EFFECT OF ROTATION AGE ON LUMBER GRADE YIELD, BENDING STRENGTH AND STIFFNESS IN JACK PINE (*PINUS BANKSIANA* LAMB.) NATURAL STANDS

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ABSTRACT

The effects of rotation age on lumber visual grade yield and lumber bending properties were studied on 142 jack pine trees sampled in three stands located in Timmins, Ontario. The stands, aged 50, 73, and 90 years were all naturally established after forest fires. The visual grading of a total of 1720 lumber pieces showed that the 50-yr-old stand produced a slightly lower Select Structural grade yield (36.1%) compared to the older stands (73 yr 42.9% and 90 yr 39.3%). When No. 2 and Better grades were combined, the 50-yr-old stand resulted in the lowest volume yield (88.2%), whereas the proportions of No.2 and Better for the 73- and 90-yr-old stands were comparable (93.0 and 92.6%, respectively). Downgrades due to decay were much higher in the 90-yr-old stand (20.6%) than in the 73- and 50-yr-old stands (5.2% and 0%, respectively). Regarding stand productivity, the 50-yr-old stand showed the highest annual stand increment of 5.25 m^3/ha/year, compared to 3.82 and 3.21 for the 73- and 90-yr-old stands, respectively. The visual grading of 782 board pieces showed no effect of stand age on board quality. In the 90-yr-old trees, wood density decreased steadily from butt to top for all the diameter classes studied (12–30 cm).

The study showed that rotation age had a significant impact on lumber bending properties. The lumber bending properties for the 50-yr-old stand were significantly lower than those of the 73- and 90-yr-old stands. The lumber strength (MOR) and lumber stiffness (MOE) values for the 50-yr-old stand were about 16% lower and 19–16% lower than those of the 73- and 90-yr-old stands, respectively. However, no significant differences in lumber bending properties were found between the two older stands. From the viewpoint of lumber properties, a moderate rotation age of about 70 years is preferred in jack pine.

Keywords: Jack pine (*Pinus banksiana* Lamb.), natural stands, rotation age, lumber bending properties, modulus of elasticity (MOE), modulus of rupture (MOR), basic wood density.

INTRODUCTION

In Canada's boreal forest, jack pine (*Pinus banksiana* Lamb.) is found in extensive pure stands established after wildfires or in mixture with black spruce (*Picea mariana* (Mill.) B.S.P.) (Morris and Parker 1991). It is used by both the lumber and pulping industries. In northern Ontario, sawlogs are in short supply, and without changes in forest management practices, the situation will continue to deteriorate (Swant 1991). On one hand, forest managers want to reduce rotation age by thinning treatments (Barbour et al. 1994; Zhang et al. 2004) and on the other hand, they do not want to alter wood quality by inducing faster growth rates. Rotation age is a silvicultural parameter that influences not only financial return but also wood properties and the quality of lumber produced (Clark III et al. 1996). Thus, a better understanding of the relationships between stand characteristics, silviculture treatments, and product quality will lead to an optimized utilization of an increasingly sought forest resource. The present study examines the effect of rotation age on lumber grade, bending strength and stiffness for 3 natural jack pine stands.

MATERIALS AND METHODS

Stands and tree measurements

This study was based on 3 jack pine stands naturally established after forest fires in 1911, 1926, and 1951. The stands, aged approximately 90, 73, and 50 years, were located in the Romeo Malette Forest Management Unit of the district of Timmins, Ontario. The main body of the boreal forest cover in this region consists of jack pine and black spruce with mixtures of white spruce, white birch, trembling aspen, and balsam fir. Since the stands were all located within a few kilometers of each other, they had very similar sandy soil and growth conditions. The 3 stands were assigned the site class 2, which corresponds to a mean height of 15.3 m by age 50. Throughout the stand rotation, no management was applied to influence tree growth.

For each sample stand, random plots were measured in order to determine the current stand density and tree diameter distribution. Trees falling into the 10-cm DBH (diameter at breast height) class (i.e. larger than 9.1 cm) or larger were defined as merchantable trees.

For each stand, 6 trees per DBH class were selected to cover all DBH classes in 2-cm intervals. There were a few exceptions where an insufficient number of trees were available for either the smallest or largest DBH classes. From the 50-yr-old stand, 44 sample trees were taken to cover 9 diameter classes (viz. 10–26 cm), 49 trees from the 73-yr-old stand covered 9 diameter classes (viz. 10–28), and 49 trees chosen from the 90-yr-old stand covered 10 diameter classes (viz. 12–30 cm). In total, 142 sample trees were selected and harvested in the fall of 2002.

For each sample tree, major tree characteristics were measured: 1) total tree height and tree height up to a 9.1-cm diameter top (10-cm DBH class), 2) DBH and stem diameter from the stump to the top at 1-m intervals, 3) live crown width and length, and 4) average diameter of the 5 largest branches. Based on these measurements, other tree characteristics were calculated, namely stem volume, stem taper, and length of the log without live crown.

Methods

All sample trees were brought to an open field with a horse, where they were bucked into 2.57-m (8-ft)-long logs. From the top of each log, a 3-cm-thick disc was sampled. A disc was also collected at the stump height. Each disc and log were assigned a number and a letter to indicate the tree and height from which they were collected. These discs were used for the evaluation of wood characteristics at Forintek's laboratory.

Each log was measured (inside bark, small and large end diameter, and length) and any defect recorded (crook, sweep, decay, etc.). The ends of the logs were spray-painted with the color identifying the stand to ensure that each log was processed in the right batch. A total of 837 logs were transported to the Tembec sawmill in Taschereau, Quebec, for lumber conversion. At the sawmill, special arrangements were made to reduce the processing speed in order to mark each piece of lumber produced. All the logs from the 3 stands were processed in the same manner from debarking to sawing. After debarking, logs were sorted into 9 groups (viz. 3, 4, 6 in.) based on log diameter/sawing pattern. Then, the logs were sawn into 2-in.-thick lumber and boards. Each piece of lumber (or board) was identified by tree number and sawlog position in the tree. All lumber samples were brought to the Forintek Laboratory in Quebec City. After kiln-drying, the lumber was dressed in a commercial planer mill.

For Canadian softwood structural lumber, there are 5 visual grades defined by the National Lumber Grades Authority (NLGA): Select Structural, No. 1, No. 2, No. 3, and Economy. The lumber was graded after drying according to the NLGA rules (NLGA 2003) by a qualified grader from the Quebec Forest Industry Council, and reasons for downgrade were also recorded.

Modulus of elasticity (MOE) and modulus of rupture (MOR) in static bending were determined for each piece of lumber, which had been previously conditioned to a moisture content (MC) of 12%. In total, 1720 pieces of lumber were tested, which included 267 of 2 by 3, 1093 of 2 by 4, and 360 of 2 by 6. Because of the trimming, a small percentage of lumber was shorter than 8 ft long (114 pieces). All the lumber pieces were tested edgewise with third-point loading in accordance with ASTM D-4761-96 (ASTM 1997). Just before the bending test, average moisture content was determined by a moisture meter for each piece of lumber. Following the ASTM D-2915-94 (ASTM 1997), MOE and MOR were adjusted to 12% MC, and MOE was standardized to a span-to-depth ratio of 21 to 1. In addition, bending width effect on MOR was adjusted for both 3- and 6-in. width lumber to a 4-in. width using the method described by Barrett and Lau (1994). In this study, the effect of stand age was evaluated at the diameter class level and at the stand level.

RESULTS AND DISCUSSION

Stem characteristics and volume

Table 1 shows the average tree DBH, stem taper, crown and branch characteristics for the 3 stands at the stand level. As expected, tree diameter increased with time. Trees from the 90-yr-old stand had shorter live crown length and a larger branch size than the two younger stands.

TABLE 1. *Selected tree characteristics for the 3 rotation ages studied (at the stand level).*

	Rotation age (years)		
Characteristic	50	73	90
No. of trees sampled per stand	44	49	49
Stand density (trees/ha)	1275	1050	725
Tree mortality in the stand (%)	19	15	34
Average DBH (cm)	16.7	19.4	22.4
Average taper (cm/m)	0.66	0.72	0.76
Average live crown length (m)	7.1	7.2	6.4
Average proportion of live crown to total tree height (%)	36.2	36.6	28.7
Average live crown width (m)	2.2	2.1	2.2
Average diameter of the 5 biggest branches in the tree (mm)	27.0	25.9	29.2

Tree mortality was much higher in the 90-yr-old stand (33%) compared to the 73- and 50-yr-old stands (15 and 19%, respectively; Table 1).

As shown in Table 2, stem taper was seen to increase steadily with tree DBH class. Differences in stem taper between the 3 stands were not consistent when comparing trees of the same diameter class. Table 2 also gives the average stem volume per tree in relation to DBH class and rotation age as well as the total merchantable volume per hectare for each stand. Since diameter and height increased with time, the stem volume at the stand level was much larger at a rotation age of 90 years. In fact, a 48% volume increase was observed between 50- and a 90-yr rotations, with average stem volumes of 205.7 and 397.1 dm^3/tree, respectively. However, the youngest stand of 50 years was the most productive, with a maximal annual stand volume increment of 5.25 m^3/ha/year compared to 3.82 and 3.21 for the 73- and 90-yr-old stands, respectively.

Wood density

Figure 1 shows that basic wood density decreased steadily from butt to top for all the diameter classes of the 90-yr-old jack pine stand. Log sorting (e.g. butt logs, top logs) based on wood density (which correlates to wood strength) could be practiced for jack pine.

Visual lumber grade yield

Figure 2 shows the distribution of lumber dimensions obtained after processing 837 2.5-m-long logs in a Quebec sawmill (Tembec Taschereau). The 90-yr-old stand produced the largest proportion of 2 by 6 lumber (31%) compared to the 2 younger stands (16–20%).

Table 3 shows the visual lumber grade yield in relation to DBH class and rotation age. The 3 jack pine stands had comparable Select Structural (SS) grade recoveries ranging between 36.1 and 42.9%, and the 73-yr-old stand produced the best yield. Economy grade lumber accounted for 2.4% or less of the total lumber volume production in this study. Grade recovery did not show

TABLE 2. *Stem taper and volume in relation to DBH and rotation age.*

DBH class (cm)	Stem taper up to a 9.1-cm top diameter (cm/m) — Rotation age (years) 50	73	90	Stem volume up to 9.1-cm top diameter (dm^3) — Rotation age (years) 50	73	90
10	0.33			64.3		
12	0.40	0.47	0.46	86.9	80.7	75.2
14	0.50	0.47	0.50	123.9	114.0	125.4
16	0.61	0.71	0.57	185.6	159.2	192.6
18	0.80	0.72	0.67	205.2	213.2	212.4
20	0.76	0.72	0.66	251.0	277.3	322.0
22	0.93	0.73	0.77	339.4	337.7	382.9
24	0.98	0.88	0.81	409.1	439.1	464.7
26	1.05	0.91	0.90	494.7	486.6	504.6
28		1.06	0.97		537.8	616.4
30			1.12			710.3
Stand level				205.7	265.3	397.1
Total merchantable wood volume (m^3/ha)				262.3	278.5	288.8
Annual stand volume increment (m^3/ha/year)				5.25	3.82	3.21

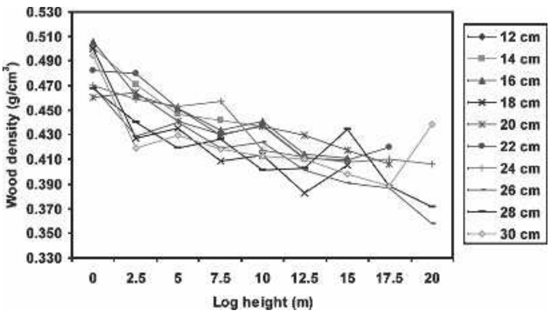

FIG. 1. Wood basic density in relation to DBH class and log height at a rotation age of 90 years.

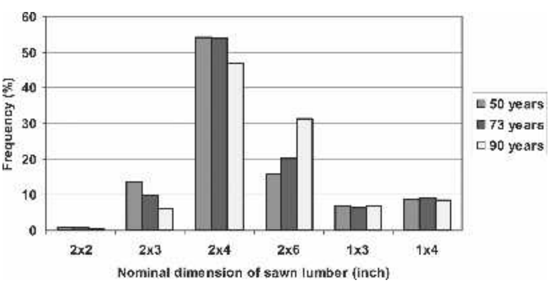

FIG. 2. Lumber dimension frequency in relation to rotation age.

a consistent pattern of variation with DBH class (Table 3).

In Eastern Canada, lumber grades Select Structural, No. 1, and No. 2 are usually sold together as No. 2 and Better. When No. 2 and Better grades were combined, the youngest 50-yr-old stand had the lowest volume recovery (88.2%), whereas the 73- and 90-yr-old stands had comparable volume recoveries of 93.0 and 92.6%, respectively.

For the three rotation ages, log position had an important impact on lumber grade yield (Table 4). Butt logs (0–2.5 m) produced the highest proportion of SS-graded lumber, and lumber quality generally decreased with increased log height in the stem. Despite their young age, the 50-yr-old butt logs produced the highest amount of SS-graded lumber (60.9%), compared to 49.6% and 56.8% for the 73- and 90-yr-old butt logs, respectively (Table 4).

Table 5 lists major defects causing lumber downgrades. When lumber downgrades to No. 3 and Economy are considered, it is clear that knots and wane were the two most important defects causing on average 59.9% of the lumber downgrades (Table 5). In the 90-yr-old stand, decay caused 20.6% of the downgrades, followed by shake (6.2%), compression wood (4.3%), and others (1.0%). For the 73- and 50-yr-old stands, downgrade due to decay was low or nonexistent (5.2 and 0%, respectively) whereas shake (30.3 and 28.3%) and compression wood (6.3 and 14.6%) were more important factors. The results show that downgrades due to

TABLE 3. *Visual lumber grade yield in relation to DBH class and stand age at harvesting (50, 73, and 90 years).*

DBH Class (cm)	SS grade (%) Rotation age (years)			No. 1 (%) Rotation age (years)			No. 2 (%) Rotation age (years)			No. 3 (%) Rotation age (years)			Economy (%) Rotation age (years)		
	50	73	90	50	73	90	50	73	90	50	73	90	50	73	90
10	0.2	0.0	0.0		0.0	0.0		0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0
12	0.7	0.2	0.0	0.9	0.2	0.0	0.7	0.3	0.2	0.5	0.7	0.0	0.0	0.0	0.0
14	1.2	0.6	0.7	0.3	0.4	0.3	2.5	2.0	0.7	2.0	0.7	0.5	0.5	0.2	0.0
16	4.0	2.4	3.5	1.1	0.6	0.4	2.8	2.4	1.3	0.5	0.7	0.5	0.6	0.0	0.0
18	3.5	3.9	2.7	0.5	1.2	0.3	3.5	3.2	1.7	1.2	0.7	0.3	0.1	0.0	0.0
20	5.9	7.2	3.8	3.8	0.4	1.4	5.3	4.5	2.4	1.8	0.5	0.5	0.3	0.1	0.0
22	8.2	7.4	5.9	4.4	3.2	2.5	6.8	4.0	3.4	1.3	0.6	0.2	0.2	0.0	0.2
24	7.3	8.7	6.3	6.4	2.7	4.6	6.1	7.9	2.8	1.7	0.4	0.9	0.6	0.3	0.1
26	5.0	7.9	5.6	3.0	3.1	4.2	2.2	7.4	3.8	0.6	0.5	1.2	0.0	0.3	0.0
28		4.6	5.0		3.2	5.5		3.1	5.8	0	1.3	0.4	0	0.3	0.1
30			5.7			5.6			5.9	0	0	2.7	0	0	0.1
Total	36.1	42.9	39.3	21.9	14.9	24.9	29.9	34.7	28.2	9.7	6.2	7.1	2.4	1.3	0.5

TABLE 4. *Visual lumber grade yield in relation to log position and rotation age (50, 73, and 90 years).*

Log height (m)	Lumber grade frequency (%) SS grade	No. 1	No. 2	No. 3	Economy	Total
50 years						
0–2.5	60.9	10.0	24.5	3.7	0.9	100.0
2.5–5	33.7	26.5	32.7	5.1	2.0	100.0
5–7.5	26.5	25.3	33.7	14.5	0.0	100.0
7.5–10	12.3	21.5	44.6	16.9	4.7	100.0
10–12.5	8.5	34.0	36.2	14.9	6.4	100.0
12.5–15	0.0	21.7	39.1	26.2	13.0	100.0
15–17.5	0.0	0.0	40.0	40.0	20.0	100.0
17.5–20	0.0	0.0	0.0	100.0	0.0	100.0
73 years						
0–2.5	49.6	8.1	34.1	6.7	1.5	100.0
2.5–5	56.5	10.4	27.0	5.2	0.9	100.0
5–7.5	45.0	22.0	30.0	3.0	0.0	100.0
7.5–10	31.4	19.8	39.5	8.1	1.2	100.0
10–12.5	22.6	19.4	50.0	8.0	0.0	100.0
12.5–15	12.8	23.1	48.7	12.8	2.6	100.0
15–17.5	7.1	14.3	42.9	28.6	7.1	100.0
17.5–20	0.0	0.0	0.0	0.0	100.0	100.0
90 years						
0–2.5	56.8	4.3	32.1	6.8	0.0	100.0
2.5–5	51.1	15.3	29.8	3.0	0.8	100.0
5–7.5	40.2	35.2	20.5	4.1	0.0	100.0
7.5–10	22.3	39.8	29.1	8.8	0.0	100.0
10–12.5	28.3	30.4	32.6	8.7	0.0	100.0
12.5–15	20.6	41.2	26.5	11.7	0.0	100.0
15–17.5	21.0	28.8	24.0	18.3	7.9	100.0
17.5–20	0.0	11.1	11.1	77.8	0.0	100.0

decay increased with longer rotation time (from 0.6% at 50 years to 13.5% at 90 years). This is related to the fact that mature to overmature trees are more likely to develop rot as their defence metabolism slows down with age. When the percentage of any lumber downgrade is con-

TABLE 5. *Lumber downgrades caused by different defects.*

	Percentage of lumber downgrade to No. 3 and Economy (%)				Percentage of any lumber downgrade (%)			
	Rotation age (years)				Rotation age (years)			
Defect	50	73	90	Average	50	73	90	Average
Knots	33.3	15.5	31.2	26.7	55.1	42.2	59.2	52.2
Wane	23.8	39.0	36.7	33.2	27.6	35.3	21.7	28.2
Decay	0.0	5.2	20.6	8.6	0.6	9.9	13.5	8.0
Compression wood	14.6	6.3	4.3	8.4	3.5	2.6	1.5	2.5
Shake	28.3	30.3	6.2	21.6	12.9	8.8	3.8	8.5
Others	0.0	3.7	1.0	1.5	0.3	1.1	0.3	0.6
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

sidered, knots and wane accounted for 80.4% of the downgrades, followed by shake (8.5%), decay (8%), compression wood (2.5%), and others (0.6%). From the viewpoint of visual grading, it is preferable to harvest at a moderate age (e.g. 70 years).

In this study, 782 one-inch-thick boards were also sawn and visually classified into Construction (no defect), Standard, Utility, and Economy grades (Table 6). The 3 stands gave very similar board grade yields. For that product, wane was clearly the dominant defect causing 87.5% of all the downgrades on average (Table 7). Thus, rotation age had little effect on board quality, which appears related to log geometry rather than rotation age.

Lumber strength and stiffness

Figure 3 shows the cumulative distribution of the number of lumber pieces tested for MOE and MOR in relation to DBH class and rotation age. As shown in Table 8, lumber strength (MOR) tended to decrease slightly with increasing DBH class. At the diameter class level, the 50-yr-old stand showed the lowest lumber stiffness (MOE) and lumber strength (MOR) values compared to the two older stands (Figs. 4 and 5). This trend was also reflected at the stand level where lumber from the youngest stand had a significantly lower MOE (9441 MPa; $P < 0.05$), which was about 19 and 16% below those of the two other rotation ages (11234 and 10927 MPa; Table 8). As for wood density (Fig. 1), MOE and MOR decreased from butt to top (Figs. 6a and b). Since there is a linear relationship between MOE and

TABLE 6. *Board grade yield (%) (782 pieces).*

Percentage (%)				
	Rotation age (years)			
Grade	50	73	90	Total
Construction	38.5	39.7	40.4	39.8
Standard	24.6	22.3	27.1	25.1
Utility	34.6	35.1	30.7	33.0
Economy	2.2	2.9	1.7	2.2
Total	100.0	100.0	100.0	100.0

TABLE 7. *Board downgrades caused by different defects.*

Percentage of any 1-inch board downgrade (%)				
	Rotation age (years)			
Defect	50	73	90	Average
Knots	11.2	3.7	11.8	8.9
Wane	84.7	93.3	84.5	87.5
Decay	0.0	1.1	1.3	0.8
Compression wood	0.8	0.0	0.0	0.3
Shake	0.9	0.0	0.0	0.3
Others	2.4	1.8	2.4	2.2
Total	100.0	100.0	100.0	100.0

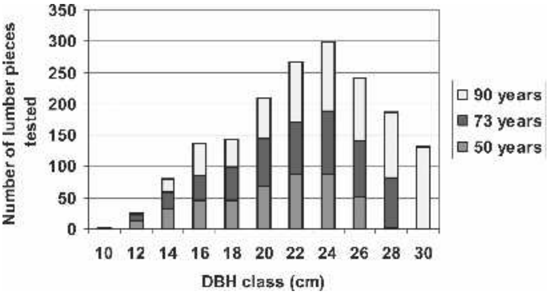

FIG. 3. Distribution of 1720 pieces of lumber tested for MOR and MOE per diameter class and rotation age.

TABLE 8. *Lumber modulus of rupture (MOR) and modulus of elasticity (MOE) at 12% equilibrium moisture content in relation to DBH class and rotation age.*

	MOR (MPa)			MOE (MPa)		
	Rotation age (years)			Rotation age (years)		
DBH Class (cm)	50	73	90	50	73	90
10	63.07			12504		
12	46.12	48.40	63.59	9780	10963	10748
14	44.33	51.63	53.56	10227	11191	11089
16	44.32	53.95	54.18	9882	12059	11993
18	45.06	51.39	49.58	10028	11914	10865
20	44.22	47.42	48.76	9634	10911	10999
22	40.82	46.67	51.39	9392	10961	11484
24	37.79	43.15	45.24	8793	9982	10770
26	41.26	44.61	47.55	9649	10459	10312
28	42.49	46.74	43.17	9554	11125	10288
30			42.22			10071
Stand level	42.32	49.06	48.45	9441	11234	10927
Arithmetic mean	42.15	47.03	47.03	9550	10897	10726
Standard deviation	12.66	13.52	14.73	1990	2056	2153
COV (%)	30.04	28.76	31.31	20.83	18.86	20.07

* A total of 1720 lumber pieces of dimensions 2 by 3, 2 by 4, and 2 by 6 inches were tested.

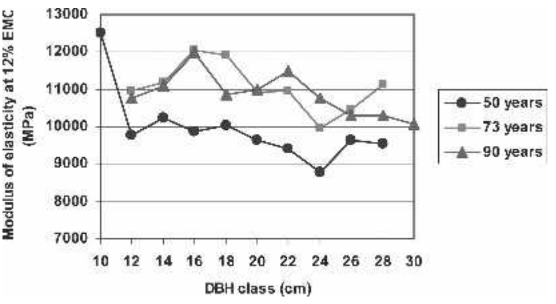

FIG. 4. Modulus of elasticity (MOE) at 12% equilibrium moisture content (EMC) in relation to DBH class and rotation age.

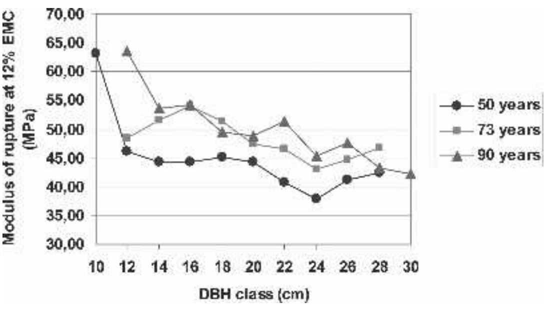

FIG. 5. Modulus of rupture (MOR) at 12% equilibrium moisture content (EMC) in relation to rotation age.

MOR, lumber MOR follows the same trend where the younger stand had a significantly lower MOE, about 16% lower (42.32 MPa) than that of the two older stands (ca. 49 and 48 MPa, Table 8). The MOE and MOR values for the 73- and 90-yr-old stands were not statistically different, likely because both stands had reached maturity. Although the differences were small between the two latter stands, the mechanical properties appeared to reach a maximum at a rotation age of 73 and thereafter diminish (Table 8). The lower bending properties of the 50-yr-old stand can be explained by the presence of a higher proportion of juvenile (immature) wood compared to the two older stands. Juvenile wood, which can occupy 20 to 35 annual rings in some species (Kennedy 1995), is known to be less stiff than mature wood due to its lower density, shorter tracheids, larger fibril angles, and thinner cell walls (Zobel and Sprague 1998; Butterfield 1997; Biblis et al. 1993; Panshin and De Zeeuw 1980).

The percentages of lumber pieces meeting the current mean-based bending stiffness (MOE) design values for visually graded lumber are presented in Table 9. For the 50-yr-old stand, all mean MOE values associated with the grades were below the required mean-based design val-

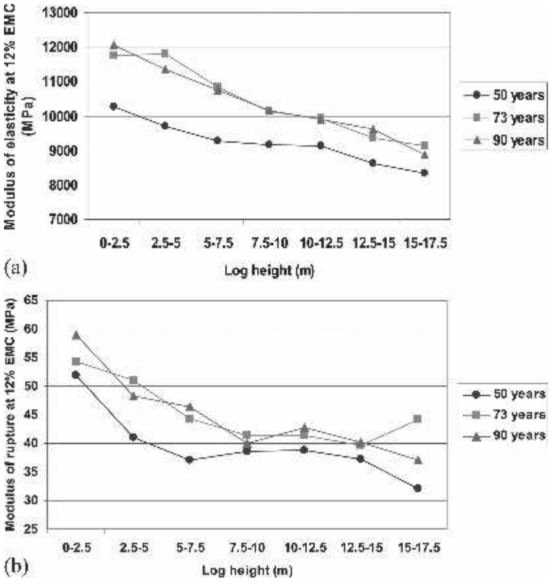

FIG. 6. a) Modulus of elasticity (MOE) and b) Modulus of rupture (MOR) at 12% equilibrium moisture content (EMC) in relation to log height and rotation age.

ues. The majority of the pieces tested (over 70%) failed to meet the mean MOE requirement for the grade. This raises the need for machine grading the lumber if the rotation age for jack pine tends to shorten in the future. However, all the MOE mean values of the 73- and 90-yr-old stands (with the exception of Grade No. 1 at 90 years) met or exceeded the mean-based MOE design values for the grade. In accordance with other pine species (Biblis et al. 1993; MacPeak et al. 1990), the percentage of acceptance to grade requirements increased with tree age. However, the present results indicate that the bending properties leveled off around a rotation age of 70 years and might even have deteriorated progressively (at the stand level) as jack pine trees became overmature (Tables 8 and 9). From the lumber stiffness and strength point of view, the 50-yr-old jack pine stand can be considered too young for harvest. On average, only 28.4% of the 50-yr-old lumber pieces tested satisfied the bending stiffness design value, compared to 60.6 and 53.5% for the 73- and 90-yr-old stands, respectively. The compliance of visual grades to the design values for bending stiffness is known to be even lower in plantation-grown species (e.g. black spruce, loblolly pine) (Zhang et al. 2002, Biblis 1990). However, this study shows that young natural forest lumber (50 years), and not only plantation lumber, have inferior mechanical properties that are related to the presence of juvenile wood. A study on Douglas-fir reports that an increase in percent juvenile wood leads to decreased density, MOR, and MOE for all grades and log positions (Barrett and Kellogg 1991). The juvenile wood may be so impaired in mechanical properties that the lumber product does not meet the design code specification for its visual grade (Kennedy 1995). In addition, growth rate and age are reported to be the most important factors affecting the MOE (MacPeak et al. 1990). However, the same authors report that the MOR of wood from short-rotation fast-grown pine trees is only marginally affected by growth and age (compared to MOE). For red pine, mean mature wood values averaged 90% greater than mean juvenile wood values for MOE, 68% greater for MOR, and 22% greater for wood density (Shepard and Shottafer 1992). For jack pine (Table 10), MOR is much less affected by age than MOE. In fact, the mean MOR of the 50-yr-old stand is only 9 and 10% lower than those of the 73- and 90-yr-old stands, respectively, compared to 19 and 16% for MOE.

Table 10 also shows the 5th percentile of MOR and mean MOR for each visual grade in the 3 rotation ages. The 5^{th} percentile of the population (here divided by grade) is that MOR value below which 5% of the population lies or above which 95% of the population values lie. The results show that the Select Structural lumber grade of the 3 rotation ages, which is the highest lumber grade, was also associated with a higher 5^{th} percentile. For the other grades, no specific hierarchical order was observed, and a No. 3 grade can even show a higher 5^{th} percentile than a No. 1 grade at a given rotation age (Table 10).

In this study, 73 years appeared to be the best rotation time for natural jack pine stands because the lumber strength and stiffness values reached their maximum, while the loss of lumber quality (downgrades) due to decay was still relatively low compared to the oldest stand (Table 5).

TABLE 9. *Percentage of lumber pieces which met the current grade requirements for bending stiffness values.*

Visual grade	Design values used Sample size in comparison with the jack pine lumber in this study[1] Mean MOE (MPa)	Sample size, Rotation age (years) 50	73	90	Mean MOE (MPa), Rotation age (years) 50	73	90	Percentage of lumber pieces which met the bending stiffness design values (%), Rotation age (years) 50	73	90
Select structural	10865	134	224	279	10099	11453	11457	26.1	63.8	61.1
No. 1	10044	93	85	179	9135	10167	10007	22.6	50.6	34.6
No. 2	10044	144	197	204	9516	10621	10667	34.7	58.9	60.8
No. 3	9296	48	39	59	8514	10212	9402	27.1	71.8	49.2
No. 1&2	10044	237	282	383	9325	10394	10337	30.0	56.4	48.6
Grand total		419	545	721	9316	10613	10382	28.4	60.6	53.5

[1] Design values based on Barrett and Lau (1994), and adjusted to 12% moisture content.

TABLE 10. *Mean MOR and the 5th percentile of MOR in relation to visual grade and rotation age.*

Visual grade	Sample size, Rotation age (years) 50	73	90	Mean MOR (MPa), Rotation age (years) 50	73	90	5th percentile MOR (MPa), Rotation age (years) 50	73	90
Select structural	134	224	278	47.39	51.78	52.30	30.36	26.46	23.86
No. 1	92	85	179	38.39	40.12	40.95	20.73	24.98	21.94
No. 2	145	195	203	41.86	45.05	46.88	22.42	20.17	20.69
No. 3	48	39	59	36.71	43.99	39.18	21.88	27.73	20.36
Economy	13	7	4	32.91	46.81	64.61	23.53	46.88	—
Grand total	432	550	723	42.00	46.98	46.96	—	—	—

A comparison of jack pine lumber stiffness (MOE) with other S-P-F species from natural forests and plantations is presented in Table 11. The 73- and 90-yr-old jack pine lumber was stiffer than natural balsam fir but weaker than natural black spruce. Interestingly, the jack pine lumber stiffness at a rotation age of 50 years corresponded roughly to the stiffness obtained in a jack pine plantation aged 60 years, (e.g. spacing 5 ft × 5 ft; Table 11).

TABLE 11. *Stiffness of the jack pine lumber in comparison with that of other (S-P-F) species grown in natural forests and plantations.*

Species	Stand type	Stand density (tree/ha)	Rotation age (years)	Source	Lumber MOE* (MPa)	Location
Jack pine	Natural	1275	50	This study (Table 8)	9182	Timmins, Ontario
Jack pine	Natural	1050	73	This study	11222	Timmins, Ontario
Jack pine	Natural	725	90	This study	10937	Timmins, Ontario
Jack pine	Natural	—	Misc.	Forintek's data bank	10726	Eastern Canada
Jack pine	Plantation	3086a	60	Zhang et al. 2004	9218	Michigan
Jack pine	Plantation	2500b	60	Zhang et al. 2004	9193	Michigan
Jack pine	Plantation	2066c	60	Zhang et al. 2004	8828	Michigan
Jack pine	Plantation	1372d	60	Zhang et al. 2004	8538	Michigan
Black spruce	Plantation	1372	48	Zhang et al. 2002	8178	Thunder Bay, Ontario
Black spruce	Plantation	3986	48	Zhang et al. 2002	9791	Thunder Bay, Ontario
Black spruce	Natural	—	Misc.	Forintek's data bank	13118	Eastern Canada
Balsam fir	Natural	—	Misc.	Forintek's data bank	10074	Eastern Canada

* at 12% equilibrium moisture content.
a, b, c and d represent spacings of 5 × 5, 5 × 5 to 7 × 7, 7 × 7 and 9 × 9 feet, respectively.

Thus, rotation age has a significant effect on lumber properties in natural jack pine stands. This is in agreement with other studies on loblolly pine (Clark III et al. 1996; Biblis et al. 1993), with the difference being that the latter refer to plantation wood. To our knowledge, no published data are available for natural jack pine. Regardless of the type of stand establishment (plantation or natural), the biological age of trees plays a crucial role for its mechanical properties, particularly for MOE. Silviculture and genetics research might help find solutions in order to obtain good quality sawlogs in a shorter rotation time, which is one of the most important objectives of intensive forest management in eastern Canada.

CONCLUSIONS

From the study of 3 natural jack pine stands aged 50, 73, and 90 years, the following conclusions can be drawn:

1. Rotation age had an impact on the whole forest to product value recovery chain. With increasing age, the number of stems per hectare decreased (i.e. tree mortality increased). Tree height, stem diameter, stem taper, clear log length and lumber volume (and value) also increased with age.
2. The 50-yr-old stand had a higher annual wood increment than the two older stands. Thus, from the viewpoint of stand productivity in volume, a short rotation age (e.g. 50) is preferred.
3. However, the lumber bending properties for the 50-yr-old stand were significantly lower than those of the 73- and 90-yr-old stands while there was little difference between the two older stands. This difference is related to the high proportion of juvenile wood in the 50-yr-old young trees, which is a function of tree age.
4. The 50-yr-old stand did not meet the mean-based design values for lumber stiffness (MOE) required for each visual grade, while the two older stands, with one exception (grade No. 1, 90 years), all exceeded the mean-based MOE values. This fact emphasizes the need to sort high juvenile wood-containing lumber based on its mechanical properties (e.g. using Machine Stress Rating (MSR)).
5. The strength and stiffness in bending generally increased with longer rotation time; but in the present study, the lumber mechanical properties of jack pine appeared to level off or reach a maximum at an age of 73 years. Thus, to maximize lumber quality in natural jack pine stands and reduce tree mortality and loss of fibers, a moderate rotation age (e.g. 70 years) would be preferred.

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