United States Department of Agriculture

Forest Service

Forest Products Laboratory

Research Paper FPL–RP–621

Effects of Uneven-Aged and Diameter-Limit Management on West Virginia Tree and Wood Quality

Michael C. Wiemann
Thomas M. Schuler
John E. Baumgras

Abstract

Uneven-aged and diameter-limit management were compared with an unmanaged control on the Fernow Experimental Forest near Parsons, West Virginia, to determine how treatment affects the quality of red oak (*Quercus rubra* L.), sugar maple (*Acer saccharum* Marsh.), and yellow-poplar (*Liriodendron tulipifera* L.). Periodic harvests slightly increased stem lean, which often causes tension wood. The grade of red oak was lower under the diameter-limit treatment compared with that of the control, but this was due primarily to tree size; in contrast, uneven-aged management improved red oak grade irrespective of tree size. Sugar maple grade was poorest in the control but similar in the two treatments, regardless of tree size. Yellow-poplar grade was best in the control, even when tree size was taken into account. Sapwood thickness range was small among all red oaks, although the sapwood of the control trees was narrower than that of the treated trees. For yellow-poplar, sapwood thickness increased with tree diameter but was independent of treatment. Sapwood thickness was extremely variable in sugar maple. It increased with diameter in both treatment sites but not in the control, and it was not significantly correlated with tree age. Young, vigorously growing sugar maples produce wide sapwood, but heartwood discoloration begins to affect the trees disproportionately as they reach maturity.

Keywords: growth rate, heartwood, red oak, sapwood, sugar maple, tree grade, yellow-poplar

June 2004

Wiemann, Michael C.; Schuler, Thomas M.; Baumgras, John E. 2004. Effects of uneven-aged and diameter-limit management on West Virginia tree and wood quality. Res. Pap. FPL-RP-621. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 16 p.

A limited number of free copies of this publication are available to the public from the Forest Products Laboratory, One Gifford Pinchot Drive, Madison, WI 53726–2398. This publication is also available online at www.fpl.fs.fed.us. Laboratory publications are sent to hundreds of libraries in the United States and elsewhere.

The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

Contents

Effects of Uneven-Aged and Diameter-Limit Management on West Virginia Tree and Wood Quality

Michael C. Wiemann, Research Scientist
Forest Products Laboratory, Madison, Wisconsin

Thomas M. Schuler, Research Forester
Northeast Research Station, Parsons, West Virginia

John E. Baumgras, Project Leader
Northeast Research Station, Princeton, West Virginia

Introduction

The quality of sawlogs is influenced by the silvicultural practices that precede their harvest. In addition to external characteristics like stem size, shape, and defects (such as surface irregularities, bird peck, and epicormic branches), internal characteristics are important. Many of these characteristics can be predicted from external evaluation but some cannot, such as the amount of sapwood and heartwood. Because wood color is not apparent in standing trees, its effect on value is not usually reflected in stumpage prices. In some hardwood species, such as red oak (*Quercus rubra* L.), the dark-colored heartwood is the most valuable portion of a log; in others, such as sugar maple (*Acer saccharum* Marsh.) and yellow-poplar (*Liriodendron tulipifera* L.), the most valuable part is the light-colored sapwood. Color is especially important in sugar maple lumber, with premiums paid for "white" sugar maple (Barrett and others 1999). Shigo (1986) distinguished heartwood (age-altered) from discolored wood (injury-altered), but we shall use the term heartwood for any dark-colored wood found in the tree center, since it is the color of the wood that determines its economic value. The heartwood in red oak and yellow-poplar is typical (age-altered), whereas that in sugar maple is injury-altered. Therefore, processes that cause injury to standing trees might be expected to affect heartwood formation in sugar maple but not in red oak or yellow-poplar, although wound-induced heartwood may also form in species that produce normal heartwood (Shigo and Hillis 1973).

The sapwood of red oak is typically less than 5 cm wide in mature trees (Forest Products Laboratory 1987), whereas that of yellow-poplar is often up to 15 cm wide (Lutz 1972). The sapwood of sugar maple may be very narrow or it may constitute the entire stem cross-section. Unlike the sapwood of red oak and yellow-poplar, the sapwood of sugar maple is extremely variable in size and shape. The reasons for these differences lie in the physiology of the trees and the mechanisms of heartwood formation. In species that form typical heartwood, a series of physiological changes takes place in the wood over time. These changes vary widely according to species, as extraneous materials diffuse from the dead parenchyma cells into the surrounding wood. In species that form injury-altered heartwood, such as sugar maple, the extraneous materials are deposited only within parenchyma cell cavities because their precursors polymerize to a large size before the parenchyma cell membranes break down (Bosshard 1968). Good and others (1955) contended that the number of living parenchyma cells in sugar maple decreases gradually with age and that the wood gradually darkens because of the deposition of colored material as the parenchyma cells die. Although the heartwood in sugar maple is wound-induced, not all wounds induce heartwood (Shigo 1986). The amount and location of discoloration are affected by the cause and location of the damage as well as by tree vigor and the ability of the tree to compartmentalize wounds (Shigo and Hillis 1973, Shortle and others 1996).

Genetics, site factors, and silvicultural treatments may be important in determining the type and amount of heartwood. Site factors include climate, previous human and natural disturbances, type of regeneration that follows disturbance, soil characteristics, and geographic features such as elevation, latitude, and topography. Silvicultural treatments include pruning, thinning, and harvesting regimes and methods.

In this paper, we compare the quality of trees subjected to uneven-aged management, diameter-limit management, and no management. Three common and commercially important species are examined: red oak, sugar maple, and yellow-poplar. The aim of this study was to determine if these management regimes improve tree and wood quality.

Methods

Study Area, Treatments, and Species

This research was part of a long-term silvicultural study implemented in 1950 on the Fernow Experimental Forest near Parsons, West Virginia. It was carried out in Study Area 2, which includes excellent growing sites; for example, northern red oak has a site index (SI_{50}) of 24 m. We compared two experimental treatments, uneven-aged management and diameter-limit cutting, with an unmanaged control. The choice of study species was based on shade tolerance ratings and heartwood characteristics. Sugar maple is very shade-tolerant, and it often produces injury-altered heartwood that is much less valuable than its sapwood. Red oak is intermediate in shade tolerance, producing typical heartwood that is much more valuable than its sapwood. Yellow-poplar is shade intolerant, and it produces typical heartwood that is less valuable than the sapwood (Trimble 1973).

Figure 1—Fernow Experimental Forest, West Virginia.

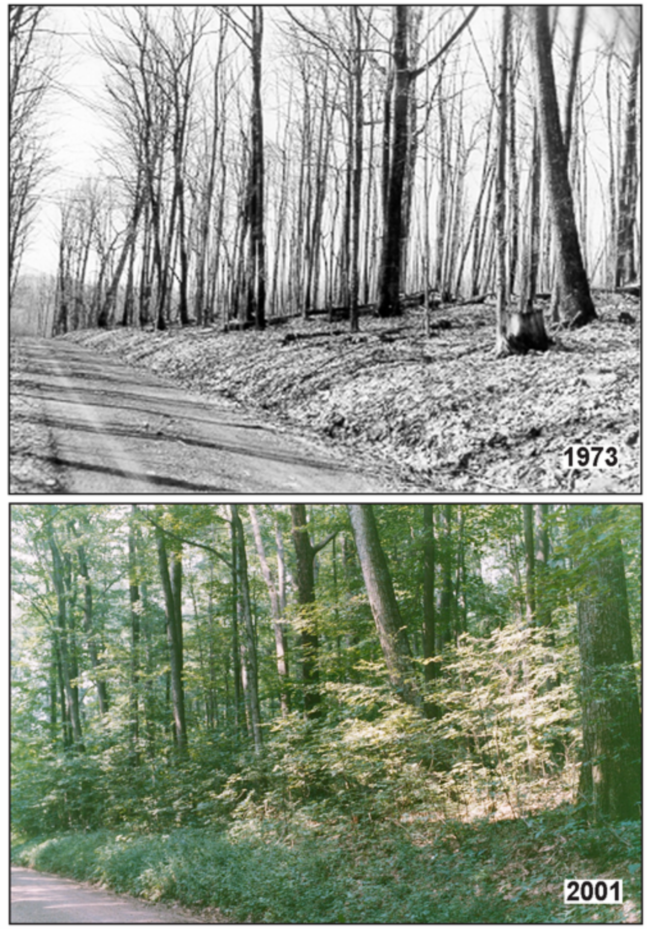

Figure 2—Unmanaged control site. Logged between 1905 and 1910.

The first logging in what became the Fernow Experimental Forest occurred between 1903 and 1911 (Trimble 1977) (Fig. 1). Our control site (Watershed 4A, 28 ha, SI_{50} = 25 m) (Fig. 2) was originally logged between 1905 and 1910 (Pan 1995), but it has not been disturbed since except for the removal of dead American chestnuts (*Castanea dentata* (Marsh.) Borkh.) around the time of World War II. In the diameter-limit site (Compartment 9B, 33 ha, SI_{50} = 23 m, established 1954), all trees greater than 43.2 cm (17 inches) diameter at breast height (DBH) are removed on a 15-year cutting cycle. No quality selection criteria are considered, except that cull trees are felled and left on site. Prior to our study, this site had been cut three times, most recently in 1986. The trees on the uneven-aged site (Compartment 20A, 10 ha, SI_{50} = 24 m, established 1952) are marked and cut to maintain a basal area of 15 m^2/ha for trees >27.9 cm (11 inches) DBH, with a planned number of trees in every diameter class up to 81.3 cm (32 inches). The poorest quality trees are selected for removal at each harvest, leaving behind the better trees to grow in the additional space. Compartment 20A has been cut five times, most recently in 1997 (USDA Forest Service, Timber and Watershed Laboratory, unpublished data). Although the sites are similar in quality and differ primarily in treatment, some site factors could not be controlled. These include percentage of slope, slope direction, and site aspect.

Study Sites, Tree Selection, and Tree Measurements

A 40-m-wide transect was set up in each silvicultural treatment site, with the starting point and direction of each transect depending on the site. Each starting point was at least 25 m from the nearest access road. The transect direction was chosen so that a transect of at least 300 m would stay within the site. The centerline of each transect was marked with string; the transect consisted of the area 20 m on each side of this centerline. In this transect, every sugar maple, yellow-poplar, and red oak with a DBH of at least 25 cm was tagged. When at least 20 trees each of two species were tagged, the transect was considered complete. Additional trees of the third species were then tagged from trees along both sides of the transect to give a total of at least 20 trees per species per treatment area.

In each treatment area, 20 trees of each species were selected using a random number table; these were the study trees. Maximum percentage of slope was measured at 25-m intervals along each transect, and the average steepest slope in each transect was calculated as the arithmetic mean of these measurements. In addition, the direction of maximum slope was measured with a compass at each 25-m interval, and average direction of maximum slope was calculated from these measurements. No corrections were applied for magnetic declination.

The DBH of each study tree was measured with a diameter tape, and the direction of maximum lean of the lower bole was determined using a compass (with no correction for declination). The angle of lean was measured using a 2-m-long aluminum rod with a plumb bob suspended from the top; the horizontal departure of the plumb bob was recorded, and the percentage of lean was calculated from the length of the rod (hypotenuse) and the horizontal departure. Lean is important because tension wood, which has inferior working properties, can form on the upper side of a leaning stem. We expected that gradual "surface slippage" caused by gravity might force the lower tree stems to lean downhill on the relatively steep slopes. The hypothesis that trees tend to lean downhill was tested non-parametrically using Tukey's studentized range based on absolute differences. Only trees with ≥5% lean were included in the test.

Tree Grading

Each tree was graded by USDA Forest Service tree graders using the criteria summarized in Hanks (1976). In some cases the re-measurement of DBH by the graders resulted in a tree being considered too small for Forest Service tree grades; in these instances, the potential grade was determined. Grading took into account attributes such as shape of cross section, amount of taper, extent of sweep or crook, and presence of lateral and epicormic branches, decay, splits, catface, or other damage.

Increment Core Extraction and Measurement

Two increment borings were taken at breast height from each tree. In most cases these borings were taken from the north and south side of the tree. Rarely, a core could not be taken from one of these directions because of bole damage; that core was then taken from the east or west side. Cores were mounted with glue in core holders so that transverse surfaces faced upwards. The tops of the cores were cut with razor blades or sanded to produce surfaces clean enough that growth rings could be counted and heartwood could be distinguished from sapwood. The criterion for separating heartwood from sapwood was wood color as observed with the naked eye. The amount of sapwood (lineal distance and number of growth rings) was measured in each core and was analyzed for each species to determine treatment effects. The total number of growth rings was also counted to estimate tree age. Radius as a function of age was plotted for the cores.

Computations and Statistical Analyses

The number of trees per hectare, basal area per hectare, and mean DBH were calculated, for each species and treatment, from the trees contained within the transects. The DBH, tree age, and sapwood thickness (in centimeters and growth rings) were compared among sites for each species.

The data were examined for normality and homogeneity of variances. The SAS GLM program, with Tukey comparisons, was used to find differences among site means for DBH, age, and sapwood thickness for each species. Pairwise *t*-tests were used to determine equality of variances.

Results

Number of Trees and Basal Area

Transect length was 275 m in the control site and 250 m in the diameter-limit and uneven-aged sites. Red oak was dominant in both number of trees and basal area per hectare in the control site, whereas sugar maple was dominant in the two treatment sites; red oak was more than twice as frequent in the control site as in either treatment site, whereas sugar maple was about one-tenth as frequent. Although yellow-poplar was equally common in the two managed sites, it was 50% more frequent in the control than in either treatment site (Table 1).

Table 1—Frequency, basal area per hectare, and mean DBH of study species

	Number of trees per hectare			Basal area per hectare (m^2)			Mean tree DBH[a] (cm)			
Site	Red oak	Sugar maple	Yellow-poplar	Red oak	Sugar maple	Yellow-poplar	Red oak	Sugar maple	Yellow-poplar	All species
Control	51	6	18	15.25	2.21	3.37	59.3 (56)	65.3 (7)	47.5 (20)	57.0 (83)
Diameter-limit	22	74	12	3.87	8.45	1.58	46.4 (22)	37.0 (74)	39.9 (12)	39.2 (108)
Uneven-aged	20	59	12	5.32	6.55	3.14	55.0 (20)	36.5 (59)	55.1 (12)	43.0 (91)

[a]Number of trees used in calculations given in parentheses.

Table 2—Transect slopes, percentage of tree lean, and tree lean azimuth at each site

	Transect slope[a]		Tree lean (%)[b]				Tree lean azimuth (°)[c]			
Site	Slope (%)	Downhill azimuth (°)	Red oak	Sugar maple	Yellow-poplar	All species	Red oak	Sugar maple	Yellow-poplar	All species
Control	26 (14–36)	105 (70–120)	11 (7.0)	11 (9.4)	3 (4.0)	9 (8.0)	160 (17)	125 (14)	175 (3)	145 (34)
Diameter-limit	31 (27–47)	285 (250–295)	13 (6.2)	9 (8.3)	3 (3.3)	8 (7.5)	280 (20)	280 (13)	255 (4)	275 (37)
Uneven-aged	30 (23–36)	290 (280–300)	11 (5.9)	7 (4.6)	7 (7.9)	9 (6.5)	310 (16)	290 (13)	315 (11)	305 (40)

[a]Transect slope includes mean percentage of greatest slope, with measurements taken every 25 m along transect center line, and mean azimuth of downhill slope. Ranges are given in parentheses.
[b]Tree lean is mean percentage of lean at breast height for all sample trees at each site (standard deviations given in parentheses).
[c]Tree lean azimuth is mean direction of lean for trees with ≥5% lean (number of trees given in parentheses).

Lean

Within each transect, maximum downhill slope varied by 50° or less in azimuth and by 22% (12°) or less in inclination, and the downhill direction in the control was opposite that in the two treatment sites (Table 2). Trees had a tendency to lean downhill, although there were many exceptions. In general, red oak leaned the most and yellow-poplar the least. Red oak had the greatest percentage of trees with at least 5% lean and yellow-poplar had the lowest percentage. In the control and diameter-limit sites, fewer than half the yellow-poplars had at least 5% lean.

At all three sites, the species with the greatest percentage of "straight trees" (≤10% lean) was yellow-poplar (85% to 95%) and the species with the lowest percentage of straight trees was red oak (35% to 50%); sugar maple was intermediate (65% to 75%) (Fig. 3). Thus it seems that the tendency to lean is a species characteristic, at least in part. However, treatment may also affect lean, since the individual trees with the greatest lean in each species were found in the treatment sites: red oak and sugar maple in the diameter-limit site and yellow poplar in the uneven-aged site. Overall, red oak had the greatest lean in the diameter-limit site, sugar maple in the control site, and yellow-poplar in the uneven-aged site.

For all sites combined, there was no difference in lean direction among species. For all species combined, the lean direction, relative to the greatest downhill slope, was different for the control than it was for the two treatment sites, which had the same lean direction; trees in the treatment sites were more apt to lean downhill than were trees in the control site. Because the downhill azimuth of the control site (105°) was opposite the downhill azimuths of the two treatment sites (285° and 290°, Table 2), the direction of prevailing sunlight may account for the different effects.

Tree Grade

The largest red oaks and sugar maples were found in the control site and the largest yellow-poplars in the uneven-aged site. Because grade is a function of both bole quality and DBH (Miller and others 1986), large trees would tend to have higher grades for similar bole evaluations. For this reason, Table 3 (percentage of trees in each grade) is divided into two categories: the grade distribution of all sample trees and the distribution of only those sample trees large enough to qualify as Grade 1 (DBH ≥ 40.6 cm).

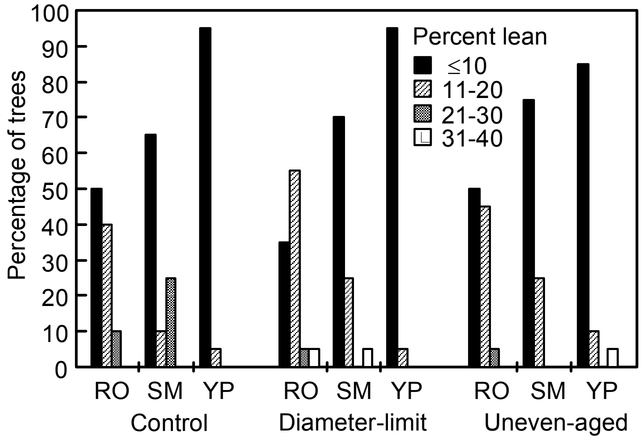

Figure 3—Percentage of trees of each species in each lean class at study sites. RO is red oak, SM sugar maple, and YP yellow-poplar.

DBH, Age, and Sapwood Thickness

The distributions of tree DBH, age, and sapwood thickness data were non-normal, and pairwise *t*-tests showed that variances were not equal. General linear models with assumptions of unequal variances were therefore used to distinguish differences among control and treatments. Age estimates were not used for trees that were hollow or had significant heart rot. The trees without age estimates were as follows: control site, two red oaks and two sugar maples; diameter-limit site, two sugar maples and three yellow-poplars; and uneven-aged site, one red oak.

Age was estimated for 56 control site trees; of these, 14 were greater than 100 years old. Of the four control site trees with hollow centers, three trees were large (>85 cm DBH) and can also be assumed to have been at least 100 years old. Six uneven-aged site trees and one (possibly two) diameter-limit site trees were at least 100 years old. The oldest red oak and sugar maple trees (166 and 202 years, respectively) were in the control site, whereas the oldest yellow-poplar (94 years) was in the uneven-aged site (Table 4). For the trees whose ages could be estimated, Figure 4 shows tree DBH as a function of tree age for each species at each site.

Red oak mean ages were not statistically different among the three sites, although the coefficient of variability (CV) was highest in the control site and lowest in the diameter-limit site (Table 4). Control sugar maple was both older and larger than sugar maple in either treatment site, and the CV of sugar maple age was greater in the control than in the treatment sites (Table 4). Control yellow-poplar was older but not larger than yellow-poplar in the treatments sites (Table 4). This is because yellow-poplar, a shade-intolerant species, has a large variance in its growth rate, which depends on degree of suppression. The mean age for yellow-poplar was for a single cohort in the control (CV = 5%), the uneven-aged site had two cohorts (CV = 35%), and the diameter-limit site had three (CV = 30%) (Table 4, Fig. 4).

Red oak DBH was significantly greater in the control site than in the diameter-limit site, but not in the uneven-aged site (Table 4). The uneven-aged and diameter-limit sites were not significantly different from each other in DBH (Table 4). This apparent contradiction is probably attributable to the high DBH variability (CV) in the uneven-aged site, which did not permit the SAS GLM program to distinguish it from either the control or diameter-limit site. Sugar maple DBH was greater in the control site than in the uneven-aged and diameter-limit sites, in which DBH was equal. Yellow-poplar DBH was the same in all three sites. DBH variability (CV) was lowest in the diameter-limit site for red oak, about equal among sites for sugar maple, and highest in the uneven-aged site for yellow-poplar. Diameter-limit management removed all of the largest oaks, which accounts for the low CV. The DBH CV for yellow-poplar was high in the uneven-aged site because this site has been subjected to partial harvests five times, each time engendering a new cohort of trees. The diameter-limit site has also been subjected to partial harvests but the largest trees have been selectively removed, reducing the DBH CV for yellow-poplar to about equal that of the control. Interestingly, the DBH CV for sugar maple was approximately equal among sites. In the control, both standard deviation (SD) and mean were larger than those values in either treatment, where they were about equal (Table 4).

Table 5 gives the mean sapwood thickness for each species/treatment/grade category. In general, sapwood was narrower in lower grade trees. Sapwood thickness values of each species at each site are also compared in Figure 5. For red oak, mean sapwood thickness in the control site was somewhat narrower than that in either treatment site (Fig. 5). Although there is a great deal of overlap, this difference is statistically significant ($p = 0.05$) (Table 4). Because sapwood is considered a defect in red oak, treatment reduced the color quality of the wood. For sugar maple, mean and median values of sapwood thickness were similar among the three sites, although the control had a wider range and included one outlier (Fig. 5)—a 54-cm-DBH, 135-year-old, Grade 1 tree with no heartwood. For yellow-poplar, mean sapwood thickness was narrowest in the control site compared with the treatment sites, again with much overlap (Fig. 5), so that the differences were not statistically significant (Table 4).

Red oak sapwood thickness, expressed in number of growth rings, was not statistically different in either treatment site compared with the control, although the two treatments were statistically different from each other (Table 4).

Table 3—Percentage of trees in each grade (including potential grade) for each treatment and species[a]

		Grade 1				Grade 2				Grade 3				Below-grade			
Sample	Site	RO	SM	YP	All	RO	SM	YP	All	RO	SM	YP	All	RO	SM	YP	All
All trees	Control	50	5	75	43	20	15	10	15	20	40	10	23	10	40	5	18
	Diameter-limit	30	20	40	23	10	15	15	13	50	50	45	50	10	15	0	13
	Uneven-aged	60	20	50	43	10	10	20	13	30	50	30	37	0	20	0	7
Trees ≥ 40.6 cm DBH[b]																	
	Control (19,19,15,53)	53	5	87	45	16	11	13	13	21	42	0	23	11	42	0	19
	Diameter-limit (12,6,11,29)	50	33	64	52	8	33	9	14	42	33	27	34	0	0	0	0
	Uneven-aged (15,9,11,35)	80	44	91	74	7	11	0	6	13	33	9	17	0	11	0	3

[a]RO is red oak; SM, sugar maple; YP, yellow-poplar; All, all three species combined. Trees at least 40.6 cm DBH were large enough to be Grade 1.
[b]Numbers in parentheses are number of red oak, sugar maple, yellow poplar, and all species combined, respectively, with ≥40.6 cm DBH.

Table 4—Diameter at breast height, age, and sapwood thickness of test species at control and treatment sites[a]

		DBH (cm)			Tree age (years)			Sapwood thickness (cm)			Sapwood thickness (rings)		
Site		Red oak	Sugar maple	Yellow-poplar	Red oak	Sugar maple	Yellow-poplar	Red oak	Sugar maple	Yellow-poplar	Red oak	Sugar maple	Yellow-poplar
Control	Mean	66.4 A	62.0 A	47.5 A	92.6 A	114.2 A	84.2 A	2.0 A	14.2 A	6.0 A	7.8 AB	71.9 A	29.0 A
	SD	20.0	12.1	10.5	28.3	36.3	4.1	0.5	5.5	2.4	1.6	19.8	5.6
	CV	30	20	22	31	32	5	26	39	40	21	28	10
	Range	35–109	39–88	28–62	58–166	66–202	75–89	1.0–3.2	4.4–26.9	1.8–10.0	5.5–10.5	30.5–122.5	19.0–39.0
Diam.-limit	Mean	46.3 B	35.1 B	40.2 A	83.3 A	74.4 B	52.9 B	2.7 B	12.9 A	7.1 A	6.6 B	54.2 B	17.4 B
	SD	10.1	8.0	8.2	6.1	14.2	15.8	0.7	4.1	1.9	1.0	13.5	4.2
	CV	22	23	20	7	19	30	26	32	27	15	25	24
	Range	28–60	25–49	27–56	73–93	54–111	36–83	1.6–4.1	5.0–19.0	4.8–11.2	5.0–9.0	29.0–76.5	9.5–24.0
Uneven-aged	Mean	55.0 AB	36.6 B	49.7 A	85.1 A	82.8 B	63.2 B	2.6 B	12.8 A	6.9 A	8.2 A	51.8 B	20.7 B
	SD	19.4	8.0	18.5	11.7	16.8	22.4	0.8	4.4	2.5	1.6	16.5	7.6
	CV	35	22	37	14	20	35	31	34	36	20	32	37
	Range	29–109	25–53	26–83	64–112	55–113	41–94	1.5–4.2	4.4–21.0	3.4–11.1	5.0–11.0	18.5–80.5	12.5–37.5

[a] Results of nonparametric tests for differences in means among treatments and species. For each column, treatment means followed by the same letter are not significantly different at the 0.05 level.

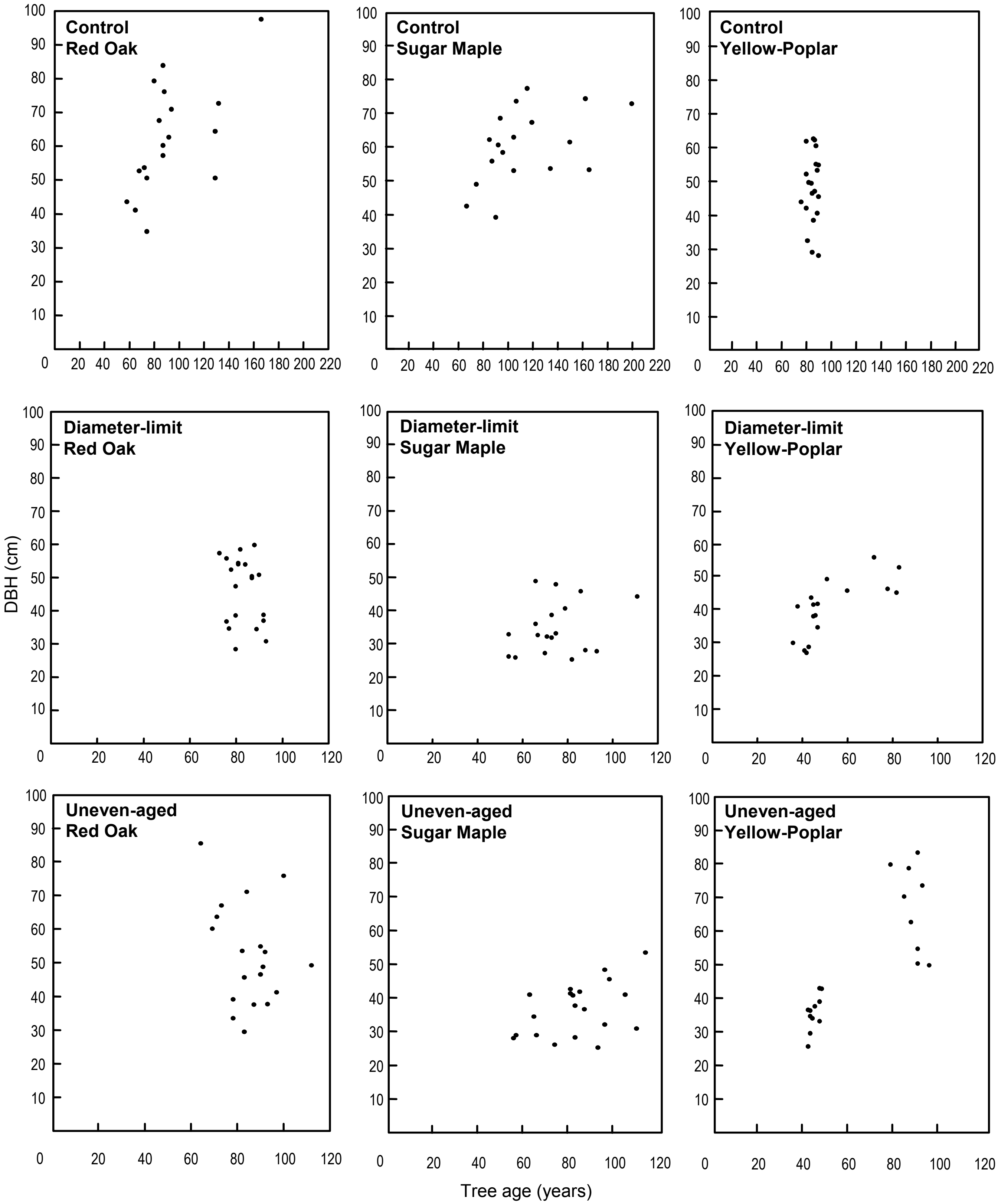

Figure 4—Diameter at breast height (DBH) as a function of tree age for each species at each site.

Table 5—Sapwood thickness for each species and treatment by grade

	Mean sapwood thickness (cm) [a]								
	Red oak			Sugar maple			Yellow-poplar		
Grade	Control	Diameter-limit	Uneven-aged	Control	Diameter-limit	Uneven-aged	Control	Diameter-limit	Uneven-aged
Grade 1	2.3 (10)	3.2 (6)	2.9 (12)	26.9 (1)	14.5 (4)	16.4 (4)	6.6 (15)	8.1 (8)	8.2 (10)
Grade 2	1.9 (4)	2.8 (2)	2.2 (2)	16.2 (3)	17.1 (3)	17.6 (2)	5.9 (2)	6.5 (3)	6.4 (4)
Grade 3	1.8 (4)	2.4 (10)	2.2 (6)	13.7 (8)	11.6 (10)	11.3 (10)	3.5 (2)	6.5 (9)	5.1 (6)
Below grade	1.2 (2)	2.3 (2)	—	12.2 (8)	11.0 (3)	10.6 (4)	1.8 (1)	—	—

[a] Numbers of trees given in parentheses.

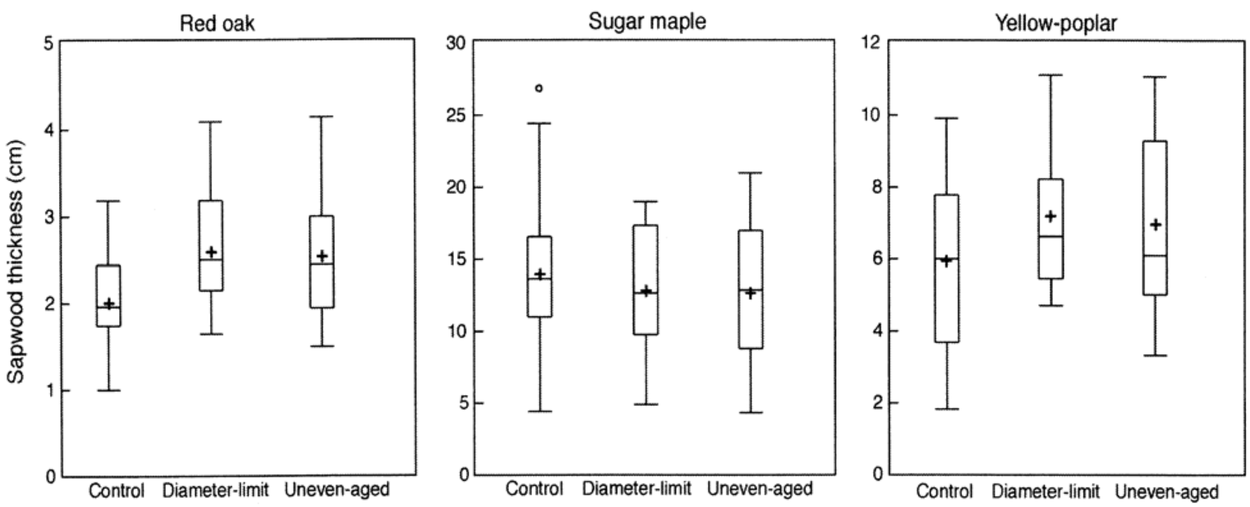

Figure 5—Distribution of sapwood thickness. Crosses indicate mean values. Each box depicts middle half of data between 25th and 75th percentiles; the horizontal line across the box marks the median value. Vertical extensions (whiskers) indicate values greater than the median – 1.5 quartile range but less than the median + 1.5 quartile range. Circle indicates an outlier (more than two standard deviations from mean).

The number of sapwood growth rings was greater in the control than in either treatment site for sugar maple and yellow-poplar. In yellow-poplar, growth rate (DBH/age) was 0.57 cm/year in the control site, but 0.92 and 0.80 cm/year in the diameter-limit and uneven-aged sites, respectively. This greater vigor in the treatment sites resulted in fewer rings of sapwood but not a statistically significant difference in centimeters of sapwood because the rings were wider (Table 4).

Sugar maple sapwood thickness is compared with diameter growth rate in Figure 6, in which sapwood thickness in centimeters (a) and number of growth rings (b) is plotted against growth rate. Diameter growth rate, equal to tree DBH divided by age, includes both the wood and the bark. For all trees combined, it is apparent that sapwood thickness was unrelated to growth rate; correlations between sapwood thickness and growth rate were non-significant for both centimeters ($r = 0.24$) and number of rings ($r = -0.04$).

Considering each site separately, sapwood thickness in centimeters was significantly and positively correlated with growth rate for the diameter-limit treatment ($r = 0.50$) and the uneven-aged treatment ($r = 0.53$). All other correlations were non-significant.

The correlation coefficients among measured variables for each species at each site are presented in Table 6. No significant relationships hold for all species at all sites. The DBH was significantly correlated with tree age for red oak at the control site but not at either treatment site; DBH was significantly correlated with tree age at only the uneven-aged site for sugar maple and at the two treatment sites but not at the control site for yellow-poplar. For red oak and yellow-poplar, the significant correlations between DBH and tree age at the control and treatment sites, respectively, can be attributed to the presence of young and old cohorts within the sites, as is evident from Figure 4. For the sugar maple in the uneven-aged site, the age and DBH ranges were wide

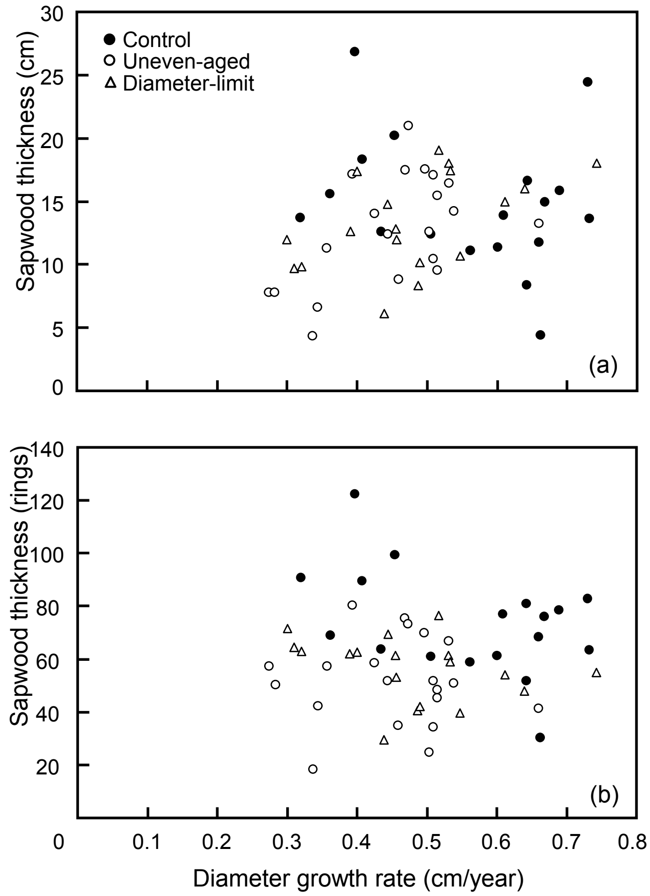

Figure 6—Sapwood thickness in sugar maple as a function of growth rate: (a) thickness in centimeters; (b) thickness in number of growth rings.

enough to register a significant (but weak) correlation (Table 6, Fig. 4).

For red oak, sapwood thickness in centimeters was significantly (positively) correlated with DBH only at the diameter-limit site; for sugar maple it was correlated at the two treatment sites but not the control site; and for yellow-poplar it was correlated at all three sites. Sapwood thickness in centimeters was significantly correlated with tree age only for yellow-poplar at the uneven-aged site, as a result of the presence of two very distinct age cohorts (Table 6, Fig. 4).

Discussion

Grade

Considering all trees regardless of DBH, the three sites showed species-related differences in grade distributions. The uneven-aged site had the largest proportion of Grade 1 red oak trees (60%) and the diameter-limit site the lowest proportion (30%). The control site had the largest proportion of Grade 1 yellow-poplar trees (75%) and the diameter-limit site the lowest proportion (40%). Grade 1 sugar maple was rare (5%) in the control site and constituted only 20% of trees in the uneven-aged and diameter-limit sites. Overall the diameter-limit site had a low proportion of Grade 1 trees (23%) and a high proportion of Grade 3 trees (50%) because large trees have been periodically removed from this site. The uneven-aged site had no below-grade red oak or yellow-poplar and the diameter-limit site had no below-grade yellow-poplar, but the control site had below-grade trees of all three species, especially sugar maple (40%) (Table 3).

In the comparison of the trees large enough to be Grade 1 (≥40.6 cm DBH), little change was evident in the control site because most of those trees (53 of 60) were large enough to be Grade 1; of these, 53% red oak, 5% sugar maple, and 87% yellow-poplar were Grade 1 (Table 3). Compared with the control, the diameter-limit site (29 trees) showed little change in grade for red oak (50% Grade 1), improved quality for sugar maple (33% Grade 1), and lower quality for yellow-poplar (64% Grade 1). The uneven-aged site (35 trees) showed great improvement in grade: 80%, 44%, and 91% of red oak, sugar maple, and yellow-poplar, respectively, were Grade 1. Considering all species combined, 45% trees at the control site, 52% at the diameter-limit site, and 74% at the uneven-aged site were Grade 1 (Table 3).

Our data indicate that compared with no management, uneven-aged management can greatly increase the proportion of high grade red oak and sugar maple. Compared with no management, diameter-limit management does not increase the proportion of high grade red oak, increases the proportion of high grade sugar maple, and decreases the proportion of high grade yellow-poplar. For large DBH (≥40.6 cm) trees, the diameter-limit site had no below-grade trees, unlike the uneven-aged site, which had 11% below-grade sugar maple, and the control, which had 11% below-grade red oak and 42% below-grade sugar maple (Table 3). This is the result of periodic felling of all cull trees in the diameter-limit site.

The interpretation of the effect of management on grade is confounded by the presence of residual (pre-1910) red oaks and sugar maples on the control site. For example, the largest oak (109 cm DBH) and the largest maple (88 cm DBH) were both culls, and they may represent poor quality trees left when the Fernow Experimental Forest was first logged.

Why the mean DBH of trees in the diameter-limit site was not significantly smaller than that of trees in the uneven-aged site (Table 4) is not clear, but it may be due to growth during the interval since the last treatment, which occurred in 1997 in the uneven-aged site but in 1986 in the diameter-limit site. Thus, the diameter-limit trees have had an

Table 6—Correlation coefficients among measured variables for individual sites and species. Italics indicate correlations significant at 0.05 level

Site	Species	Variable	Tree age (years)	Sapwood (cm)	Sapwood (rings)
Control	Red oak	DBH	*0.60*	–0.32	*0.62*
		Tree age	—	–0.30	*0.56*
		Sapwood (cm)	–0.30	—	–0.30
	Sugar maple	DBH	0.46	0.09	0.11
		Tree age	—	0.41	*0.52*
		Sapwood (cm)	0.41	—	*0.89*
	Yellow-poplar	DBH	0.05	*0.80*	0.32
		Tree age	—	–0.27	0.22
		Sapwood (cm)	–0.27	—	*0.49*
Diameter–limit	Red oak	DBH	–0.24	*0.69*	–0.18
		Tree age	—	–0.22	*–0.66*
		Sapwood (cm)	–0.22	—	–0.02
	Sugar maple	DBH	0.27	*0.72*	0.03
		Tree age	—	0.25	*0.49*
		Sapwood (cm)	0.25	—	*0.63*
	Yellow-poplar	DBH	*0.72*	*0.74*	*0.52*
		Tree age	—	0.45	*0.65*
		Sapwood (cm)	0.45	—	*0.53*
Uneven-aged	Red oak	DBH	–0.29	0.40	–0.11
		Tree age	—	0.02	0.00
		Sapwood (cm)	0.02	—	*0.61*
	Sugar maple	DBH	*0.46*	*0.81*	0.40
		Tree age	—	0.23	0.40
		Sapwood (cm)	0.23	—	*0.72*
	Yellow-poplar	DBH	*0.83*	*0.68*	*0.54*
		Tree age	—	*0.57*	*0.78*
		Sapwood (cm)	*0.57*	—	*0.70*

additional 11 years of growth compared with the uneven-aged trees, reducing the effect of the selective removal of large-diameter trees. Note that the largest tree in the uneven-aged site was 109 cm DBH, but the largest tree in the diameter-limit site was only 60 cm DBH (Table 4). Thus, the largest trees had in fact been removed from the diameter-limit site even though their mean DBH measurements were not significantly different.

Age

As Table 4 indicates, the mean age of control site trees was greater than that of the trees in the two treatments, as expected, although the differences were not statistically significant for red oak because of its high variability. We emphasize that the ages obtained are not maximums, since the increment borer did not always hit the pith. Nevertheless, the ages of the oldest red oak and sugar maple trees exceed the elapsed time since the earliest timber harvesting at all three sites, indicating that old-growth species composition (primarily from the old-growth understory) is still a factor in current composition and structure. The ages of the oldest yellow-poplars, on the other hand, correspond to the elapsed time since the earliest timber harvesting at all three sites, indicating the relictual importance of that harvesting.

Interestingly, the age distributions showed low variability (SD = 4.1 years) for yellow-poplar in the control site and high variability (SD = 15.8 and 22.4 years) for both treatments of yellow-poplar (Table 4). Because yellow-poplar is shade intolerant, the population of trees in the control primarily consisted of individuals that originated after the logging of the early 1900s. In contrast, new yellow-poplar trees originated after treatments in the uneven-aged and diameter-limit sites.

The variability (range, SD, and CV) in age of red oak and sugar maple was highest in the control site and lowest in the diameter-limit site (Table 4). The control site contained old-growth oaks and maples as well as young trees of these species. Uneven-aged and diameter-limit management periodically removed some of the largest trees of these species, reducing the range and variability.

Several different patterns are evident from Figure 4. Two distinct age classes are present for red oak in the control site (58 to 94 years and >128 years, corresponding to the periods 1907–1943 and prior to 1872, respectively) and yellow-poplar in the uneven-aged site (41 to 47 years and 77 to 94 years, corresponding to the periods 1954–1960 and 1907–1924, respectively). In contrast, some species and sites showed very uniform age, especially yellow-poplar in the control site (75 to 89 years, 1912–1926) and, to a lesser extent, the red oaks in the diameter-limit site (73 to 93 years, 1918–1929). Obviously, the yellow-poplar trees in the control site all originated over a short interval after logging in the beginning of the 20th century. Some yellow-poplars in the uneven-aged site also originated during this period, but another cohort followed the first experimental harvest in 1952. The age distributions of the other species and sites are less clear. A cohort of 12 yellow-poplar trees originated on the diameter-limit site (initiated 1954) between 1954 and 1965, but this site also contains yellow-poplars that originated between 1918 and 1950. Sugar maple age seemed to be fairly evenly distributed at all three sites, although the control site contained older sugar maples than did the uneven-aged or diameter-limit site (Fig. 4, Table 4).

Growth Rate

Growth patterns were affected by treatments as well as natural events, as shown by the comparison of inside-bark radius as a function of tree age for trees with cores that hit pith (Figs. 7 to 9). At the control site (Fig. 7), three trees—a 166-year-old red oak and 202- and 116-year-old sugar maples—were growing on the site prior to the harvest of the early 1900s. At that time, DBH would have been about 30 cm for red oak and 25 cm for the older sugar maple, based on measurements from the cores. The increase in growth rate subsequent to the harvest is clearly shown by the inflection points corresponding to 1908. Growth rate increased at that time but has gradually been slowing,

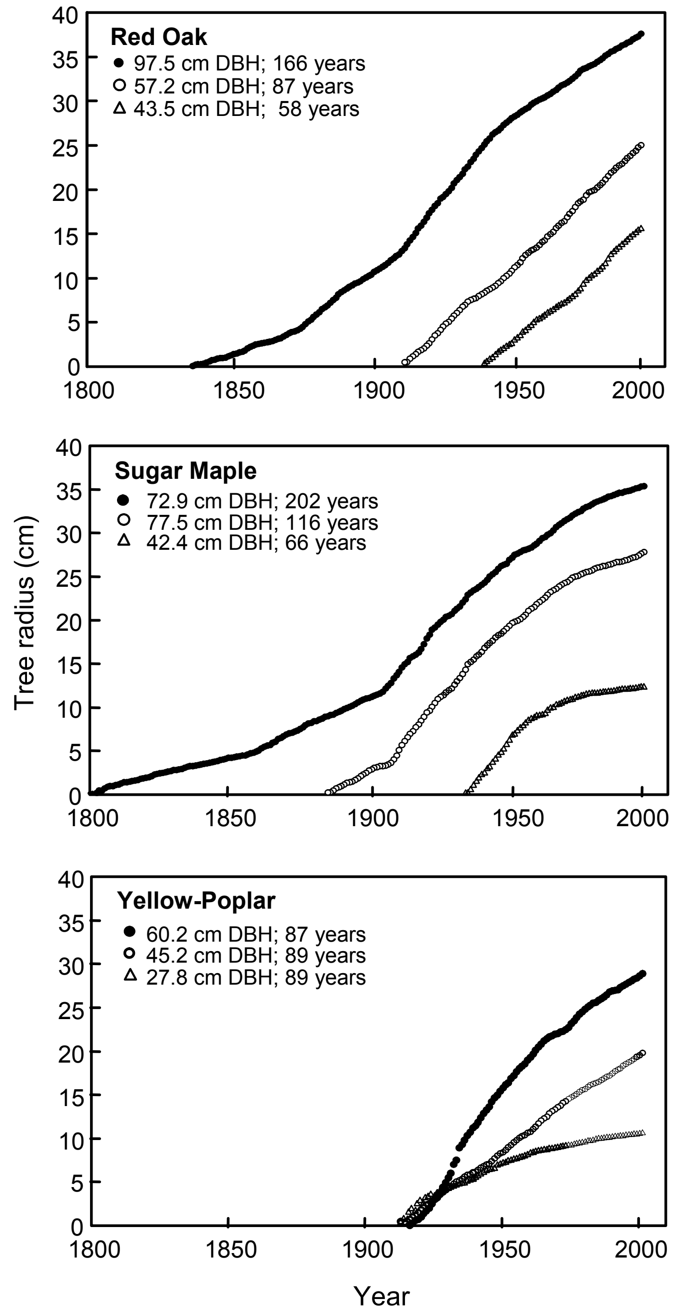

Figure 7—Growth patterns of selected trees in control site. Tree radius is radius inside bark, determined by measurement of core that reached pith.

especially for sugar maple. The growth rate of the two smaller red oaks of Figure 7 has been constant, but that of the smaller sugar maple has decreased with age. The red oaks in the control are still vigorous, whereas the sugar maples have entered a slow growth stage.

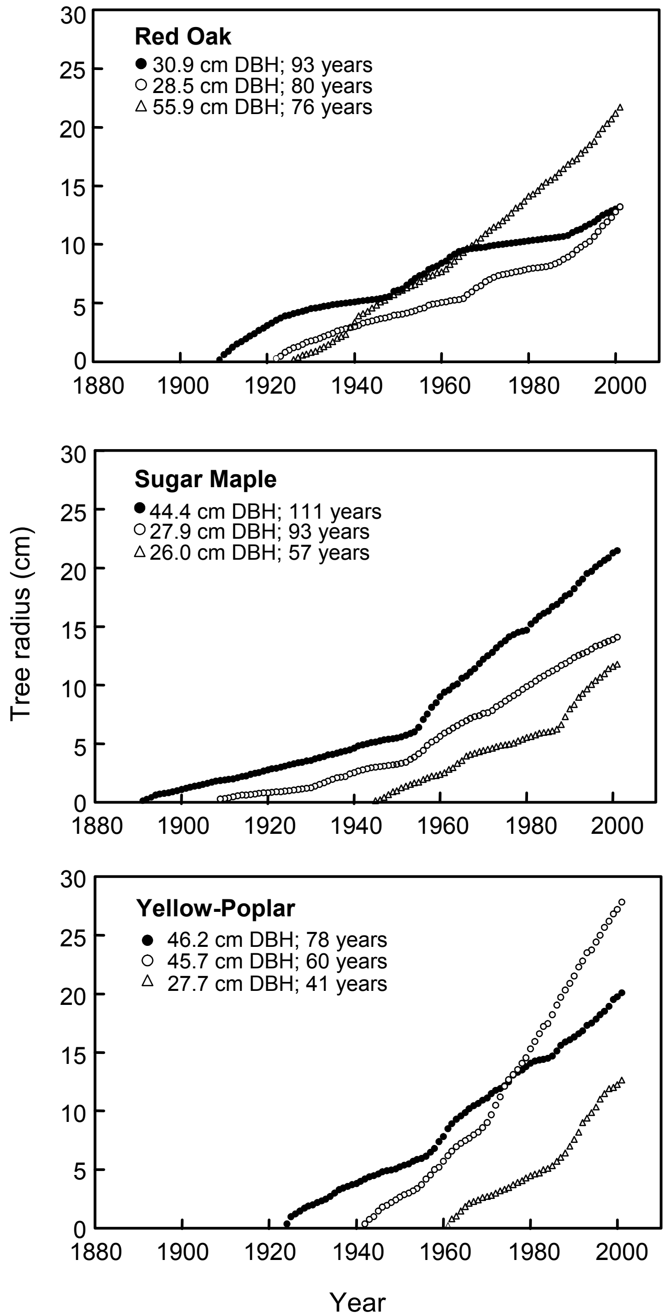

Figure 8—Growth patterns of selected trees in diameter-limit site. Tree radius is radius inside bark, determined by measurement of core that reached pith.

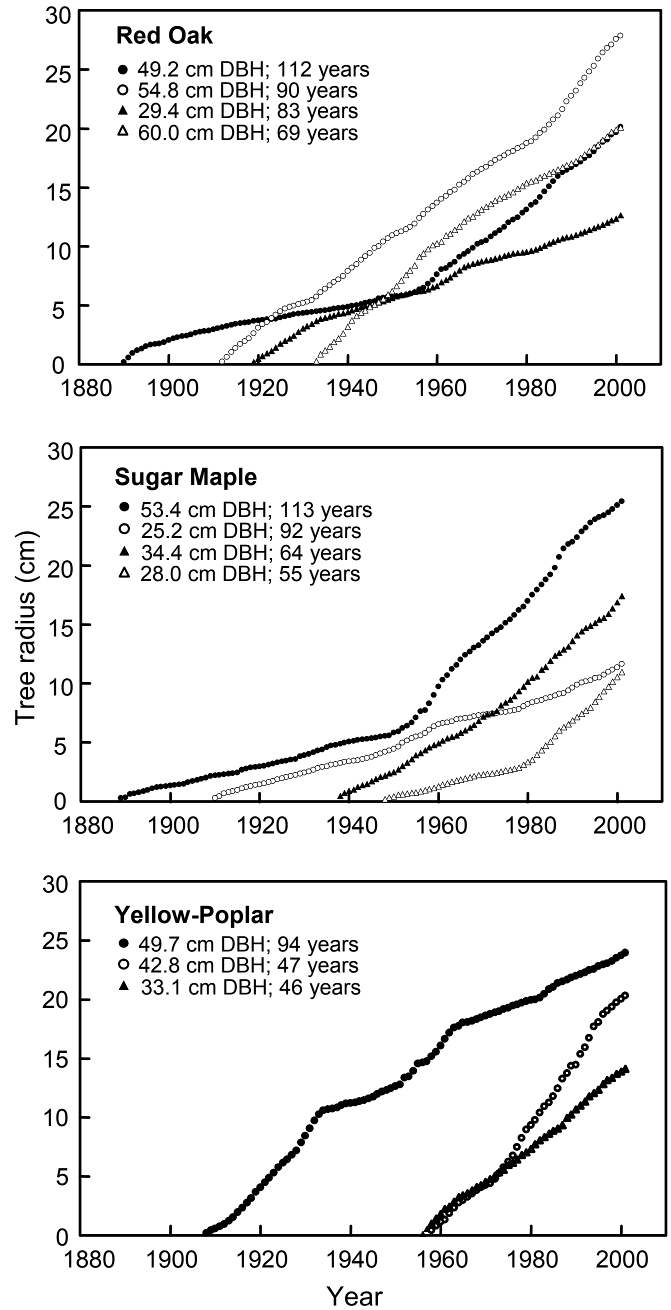

Figure 9—Growth patterns of selected trees in uneven-aged site. Tree radius is radius inside bark, determined by measurement of core that reached pith.

The yellow-poplars in the control site (75 to 89 years old) originated subsequent to the harvest of the early 1900s. One tree depicted in Figure 7 has been growing at a uniform rate, whereas the growth rates of the other two have been slowing. The smaller of these two trees grew slowly under suppressed conditions, whereas the larger tree grew rapidly.

Surprisingly, the diameter-limit site contained some old trees. Figure 8 includes the growth pattern of a 111-year-old sugar maple, which was slow and uniform until the compartment was established in 1954, after which the growth rate increased. In 1954, the DBH of this tree would have been about 14 cm. Figure 8 also depicts a 93-year-old

Table 7—Mean tree DBH and sapwood thickness (SWT) in large (≥40.6-cm DBH) sugar maple trees in each grade[a]

	Mean DBH and sapwood thickness (cm)									
	Grade 1		Grade 2		Grade 3		Below-grade		All grades	
Site[b]	DBH	SWT	DBH	SWT	DBH	SWT	DBH	SWT	DBH	SWT
Control (1,2,8,8,19)	54	27	74	18	62	14	63	12	63	14
Diameter-limit (2,2,2,0,6)	47	17	43	18	48	16	—	—	46	17
Uneven-aged (4,1,3,1,9)	44	16	53	21	41	15	43	16	44	17

[a]Trees at least 40.6 cm DBH were considered large enough to be Grade 1.

[b]Numbers in parentheses are number of trees in each grade category.

red oak that grew relatively rapidly after the initial harvest but gradually decreased in growth rate until establishment of the compartment. Growth rate then increased, slowed, and increased once again, coinciding with a partial harvest in 1985. In addition, Figure 8 depicts two red oaks that are similar in age (80 and 76 years) but have different diameters (28.5 and 55.9 cm DBH). Both trees grew at a relatively uniform rate, although the smaller tree grew much more slowly until the partial harvest of 1985.

Of the two younger sugar maples in Figure 8, the 93-year-old tree originated after the initial cut and the 57-year-old tree originated 10 years prior to the establishment of the compartment in 1954. The older of these trees responded to the establishment of the compartment with increased growth rate, whereas the younger was unaffected by this event. However, the younger tree responded to the treatment in 1985, whereas the older one did not.

The growth rate of the oldest of the three yellow-poplars in Figure 8 (78 years) was relatively uniform and then increased after the establishment of the compartment in 1954. The growth rate of the 60-year-old tree increased after treatment in 1970 but not in 1986, whereas the growth rate of the 41-year-old tree increased after the 1986 treatment.

The uneven-aged site also contained trees that were present prior to the initial harvest. The growth patterns of two of these trees, a 112-year-old red oak and a 113-year-old sugar maple, are shown in Figure 9. Both of these trees showed slow growth until the compartment was established in 1952, at which time their growth rate increased. These trees would have been about 14 cm and 12 cm DBH, respectively, in 1952.

Figure 9 also shows growth rates for three additional red oaks, three additional sugar maples, and three yellow-poplars. One yellow-poplar originated immediately after the initial harvest and two after compartment establishment. Some of these trees had relatively uniform growth rates, but the 47-year-old yellow-poplar and 55-year-old sugar maple obviously responded to 1973 and 1977 thinnings, respectively.

Sapwood Thickness

An *a posteriori* comparison of sapwood thickness in sugar maple trees in the control site indicated a general trend toward narrower sapwood in lower grade trees. The mean sapwood thickness was 27 cm for the single Grade 1 tree (outlier in Fig. 5), 16 cm for the three Grade 2 trees, 14 cm for the eight Grade 3 trees, and 12 cm for the eight below-grade trees (Table 5). If this trend can be substantiated, it indicates that the external indicators of grade are reflected in the quality of wood color in sugar maple. Table 7 extends this comparison to the treatments, comparing only sugar maple trees large enough to be Grade 1. We emphasize that these are unplanned comparisons and should only be used to define areas of future research. In the control site, the trend for sapwood thickness for Grades 1, 2, 3, and below-grade trees (27, 18, 14, and 12 cm, respectively) was essentially the same as that for all trees because only one tree (a Grade 2) was too small to make Grade 1. In the treatment sites, in which many trees were too small to be Grade 1, Grade 2 trees had the widest sapwood and Grade 3 the narrowest (Table 7). Although no statistically valid inferences can be made from these comparisons, they do suggest that management can improve the color quality of large sugar maple trees, in spite of the possibility that logging damage in the treatment sites might cause heartwood formation.

As tree diameter increases, sapwood can decrease in thickness yet maintain a constant cross-sectional area. This is a possible explanation for the narrower sapwood in red oak in the control site compared with red oak in the treatment sites. The red oaks in the control site were larger than those in the diameter-limit site, but their mean sapwood thickness was smaller (Table 4). Figure 10 shows sapwood thickness

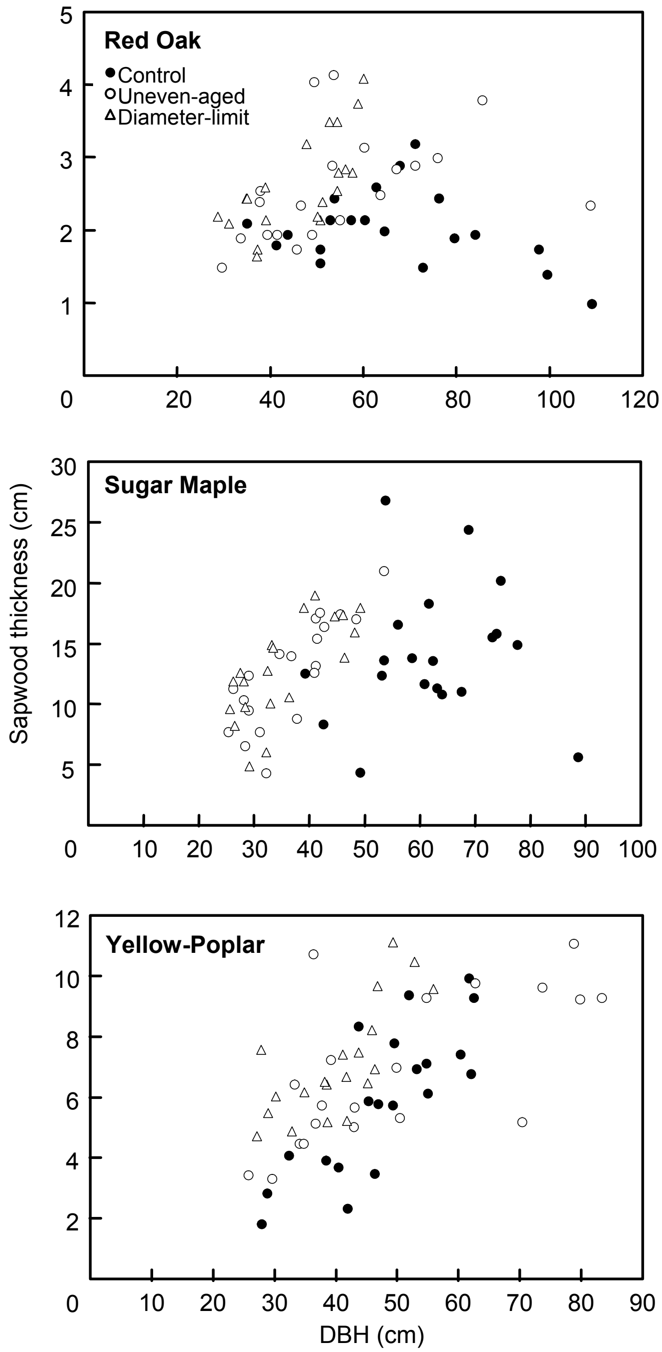

Figure 10—Sapwood thickness, in centimeters, as a function of tree DBH.

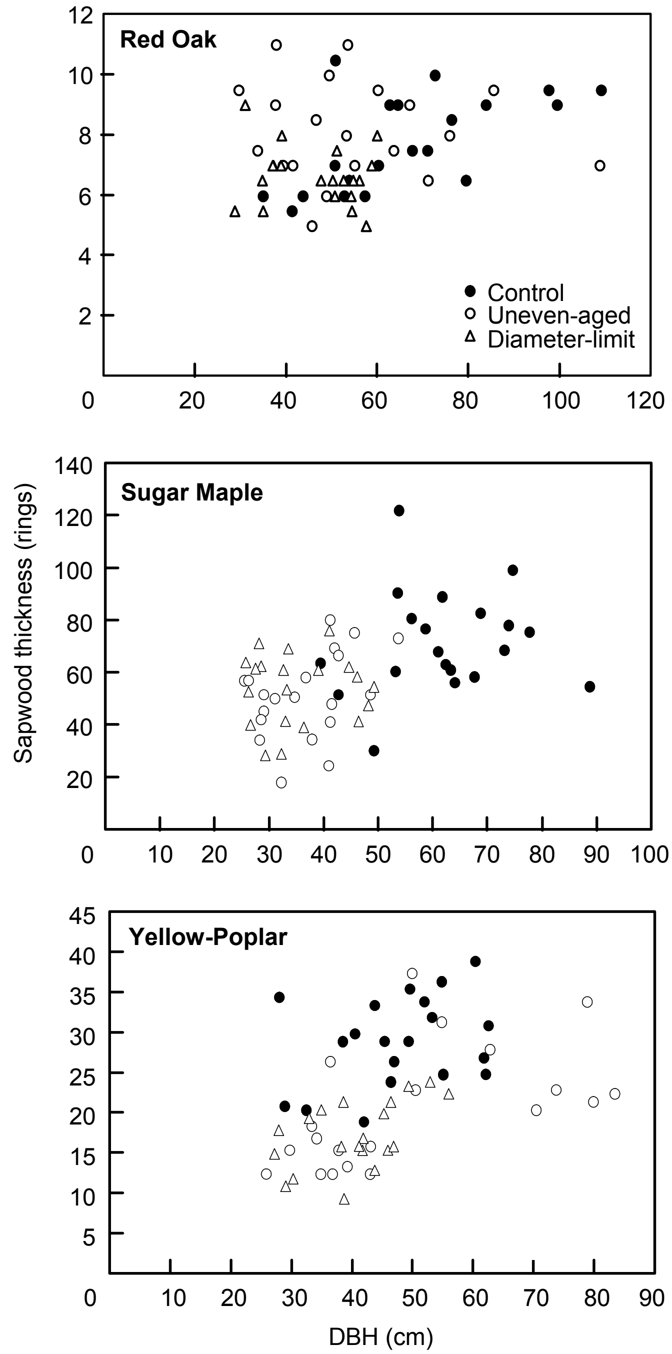

Figure 11—Sapwood thickness, in growth rings, as a function of tree DBH.

in centimeters as a function of DBH. Examination of the points corresponding to the control shows that, in red oak, sapwood thickness may be constant until the trees reach a large size (in this case, about 85 cm DBH), then becomes narrower. Clearly, more data are needed to establish the effect of tree size on sapwood thickness in red oak. A comparison of sapwood cross-sectional area with DBH might have revealed a trend, but because the stems of the large trees were sometimes extremely irregular and sapwood thickness was based on only two measurements, the computation of area would be subject to large errors (see Wiemann and others 2002). A significant correlation between red oak DBH and number of sapwood rings in the control, and the lack of such correlation in the treatments (Table 6), is apparent in Figure 11, which shows sapwood thickness in number of growth rings as a function of DBH.

The sugar maples at the control site were larger than those at either treatment site, but sapwood thickness, in centimeters, did not differ among sites (Table 4, Fig. 10). Sapwood thickness in rings, however, was greater at the control site than at either treatment site (Table 4, Fig. 11). The combination of older, larger trees with more numerous (but narrower) sapwood rings at the control site, compared with the trees at the two treatment sites, resulted in similar lineal sapwood thickness values among the three sites.

Because sugar maple does not form normal heartwood, the amount of sapwood is not directly related to the sap transport requirements of the tree and the explanation used for red oak does not apply. We thought that the partial harvests in the two treatment sites might have resulted in residual stand damage, which would have resulted in more frequent and more extensive heartwood formation in the remaining sugar maples. Apparently this did not occur. Greater heartwood would be manifested as narrower sapwood in trees of equal diameter. The control site sugar maples were larger than the maples at the treatment sites, but their mean sapwood thickness was not; therefore heartwood in the control site was larger than that of either treatment.

Old sugar maples, such as those found in the control site, may be less able to fend off the effects of damage. The effects of age and treatment can be separated by comparing only trees within an age cohort. Comparing sapwood of only trees within the 50-year age range of 65 to 115 years (control site, 13 trees, 12 cm DBH, 64 rings; diameter-limit site, 15 trees, 14 cm DBH, 58 rings; uneven-aged site, 16 trees, 13 cm DBH, 54 rings) does not suggest that treatment reduces sapwood thickness, either in centimeters or number of growth rings, although we emphasize that these are *a posteriori* comparisons.

Sapwood may be wider in vigorously growing sugar maple trees at least until they reach senescence and DBH might be useful as a predictor of sapwood thickness if the trees are growing vigorously, as they were in the two treatment sites, but not after trees have reached senescence, as was frequently the case in the control. Tree age seems to be useless as a predictor of sapwood thickness in sugar maple regardless of treatment (Table 6). Perhaps this is because heartwood formation in sugar maple is a stochastic event with the causal agents, crown or root damage, periodically affecting young and old trees alike. Nonetheless, it is somewhat surprising that the stand interventions of the two treatments did not produce more injury-altered heartwood, with a concomitant reduction in sapwood thickness. As in red oak, cross-sectional area might provide a more meaningful evaluation of sapwood because it more directly affects tree physiology. However, since sapwood thickness is based on only two radii and many sugar maple stems are irregular in cross section, the errors in such an analysis are likely to be large.

Diameter at breast height is a predictor of sapwood thickness in yellow-poplar regardless of treatment; larger trees require wider sapwood. Because yellow-poplar produces typical heartwood, stand history would not be expected to affect sapwood thickness except to the extent that it affects overall tree size, as evident in Figure 4.

Conclusions

Silvicultural treatments affected species frequency distributions and tree size and age. Periodic cuttings favored sugar maple. Tree diameter range was dependent on species and treatment, with tree size distributed into one, two, or three cohorts; these were related to longevity, periodicity of harvests, and light requirements of each species. As a result of the opening of canopy gaps, periodic harvests increased the probability that some stems would exhibit severe lean (>30%), which would increase the likelihood of tension wood in these stems. For some species, treatment also affected tree grade. Overall grade of red oak was lower under the diameter-limit treatment compared with uneven-aged treatment, and sugar maple grade was lowest in the control site. This was true even when the effects of tree DBH were removed.

In red oak, where wide sapwood is a defect, the range of sapwood thickness among all 60 trees was only 1.0 to 4.2 cm, with the treatments producing wider sapwood than did the control. In yellow-poplar, where wide sapwood is desirable, sapwood thickness increased with tree diameter but was independent of treatment.

Sapwood thickness was extremely variable (4.4 to 26.9 cm) in sugar maple. Sapwood thickness was significantly correlated with DBH and growth rate in the two treatments but not in the control, and surprisingly it was not significantly correlated with tree age at any site. Vigorously growing sugar maples produce wide sapwood, but heartwood discoloration begins to disproportionately affect the trees as they reach maturity. Whereas the largest maples in the control may have included poor quality residuals, the largest maples in the two treatment sites were products of vigorous growth. Therefore, to maximize the yield of "white" maple, it is important to harvest the trees before they enter senescence; this means that both age and DBH must be taken into account to ensure high color quality.

In conclusion, for the three species studied, we found that managing stocking to increase individual tree growth was consistent with producing desirable heartwood/sapwood characteristics. Concerns that repeated stand interventions might increase the production of wound-induced heartwood in sugar maple were unfounded. Periodic reductions in stocking did increase growth rates as expected, but this did not alter sapwood width in either sugar maple or yellow-poplar, and the effects in red oak were small. However, we expect the long-term use of uneven-aged management will eventually lead to dominance by shade-tolerant species, effectively excluding both yellow-poplar and northern red oak. Alternatively, if even-aged management is used, our results clearly suggest that thinning to enhance growth and manage stem quality would not have a detrimental impact on desirable heartwood/sapwood characteristics.

Acknowledgments

Neal Bennett assisted with tree measurements and Bob Rosier and Rick Hovatter graded the trees. Help with core extraction was provided by Bob Rosier, Rick Hovatter, and Jane Rodrigue. Cores were measured by Jane Rodrigue and Deborah Butler. Cherilyn A. Hatfield and James W. Evans performed the statistical analyses. Daniel Yaussy gave an excellent review of the manuscript that included many helpful suggestions for the statistical analyses and presentation of results. Regis Miller, David McKeever, and two anonymous reviewers also commented on the manuscript, and we thank them for their suggestions. The production team for the final report consisted of JoAnn Benisch, Mary Collet, and Noreen Esser.

Literature Cited

Barrett, G.; Barrett, R.; Johnson, A.; Warfield, G. eds. 1999. Weekly Hardwood Review. 14(45).

Bosshard, H.H. 1968. On the formation of facultatively colored heartwood in *Beilschmiedia tawa*. Wood Science Technology. 2: 1–12.

Forest Products Laboratory. 1987. Wood handbook: Wood as an engineering material. Agric. Handb. 72. (Rev.) Washington, DC: U.S. Department of Agriculture, Forest Service. 466 p.

Good, H.M.; Murray, P.M.; Dale, H.M. 1955. Studies on heartwood formation and staining in sugar maple, *Acer saccharum* Marsh. Canadian Journal of Botany. 33: 31–41.

Hanks, L.F. 1976. Hardwood tree grades for factory lumber. Res. Pap. NE–333. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeast Research Station. 92 p.

Lutz, J.F. 1972. Veneer species that grow in the United States. Res. Pap. FPL–RP–167. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 127 p.

Miller, G.W.; Hanks, L.F.; Wiant, H.V. 1986. A key for the Forest Service hardwood tree grades. Northern Journal of Applied Forestry. 3: 19–22.

Pan, C. 1995. Climatic aspects of forest growth in an Appalachian watershed. Morgantown, West Virginia: College of Agriculture and Forestry, West Virginia University. 132 p. Unpublished M.S. thesis.

Shigo, A.L. 1986. A new tree biology. Durham, NH: Shigo and Trees Associates. 595 p.

Shigo, A.L.; Hillis, W.E. 1973. Heartwood, discolored wood, and microorganisms in living trees. Annual Review of Phytopathology. 11: 197–222.

Shortle, W.C.; Smith, K.T.; Dudzik, K.R. 1996. Decay diseases of stemwood: detection, diagnosis, and management. In: Raychaudhuri, S.P.; Maramorosch, K., eds. Forest trees and palms: diseases and control. New Delhi and Calcutta: Oxford & IBH Publishing Co. pp. 95–109.

Trimble, G.R. 1973. The regeneration of Central Appalachian hardwoods with emphasis on the effects of site quality and harvesting practice. Res. Pap. NE–282. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeast Research Station. 14 p.

Trimble, G.R. 1977. A history of the Fernow Experimental Forest and the Parsons Timber and Watershed Laboratory. Gen. Tech. Rep. NE–28. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeast Research Station. 46 p.

Wiemann, M.C.; Brown, J.P.; Bennett, N.D. 2002. Comparison of methods to determine disk and heartwood areas. Res. Pap. NE–720. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeast Research Station. 15 p.