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CONTENTS

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ABSTRACT

Ten overstory red spruce were selected from a thinned stand and 10 from an unthinned stand. Average age of sample trees was approximately 80 years. A 1.8- to 2.4-m log was removed from the base of each tree and a 5-cm thick diametric flitch, centered on the pith, was cut from each log. A clear, 0.3-m section was removed from each board and cut along the pith to produce two radially opposing sample boards. Microbending specimens and ASTM standard-size test samples were prepared from the sample boards and used for determinations of specific gravity, strength, and stiffness.

Specific gravity reached a maximum at age 53 in the thinned stand and age 72 in the unthinned stand, after which it remained relatively constant. Stiffness reached a maximum at ages 35 and 50, and bending strength at ages 41 and 54; both remained relatively constant with further increases in age. Stiffness showed the largest relative difference between juvenile and mature wood, 22 percent, and specific gravity the smallest difference, 8 percent. Thinning did not adversely affect any of the properties, even though the width of some growth rings was increased by three to four times.

These results suggest that 1) growth of mature red spruce stands can be increased by thinning without affecting wood physical properties, and 2) intensive management practices designed to shorten the rotation age may lead to stands that have not begun to produce mature wood before they are harvested. These short-rotation stands will contain a higher percentage of juvenile wood than stands presently being harvested, which means that pulp yields will decrease and the material will be less suitable for structural lumber.

INTRODUCTION

Thinning a young stand frequently leads to a reduction in wood quality, because the accelerated growth that occurs during the juvenile period produces a high proportion of juvenile wood in the bole. Juvenile wood has different characteristics than mature wood, including a lower specific gravity, shorter fibers, thinner cell walls, greater microfibril angle and greater cell diameter. Increased longitudinal shrinkage is characteristic of structural lumber and boards containing large amounts of juvenile tissue.

Senft (22) estimated the effect of shortened rotation length on the percent of juvenile wood and physical strength properties of loblolly pine. He projected that the butt log of a loblolly pine grown on a 30-year rotation would contain 35 percent juvenile tissue; however, on a 60-year rotation only 10 percent of the tissue would be juvenile. Reducing the rotation age from 60 to 30 years would cause the weighted mean bending strength to drop from 75.2 MPa to 68.0 MPa. Senft and Bendtsen (21) calculated that a piece of 5x20-cm dimension lumber from juvenile wood would have the equivalent strength of a 5x15-cm piece sawn from mature wood, with an added production cost of 50 to 60 percent.

Pearson and Gilmore (17) reported that longitudinal shrinkage in loblolly pine juvenile wood was five times greater than in mature wood. Large amounts of juvenile wood in structural lumber are thought to be the cause of the "rising truss" phenomenon, a relatively new problem occurring with increasing frequency (7). This problem results from the increased longitudinal movement of the juvenile wood in the lower chord of house trusses as moisture content changes. This movement causes the truss to rise, separating the ceiling from the room partition.

Because thinning a young forest stand leads to a greater proportion of juvenile tissue in the bole, it may be desirable to delay thinning until the later stages of the juvenile period or until the beginning of the mature phase of the stand if high density and strength are of major importance. Thinning an older stand will, however, only produce high quality wood if the properties of that wood are not adversely affected by the increased growth rate following thinning.

Many investigators have shown that variation in the wood properties of pines is not associated with growth rate and have concluded that variation in wood properties is related primarily to age (6, 18, 24). In contrast, research on spruces suggests that specific gravity may be negatively correlated with growth rate (4, 5, 9, 25, 26).

To time thinnings appropriately so that wood properties are not adversely affected, it is necessary to know the approximate age at which the juvenile phase ends and the mature phase begins. According to Bendtsen (2), this occurs between ages 5 and 20 for most species. In this report we refer to the approximate age at which a wood property attains mature characteristics as the "point of maturity" (POM) (27). Because different wood properties are important in different products, POM should be determined for the properties of specific importance to the intended use of the wood.

To establish the effects of age and growth rate on the wood properties of red spruce (*Picea rubens* Sarg.), a long-term project is underway at the College of Forest Resources of the University of Maine. The objectives of the work reported here were to determine: 1) the POM in red spruce for specific gravity (SG), modulus of rupture or bending strength (MOR), and modulus of elasticity or stiffness (MOE) and 2) if the increased growth rates in older trees following thinning adversely affect these properties. Red spruce was chosen because the red spruce forest type occupies more than 400, 000 ha in Maine (20) and because of its importance to both the pulp and paper industry and the structural lumber industry of the state.

METHODS AND MATERIALS

Study Area

Two old-field red spruce stands were selected on Yale University's Bowen Forest in Mount Holly, Vermont. One stand, approximately 78 years old (based on the average age of sampled trees at the stump), had been thinned in 1953. East-west strips were cut and a selection thinning in the residual stand followed. Blowdown following the thinning and the subsequent salvage left a stand averaging 125 to 150 red spruce/ha. The other stand, approximately 84 years old (based on the average age of sampled trees) and not thinned, served as a control. Density of this stand was about 550 red spruce/ha. Both stands were on moderately well and well drained, very stony, fine sandy loam soils of the Peru and Marlow series. Basal area of the control stand was approximately 36 m^2/ha, 32 m^2/ha of which were red spruce, and basal area of the thinned stand was approximately 16 m^2/ha, 10 m^2/ha of which were red spruce.

Specimen Preparation and Testing

In 1984, ten trees, free from visible defects, were selected to represent the diameter range of overstory trees in each stand. The characteristics of these trees are presented in Table 1.

The trees were felled, and a log, 1.8-to 2.4-m long, was removed from the base of each. In addition, a 5-cm thick cross-section disc was taken at the top of the first 5-m log, about 7.6 m above the base of the tree. Volume growth in the lowest 7.6 m of each tree was calculated.

Table 1. Characteristics of red spruce study trees.

		Characteristic	
Stand	Dbh (cm)	Height (m)	Live Crown Ratio
Control	27.9[a]	21.9	0.37
	20.8-37.1[b]	19.4-25.0	0.28-0.48
Thinned	33.5	20.0	0.62
	29.5-37.3	18.5-22.1	0.52-0.74

[a] Mean

[b] Range

A diametric flitch, about 5-cm wide, was cut from the bottom log of each study tree. A clear 0.3-m section was removed from the flitch and longitudinally cut along the pith, producing two radially opposing sample boards for each tree (Fig. 1). Each sample board was machined to 0.32 cm thickness.

Microbending specimens were serially cut from the point of thinning to the pith and to the bark employing the sample preparation technique developed by Bendtsen and Senft (3) and modified by Wolcott *et al.* (28). The microbending specimens were 5.72 cm long and 0.32 cm deep. The specimen width varied but was greater than 0.32 cm and equal to the width of two or more entire growth rings (minus 0.08 cm saw kerf).

Three standard ASTM 2.54x2.54x40.64-cm bending specimens (ASTM D 143) were also cut from the diametric flitch from each treatment and control tree as follows:

1. Beam #1 was cut adjacent to the pith to represent early juvenile wood properties.
2. Beam #2 was cut on the pith side just interior to the year of thinning. These beams were used for determination of the mechanical properties of wood in each tree during the period preceding thinning.
3. Beam #3 was cut on the bark side just exterior to the year of thinning. These beams were used for determination of properties of wood produced following thinning.

The microbending flexure tests were conducted with the wood in the green condition (45 percent or greater moisture content) using a table-top Instron universal testing machine, with a cross-head speed of 0.05 cm per minute and a test span of 4.45 cm. The year of formation of the first and last growth ring in each microbending specimen was recorded. The width of each growth ring was

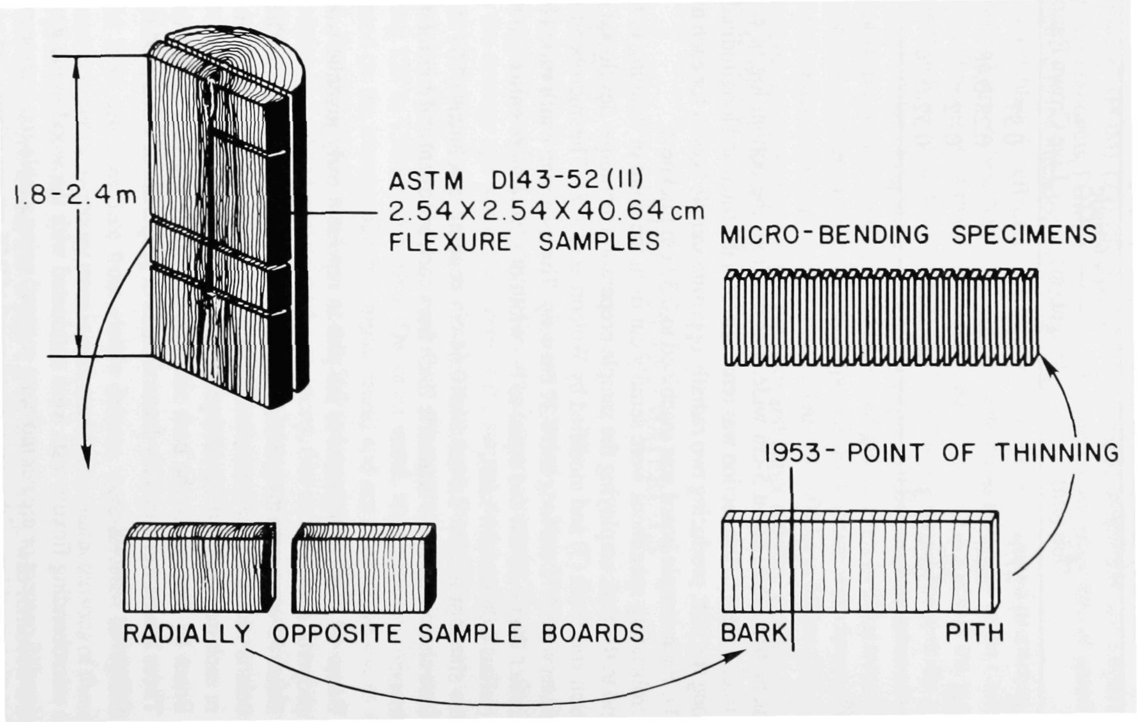

Figure 1. General procedure for the preparation of microbending specimens.

measured from a radial section adjoining each sample board, using a digital micrometer. Specific gravity of all beams, both microbending and ASTM, was determined from oven-dry weight and green volume. The green volume of each specimen was calculated from measurements of the dimensions made with dial calipers before testing.

The larger, standard-size flexural samples were tested according to ASTM Standard D143-83.

Analytical Methods

The effect of thinning on radial growth was examined using both paired and unpaired t-tests. Mean ring widths for the ten growing seasons preceding thinning (including the year of thinning) were tested against mean ring widths for the ten growing seasons following thinning, as well as against mean ring widths for the total post-thinning period, using a paired t-test. An unpaired t-test was used to test for the significance of the mean difference between changes in ring width for the thinned and control trees from the pre- to post-thinning period.

Segmented regression analysis was used to differentiate between juvenile and mature wood. A linear regression of wood property over age was used for the juvenile period and a constant (line with zero slope) for the mature period. The line segments were selected so as to minimize the residual sum of squares. The intersection of the two lines was designated as the POM. Initially, it was felt that the relationship between wood properties and age might be quadratic in the juvenile wood and linear in the mature wood. This was based on Bendtsen's (2) observations on the rate of change in wood properties over time. However, application of the quadratic term in the juvenile phase and the linear term in the mature phase proved nonsignificant for each case.

The segmented regression was applied to the entire data set from each stand. There was too much variability among data points for most trees, however, to use the method on an individual-tree basis as was done by Loo *et al.* (13). We chose not to attempt to visually estimate the POM for each tree, because this could have led to overestimates for some trees and underestimates for others, or possibly a consistent over- or underestimate. Bendtsen and Senft (3) tested three methods for determining the "demarcation age" and found none satisfactory for use on an individual tree basis. The wood in each microbending sample was classified as either juvenile or mature with respect to SG, MOR, and MOE based on the results from the segmented regression analysis. Linear regression was used to analyze the effect of SG on MOR and MOE.

Analysis of variance was used to test for differences in SG, MOR, and MOE of the ASTM specimens. The analysis of variance was based on a linear model of the form:

$$SG, MOR, MOE = \mu_{ij} + S_i + B_j + SB_{ij} + \varepsilon_{ij}$$

where: S = stand: thinned or control
B = beam: 1, 2, & 3 as designated in the sample preparation.

A change in SG, MOR, or MOE due to thinning would be reflected in a significant stand x beam interaction. The Waller-Duncan K-ratio t-test was used to determine differences among beam locations.

Tests that showed significance at $P \leq 0.05$ were termed significant and those that showed significance at $P \leq 0.01$ highly significant.

RESULTS AND DISCUSSION

Effect of Thinning on Growth

Mean annual radial growth of trees from the thinned stand during the ten years following thinning was greater than during the ten years preceding thinning; the difference was highly significant. For the control stand, mean radial growth rate for the post-thinning period was less than that for the pre-thinning period by a highly significant amount. The mean difference between the changes in radial growth rates for the two stands was also highly significant. The same level of significance applied when mean annual radial growth for the ten years preceding thinning was tested against that for the total post-thinning period.

Mean radial growth rate of trees from the thinned stand increased from 1.4 mm/yr for the ten years prior to thinning to 2.1 mm/yr for the ten years after thinning (Table 2). Over the entire post treatment period average growth was 2.2 mm/yr. Growth rates of trees from the control stand were 1.1 mm/yr and 0.9 mm/yr for the same periods. For the total post-thinning period, mean growth of trees from the control stand was 0.8 mm/yr, 36 percent of growth of the thinned trees.

The effect of thinning is also evident in the mean growth rate of the ten slowest and ten fastest growing annual rings (one of each/tree) during the post-thinning period (Table 2). During the total post-thinning period, mean growth of the narrowest rings from trees from the thinned stand was more than twice the growth of the narrowest rings from trees from the control stand (0.92 mm/yr vs. 0.41 mm/yr), whereas growth of the widest rings was nearly three times as great (3.81 mm/yr vs. 1.34 mm/yr). Similar ratios applied during the ten-years-after-thinning period.

Trees from the thinned stand continued to increase in growth after the first ten years following thinning, whereas growth of trees from the control stand

Table 2. Radial growth rates of red spruce study trees during four different growth periods. (mm/yr)

	Growth Period			
Stand	Total Pre-thinning	Total Post-thinning	Ten Years Before thinning	Ten Years After thinning
	2.24[a]	0.80	1.11	0.93
Control	0.81[b]-4.58[c]	0.41-1.34	0.80-1.45	0.62-1.26
	2.23	2.23	1.42	2.07
Thinned	1.02-4.35	0.92-3.81	0.99-1.91	1.19-3.06

a Mean radial growth rate

[b] Mean growth rate of the 10 narrowest rings (one ring/tree)

[c] Mean growth rate of the 10 widest rings (one ring/tree)

decreased during the same period. Some thinned trees did not attain maximum growth until late in the post-thinning period. For example, average growth as determined from a sample board from one tree was 3.9 mm/yr during the seven years (age 72 through 78) before the tree was felled, and average growth as determined from a sample board from another tree was 4.0 mm/yr for the four years (age 60 through 63) before the tree was felled.

Thinning had a pronounced effect on volume growth in the lower bole (0.3 m to 7.6 m in height). Mean volume growth of trees from the thinned stand was 377.5 dm^3 after thinning. For trees from the control stand, mean volume growth was 153.6 dm^3 for the same period.

Point of Maturity

The relationship among the POMs for SG, MOR, and MOE, based on the microbending specimens, was similar in both stands (Table 3). MOE reached the POM first and SG reached the POM last. Trees from the thinned stand reached the POM for SG almost 20 years earlier than trees from the control stand and about 15 years earlier for both MOR and MOE. Relationships between the various properties at different ages of the vascular cambium are presented in Figures 2 through 4 for the thinned stand. Relationships for the same properties vs. age in the control stand were essentially similar to the thinned stand except that the POM for each property was later.

Haygreen and Bowyer (8) state that the demarcation age for juvenility "depends upon the property or properties used to define the zone." It is possible that anatomical characteristics that reflect maturation early could cause MOR and MOE to reach the POM earlier than does SG. Onilude (15) observed that, for

Table 3. Age at maturity for specific gravity (SG), modulus of rupture (MOR), and modulus of elasticity (MOE) in the control and thinned red spruce stands. (Age in Years)

	Wood Property		
Stand	SG	MOR	MOE
Control	72	54	50
Thinned	53	41	35

loblolly pine, there were significant age trends for three anatomical properties that were closely correlated to mechanical properties in microbending specimens and that were independent of SG. This finding may help to explain the consistent differences in POM among SG, MOR, and MOE, but it is unrelated to the differences in POM for each property between stands.

The juvenile period is thought to be extended when stand density is low at a young age (1, 12, 14). A low initial stand density will lead to slower crown recession and to greater crown vigor over a longer period of time. If density of the control stand was initially lower than density of the thinned stand, it is quite possible that the juvenile period of the control stand could have been extended. However, based on the virtually identical radial growth rates for the pre-thinning period (2.24 mm/yr for the control stand vs. 2.23 mm/yr for the thinned stand) it appears that early densities of the two stands were probably similar. This suggests that differences in POMs between the two stands may be due at least in part to genetic differences.

The earlier POM for all properties in the thinned stand does not appear to be the result of thinning. The mean POM for MOE of trees sampled in the thinned stand occurred at about the age at which the stand was thinned. POM for MOR occurred 6 years after thinning and for SG 18 years after thinning. It must be emphasized that the mean age at the points where the samples were taken was less than the mean stand age.

Based on this study, it appears that red spruce may not begin to produce wood mature for SG, MOR, and MOE until much later than many other species. Bendtsen and Senft (3) reported that loblolly pine reached maturity for SG, MOR, and MOE by age 13 and that the values of these properties remained relatively constant in succeeding years. The same properties reached maturity in eastern cottonwood by age 17 or 18. Loo *et al.* (13) sampled 22-year-old loblolly pine trees and reported that SG reached maturity at about age 13, with a range of 4 to 20 years, but that tracheid length continued to increase through age 22. Megraw and Nearn (14), however, who studied Douglas-fir, found that SG of 40-year-old trees continued to increase through age 40.

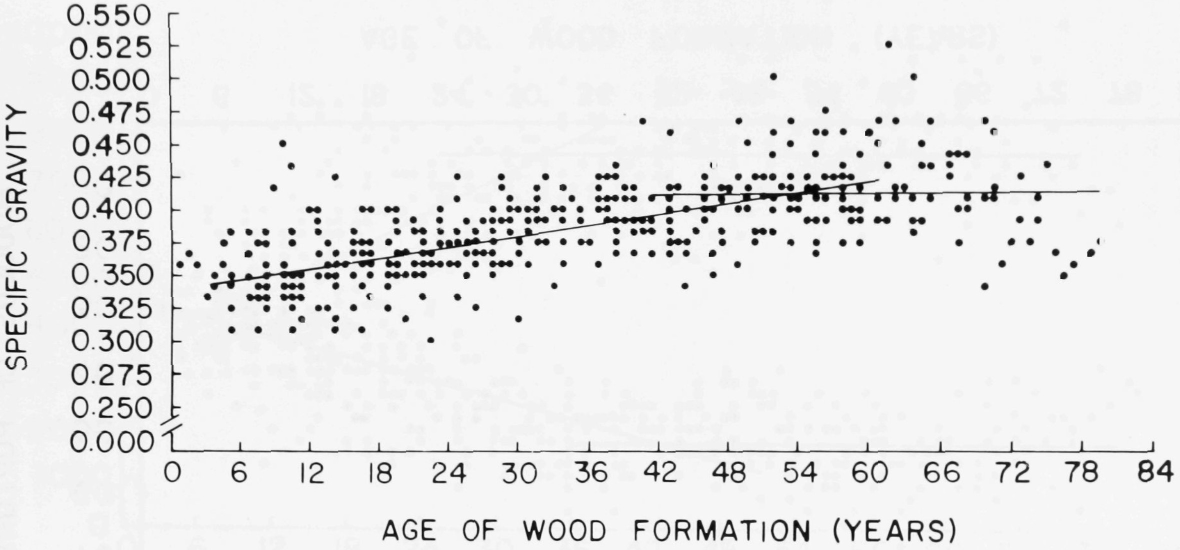

Figure 2. Specific gravity vs. age relationship for red spruce from the thinned stand. The point of maturity occurs at approximately age 53.

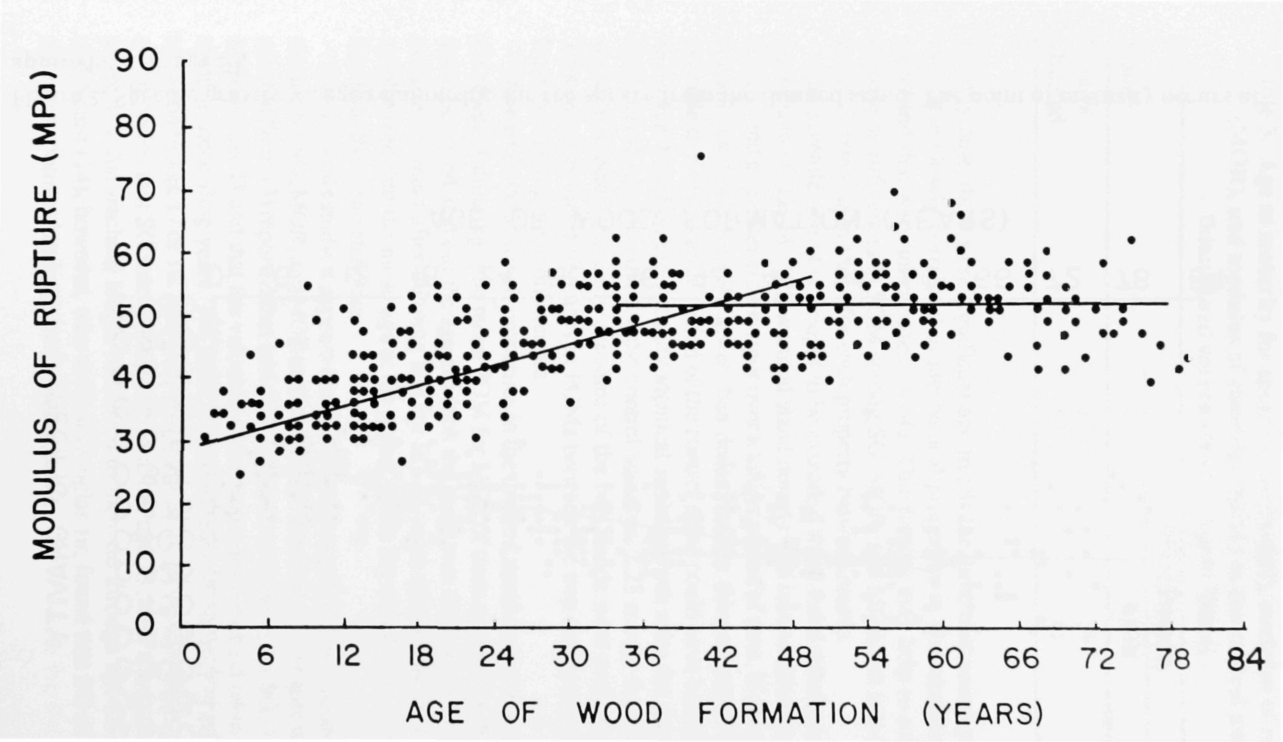

Figure 3. Modulus of rupture vs. age relationship for red spruce from the thinned stand. The point of maturity occurs at approximately age 41.

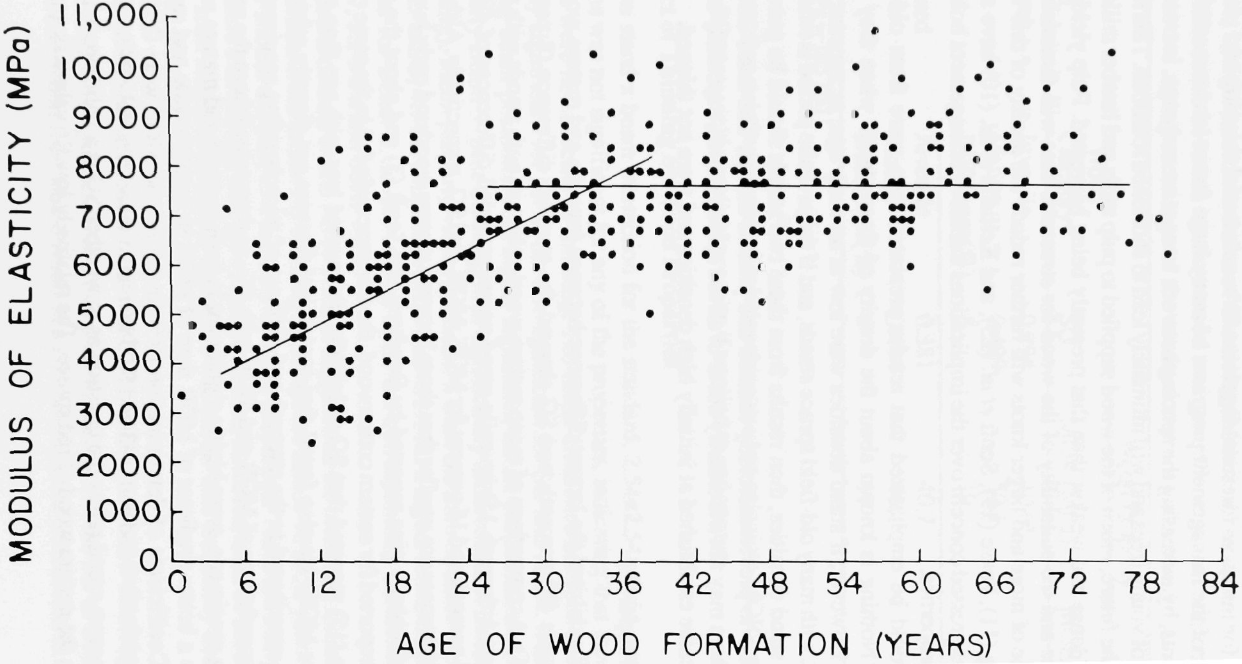

Figure 4. Modulus of elasticity vs. age relationship for red spruce from the thinned stand. The point of maturity occurs at approximately age 35.

The late POM exhibited by wood properties of red spruce has major implications for intensive forest management. Precommercial thinning and planting are part of the management programs of many large forest landowners. These treatments, by increasing the spacing between trees at an early age, increase the growth of young trees and will ultimately lead to shortened rotations. This means that in the future, much of the wood supplied to pulp mills and lumber mills may be less dense and weaker than that presently being harvested. Pulp yields will decrease and the suitability of the wood for structural uses will diminish. The presence of more and larger knots will further reduce the quality of this wood. Kellogg (11), Pease (19), Senft *et al.* (23), and Kellison *et al.* (10) have all recently expressed concern over the implications intensive management holds for wood properties.

It should be emphasized that results presented here were from old-field stands. Nothing is known about the density of these stands when they were young. However, if stand densities were low at an early age, as appears to be the case with many old-field spruce stands, and if the juvenile period is extended by low stand densities, then results from these two stands should be generally applicable to precommercially thinned and planted stands. The late POMs reported here may not necessarily occur in all red spruce stands, especially stands that became established at initially high densities and were not thinned.

Wood Properties

MOE exhibited the largest difference between juvenile and mature wood in both stands (22 percent), and SG showed the smallest difference (8 percent) (Table 4). A comparison of mean mature wood values in both stands with mean early (age 1 through 15) juvenile wood values revealed differences of 49 percent, 38 percent, and 16 percent for MOE, MOR, and SG, respectively. Although these differences are smaller than those between mature wood and early juvenile wood of loblolly pine reported by Bendtsen and Senft (3) and about the same as they reported for eastern cottonwood, the differences do fall in the same order. Onilude (15) reported that SG of loblolly pine varied less with age than either MOR or MOE. He also found that anatomical features not directly related to density contributed to the strength and stiffness of microbending specimens.

The correlations of MOR and MOE with SG, as determined from the microbending specimens, were highly significant in both juvenile and mature wood. SG was a better predictor of MOR than of MOE in both juvenile and mature wood. Coefficients of determination (R^2) for MOR and MOE were 0.58 and 0.27 in juvenile wood and 0.43 and 0.05 in mature wood. The low R^2 for MOE in the mature wood raises the question as to whether SG is a valid predictor of MOE in the mature wood of red spruce. The relatively low R^2 values in general

Table 4. Mean values of specific gravity (SG), modulus of rupture (MOR), and modulus of elasticity (MOE) of red spruce. (*Differences between mature wood and juvenile wood are expressed as a percentage of the mean mature wood value.*)

			Wood Property	
Stand	Wood Category	SG	MOR (MPa)	MOE (MPa)
Control	Juvenile	0.394	40.6[a]	6240.3
	Mature	0.429	50.1	8040.5
	Difference(%)	8	19	22
Thinned	Juvenile	0.381	40.7	5965.4
	Mature	0.414	49.1	7609.2
	Difference(%)	8	17	22

[a] 1MPa = 145 PSI

suggest that existing empirical relationships used to calculate MOR and MOE from SG may yield unreliable results if applied to red spruce.

Effect of Thinning on Wood Properties

The stand x beam interaction for the standard, 2.54x2.54x40.64-cm ASTM beams was not significant for any of the properties, indicating that these properties were not affected by thinning. The mean difference between stands was highly significant for MOE but not significant for SG and MOR. Differences among beam positions were highly significant for all properties, and for each property Beam 3 (post-thinning) was significantly different from Beam 2 (pre-thinning). Mean property values for Beam 3 from the thinned stand were 0.024 higher in SG, 4.7 MPa higher in MOR and 623.1 MPa higher in MOE than mean values for Beam 2. In the control stand the corresponding differences were 0.017, 5.1 MPa and 667.9 MPa.

Results of tests on the ASTM beams suggest that the increased radial growth of residual trees following thinning in red spruce stands 40 to 50 years old and older should not lead to a decrease in wood properties. There are many stands in Maine that fall into that age range. Great care, however, must be used in thinning such stands to avoid the excessive windthrow that frequently occurs following thinning.

Implications for Pulp and Paper and Structural Lumber Industries

Kellogg (11) estimated that a two percent decrease in the SG of Douglas-fir and western hemlock would result in a 28 million dollar annual loss in revenue to pulp mills in coastal British Columbia, based on a two percent reduction in pulp yield, and a 4.5 million dollar loss to sawmills due to a reduction in lumber grade. The SG values reported here indicate that growing red spruce on a rotation of 40 to 50 years may lead to a decrease in SG of at least two percent relative to that of trees presently being harvested. This reduction in SG will certainly lead to a loss in yield and a decrease in revenue to Maine pulp mills. A simple example, following that of Kellogg (11), illustrates this. Assume a 500 metric ton/day kraft mill operating at 95 percent capacity, and a bleached pulp price of $400/metric ton. If the mean SG of the wood supplied to this mill drops from 0.40 to 0.38 (five percent), annual pulp output could drop by as much as 8,700 metric tons and annual revenue by 3.5 million dollars. To maintain the original output using the lower density wood, the mill would have to operate at 100 percent capacity. Even operating at 100 percent capacity, some revenue would be lost because of the extra costs required to handle and pulp the additional wood. Also, the mill would have to purchase approximately 50,000 m^3 of additional wood/year.

Attention must also be paid to "non-density" aspects of wood grown under short rotations and their possible effects on pulp yield. Trees growing at a wide spacing from an early age will develop large branches that are retained for many years. Compression wood tends to form on the underside of the branches of conifers. The chemical composition of this wood differs markedly from that of "normal" wood. Lignin content is 20 to 30 percent greater and cellulose content about 20 percent less (16). This large change in the lignin-cellulose ratio reduces the suitability of compression wood for pulp and paper manufacture.

The decrease in mechanical properties that will accompany wood grown under short rotations will lead to lower strength of boards and structural members sawn from this wood. Also, the increase in juvenile wood will accentuate problems associated with drying. Knots will present a major problem, because they have a direct effect on how lumber behaves. Sound, tight knots increase the compression strength, hardness, and shear characteristics of the wood (16). However, a major loss in mechanical properties is associated with grain distortion in the wood around the knot, the greatest loss of strength coming in lumber or timbers subjected to bending stresses (16). Thus, the large number of knots in wood from precommercially thinned stands makes such wood less suitable for uses where it is subject to bending.

CONCLUSIONS

Within the limitations of our measurements on microbending specimens and standard ASTM 2.54x2.54x40.64-cm beams, the following conclusions were drawn:

1. Red spruce may not begin to produce wood mature for SG, MOR, and MOE until much later than has been reported for other species,possibly not until age 50 or later in stands growing at a wide spacing from an early age.
2. MOE reaches maturity first and SG last. There may be 20 years between the POMs for these properties.
3. There are large differences in the POM for a given property among stands.
4. Thinning does not cause a reduction in either SG, MOR, or MOE.
5. Intensive management to shorten rotations (to perhaps 50 years or less) may lead to the production of wood with properties considerably different and generally less favorable for the pulp and paper and structural lumber industries than properties of wood presently being harvested from older stands.

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