trees was obtained in the 1111 trees/ha plantation, while the lowest was in the 4444 trees/ha plantation. Wood density and the moduli of elasticity and rupture did not change significantly between the six plantation spacings, but the largest branch diameter was significantly higher in the 1111 trees/ha (3.26 cm mean diameter) compared with the 4444 trees/ha spacing (2.03 cm mean diameter). Based on this study, a wide range of spacing induced little negative effect on the measured wood properties, except for the size of knots. Increasing the initial spacing of jack pine plantations appears to be a good choice if producing large, fast-growing stems is the primary goal, but lumber mechanical and visual properties could be decreased due to the larger branch diameter.

Keywords: plantation spacing; jack pine; growth; wood density; moduli of elasticity (MOE); moduli of rupture (MOR)

1. Introduction

Tree spacing is an important silvicultural tool that influences the sequence of future silvicultural treatments required and, ultimately the stand attributes at harvesting age [1]. At the stand level, numerous studies have already shown that stand volume increases with narrower plantation spacing, up to a certain level [2–4]. Past this threshold, narrower plantation spacing can decrease individual volume growth and increase tree mortality through excessive intraspecific competition [3,5–7]. Conversely, a wider plantation spacing will favor diameter growth and a higher survival rate, but will also increase stem taper. Higher stem taper values reduce the merchantable volume of the individual trees, for a given diameter at breast height [8].

The effect of tree spacing on the growth of individual trees is also a key issue in boreal plantations where tree size can be an important limiting factor for lumber recovery [9]. However, an increased growth rate of individual trees may affect wood properties, and can therefore influence the performance and value of end-use products [10]. Understanding wood quality is important to meet a more diversified wood product demand from the industry, especially in plantations where it is expected that faster growth may lead to a shorter rotation age and consequently increase the juvenile wood proportion [11]. Furthermore, trees forming larger tree rings can result in a decrease in wood quality parameters like density [12,13]. This has been reported to be mainly the consequence of a difference in the earlywood/latewood proportion between slow and fast growing trees. Fast growing trees typically produce a higher percentage of earlywood, and in some cases lower density latewood, compared with slow growing trees (Zhang [14] (*Picea mariana*); Wang et al. [15] (*Picea mariana*); Makinen et al. [16] (*Picea abies*)). Stem form is also an issue worth considering in plantations. Notably, stem deformation has been observed to be more frequent in plantations, a fact that can significantly reduce the quantity of end-use products [17,18].

Tree spacing influences individual tree growth, and in turn wood properties and tree morphology. Faster radial growth rate often leads to a lower wood density in conifers, which is strongly linked to wood mechanical resistance [19–21]. This is especially true in plantations with shorter rotations than their natural stand counterparts due to a higher proportion of low quality juvenile wood [22]. Fewer stems per hectare is also known to negatively influence stem taper, increase stem deformations at a young age, and increase knot size resulting from a higher branch longevity and growth (Larson [23] (*Larix laricina*); Krause et al. [18] (*Picea mariana*); Vincent and Duchesne [24] (*Picea glauca*, *Pinus banksiana*)).

The two main tree species planted in the boreal forest of Quebec, Canada are black spruce (*Picea mariana* (Mill.) B.S.P.) and jack pine (*Pinus banksiana* Lamb.) [25]. Jack pine accounted for 20% of the total planting between 2010 and 2014, which represents approximately 30 million trees per year [25]. Plantations are known to have higher growth rate caused by a more photosynthetic activity as a result of a higher number of branches and a longer living crown compared with that of natural stands [26–29]. The combinations of knot size and growth rate can influence wood quality, but datasets to quantify tree growth and wood quality at the individual tree level in boreal plantations remain scarce, particularly in the case of jack pine. This aimed to establish a link between tree growth and wood quality for jack pine planted at different spacings in an experimental study site in the boreal zone of Quebec, Canada. Focusing on individual trees, the objective of the study was to assess the effect of different spacings on dominant tree growth, morphology, and wood properties 25 years following planting. More specifically, we aimed to determine whether a positive growth response to wider spacing would affect tree morphology or the properties of the woody material.

We hypothesized that a wider initial spacing would increase the secondary growth (diameter at breast height (DBH), volume) of individual trees, which in turn would affect (i) tree morphology by increasing stem taper, live crown ratio, and the diameter of the largest branch; and (ii) wood quality attributes defined as the proportion of latewood, wood density (mean ring, earlywood, and latewood), and the moduli of elasticity and moduli of rupture (MOE, MOR).

2. Materials and Methods

2.1. Study Site

The experimental site was established in 1987 near the municipality of Saint-David-de-Falardeau, QC (Canada) (48°38′06″, −71°12′16″) and it is located in the eastern yellow birch (*Betula alleghaniensis* Britt.)/balsam fir (*Abies balsamea* L.) bioclimatic sub-domain [30]. Soils were humo-ferric podzols (Humods Spodosols) located on a fluvioglacial outwash. The climate in this region is cold and humid with monthly mean temperatures varying from −15.9 °C in January to 18.6 °C in July, a mean annual temperature of 2.8 °C, and annual precipitation of 934 mm, 24% of which falls as snow (1971 to 2000 data from Shipshaw weather station (48°27′00″, −71°13′00″)) [31].

2.2. Experimental Design

A three complete blocks design with plantation spacing as the main factor was used. Each of the three experimental blocks had an area of 5400 m^2. The initial tree spacings (6) ranged between 1111 and 4444 trees/ha (Table 1). Site preparation was done in 1986. First, a disk plough created furrows ranging between 25 and 40 cm in depth and 70–80 cm in width. A harrowing was then done to mix soil horizons, therefore eliminating the furrows. The plantation was established in 1987 with 2 + 0 bareroot seedlings of jack pine (seed lot 84L35i; MFFPQ) (see Table 1). No release or thinning treatments have been executed since planting. In the summer of 2013, we established a 900 m^2 sampling plot (30 m × 30 m) in each repetition of each plantation density.

Table 1. Jack pine plantation densities used for the experiment and their corresponding spacing.

Density (Tree/ha)	Spacing (m)
1111	3 × 3
1666	2 × 3
2222	1.5 × 3
2500	2 × 2
3333	1.5 × 2
4444	1.5 × 1.5

2.3. Growth Measurements

At the time of sampling, fifteen trees were identified in each experimental plot. Tree mortality commonly occurs in plantations [3,5–7], but because our aim was to quantify the effect of tree spacing, only trees surrounded by all their initially planted neighbours were randomly considered in our selection. We then selected five dominant stems from the 15 trees, which consisted of the trees with the five largest values of diameter at breast height (DBH). Dominant trees were chosen to assess trees with the maximum growth potential in each spacing treatment and to avoid sampling trees likely to die from competition-induced mortality before the end of the rotation. For every stem selected, we measured the total height and stem diameter at 0.3, 0.8, 1.3, 1.8, and 2.3 m from ground level. In addition, the length of the live crown, length of the longest branch, and diameter of the largest branch were recorded. Stem taper was expressed as the ratio between the stem diameter at 0.3 m and the stem diameter at 2.3 m. Stems were then felled, and stem disks were harvested at 0.3 m and at every meter to quantify radial growth. Stem disk preparation, measurements, and analyses followed standard protocols used in dendroecology [32]. Cross dating was done manually and validated with COFECHA [33]. Height, diameter, and volume growth calculation from stem analyses were performed using the XLStem option in WinDendro [34] based on Carmean [35] who used the mean annual radii growth and age of all stem disks. Annual height growth was estimated by using the age difference between two successive stem sections. The utilization of the annual height growth combined with the annual radial growth then allowed us to estimate the annual volume growth using the truncated cone formula [18]:

$$\text{Volume} = 1/3 \cdot \pi \cdot h\ (a^2 + ab + b^2)$$

where h = stem section height, a = largest radius, b = smallest radius.

2.4. Wood Density

A radial profile of wood density was obtained from a stem disk taken at 0.3 m in order to ensure that the chronosequence produced had the most growth rings free of root system influence. From each sample disk, a pith-to-bark strip of 25 mm in tangential direction by 1.7 mm in the longitudinal direction was cut using a twin-blade circular saw and stored in a conditioning room set to a temperature of 20 °C and relative humidity of 65% until constant mass corresponding to an equilibrium moisture content of approximately 12% was reached. Sample preparation included the removal of extraneous compounds by extracting with cyclohexane/ethanol (2:1) solution for 24 h and then with hot water for a further 24 h. Pith-to-bark density profiles were then measured using a QTRS-01X Tree Ring Analyzer (Quintek Measurement Systems Inc., Knoxville, TN, USA). The samples were scanned in the longitudinal direction with an X-ray beam at a resolution of 40 µm [36]. This process produced annual ring density, early- and latewood density, and latewood percentage values for the given spacing. The boundary between early- and latewood was defined according to the maximum derivative method using a six-degree polynomial with the Matlab® software [37]. Mean annual ring-, early-, and latewood density were calculated individually for the six spacing levels. Mean density values were also evaluated by regrouping tree rings classified as juvenile and mature wood separately. To determine the changes from juvenile to mature wood, the annual ring area was analyzed for each tree according to the method suggested by Sauter et al. [38] and Alteyrac et al. [39]. The transition was assessed for each tree using segmented linear regression. As there is no standardized method to discriminate between juvenile and mature wood, we chose to base our breaking point on ring area, which had a more evident segmentation compared with other properties (e.g., maximum density). The mean number of tree rings in the juvenile wood varied between seven for the narrowly spaced jack pine and nine for the widest spacing. After a cambial age of twelve years, all tree samples were classified as mature wood.

2.5. MOE and MOR Tests

Bending tests were performed according to ASTM D143-09 standard for small clear specimens on samples (2.5 cm × 2.5 cm × 41 cm) collected from the stem at a height of between 0.5 and 1 m [40]. Consecutives samples were taken close to the pith (sample A, cambial age 0 to maximum 8) going outwards to the bark (sample B, cambial age over 12). All samples were conditioned at 20 °C and 65% relative humidity until they reached a stable moisture content of ca. 12%. During the bending tests, the pith side of each sample was oriented upwards. The MOE and MOR were assessed using an MTS-Alliance RT/100 machine (TestResources Inc., Shakopee, MN, USA). Samples were either classified as "A", containing mainly juvenile wood, or "B" a combination of juvenile and mature wood.

2.6. Statistical Analyses

One-way analysis of variance (ANOVA) for a randomized block design was used for total height, DBH, stem volume, stem taper, largest branch diameter, longest branch length, and live crown ratio as dependent variables with plantation spacing as the main factor in the fixed part of the model. Wood quality parameters (percentage of latewood, earlywood density, latewood density, and ring average density) were submitted to two-way ANOVA with fixed effects consisting of plantation spacing as the main factor, wood type (juvenile vs. mature) as the sub-factor, and their interaction. Two-way ANOVAs were performed on MOE and MOR, this time with fixed effects consisting of plantation spacing as the main factor, distance from the pith (sample A vs. sample B) as the sub-factor, and their interaction. In all analyses the experimental blocks were considered as random effects. The MIXED procedure of SAS (SAS Institute, Cary, NC, USA) was used for all analyses [41]. Fisher's protected least significant difference (LSD) tests were used to compare differences between treatments ($\alpha = 0.05$). We used the Kenward-Rogers method of degrees of freedom approximation, as it performs better than other testing procedures under small sample conditions [42]. Normality and homoscedasticity were verified using standard graphical approaches. Natural logarithmic transformations were made when necessary; back-transformed means and 95% confidence intervals with bias correction are presented when appropriate [43]. Because the interaction between wood type and spacing was significant for % of latewood, earlywood density, and latewood density, the SLICE command in the MIXED procedure was applied after the ANOVA to determine if each wood type was influenced significantly by the spacing treatment. When either wood type was not significantly influenced by spacing, we presented overall results for the wood type, provided that the latter had a significant effect.

3. Results

3.1. Growth Rate

Plantation spacing had a significant effect on DBH and stem volume for dominant stems (Table 2, Figure 1a,b). The two widest spacings (1111, 1666 trees/ha) had DBH values 17% higher than the 2222, 2500, and 3333 trees/ha (15.36 cm ± 0.68 vs. 13.09 cm ± 0.68). The latter three densities had DBH value 19% higher on average than the 4444 trees/ha spacing (11.00 cm ± 0.69). For stem volume, no significant difference was found between 1666 and 3333 trees/ha (100.06 dm^3 ± 13.92). The 1111 trees/ha spacing (137.73 dm^3 ± 13.87) was 37% higher than those and 96% higher than the 4444 trees/ha spacing (70.00 dm^3 ± 13.87). Contrary to DBH, tree height (12.58 m ± 0.58) and stem taper (0.16 ± 0.01) were not significantly affected by the plantation spacing (Table 2).

Table 2. Analysis of variance (ANOVA) results for jack pine height, diameter at breast height (DBH, 1.3 m), stem volume and taper, live crown ratio, largest branch diameter, and longest branch, 25 years following planting in eastern Canada. *ndf*: numerator degrees of freedom, *ddf*: denominator degrees of freedom; calculated using the Kenward-Roger method. Bold indicates significance ($p \leq 0.05$).

Effect (Fixed)		**Height**			**DBH**			**Volume**			**Stem Taper ***		
	ndf	*ddf*	*F*	*Pr > F*	*ddf*	*F*	*Pr > F*	*ddf*	*F*	*Pr > F*	*ddf*	*F*	*Pr > F*
Spacing	5	10	0.82	0.565	9.6	9.58	**0.002**	10	3.70	**0.037**	251	0.65	0.659
		Live crown ratio			**Biggest branch diameter**			**Longest branch ***					
	ndf	*ddf*	*F*	*Pr > F*	*ddf*	*F*	*Pr > F*	*ddf*	*F*	*Pr > F*			
Spacing	5	12.4	4.43	**0.015**	11.9	4.48	**0.016**	78	4.40	**0.001**			

* Analyses performed on ln-transformed data.

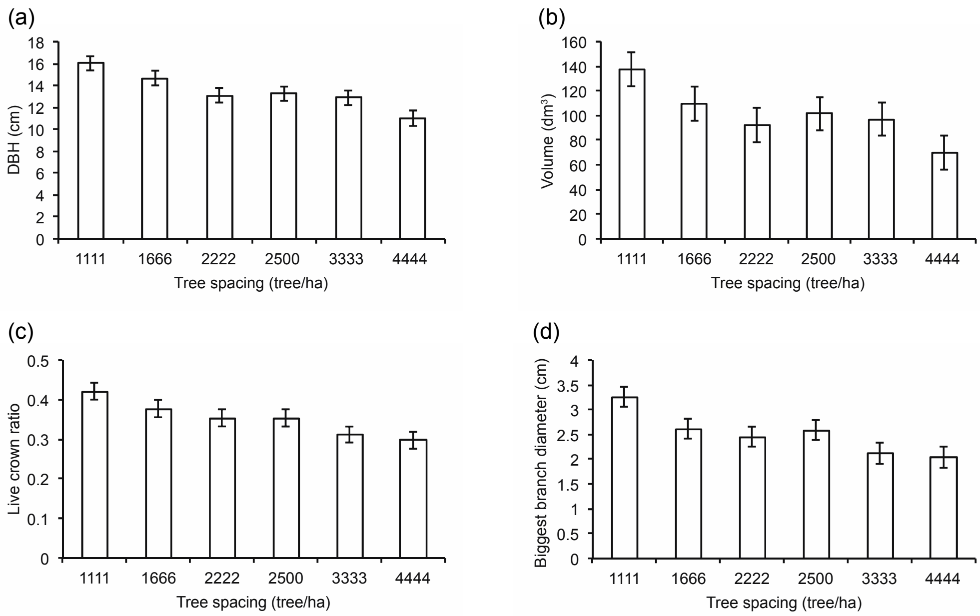

Figure 1. Effect of tree spacing on diameter at breast height (DBH) (**a**); stem volume (**b**); live crown ratio (**c**); and largest branch diameter (**d**) for jack pine 25 years following planting in Quebec, Canada. Data presented are the means (±SE).

An increase in both DBH and height increment rate was measured between 1988 and 1994 (Figure 2a,b); afterwards, height growth stabilized before declining slightly. We observed a 70% decline in DBH growth between 1994 and 2006; the DBH growth was then approximately 2 mm per year, regardless of plantation spacing. Instead, volume growth rate of individual trees increased linearly from 1988 to 2002 approximately when it reached an asymptote (Figure 2c). The highest growth rate was measured for the 1111 trees/ha spacing and was approximately twice that of the 4444 trees/ha spacing in 2012.

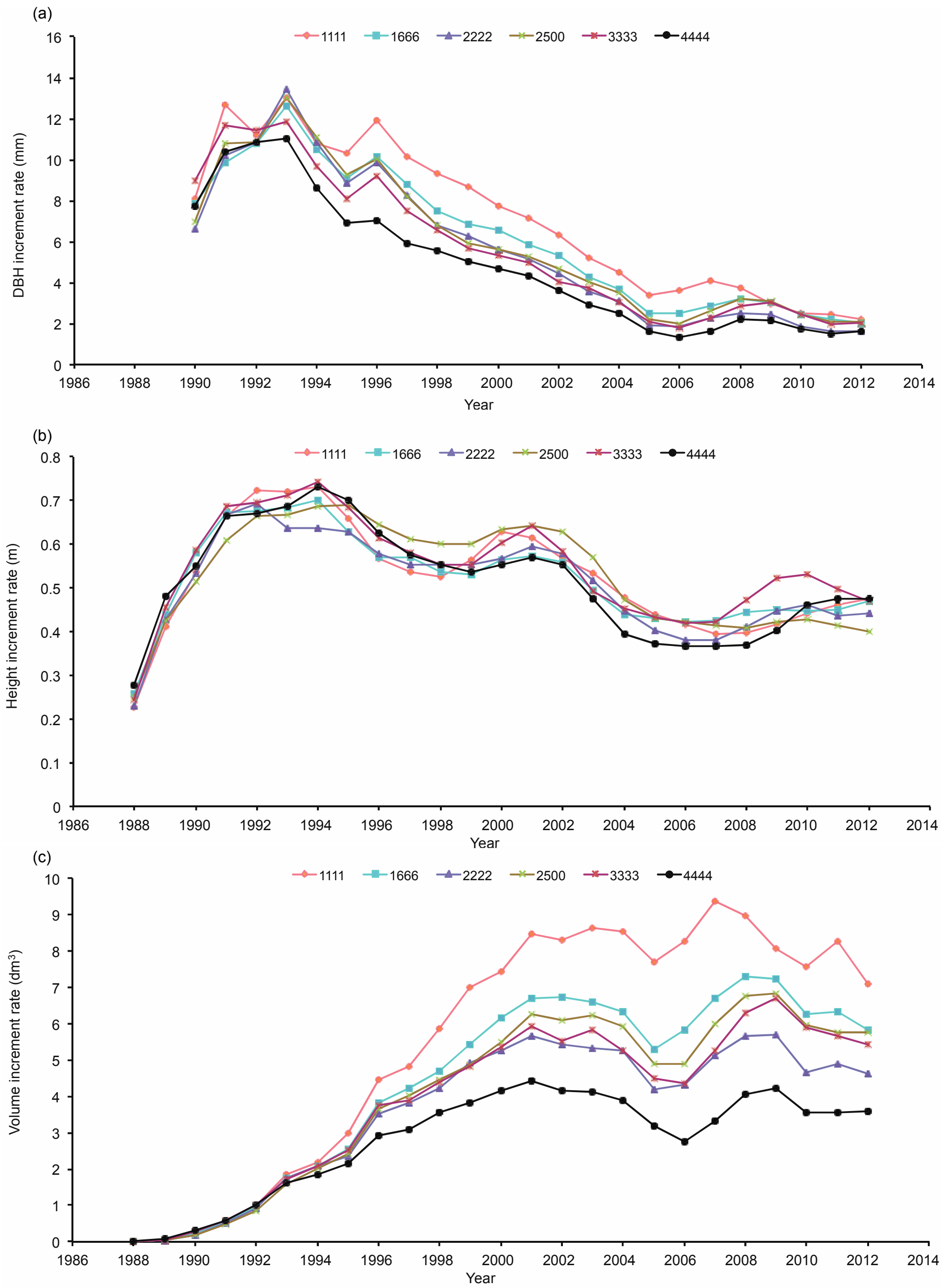

Figure 2. Annual diameter at breast height (DBH) (**a**); height (**b**); and (**c**) stem volume increment rate at different tree spacing for jack pine 25 years following planting in Quebec, Canada.

3.2. Tree Morphology

Plantation spacing did not influence stem taper but had a significant effect on the live crown ratio, largest branch diameter, and length of the longest branch for the dominant jack pines (Table 2). The largest crown ratio was found in the 1111 trees/ha spacing (0.42 ± 0.02) and was 38% higher than that of 3333 and 4444 trees/ha (0.30 ± 0.02) (Figure 1c). The diameter of the largest branch was also bigger in the 1111 trees/ha spacing (3.26 cm ± 0.21), being 57% higher than in the 3333 and 4444 trees/ha (2.07 cm ± 0.21) (Figure 1d). Regression analysis showed that the diameter of the largest branch was positively correlated to the tree DBH, regardless of the plantation spacing, with an R^2 value of 0.38 ($p < 0.001$) (Figure 3a).

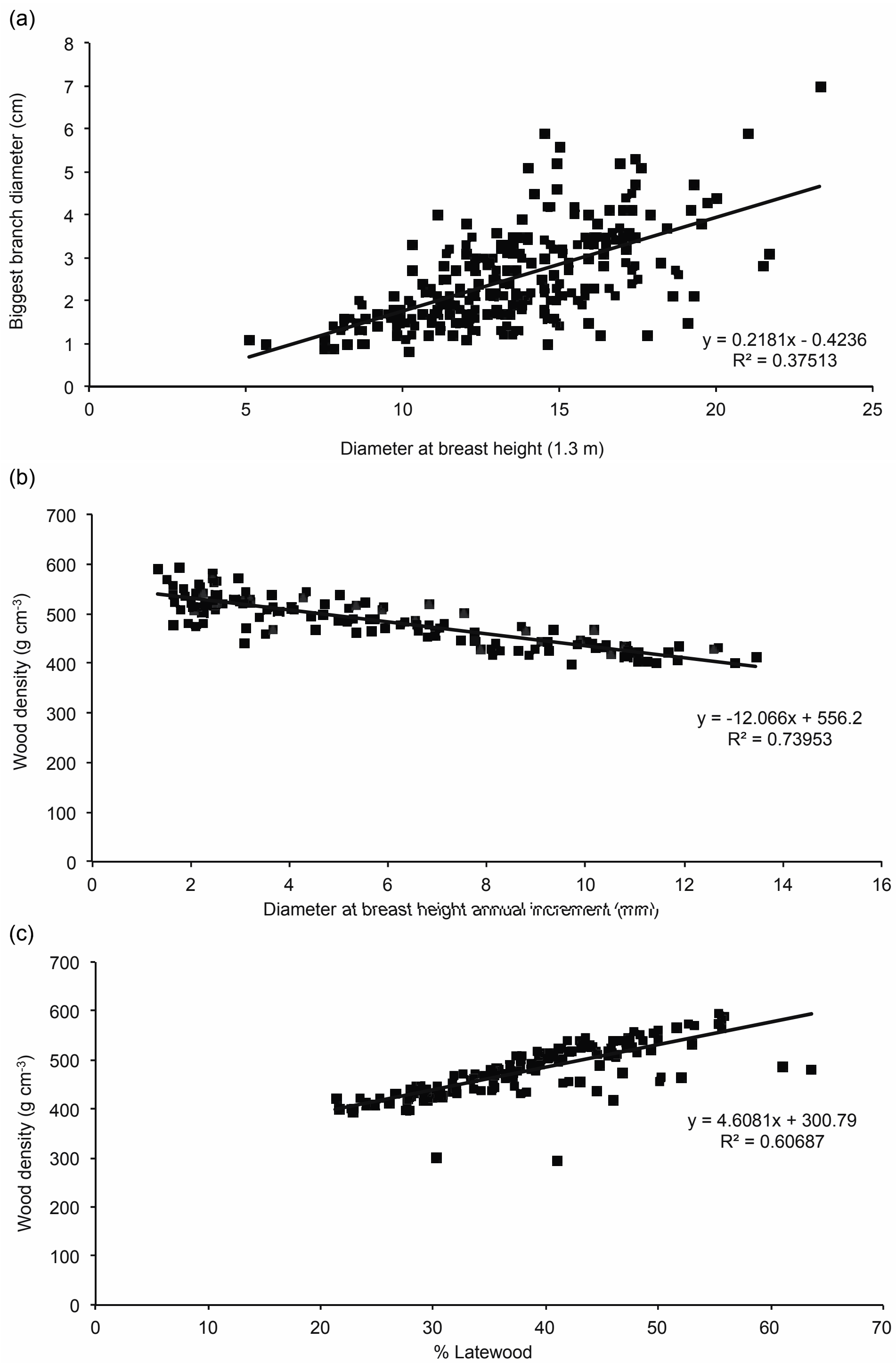

Figure 3. Relationship between diameter at breast height (DBH) and largest branch diameter (**a**); DBH annual radial increment and wood density (**b**); and percentage of latewood and wood density (**c**) for jack pine 25 years following planting in Quebec, Canada.

3.3. Wood Properties

Generally, the plantation spacing had an impact on the number of juvenile wood rings, which increased from 7 to 9 years from the narrowest to the widest spacing (Table 3).

Table 3. Jack pine number of juvenile tree rings (mean (SE)) for each plantation density.

Density (Tree/ha)	Number of Juvenile Tree Rings
1111	9.1 (2.2)
1666	7.7 (2.0)
2222	8.3 (0.5)
2500	8.1 (1.4)
3333	8.1 (1.1)
4444	7.1 (1.4)

A significant interaction between wood type (juvenile/mature) and plantation spacing was found for % of latewood, earlywood, and latewood densities (Table 4). However, the post hoc analysis revealed that the proportion of latewood and the latewood density, for each wood type, was not influenced by plantation spacing. The ANOVA showed a significant effect of wood type for both variables, which were higher in mature wood than juvenile wood (Table 4, Figure 4a,c).

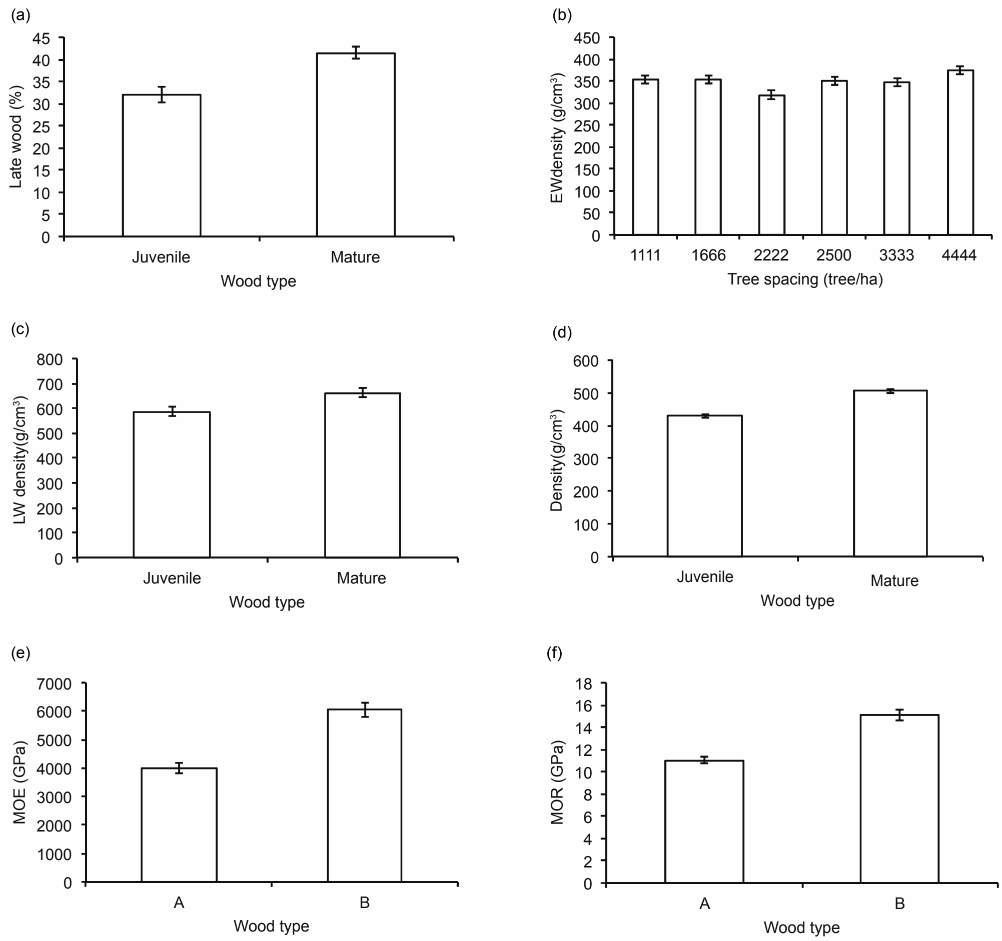

Figure 4. Effect of wood type on percentage of latewood (**a**); latewood density (**c**); mean wood density (**d**); modulus of elasticity (MOE) (**e**); modulus of rupture (MOR) (**f**); and effect of tree spacing on the earlywood density of juvenile wood (**b**) for jack pine 25 years following planting in Quebec, Canada. Data presented are the means (±SE).

Table 4. Analysis of variance (ANOVA) results for jack pine percentage of latewood, earlywood, latewood, and average wood density 25 years following planting in eastern Canada. *ndf*: numerator degrees of freedom, *ddf*: denominator degrees of freedom; calculated using the Kenward-Roger method. Wood type refers to juvenile or mature wood. Bold indicates significance ($p \leq 0.05$).

Effect (Fixed)		% Latewood			Earlywood Density			Latewood Density			Wood Density		
	ndf	*ddf*	*F*	*Pr > F*	*ddf*	*F*	*Pr > F*	*ddf*	*F*	*Pr > F*	*ddf*	*F*	*Pr > F*
Spacing (S)	5	93.5	1.54	0.185	9.96	1.94	0.175	12.2	0.32	0.892	10.4	1.33	0.323
Wood type (WT)	1	1996	184.96	**<0.001**	1977	19.20	**<0.001**	1977	1110.73	**<0.001**	1976	777.32	**<0.001**
S × WT	5	1996	2.91	**0.013**	1977	6.07	**<0.001**	1977	5.45	**<0.001**	1976	1.50	0.187

Earlywood density was similar between wood types and plantation spacings with the only exception being juvenile wood in the 2222 trees/ha, which was 12% lower than the other spacings (318 g·m^{-3} ± 9.58 vs. 355 g·m^{-3} ± 9.20) (Figure 4b).

MOE or MOR were not dependent on plantation spacing (MOE: 5017.26 GPa ± 211.89; MOR: 13.05 GPa ± 0.38) and were both higher (51% for MOE and 36% for MOR) in the wood sample closest to the bark (sample B) (Table 5, Figure 4e,f).

Table 5. Analysis of variance (ANOVA) results for jack pine modulus of elasticity (MOE) and modulus of rupture (MOR) 25 years following planting in eastern Canada. *ndf*: numerator degrees of freedom, *ddf*: denominator degrees of freedom; calculated using the Kenward-Roger method. Bold indicates significance ($p \leq 0.05$)

Effect (Fixed)		MOE			MOR		
	ndf	*ddf*	*F*	*Pr > F*	*ddf*	*F*	*Pr > F*
Spacing (S)	5	12.1	1.37	0.301	10.2	0.62	0.691
Sample location (SP)	1	19.3	51.74	**<0.001**	95.5	52.88	**<0.001**
S × SP	5	12.6	1.11	0.404	90.5	0.88	0.500

The mean ring density was not influenced by plantation spacing, but was 17% higher in the mature wood (505.56 g·m^{-3} ± 5.89 vs. 430.39 g·m^{-3} ± 6.14) (Table 4, Figure 4d). Mean ring density increased slightly over the years from plantation establishment (Figure 5a) and the same trend was observed for latewood percentage (Figure 5b). Regardless of tree spacing, the diameter of the largest branch was positively correlated with DBH (Figure 3a; $p < 0.001$). Also, mean ring density was negatively correlated with DBH annual increment and positively correlated with the % of latewood, with R^2 values of 0.74 and 0.61, respectively ($p < 0.001$ for all regressions analyses) (Figure 3b,c).

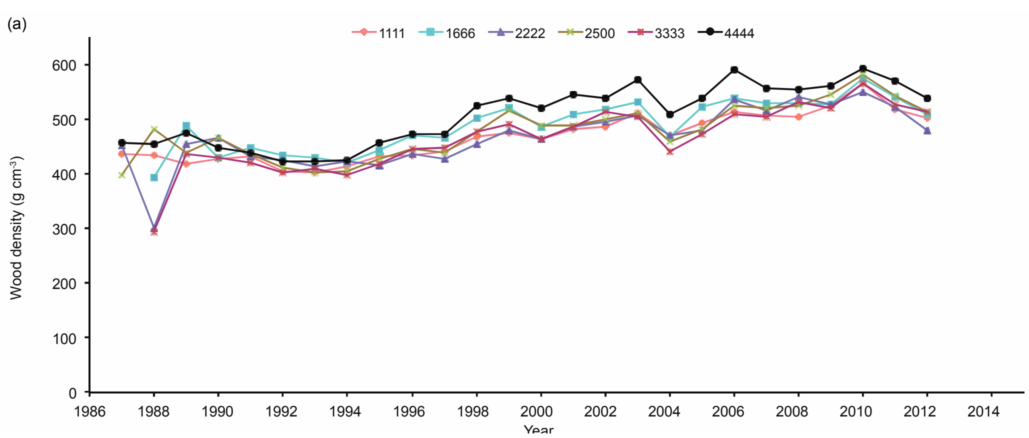

Figure 5. *Cont.*

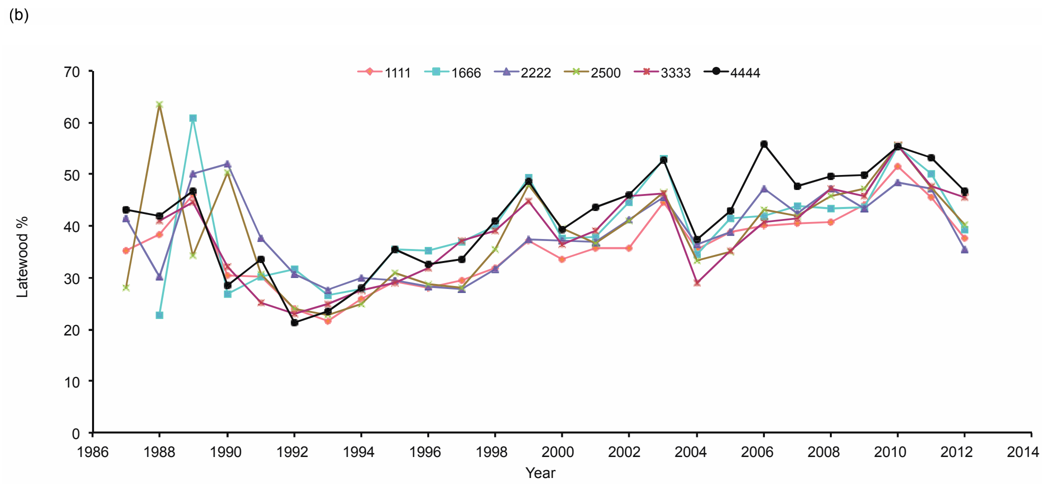

Figure 5. Annual wood density (**a**) and percentage of latewood (**b**) at different tree spacing for jack pine 25 years following planting in Quebec, Canada.

4. Discussion

4.1. Spacing and Tree Growth

Plantation spacing is known to influence tree growth and the morphology of individual trees [44]. In this study spacing had a significant impact on the DBH, but not on tree height. McEvoy [45] and Cardoso et al. [4] already reported/stated that spacing did not affect the height growth of dominant stems in *Pinus taeda*, probably because the tree densities were too low to create a high enough level of light competition to impair height growth. In our study, stem height inside each plot varied less than 1.5 m due to the selection of only dominant trees, suggesting light accessibility was similar between trees. If suppressed, co-dominant, and dominant trees had been selected, spacing would likely have influenced not only height growth but also tree mortality [46]. However, several authors reported a significant increase in diameter growth for different trees species in plantations with a low number of trees per hectare, due to a better tree crown development [2,47].

Contrary to our hypothesis, and to Sharma and Parton [48] who found an important decrease of stem diameter with tree height in jack pine, the plantation spacing gradient from 1111 to 4444 trees per hectare did not affect the taper of the jack pine stems 25 years after plantation. It seems that the DBH increase was not sufficient to change the stem taper. By looking at the chronosequence of DBH growth, the narrowest and widest plantation spacings differed from the intermediate ones starting from the planting age of seven years. These differences lasted only a limited period of time. As the study site is located at the northern limit of the eastern yellow birch/balsam fir bioclimatic sub-domain [30] and on humo-ferric podzols, the growth conditions can be considered to be "poor".

In our study, the differences of DBH with regard to plantation spacing seem to result from the early growth stage by developing a longer living crown at the widest spacing of 1111 trees/ha compared with the narrowest spacing of 4444 trees/ha. Diameter growth has been positively related to photosynthetic biomass and its efficiency [26,27,47], as well as to the relationships between crown ratio and stem taper [28,49–51]. Shade intolerant tree species, such as jack pine [52], exhibit a more open crown and a high photosynthetic capacity [53] and the dominant trees of this species seems to benefit from the sunlight access during the first years after plantation establishment. A reduction of photosynthesis and carbon production is normally observed when intra- and inter-specific competition occurs (crown closure). Twenty-five years after plantation, crown closure was not observed in the 1111 trees/ha plots (data not shown). Thus, crown closure cannot explain the decreasing diameter growth starting only 10 years after plantation in all plantation spacings. The photosynthetic efficiency might decrease rapidly for dominant jack pine without regard to plantation spacing. Under such slow growing conditions, we can speculate that it took several years to reach crown closure conditions even in the narrowest spacing. Such delay in the induction of competition between stems could explain the limited differences in stem taper.

The higher individual stem volume was obtained in the widest plantation spacing, which is in line with the results of several other studies [4,13,47,54]. Light penetration in the plantation with the widest spacing lengthened the survival of the lower branches so that their diameter and axial growth continued over a longer time span [3,52,55]. Branches in the lower crown have been reported to be dependent on local competition and the upper branches are more related to factors such as climate and site fertility [56]. The longer living crown increased the overall needle biomass and global photosynthesis rate of the individual tree, thereby producing more assimilates during the growing season [29]. Assimilates can be stored during non-photosynthetic periods and used for tree growth during the vegetation period and this can explain the tree volume increment [57]. A positive relationship between stem and branch diameter was obtained to support this statement.

4.2. Spacing and Wood Quality Attributes

Spacing distance did not influence any of the measured wood quality attributes, except for branch diameter and live crown ratio. It has already been reported that with an increase of radial growth in plantations with wider spacings, the earlywood proportion often increases [6,58], which is characterised by large cell lumen and relatively thin cell walls [59], and can consequently result in a decrease of the overall ring density. However, after 27 years of growth, no difference was found for the annual wood density. The annual wood density in jack pine seems not to be influenced by the plantation spacing over time, based on the observation that the wood density followed the same trend in the six different spacings. Thus, the stated decrease in wood density with an increase in plantation spacing [6,58] did not apply in our experimental plots. Nevertheless, the negative relationship found between annual wood density and DBH annual increment reveals the overall tendency that smaller trees form annual rings with higher wood density. By considering only wood density, plantations with a low number of trees/ha could be favoured if the objective is to maximize individual tree volume without significantly reducing wood density. Latewood density and percentage were also similar between the six plantation spacings, but a positive relationship was found between the percentage of latewood and annual ring density as well as a negative relationship with annual DBH annual increment. This means that during the formation of larger tree rings, the annual ring density and percentage of latewood generally tends to decrease. We can speculate that with a decreasing number of trees per hectare, the ring width increases whereas the latewood percentage could further change resulting in a negative impact on wood quality. However, since the gain in diameter growth was limited in time for wider spacings, we could not detect any changes in annual ring density or latewood percentage.

By looking at small clear samples, spacing seemed to have no effect on mechanical properties (MOE, MOR). The literature reported a significant increase of MOE with an increasing number of stems per hectare for different tree species [10,60–64]. The differing annual growth rate between plantation spacings seems to be insufficient to generate a noticeable difference in mechanical properties, but different results could be obtained by testing larger size samples [65]. On small clear samples, our results are partially in accordance with the work of Schneider et al. [66] for jack pine where the MOR, but not MOE, was affected by ring width. However, the higher values of branch diameter and larger number of overall branches (living and dead ones) at a wider spacing can affect mechanical properties when tested on pieces of commercial dimensions [67].

4.3. Wood Quality and Juvenile—Mature Wood

All studied wood quality parameters in the juvenile wood presented lower values than those of mature wood. Juvenile wood is known to form a lower wood density, shorter tracheids, lower latewood percentage, thinner cell walls, and smaller tangential cell dimensions [68]. Conversely, mature wood is more constant for the same wood parameters [69]. The influence of initial spacing has already been reported on the number of rings formed exhibiting juvenile wood characteristics in black spruce [70]. However, no relationship between spacing and juvenile wood formation has been reported more frequently [39,71,72]. The absence of a relationship was attributed to an insufficient range of stems per hectare in several studies [39]. Even with an increased number of juvenile tree rings in the widest spacing (approximately nine years) compared with the narrowest (approximately seven years), the difference seems small. However, because of a faster growth, the juvenile wood area was 2.5 times higher in trees from the 1111 stems/ha plantation compared to the 4444 stems/ha plantation (2319 mm^2 vs. 918 mm^2). There is a possibility that planting at less than 1000 stems/ha would induce a reduction in MOE and MOR values, which was not detected by the testing of small clear samples. Other studies, such as Zhang et al. [73] for ponderosa pine and Amateis et al. [74] for loblolly pine, found a correlation between initial plantation spacing and the modulus of elasticity. The absence of relationships between spacing and mechanical properties in this study might have differed if samples with knots had been tested compared to clear wood samples without or very small knots.

Overall, spacing did not significantly reduce the measured wood properties in this study, except for an increase in knot size. Pruning at an early age could reduce knot size, but this type of treatment is expensive. It is unlikely that the increased wood quality from pruning would make this treatment cost effective, especially in boreal plantations where the small tree size is an important limiting factor for lumber recovery. Therefore, wider initial spacing can be suggested for jack pine in plantations if increasing volume growth at the individual level is the prime goal.

5. Conclusions

Increased spacing between individual jack pine had the expected effect of increasing radial growth, especially in the lower stem. No significant reduction was found in wood density and mechanical resistance on small clear samples in relation to plantation spacing. However, the diameter of the largest branch increased with increasing distance between planted trees and should influence the overall mechanical properties of boards. Mechanical properties (MOE, MOR) were only affected by the position of the samples (juvenile/mature), but not by spacing. Based on these results, plantations with fewer trees per hectare could be prescribed for jack pine to increase individual volume growth. To ensure that wood quality of the overall stem is maintained, the increase of juvenile wood formation in relation to wider plantation spacing should be considered. Furthermore, other parameters, such as tracheid shape (length, diameter), microfibril angle of the cell wall, etc. should be examined to obtain a comprehensive overview of the relationship between wood quality attributes and spacing in jack pine plantations. The increased number and size of knots can also downgrade lumber for construction; this parameter should be further investigated. Finally, a low number of trees per hectare can also lead to other defects at early age like stem deformations, snow damage, etc. Further studies should therefore include those parameters and cover a longer lifespan.

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