Impact of initial spacing and precommercial thinning on jack pine tree growth and stem quality

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ABSTRACT

The objective of this paper was to investigate the impact of initial spacing and pre-commercial thinning (PCT) on tree growth, characteristics and stem quality in plantation-grown jack pine (*Pinus banksiana* Lamb.) after 58 years of growth. Four spacings including three initial spacings without PCT treatment, i.e., 1.52×1.52 m (5×5 ft), 2.13×2.13 m (7×7 ft) and 2.74×2.74 m (9×9 ft) and one initial spacing with PCT treatment (5×5 ft thinned to 7×7 ft at age 14), were chosen to analyze diameter at breast height (DBH) distribution, survival, and various tree and stem quality characteristics (e.g., DBH, total tree height, stem volume, crown size, branch, taper, sweep and wobbling). Tree mortality during the first 25 growth years was quite low for all four spacings, while after 25 years, survival for the four spacings rapidly declined. The decrease in survival for spacing 5×5 was the steepest, followed by spacings 7×7 , 9×9 and finally the PCT-treated stand. DBH distributions for all four spacings were significantly different from each other, and five years after PCT, the 5×5 to 7×7 spacings had a similar DBH distribution to that of the constant 7×7 spacing. Mean DBHs differed significantly among the initial spacings. The 5×5 spacing produced significantly smaller trees than did the other three spacings through the years, and the 9×9 spacing produced significantly larger trees. PCT had positive effects on DBH growth, and yielded longer merchantable stems and better stem quality. PCT had little effect on crown development. Initial spacing significantly affected diameter growth, crown width and branch development, commercial stem length and volume, stem taper and stem deformation. Narrower spacing produced smaller but better quality stems. Spacing 7×7 had the worst stem quality in terms of overall sweep and wave-like transversal deformation (wobbling). A narrow initial spacing followed by a PCT treatment may provide a compromise solution for both tree growth and stem quality.

Key words: Initial spacing, thinning, survival, tree growth, stem quality

RÉSUMÉ

L'objectif de cet article était d'étudier l'incidence de l'espacement initial et de l'éclaircie précommerciale (EPC) sur la croissance des arbres, les caractéristiques et la qualité des tiges de pin gris issu (*Pinus banksiana* Lamb.) de plantation après 58 ans de croissance. Quatre espacements comprenant trois espacements initiaux sans traitement d'EPC, c'est-à-dire, $1,52$ m $\times$ $1,52$ m (5 pieds $\times$ 5 pieds), $2,13$ m $\times$ $2,13$ m (7 pieds $\times$ 7 pieds) et $2,74$ m $\times$ $2,74$ m (9 pieds $\times$ 9 pieds) et un espacement initial suivi d'une EPC (5×5 éclairci à 7×7 à 14 ans) ont été retenus pour étudier la distribution du diamètre à hauteur de poitrine (dhp), le taux de survie et les différentes caractéristiques de la qualité des arbres et des tiges (par ex., le dhp, la hauteur totale de l'arbre, le diamètre de la cime, les branches, le défilement, la courbure et le balancement). La mortalité des tiges au cours des 25 premières années de croissance a été très faible dans le cas des quatre espacements, tandis qu'après 25 ans, la survie des tiges de ces quatre espacements a décliné rapidement. La chute de la survie dans le cas de l'espacement de 5×5 a été la plus prononcée, suivie des espacements 7×7 , 9×9 et finalement par le peuplement traité par EPC. La distribution des dhp pour les quatre espacements était significativement différente les uns des autres et cinq ans après l'EPC, l'espacement de 5×5 éclairci à 7×7 démontrait une distribution des dhp semblable à l'espacement constant de 7×7 . Le dhp moyen variait de façon significative selon les espacements initiaux. L'espacement initial de 5×5 a engendré des arbres significativement plus petits que dans le cas des trois autres espacements au cours des ans et l'espacement 9×9 a produit des arbres significativement plus gros. L'EPC a entraîné des effets positifs sur l'augmentation du dhp et a produit des tiges marchandes plus longues et de meilleure qualité. L'EPC a eu peu d'effet sur la croissance de la cime. L'espacement initial a eu une incidence significative sur la croissance en diamètre, le diamètre de la cime et le développement des branches, sur la longueur de la tige marchande et son volume, sur le défilement de la tige et sa déformation transversale. Un espacement plus étroit a engendré des tiges plus petites mais de meilleure qualité. L'espacement 7×7 a entraîné la pire qualité de tige en terme de courbure générale et de déformation transversale semblable à des ondulations. Un espacement initial étroit suivi d'une EPC pourrait constituer une solution de compromis tant au niveau de la croissance de l'arbre que de la qualité de la tige.

Mots clés : espacement initial, éclaircie, survie, croissance de l'arbre, qualité de la tige

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Introduction

Reforestation programs in Canada have increased substantially since the 1970s in order to sustain long-term wood supply and to preserve forest resources. Jack pine (*Pinus banksiana* Lamb.) is one of the most commercially important reforestation species in eastern Canada, with over one hundred thousand hectares of jack pine plantations established each year (Canadian Council of Forest Ministers 1996). In general, jack pine trees from plantations have inferior form compared to those from natural stands. Furthermore, a number of jack pine plantations established in Ontario and neighbouring jurisdictions since the 1960s produced trees with some degree of stem deformation (e.g., sweep and crook; Armson 1977, Heikurinen 1977, Segaran *et al* 1978, Nichols and Alm 1983, Beaudoin 1993). Traditionally, this species has been managed for maximum volume, but wood quality for lumber and paper manufacturing is not constant among each unit volume of wood grown. Consequently, it makes sense to manage jack pine stands for high quality wood and maximum value rather than merely wood volume. To this end, questions are arising as to how forest management decisions, such as initial spacing, thinning, pruning, and rotation age affect tree growth, stem and wood qualities of jack pine.

Initial spacing and precommercial thinning (PCT) are among the most effective tools used to control tree growth and wood quality (e.g., Evert 1971, Daniel *et al* 1979, Bell *et al* 1990, Zhang *et al* 2002). For decades, the relationships of initial spacing with tree growth and yield have been intensively studied to determine optimum spacing. Similarly, the effect of initial spacing on wood characteristics and properties have also been evaluated for many species such as black spruce (Zhang *et al* 2002, Zhang and Lei 2005), Douglas-fir, western hemlock and western red cedar (Smith 1980), red pine (Stiell and Berry 1973a) and white spruce (Stiell and Berry 1973b). Generally, while wider spacing will accelerate the diameter and stem volume growth of individual trees (Stiell and Berry 1973a, b; Bella and DeFranceschi 1974, 1980, Zavitkovski and Dawson 1978), improve tree survival (Janas and Brand 1988, Bowling 1998), and reduce rotation age (Morris *et al* 1994, Bowling 1998), it has been recognized that this has negative effects on stem and wood quality (Poynton, 1959–1960, Smith 1980, McClain *et al* 1994, Zhang *et al* 2002). Specifically, increased spacing in jack pine plantations increases branch angle, diameter and length (Magnussen and Yeatman 1987a, b).

The objective of this study was to examine the impact of density reputation on tree growth, tree characteristics and stem quality of jack pine after 58 years of growth. The information produced from this study should provide a better understanding of the effect of density manipulation on product quality and hence result in improvements in forest management practices.

Materials and Methods

Materials

The sample trees came from one of the oldest jack pine initial spacing trials in northern Michigan (Wellston, Manistee County, Michigan (approx. 44°11'40"N, 85°54'30"W)). The trial was established in 1941 by the USDA with one-year-old seedlings. The site index was 12–15 m (Godman and Cooley, 1970). The spacing trial covered five spacings, i.e., 0.46 × 0.46 m (1.5 × 1.5 ft), 0.91 × 0.91 m (3 × 3 ft), 1.52 × 1.52 m (5 × 5 ft), 2.13 × 2.13 m (7 × 7 ft), and 2.74 × 2.74 m (9 × 9 ft), with each spacing replicated five times on square 0.162-ha plots arranged in a Latin Square Design (Rudolf 1951, Guilkey and Westing 1956, Godman and Cooley 1970). At age 14 (in 1954), thinning was carried out on selected blocks. In this analysis, three initial spacings (5 × 5, 7 × 7, and 9 × 9) were selected to evaluate the impact of initial spacing on tree growth, characteristics and stem quality. Additionally, a 5 × 5 initial spacing that was thinned to a 7 × 7 spacing at age 14 (5 × 5 to 7 × 7) was also included to determine the potential benefits of PCT. Measurements were carried out by the USDA at ages 14, 15, 20, 23, 32, 36 and 48. In 1998, the Ontario Ministry of Natural Resources (OMNR) carried out the last measurement for the stands. All trees in the plots of the selected spacings (viz. 5 × 5, 7 × 7, 9 × 9, and 5 × 5 to 7 × 7) were marked and measured for diameter at breast height (DBH) and survival status during each measurement. These measurements provided DBH class frequency distributions through the growth years for each of the four treatments. Five sample trees from each commercial 2 cm-width DBH class (≥ 10 cm) were randomly selected from each treatment to evaluate various tree characteristics and stem quality. However, there were a few exceptions where an insufficient number of trees was available from either the smallest or largest DBH classes. In addition, a few sample trees were missing and/or damaged during transportation. Specifically, from the 5 × 5 spacing, 35 sample trees were selected to cover 9 DBH classes (viz. 10–26 cm); 40 trees from the 5 × 5 to 7 × 7 spacing were selected to cover 8 DBH classes (viz. 12–26 cm); 34 trees from the 7 × 7 spacing covered 9 DBH classes (viz. 12–28 cm); and 36 trees from the 9 × 9 spacing were selected covering 10 DBH classes (viz. 12–30 cm). In total, 145 trees were used in this study.

For each sample tree selected, various tree characteristics were measured, including DBH, live crown length, crown widths in the north-south direction and in the west-east direction, total tree height, height to the base of the live crown, and height to the 10-cm diameter top (merchantable height). The diameters of the five largest branches in each sample tree were measured to serve as a branch diameter index as described by DeBell *et al* (1994). The presence and sizes of forks on the stem were also recorded for each sample tree. Table 1 provides the summary statistics of the 145 sample trees.

Table 1. Summary statistics for tree characteristics of the 145 plantation jack pine sample trees collected from three initial spacings of 5 × 5, 7 × 7 and 9 × 9 ft and one PCT stand (5 × 5 to 7 × 7 ft) thinned at age 14

Treatment	Statistic	DBH (cm)	Total Height (m)	Length below live crown (m)	Taper (cm/m)	Merchantable volume (dm ³)
5 × 5	Mean	17.9	17.5	12.5	0.76	181.3
	Std. Dev. ¹	4.33	2.17	1.33	0.18	116.0
	minimum	10.8	12.6	9.1	0.53	16.7
	maximum	26.9	21.8	15.1	1.31	474.0
5 × 5 to 7 × 7	Mean	17.9	17.8	13.0	0.77	196.0
	Std. Dev.	4.55	2.09	1.05	0.14	133.5
	minimum	11.1	11.3	9.7	0.48	12.5
	maximum	25.4	21.4	14.8	1.28	422.2
7 × 7	Mean	19.6	17.4	12.6	0.86	231.8
	Std. Dev.	4.24	1.51	1.28	0.17	127.2
	minimum	12.2	14.5	9.3	0.59	43.3
	maximum	27.4	19.7	14.6	1.35	483.1
9 × 9	Mean	19.9	17.2	11.9	0.90	231.4
	Std. Dev.	4.87	2.07	1.03	0.18	143.9
	minimum	12.6	13.3	10	0.61	15.3
	maximum	29.1	21	13.7	1.42	509.1

¹ standard deviation.

Methods

After delimbing, the stems were trucked to a nearby farm and then transported to a sawmill located in Quebec for processing. In the sawmill yard, each stem was scanned with Forintek's portable scanner (C1-Scan&Snap-Scan, COMACT Optimization). The scanner measured and recorded two cross-sectional diameters along the stem at 5-cm intervals from butt to top, and the location of each cross-sectional sample in 3-D space. With the scanned data, stem volume up to the 10-cm diameter top (merchantable stem volume), average stem taper (based on the 10-cm diameter top), and overall stem sweep (ratio of the largest deviation in cm along the stem to the stem length in m) were determined.

Besides stem sweep, back and forth transversal bending of the stem surface along the stem axis was noticed in all sampled trees (Fig. 1). Here, the term "wobbling" is used to describe this frequently occurring and wave-like stem deformation. Stem wobbling was related to the wave-like transversal deviations of the stem cross sections from the centroid-to-centroid straight line running from end to end. For each transversal back-and-forth cycle, it was measured at the point of greatest distance from the straight line. Frequency of wobbling per unit stem length, as well as average and largest wobbling degrees (ratio of the transversal deviation to the stem diameter at the deviation) for each sample tree were calculated based on the scanned data to evaluate density manipulation effects, if any. The higher the occurrence frequency per unit stem length and wobbling degree, the worse the stem quality. This study omitted wobbling whose degree was less than 10%.

After scanning, each stem was systematically bucked into 8-ft logs with a 4-in overlength (2.54 m). Information on log quality and lumber recovery, as well as the identity of each piece of lumber, was recorded during the log to lumber conversion process.

A Kolmogorov-Smirnov (K-S) test was conducted for differences in diameter distributions. The numbers of trees in each 1-cm diameter class were calculated for each treatment to further examine the diameter distributions. The numbers of trees per hectare for each of the four spacings were not the same for a given age because of differences in mortality and initial planting density. Therefore, diameters associated with successive quantiles (percentiles) of the distributions were determined to produce empirical versus empirical quantile-quantile (Q-Q) plots. An empirical versus empirical Q-Q plot graphically compares the distributions of two variables at each percentile. While a point on the unity line in the Q-Q plot suggests that the two variables have identical DBH values at the quantile, various departures from the unity line in the plot suggest different distributions.

In this study, the impact of density regulation was examined at two levels. At the DBH class level, we compared trees of the same DBH class from the four treatments. Additionally, based on the DBH class frequency distributions in 1998, weighted means of various tree characteristics measured on the sample trees were calculated for each spacing, allowing comparisons between the four spacings at the stand level. The weighted mean for each variable was calculated using the following equation:

$$[1] \quad M_w = \frac{\sum(n_i \bar{M}_i)}{\sum n_i}$$

where M_w is weighted mean value of variable M across all DBH classes, n_i is number of sample trees in the i^{th} DBH class, $i = 1, 2, 3, \dots$, $\bar{M}_i$ is mean value of the variable M over all sample trees within the i^{th} DBH class.

Fig. 1. Stem shape projection (West-East direction) and 3-D display of a jack pine tree sample.

Results and Discussion

Descriptive statistics for DBH across stand age from the four spacings are listed in Table 2. A Student-Newman-Keuls (SNK) means separation test was performed to evaluate the differences in mean DBH among the four spacings (Table 2). To evaluate the effect of density regulations on various tree characteristics, SNK multiple comparisons for means of various tree characteristics were conducted. The homogeneity of variances for the various tree characteristics and stem quality was assessed using Levene's test before applying the SNK multiple comparisons. Table 3 displays the P values of the Levene's test and SNK results. The homogeneity of variances held for all variables.

DBH

Average tree diameter increased steadily with increasing initial spacing in plantation-grown jack pine for all ages, as others have reported (e.g., Zhang and Chauret 2001). The SNK

results (Table 2) indicated that the mean DBH of spacing 5×5 was significantly smaller than those of the other spacings for all ages, and the mean DBH of spacing 9×9 was significantly greater than those of the others for all ages except for spacing 7×7 at ages 14, 15 and 58. However, there was no statistical difference in mean DBH between the 7×7 and 5×5 to 7×7 spacings from age 20 to age 48. At age 58, mean DBHs were significantly different between the 7×7 and the 5×5 to 7×7 spacings. This implies that trees in the 5×5 to 7×7 spacing grew so fast that within five years after PCT treatment, the mean DBH became similar to that of spacing 7×7 , suggesting that the PCT treatment may have accelerated tree diameter growth. However, the mean DBH of the thinned stand was still somewhat smaller than that of spacing 7×7 , which demonstrates the importance of early growth.

Quadratic mean DBH (DBHq) at age 58 was significantly distinct among the four spacings (Table 3). It was not surprising that the widest spacing of 9×9 produced the largest

Table 2. Descriptive statistics for DBH across stand age for jack pine spacing trial plots planted at three different initial spacings of 5×5 , 7×7 , and 9×9 ft and one PCT stand (5×5 to 7×7 ft) thinned at age 14

Stand age (Years)	Treatment	Mean ¹	Minimum	Maximum	Std. Dev. ²
14	5×5	5.8 ^C	2.2	8.6	1.5
	5×5 to 7×7	—	—	—	—
	7×7	7.0 ^A	1.7	10.6	1.9
	9×9	6.7 ^A	3.0	9.6	1.5
15	5×5	6.3 ^C	2.2	9.3	1.6
	5×5 to 7×7	6.9 ^B	3.8	11.1	1.2
	7×7	7.6 ^A	2.0	11.9	2.0
	9×9	7.5 ^A	3.8	10.4	1.6
20	5×5	7.9 ^C	2.7	12.1	2.0
	5×5 to 7×7	9.5 ^B	5.5	14.4	1.6
	7×7	9.7 ^B	3.0	14.9	2.5
	9×9	10.4 ^A	6.3	13.7	2.0
23	5×5	8.6 ^C	2.7	14.4	2.1
	5×5 to 7×7	10.2 ^B	5.5	15.7	1.8
	7×7	10.3 ^B	3.0	16.2	2.4
	9×9	11.3 ^A	2.7	18.2	2.6
32	5×5	11.0 ^C	6.0	17.5	2.1
	5×5 to 7×7	12.4 ^B	5.8	19.0	2.4
	7×7	12.7 ^B	4.8	19.5	2.6
	9×9	14.2 ^A	2.7	23.3	3.0
36	5×5	12.1 ^C	6.0	19.0	2.4
	5×5 to 7×7	13.5 ^B	8.8	20.8	2.6
	7×7	14.0 ^B	4.8	21.0	2.8
	9×9	15.6 ^A	7.6	24.8	3.0
48	5×5	15.2 ^C	9.3	22.8	2.8
	5×5 to 7×7	16.3 ^B	10.6	25.3	3.0
	7×7	16.9 ^B	10.4	26.1	3.0
	9×9	18.1 ^A	10.1	29.7	3.3
58	5×5	17.2 ^C	10.5	26.0	3.6
	5×5 to 7×7	18.3 ^B	11.4	26.6	3.4
	7×7	19.5 ^A	13.2	32.9	3.2
	9×9	20.1 ^A	6.1	31.9	3.7

¹Means with the same letter within a stand age were not significantly different at $p < 0.05$.²Standard deviation.

DBHq, and the narrowest spacing of 5×5 produced the smallest, while DBHq of the thinned stand (5×5 to 7×7) was intermediate between spacings 5×5 and 7×7 .

Survival

There were 867, 713, and 670 trees per hectare remaining after 58 years (1998) of growth in the 5×5 , 7×7 and 9×9 spacings, respectively. Fig. 2 illustrates the percentage of surviving trees over the growth years. Fourteen years after planting, seedling survival averaged 91, 89, and 93% for the 5×5 , 7×7 and 9×9 spacings, respectively. During the first 25 growth years, mortality for each of the four spacings was relatively moderate and mortality differences among the spacings were small. Cumulative survival in 1963 for the 5×5 to 7×7 spacings appeared to be slightly better than for the three initial spacings. After 1963, survival rates for each of the four spacings declined steeply (Fig. 2), suggesting that mortality occurred mostly after crown closure. On the other hand, sur-

vival rates at all ages increased steadily with increasing initial spacing from 5×5 ft to 9×9 ft, and this is consistent with Zavitskovski and Dawson (1978), as they reported that wider initial spacing improves survival. The thinned stand of 5×5 to 7×7 had an even better survival rate than the comparable unthinned spacing (Fig. 2), suggesting that PCT effectively improves tree survival in jack pine plantations.

DBH distribution

The K-S test was conducted by age among spacings and between any possible pair of the four spacings, i.e., 5×5 vs. 7×7 , 5×5 vs. 9×9 , 5×5 vs. 5×5 to 7×7 , 7×7 vs. 9×9 , 7×7 vs. 5×5 to 7×7 , and 9×9 vs. 5×5 to 7×7 . Overall, the K-S test indicated that diameter distributions from the four spacings were significantly different ($p < 0.001$) at any age. Diameter distributions were significantly different ($p < 0.001$) from each other at all ages except those at spacings 7×7 and 9×9 ($p < 0.105$) at age 15.

Table 3. Weighted means of tree characteristics and stem quality averaged across all DBH classes for the 5×5 , 7×7 , 9×9 and 5×5 to 7×7 spacings

Variables		Spacing				Levene's
		5×5	5×5 – to – 7×7	7×7	9×9	P value
Diameter	Quadratic mean DBH (cm)	17.6 ^D	18.6 ^C	19.6 ^B	20.5 ^A	0.2037
Height	Total tree height (m)	17.3 ^A	17.9 ^A	17.5 ^A	17.7 ^A	0.2314
	Height up to 10 cm top (m)	9.8 ^C	11.0 ^B	11.7 ^A	11.5 ^{A B}	0.2161
Volume	merchantable volume (dm ³)	162.9 ^D	204.3 ^C	223.4 ^B	235.6 ^A	0.3501
Crown	Crown length (m)	4.7 ^B	5.0 ^B	4.9 ^B	5.7 ^A	0.0903
	Live crown ratio (%)	26.3 ^B	27.1 ^B	28.1 ^B	31.9 ^A	0.2574
	Crown width (m)	2.7 ^C	2.8 ^C	3.5 ^B	3.8 ^A	0.8175
Branch	5 biggest branch diameter (cm)	30.8 ^C	33.6 ^B	35.1 ^B	37.9 ^A	0.188
Taper	Taper (to 10cm top) (cm/m)	0.71 ^C	0.76 ^B	0.80 ^B	0.88 ^A	0.743
Sweep	Overall stem sweep (cm/m)	1.04 ^B	0.98 ^B	1.34 ^A	1.04 ^B	0.1099
Wobbling	No. of occurrences/m (W-E)	3.7 ^A	3.9 ^A	3.8 ^A	3.6 ^A	0.1598
	No. of occurrences/m (N-S)	3.4 ^B	3.7 ^{A B}	4.1 ^A	3.1 ^B	0.1117
	Average wobbling (W-E) (%)	38.2 ^B	33.1 ^B	47.4 ^A	35.1 ^B	0.0769
	Average wobbling (N-S) (%)	34.2 ^B	34.4 ^B	44.2 ^A	37.4 ^{A B}	0.5257
	Largest Wobbling (W-E) (%)	64.3 ^B	59.8 ^B	94.7 ^A	64.9 ^B	0.1317
	Largest Wobbling (N-S) (%)	61.0 ^B	61.9 ^B	86.9 ^A	67.3 ^B	0.376

Note:

1. Means followed by the same letter within a row are not significantly different at $p < 0.05$.

2. Percentage wobbling was calculated as percentage ratio of bole deviation to stem diameter at deviation.

Empirical versus empirical Q-Q plots for two pairs of spacings (i.e., 7×7 vs. 5×5 to 7×7 and 7×7 vs. 9×9) were produced at ages 15 and 58 for diameter distributions (Fig. 3). There were obvious differences between spacings 7×7 and 5×5 to 7×7 at both ages 15 and 58, and between spacings 7×7 and 9×9 at age 58, as the points of diameter pairs for each percentile deviated far from the unity line. No apparent difference could be observed between spacings 7×7 and 9×9 at age 15. As expected, wider spacing produced bigger trees (Fig. 3). Though DBHs in each quantile from the PCT stand were considerably smaller than those from the 7×7 initial spacing (Fig. 3) due to the slower early growth before thinning, PCT appeared to benefit DBH growth, as the Q-Q plot for age 58 demonstrates a more consistent tendency with the unity line than it does for age 15.

Tree height, volume and crown size

Tree height increased steadily with increasing DBH for all four spacings (Table 4). Tree heights of the same DBH class were not significantly different among the four spacings except for DBH classes 12 and 20 cm. At the stand level, the SNK tests did not show significant differences in total tree height among the four spacings (Table 3). In terms of merchantable height, trees of the same DBH class among the four spacings were not significantly different (Table 4). The SNK means separation test, however, showed that the two widest spacings (7×7 and 9×9) produced significantly longer merchantable stems than did the narrowest spacing ($p < 0.05$), and the PCT stand (5×5 to 7×7) produced an intermedi-

Fig. 2. Tree survival over growth years for three initial spacings of 5×5 , 7×7 and 9×9 ft and one PCT stand (5×5 to 7×7 ft) thinned at age 14.

ate merchantable height (Table 3). There were no differences in merchantable height between the two widest spacings. Merchantable height of the PCT stand was significantly longer than that of the unthinned 5×5 spacing but significantly shorter than that of spacing 7×7 (Table 3). Merchantable height dramatically increased with increasing DBH up to 20 cm. It tended to be constant for trees larger than 20 cm.

Fig. 3. Empirical versus empirical Q-Q plots for diameter distributions of the 7×7 and 5×5 to 7×7 spacings (left), and the 7×7 and 9×9 spacings (right) for ages 15 and 58. The diagonal line is the unity line indicating equality of diameters at each percentile.

For a given DBH class, the differences in average merchantable stem volume per tree among the four spacings were not statistically significant except for the 22-cm DBH class (Table 4). Merchantable volume of individual stems increased with initial spacing, and stem volume of the thinned treatment was greater than that of the unthinned 5×5 spacing and less than that of the 7×7 spacing (Table 3). The thinned stand produced considerably more merchantable stem volume per tree (20.3%) than the unthinned 5×5 spacing; however, it produced only 9% less than spacing 7×7 , suggesting that while being somewhat of a compromise, PCT has a positive effect on the merchantable stem volume of individual trees. This demonstrated similar patterns to merchantable tree height, where the difference in merchantable height between spacings 5×5 and 5×5 to 7×7 was larger than that between spacings 7×7 and 5×5 to 7×7 , while the quadratic mean DBH of the thinned stand was intermediate to those for spacings 5×5 and 7×7 .

There were no significant differences in live crown length of the same DBH class among the four spacings except for the 26 cm DBH class (Table 4). As expected, live crown length increased with increasing DBH. There were no significant differences in live crown length among DBH classes of the same treatment. Spacing 9×9 produced a remarkably longer live crown than did the other three spacings, among which no obvious differences could be found (Table 3). A similar trend was applicable to the proportion of live crown length to total tree height (Tables 3 and 4).

Live crown width increased noticeably with tree diameter (Table 4). Generally, trees of the same DBH class from the wider initial spacing had a larger live crown width. The SNK test indicated significantly different crown widths among the three initial spacings (Table 3). This suggests that a tree grown in a more widely spaced plantation generally produces a larger crown (Maeglin 1967, Wambach 1967, Reukema 1979, Smith 1980, McClain *et al* 1994, Zhang *et al* 2002). However, trees from spacings 5×5 and 5×5 to 7×7 demonstrated comparable live crown widths for all DBH classes (Table 4). The SNK test further designated an insignificant difference between the two spacings (Table 3). This indicates that PCT treatment does not significantly affect the development of live

crown width. As larger crown width usually implies more and bigger knots and thus lower wood quality (McClain *et al* 1994, Zhang *et al* 2002), increasing the initial spacing may have a negative impact on wood quality. Therefore, PCT treatment for the narrow initial spacing is a possible solution to not only accelerate tree growth but also improve stem quality.

Stem quality

Forks on stems are considered as a serious stem deformation, as forks greatly reduce the diameter along the stem and usually produce big knots and crooks. The development of forks in plantation-grown jack pine occurred quite high on the stem and produced a dominant leader. Out of the 145 trees collected in this study, 30 trees had forks, which represented 20.7% of the total sample. Stand density did not appear to affect the development of forks since trees with forks were fairly uniformly distributed over the four spacings (Table 4). There were 22.9, 26.5, 16.7 and 17.5 % of sample trees affected by fork for spacings 5×5 , 7×7 , 9×9 , and 5×5 to 7×7 , respectively. The occurrence of fewer trees affected by forks in the thinned stand may be due to the PCT operation, in which some of the trees with forks were removed. Trees with forks were well distributed between DBH classes in each of the four spacings. In addition, there were no obvious differences in the percentage of trees affected by forks for the same DBH class among the four spacings.

The average diameter of the five biggest branches increased steadily with increasing DBH (Table 4). There were no significant differences in branch diameter among trees of the same diameter for the four spacings. At the stand level, branch diameters increased with increasing initial spacing (Table 3). The SNK means separation test indicated significant distinctions in branch diameter among the three initial spacings and insignificant difference between spacings 7×7 and 5×5 to 7×7 . Table 5 lists the knot size restriction required by the National Lumber Grades Authority (NLGA 1996) for the Select Structural grade of different nominal lumber widths. The branch diameters of all four spacings for all DBH classes were greater than the restricted knot sizes for "2 $\times$ 3" and "2 $\times$ 4," and a large percentage of branches also exceeded the

Table 4. Tree characteristics and stem quality by DBH class measured on the 145 sample jack pine trees collected from 3 initial spacings of 5×5 , 7×7 , and 9×9 ft and one PCT stand (5×5 – to – 7×7 ft) thinned at age 14

Variable	Treatment	DBH class (cm)										
		10	12	14	16	18	20	22	24	26	28	30
Total height (m)	5 × 5	12.6	15.4 ^A	15.9	16.7	17.1	19.8 ^A	18.9	19.1	21.1	—	—
	5 × 5 to 7 × 7	—	15.9 ^A	14.6	17.6	18.3	18.7 ^{AB}	19.7	19.8	20.2	—	—
	7 × 7	—	15.5 ^A	15.7	16.8	17.5	17.0 ^B	18.2	18.9	18.0	19.4	—
	9 × 9	—	13.4 ^B	14.9	15.8	17.4	18.2 ^{AB}	18.0	18.8	19.3	18.8	20.0
Merchantable height (m)	5 × 5	1.8	3.5	6.9	10.0	10.9	13.1	13.7	12.0	13.1	—	—
	5 × 5 to 7 × 7	—	4.1	5.5	9.5	11.9	13.3	14.0	13.9	13.8	—	—
	7 × 7	—	4.7	6.3	9.4	11.7	12.0	13.7	13.5	13.4	12.0	—
	9 × 9	—	3.9	5.1	8.9	11.1	11.9	12.7	13.6	14.2	13.3	13.3
Merchantable volume (dm ³)	5 × 5	17.0	34.6	78.7	134.4	164.4	232.3	301 ^{AB}	316.4	474.0	—	—
	5 × 5 to 7 × 7	—	39.9	60.0	125.7	189.6	251.5	327 ^A	383.9	406.1	—	—
	7 × 7	—	49.7	71.6	124.8	185.2	231.1	309 ^{AB}	352.9	432.2	422.2	—
	9 × 9	—	38.4	58.8	119.8	177.5	237.2	278 ^B	337.3	444.5	477.4	489.3
Crown length (m)	5 × 5	3.5	3.0	3.3	3.5	4.6	6.4	6.5	7.2	9.5 ^A	—	—
	5 × 5 to 7 × 7	—	2.9	2.8	4.5	5.1	5.7	5.8	6.9	7.0 ^B	—	—
	7 × 7	—	2.8	3.6	3.5	5.3	5.0	5.2	5.9	5.8 ^B	6.6	—
	9 × 9	—	2.4	3.9	3.6	5.7	6.6	5.2	6.3	6.7 ^B	7.6	6.9
Live Crown ratio (%)	5 × 5	27.8	20.1	21.0	21.0	26.7	32.1	33.9	37.4	45.0 ^A	—	—
	5 × 5 to 7 × 7	—	18.4	19.1	25.7	27.9	30.4	29.6	35.1	34.6 ^B	—	—
	7 × 7	—	17.6	23.3	20.7	30.7	29.2	28.2	31.1	32.4 ^B	34.0	—
	9 × 9	—	18.0	25.9	23.0	32.6	36.5	28.6	33.4	34.8 ^B	40.8	34.5
Crown Width (m)	5 × 5	2.2	2.0 ^B	2.2	2.7	2.6 ^B	2.9 ^B	3.5	3.7	4.5	—	—
	5 × 5 to 7 × 7	—	1.5 ^B	2.3	2.6	2.5 ^B	3.0 ^B	3.3	4.1	3.6	—	—
	7 × 7	—	1.7 ^B	2.3	2.9	3.5 ^A	3.7 ^A	3.9	3.7	4.7	4.1	—
	9 × 9	—	2.9 ^A	2.6	3.1	3.5 ^A	4.0 ^A	3.8	4.6	5.0	4.6	4.3
Fork occurrence (%)	5 × 5	2.9	2.9	3.7	5.5	0	6.2	0	0.5	1.9	—	—
	5 × 5 to 7 × 7	—	0	7.8	1.8	0	0	0	0.6	2.3	—	—
	7 × 7	—	0.9	0	0	0	4.8	2.5	4.8	0	0	—
	9 × 9	—	1.6	1.9	0	0	4.5	4.2	4.8	2.4	0.4	0
Branch diameter (cm)	5 × 5	20.0	24.0	26.8	29.5	32.4	32.0	38.0	40.7	48.4	—	—
	5 × 5 to 7 × 7	—	23.5	25.1	29.9	32.6	37.2	40.2	42.9	43.4	—	—
	7 × 7	—	24.5	22.8	30.3	30.7	37.3	40.5	44.7	53.4	39.6	—
	9 × 9	—	28.0	24.3	27.9	33.8	41.7	38.7	43.3	47.9	58.5	48.8

Table 4. Tree characteristics and stem quality by DBH class measured on the 145 sample jack pine trees collected from 3 initial spacings of 5×5 , 7×7 , and 9×9 ft and one PCT stand (5×5 – to – 7×7 ft) thinned at age 14 (continued)

Variable	Treatment	DBH class (cm)										
		10	12	14	16	18	20	22	24	26	28	30
Taper (cm/m)	5 × 5	1.31	0.72	0.61 ^B	0.62	0.69	0.69 ^C	0.85	0.93	1.16	—	—
	5 × 5 to 7 × 7	—	0.73	0.76 ^{AB}	0.63	0.72	0.77 ^{BC}	0.82	0.93	0.90	—	—
	7 × 7	—	0.75	0.85 ^A	0.73	0.69	0.81 ^B	0.92	0.89	1.19	1.10	—
	9 × 9	—	0.76	0.90 ^A	0.71	0.78	0.90 ^A	0.90	1.04	1.07	1.21	1.07
Sweep (cm/m)	5 × 5	0.9	0.9 ^B	1.0 ^B	1.0	1.1 ^B	0.9	1.2	1.1	1.5	—	—
	5 × 5 to 7 × 7	—	1.1 ^B	1.0 ^B	0.8	0.9 ^B	1.0	0.8	1.3	1.1	—	—
	7 × 7	—	1.9 ^A	1.9 ^A	0.7	1.8 ^A	1.0	1.6	1.4	1.5	1.2	—
	9 × 9	—	1.4 ^B	0.9 ^B	1.4	0.8 ^B	0.9	1.1	1.1	2.1	1.0	0.8
Wobbling (W-E) (%)	5 × 5	21.4	36.1	34.0	41.4	39.0	39.1	39.8	34.1	58.7	—	—
	5 × 5 to 7 × 7	—	28.6	29.7	31.4	31.4	38.8	29.5	41.8	26.8	—	—
	7 × 7	—	47.5	34.9	33.3	60.4	43.8	53.7	43.4	55.8	30.6	—
	9 × 9	—	24.4	37.4	49.3	36.4	27.8	38.8	33.1	45.1	34.7	24.5

Note:

1) Fork occurrence is the percentage of trees with forks within the stand.

2) Means followed by the same letter or without any letters within a column for each variable are not significantly different at $p < 0.05$.

restriction for “ 2×6 ”. This suggests that knottiness is a major defect causing lumber downgrade in plantation-grown jack pine. The increase in branch diameter with increasing tree spacing is coincident with the development of tree diameter. Consequently, wood produced from a more widely spaced stand containing more large trees has a larger average knot diameter and hence inferior strength properties than wood produced in a denser stand (Zhang *et al* 2002).

Stem taper has a great effect on product recovery (Kellogg and Warren 1984). It is not constant along a stem, i.e., the butt segment of stem has the largest taper, followed by the top segment, while the middle part of stem has the smallest taper. In practice in the lumber industry, stem taper is considered constant and is represented by an overall stem taper. For most of the DBH classes, the overall stem taper of the same DBH class was not significantly different among the four spacings; however, an increasing trend with increasing initial spacing could be observed (Table 4). Stem taper decreased from 0.88 to 0.71 (Table 3) with increasing initial stand density from 1385 (9×9) to 4306 trees/ha (5×5), and the differences among the three initial spacings were significant (Table 3). The 5×5 to 7×7 spacing had a significantly larger taper than did the 5×5 spacing but a comparable taper to the 7×7 spacing. Compared to previous study results for balsam fir (Zhang *et al* 1998) and black spruce (Zhang and Chauret 2001), plantation-grown jack pine had an appreciably smaller stem taper than did balsam fir and black spruce trees of the same DBH class from comparable stand densities.

Sweep and crook are very important parameters describing stem quality. They have a direct and negative effect on lumber yield (Dobie and Middleton 1980, Cown *et al* 1984, Kellogg and Warren 1984, Cahill and Cegelka 1989). The occurrence of stem deformations like sweeps or crooks in plantation-grown jack pine for this study was fairly common and serious, and stems appeared to have irregular bumpy external shapes and wobbly boles (Fig. 1). Trees of 12-, 14- and 18-cm DBH classes from the 7×7 spacing had the most serious overall sweeps (Table 4) while trees of the other DBH classes did not appear to be significantly different in degree of overall stem sweep among the four spacings. With increasing tree diameter, overall stem sweep for the four spacings tended to fluctuate randomly. The thinned stand had the smallest range in stem sweep, from 0.8 to 1.3 cm/m, while spacing 9×9 had the largest range, from 0.8 to 2.1 cm/m. At the stand level, however, spacing 7×7 produced a distinct sweep compared to the other treatments (Table 3). Of the 10 most curved sample trees, eight were from spacing 7×7 (4.28, 2.91, 2.56, 2.53, 2.24, 2.19, 2.02 and 1.93 cm/m), while only two came from spacing 9×9 (4.43 and 2.40 cm/m).

The number of wobbling occurrences per meter was quite high for all spacings (Table 3). No significant difference in wobbling occurrence was observed among the four spacings in the west-east direction; however, spacing 7×7 seemed to suffer higher risks of wobbling than the other two initial spacings in the north-south direction. The average and largest wobbling degrees did not appear significantly different for trees of the same DBH class among the four spacings (Table 4). The average wobbling degree was fairly high (over 30% of tree bole deviated from the vertical line; Table 3), and obviously this would greatly depress lumber volume yield. Spacing 7×7 had much more serious stem deformation compared to the other spacings based on both average and

Table 5. Knot size restriction required by the NLGA (1996) for the Select Structural grade of different nominal lumber widths

Nominal Lumber width (inches)	Maximum allowable knot size			
	Knots at edge		Knots at centerline	
	(in inches)	(in mm)	(in inches)	(in mm)
2 × 3	1/2	12.7	1/2	12.7
2 × 4	3/4	19.1	7/8	22.2
2 × 6	1 1/8	28.6	1 7/8	47.6

largest wobbling degrees (Table 3). Generally, effects of sweep and crook, as well as gentle wobbling, i.e., sinuosity (Warensjö *et al* 2002) along a stem may be diminished to a large degree during lumber conversion by jump cutting and optimized bucking. Moreover, with modern sawmill technologies such as curve-sawing, the gentle sweep or sharp crook should not be a big problem. However, frequently occurring wobble in a stem will cause permanent loss in lumber recovery.

Conclusions

The results from this study clearly demonstrated the direct effect of density regulation (initial spacing and PCT) on tree growth and stem quality. Tree mortality during the first 25 growth years was quite mild for all four spacings, while after 25 years, survival of the four spacings rapidly declined, where the decrease in survival for spacing 5 × 5 was the steepest, followed by spacings 7 × 7, 9 × 9 and the PCT stand. DBH distributions of all four treatments were significantly different from each other, and five years after PCT, trees growing in the PCT stand started to have similar DBH to those in spacing 7 × 7. Mean DBH differed significantly among the three initial spacings. Narrower spacing produced significantly smaller trees than did wider spacing through the growth years. PCT had positive effects on DBH growth, and yielded longer merchantable stem and better stem quality. PCT had little effect on crown development. Initial spacing significantly affected diameter growth, crown width development, commercial stem length and volume, knottiness size, stem taper and stem deformation. Narrower spacing produced smaller trees, but better quality stems. Spacing 7 × 7 had the worst stem quality in terms of overall sweep and wave-like transversal deformation. Denser initial spacing combined with PCT may provide a possible solution for accelerating tree growth and improving stem quality.

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