STEM QUALITY OF OAK IN 15-YEAR-OLD STANDS: INFLUENCE OF SPECIES WITHIN HARVESTING TREATMENT AND FENCING

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ABSTRACT

The effect of harvesting treatment, fencing, and species on the stem quality of oak (*Quercus* spp.) was evaluated in mixed-hardwood stands on the Allegheny Plateau in central Pennsylvania. The regeneration harvests included commercial clearcut that removed most stems ≥ 15 cm dbh and a clearcut with timber stand improvement (TSI) that removed all stems ≥ 2.5 cm dbh. Half of each area was fenced with 2.4-m-tall woven wire to prevent browsing by deer (*Odocoileus virginianus*) on the regeneration. After 15 years, the number of stems ≥ 2.5 cm dbh ranged from 4,865 to 8,416/ha and basal area ranged from 11.2 to 16.8 m^2/ha. Growth from age 10 to 15 ranged from 4.9 to 6.7 m^2/ha or about 1 m^2/ha/yr. The fenced portion of each treatment had more stems and basal area than the unfenced portion. The commercial clearcut had more stems and basal area than the clearcut with TSI. Oak composition before harvest was 70 to 80 percent of basal area. At age 15, oak composition ranged from 8 to 41 percent of basal area. Red maple (*Acer rubrum*) and black cherry (*Prunus serotina*) along with oaks were the dominant species in the new stands. Potential quality of oak stems was rated by use of a quality classification system that included crown class, crook and sweep, number of limbs, and presence of forks, rot, and seams. Other variables measured included dbh, total height, height to base of live crown, and live-crown ratio. Rot and seams occurred in only 2 percent of the stems. and appeared to occur randomly. Forks in the first 2.4 m of the tree bole also were rare (occurrence of 5 to 13 percent), but were more common in the second 2.4 m (22 to 68 percent). Species had a greater effect on stem quality than other factors. Northern red oak (*Q. rubra*) had the best quality followed by chestnut oak (*Q. prinus*). White oak (*Q. alba*) and black oak (*Q. velutina*) were significantly lower in quality followed by scarlet oak (*Q. coccinea*). Northern red oak had significantly better stem quality than white, black, or scarlet oak. Scarlet oak's poor quality was related to its inherent limb retention. Both fencing and harvesting treatment influenced stem density. In general, the higher the stand density, the better the quality of the stems.

INTRODUCTION

The development of stem quality in young stands and the effect of thinning treatments (manipulation of stand density) on quality have been studied in only several species, e.g., northern hardwoods, Appalachian hardwoods, and oaks (Marquis, 1969; Goodman and Books, 1971; Della-Bianca, 1983; Sonderman, 1984, 1986; Sonderman and Rast, 1987). Most revealed that too low a stand density (too heavy a thinning) results in lower stem quality than that found in unthinned stands or in stands maintained at 60 percent or higher relative density (stocking). Sonderman (1984, 1986) showed that as stand density decreased, limb-related defects increased, especially the number of epicormic branches and live limbs present. Stem defects result in lower stem quality in young hardwood trees; most of these defects are related to limbs (Della-Bianca, 1983; Sonderman, 1986). This research points out the tradeoffs between the more rapid diameter growth favored by heavy thinning versus the development of good-quality stems favored by high stand densities. Species plays a critical role in stem quality due to species differences in natural pruning and formation of epicormic branches (Della-Bianca, 1983; Sonderman, 1986; Sonderman and Rast, 1987). The purpose of the research reported here is to evaluate the stem quality of oak (*Quercus* spp.) in young stands and determine the influence of harvesting treatment, fencing, and species on stem quality.

METHODS

Study Area and Design

The study area was located in central Pennsylvania on the Allegheny Plateau along the west branch of the Susquehanna River in Clinton County. The elevation was 433 to 457 m above sea level and the aspect was east to southeast. The site was level to gently sloping with an average slope of 5 percent. The site index was 18.3 to 19.8 m for oak (Schnur, 1937; Carmean, 1971, 1972). The 60-year-old mixed-oak forest was dominated by white oak (*Quercus alba*), black oak (*Q. velutina*), and red maple (*Acer rubrum*) with smaller amounts of chestnut oak (*Q. prinus*), scarlet oak (*Q. coccinea*), northern red oak (*Q. rubra*), hickory (*Carya* spp.), pitch pine (*Pinus rigida*), black cherry (*Prunus serotina*), and blackgum (*Nyssa sylvatica*) (Tables 1-2). The initial stand density ranged from 23.46 to 25.05 m^2/ha of basal area and 1,100 to 1,653 stems/ha. The entire area had been defoliated by gypsy moth (*Lymantria dispar*) during May-June 1981. Deer (*Odocoileus virginianus*) populations in the area exceeded the carrying-capacity goal set by the Pennsylvania Game Commission at the time the study was installed. Between years 5 and 10, considerable cutting in the area along with increased hunting pressure reduced deer browsing in the study area. This created conditions in which stems were able to grow beyond the reach of deer into the lower diameter classes. This location was the first of two replicates of the study. The latter, installed in Jefferson County, Pennsylvania, is not yet 15 years old, so data from this replicate were not included in this analysis.

Two harvest treatments were applied in the winter of 1981-82. A commercial clearcut removed all economically useable stems and nonmerchantable stems were left standing. Most stems $\geq$15 cm dbh were cut. A clearcut with timber stand improvement (TSI) removed all merchantable stems and all other stems $\geq$2.5 cm dbh were cut and left on the site. Harvested plots were 2.9 ha; a 0.81-ha area in the center was the measurement plot with the remaining area as a buffer. The measurement plot was split into two 0.405-ha areas; one was fenced with a 2.4-m-tall woven wire fence and the other was left open. Five 1.83-m-radius subplots were established in each harvest-fence treatment combination (4 plots X 5 subplots = 20 total) for the measurement of tree regeneration, woody shrubs, and herbaceous plant cover.

Complete inventories of all woody stems $\geq$2.5 cm dbh were conducted in the four plots in 1981 (prior to harvest), 1991 (10 years after harvest), and 1996 (15 years after harvest). Regeneration plots were measured prior to defoliation and harvest in early 1981, the first year after harvest in 1982, annually through 1986, and in 1991 and 1996. Counts of woody stems were divided into four height classes: 0 to 30 cm, 30 to 90 cm, 90 to 150 cm and > 150 cm but < 2.5 cm dbh. The height of the tallest stem of each major tree species on the regeneration plot was measured. Herbaceous plant cover was estimated visually as 0 to 100 percent for each of six plant groups and total coverage. In 1991, the inventory of all stems and the regeneration plots included the same stems, so there are two estimates of stems/ha. In 1981 and 1996, the regeneration plots did not include the stems that were ≥ 2.5 cm. In 1996, the heights of 10 dominant or codominant red maple and black cherry stems per treatment combination were measured at random along with the height of the tallest stem of each species ≥ 2.5 cm dbh on the regeneration plot.

Table 1. Density of original plots and 10- and 15-year-old plots after harvesting by harvesting and fencing treatment combinations for stems and basal area (treatment combinations are from one replicate only)

	Clearcut		Clearcut w/TSI	
Age and density	Fenced	Unfenced	Fenced	Unfenced
Original (60 years old)				
Stems (no./ha)	1263	1653	1100	1240
Basal area (m^2/ha)	23.46	25.03	24.06	25.05
10-year-old stand				
Stems (no./ha)	7005	5841	8856	5303
Basal area (m^2/ha)	11.25	9.85	10.03	5.65
15-year-old stand				
Stems (no./ha)	6558	4865	8416	5683
Basal area (m^2/ha)	16.76	14.72	16.71	11.16
Change (15 year to 10 year)				
Stems (no./ha)	-447	-976	-440	380
Basal area (m^2/ha)	5.51	4.87	6.68	5.51

Measurements of Stem Quality

In October 1996, stem quality was measured on 15-year-old oak trees in the four treatment plots by a technique developed by Sonderman and Brisbin (1978). All (or most) stems ≥ 5 cm dbh were sampled for northern red, black, scarlet, and chestnut oak, and 20 to 30 stems ≥ 7.5 cm dbh were sampled randomly for white oak (Table 3). The variables used included dbh, crown class (dominant, codominant, intermediate, or suppressed), total height, height to base of live crown (bole length), live-crown ratio, crook and sweep (deviation from straight), limbs in the first 2.4 m of the tree bole (live and dead >8 mm diameter, stopping at 17 limbs), limbs in the second 2.4 m (live and dead >8 mm diameter, stopping at 17 limbs), total limbs in the first 4.8 m (adding the first two bole counts, maximum of 34), forks in the first and second 2.4 m, and rot or seam in the first and second 2.4 m. Values recorded for these variables are then converted to quality scores that represent the potential of that tree to produce high-quality wood (Sonderman 1979). The presence of rot or seam or a fork resulted in the tree being rated as a cull (total point score of 0). Crown class was converted to a score based on: dominant = 4, codominant = 3, intermediate = 2, suppressed = 1. Sweep and crook were converted to a score based on deviations (in cm): < 2.5 cm = 4; > 2.5 and < 10 cm = 3; > 10 and < 15 cm = 2; > 15 and < 20 cm = 1; > 20 cm = 0. Total numbers of limbs in the first 4.8

m were converted to a limb-count score based on: 1 to 2 limbs = 4; 3 to 4 = 3; 5 to 8 = 2; 9 to 16 = 1; and 17+ = 0. Scores for crown class, crook and sweep, and limb count were added to obtain tree-quality scores which were grouped in four classes: good (10 to 12), fair (8 to 9), poor (1 to 7), and cull (0) (Sonderman 1979), and in numerical classes (4, 3, 2, 1, respectively) for analysis.

Table 2. Composition of original plots and 10- and 15-year-old plots after harvesting by harvesting and fencing treatment combinations (treatment combinations are from one replicate only)

	Composition (% of basal area)									
Treatment	White oak	Black oak	Northern red oak	Chestnut oak	Scarlet oak	All oaks	Red maple	Black cherry	Pin cherry	Other species
Clearcut unfenced										
Original	62	14	4	1	3	84	11			5
10 year old	28	4	1	1	2	36	54	2		8
15 year old	31	4	3	1	2	41	48	4		7
Clearcut fenced										
Original	38	22	7	11	3	81	10			9
10 year old	17	5	2	7	1	32	37	7	8	16
15 year old	17	5	3	8	2	35	33	9	11	12
Clearcut w/TSI unfenced										
Original	53	25	T[a]	T	2	80	15			5
10 year old	8	1	1			10	76	13	1	0
15 year old	6	2	T			8	70	19	1	2
Clearcut w/TSI fenced										
Original	58	19	1	1	4	83	11			6
10 year old	17	2	1	T	1	21	30	30	12	7
15 year old	18	1	1	1	2	23	25	33	11	8

[a] T= trace amount (<0.5%).

Table 3. Number of stem-quality sample trees by harvest and fence treatment combination for each oak species

Plot	White oak	Scarlet oak	Chestnut oak	Northern red oak	Black oak	Total
Clearcut unfenced	32	9	6	19	19	85
Clearcut fenced	27	6	27	22	19	101
Subtotal	59	15	33	41	38	186
Clearcut w/TSI unfenced	21	2	--	1	7	31
Clearcut w/TSI fenced	23	9	4	10	10	56
Subtotal	44	11	4	11	17	87
Total	103	26	37	52	55	273

Data Analysis

Means and standard deviations were calculated by species within harvest and fence treatment combinations for stem-quality variables and by time for regeneration plots. Patterns of stand development could not be tested statistically because only one replication was used. Similarly, the effects of harvesting treatment and fencing on stem quality are confounded by plot, so differences due to those treatments cannot be separated from inherent plot differences until the second replication is measured. However, the effect of species on stem quality can be tested statistically. All discussed differences in stem quality due to harvesting and fencing treatments are based solely on observations. Stem-quality variables and scores were analyzed by analysis of variance (General Linear Model, Systat; SPSS 1996) using a factorial design followed by Fischer's LSD pairwise means separation using the Bonferroni Adjustment to test for differences between species within fencing and harvesting treatment combinations. The Bonferroni Adjustment for plots with five species was $\alpha = 0.05/10 = 0.005$ needed for significance; for plots with four species, the adjustment was $\alpha = 0.05/6 = 0.0083$ needed for significance.

RESULTS

Stand Development

The pretreatment (60-year-old) stands were relatively uniform in number of stems and basal area (Table 1). Residual stems in the commercial clearcut ranged from 220 to 300/ha. After 15 years, regeneration from seedlings, seedling-sprouts, and stump sprouts resulted in 4,865 to 8,416 stems/ha ($\geq$ 2.5 cm dbh) and a basal area ranging from 11.2 to 16.8 m^2/ha. For both harvesting treatments, fenced areas had more stems and basal area per hectare than the unfenced areas at both age 10 and 15 (Table 1). Since three of the treatment combinations were stocked sufficiently, mortality occurred between age 10 and 15, but the unfenced clearcut with TSI was understocked and increased in stems $\geq$ 2.5 cm during that time (Table 1). Growth from age 10 to 15 ranged from 4.9 to 6.7 m^2/ha or about 1 m^2/ha/yr (Table 1). The increase in basal area in the commercial clearcut from age 10 to 15 was 49 percent regardless of fencing; the increase in the fenced clearcut with TSI was 67 percent compared to 98 percent in the unfenced clearcut with TSI. The large percentage

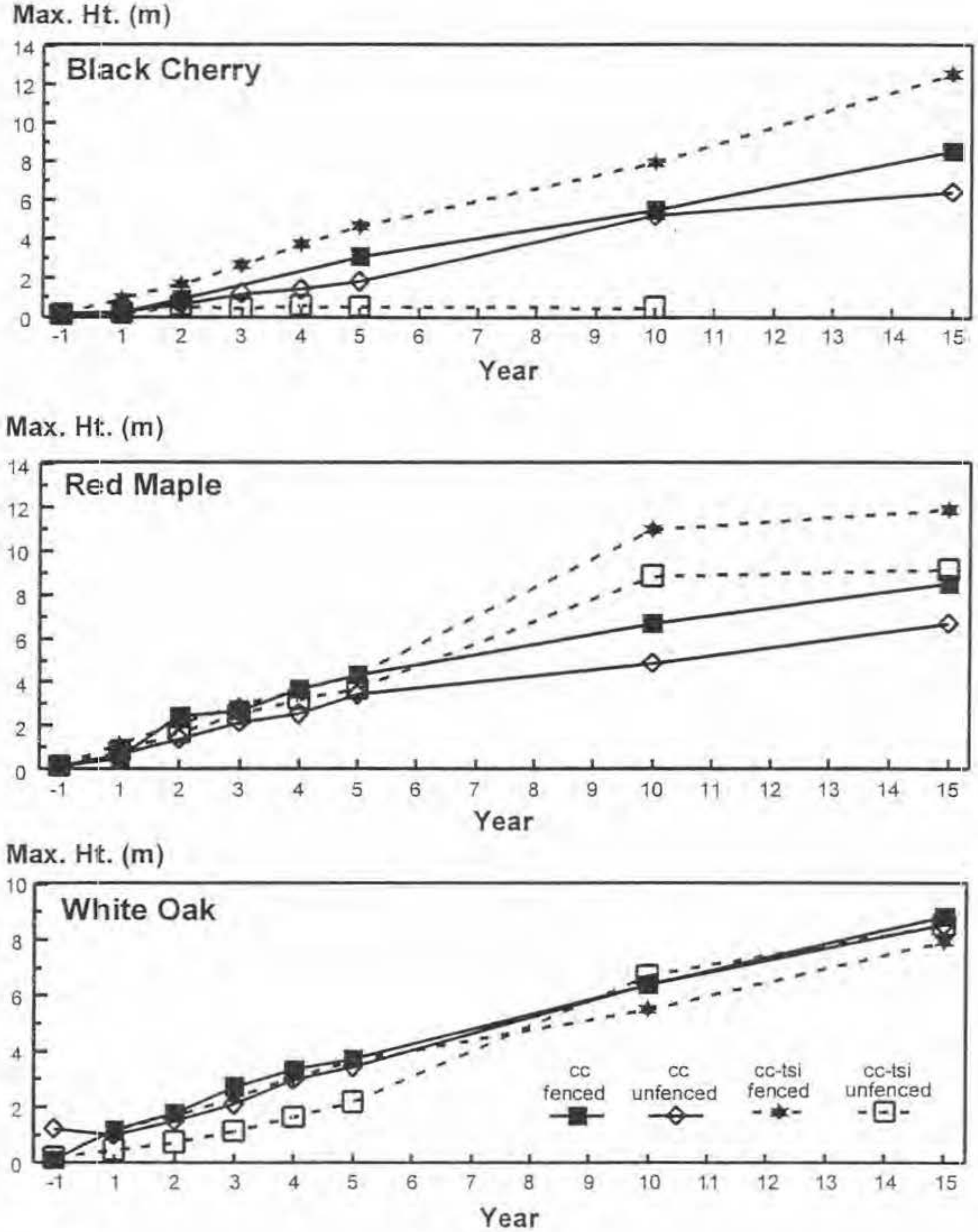

Figure 1. Maximum height (m) of regeneration of white oak, red maple, and black cherry by harvesting and fencing treatments over a 17-year period from just prior to treatment to 15 years after treatment.

increase in the latter plot was due to the understocked condition at age 10 as well as the large amount of ingrowth that occurred. These differences in stand density contribute to differences in stem quality.

The initial composition of oak was 80 to 84 percent of the basal area with red maple accounting for 10 to 15 percent. However, the composition among oak species present varied slightly, with white oak the major component followed by black oak (Table 2). By age 10, the composition was considerably different, with oaks accounting for 10 to 36 percent of the basal area. Fencing influenced composition considerably; fenced plots contained both black cherry and pin cherry (*Prunus pensylvanica*) as well as a greater variety of other species. Also, unfenced plots had fewer black cherry and other species and virtually no pin cherry compared to fenced plots. Red maple was the dominant species in all plots at age 10 but was most abundant in unfenced plots. At age 15, oak composition ranged from 8 to 41 percent of basal area and had increased in relative abundance in all but one plot; red maple decreased in relative abundance in every plot. There was a large increase in black cherry in the plot in which oak decreased. The commercial clearcut had more oak than the clearcut with TSI. Red maple and black cherry were the dominant species in the new stands as shown by their increase in maximum height over time (Fig. 1) and basal areas, though oak remained a strong component in all but one unfenced plot. Fencing had no effect on the height growth of white oak, but did result in taller red maple and black cherry stems (Fig. 1).

Stem Quality

The harvest and fence treatments and their interaction as confounded by plot had the largest influence on stem quality (see Table 4), but could not be separated from plot effects. This pattern of mean squares held for all tree-quality variables. The interaction between fencing and harvesting results from opposite patterns of tree quality between fenced and unfenced areas of the two harvesting treatments. I observed that stem quality was better in plots with higher stem densities; fencing had no consistent effect on overall stem quality. Stem quality was significantly affected by species for two harvest-fence combinations (Table 5). Northern red oak had the best quality followed by chestnut oak but the differences were not significant. Black oak and white oak were even lower in quality and scarlet oak had the lowest quality. These three species were not significantly different. Northern red oak had significantly better stem quality than white, black, or scarlet oak.

Table 4. Analysis of variance for stem-quality classes by harvesting treatment, fencing treatment, and species (R^2=0.906); only species tests are valid, so F-ratios and P-values for harvest and fence treatments are not presented

Source	Sum of squares	df	Mean square	F-ratio	P-value
Harvest	391.7	1	391.7	--	--
Fence	293.2	1	293.2	--	--
Species	439.3	4	109.8	352.1	< 0.001
Fence*harvest	304.3	1	304.3	--	--
Harvest*species	330.2	4	82.6	264.7	< 0.001
Fence*species	311.5	4	77.9	249.7	< 0.001
Species*harvest*fence	286.6	4	71.6	229.7	< 0.001
Error	79.2	254	0.3		

Table 5. Stem-quality ratings least squares means by species and Fischer's LSD pairwise mean comparison test using Bonferroni Adjustment (means followed by same letter within column not significantly different at α-level = 0.005 for five species comparisons and α-level = 0.0083 for four species comparisons)

Species	Clearcut unfenced	Clearcut fenced	Clearcut w/TSI unfenced	Clearcut w/TSI fenced
White oak	1.69 b	1.59 a	1.38 a	1.52 b
Scarlet oak	1.56 b	1.67 a	1.00 a	1.11 b
Chestnut oak	1.83 ab	1.52 a	--	2.00 ab
Northern red oak	2.26 a	1.64 a	2.00 a	2.20 a
Black oak	1.74 b	1.68 a	1.14 a	1.70 ab

Of the factors determining tree-quality ratings, rot and seams were the least important: only 2 percent of the stems had rot or seams, which appeared to occur randomly. Forks in the first 2.4 m of the tree bole were rare: they were found in 5 to 13 percent of the stems (average: 9.5 percent). Forks in the second 2.4 m were more common (22 to 68 percent, average: 36 percent). I observed that the clearcut with TSI, which had the lowest stem density, had the highest proportion of forks in the second log; the rate was twice that for the other treatment combinations. The proportion of culls was roughly that of forks (30 to 67 percent).

Of the three factors determining tree-quality score, crown class was the least important as 60 to 90 percent of the trees were codominant and had the same score. Species did not influence crown class. Crook and sweep was next in importance with 20 to 50 percent of the trees in only three of five crook/sweep classes and no differences due to species. Total limb count was the most important factor determining tree quality and it did vary with species (Tables 6-7). Analyses of variance are not given for limb variables (limbs in first 2.4 m and second 2.4 m and total limbs in 4.8 m; R^2 values = 0.912, 0.948, and 0.956, respectively), but were similar to the results for limb count in Table 6. All of the limb variables showed similar patterns of differences by species (Table 7). Converting to limb-count classes reduced or eliminated species differences primarily by separating northern red oak from the other oaks. Scarlet and black oak had significantly more limbs, white oak was intermediate in limb count, and chestnut and northern red oak had significantly fewer limbs (Table 7). I observed that the clearcut with TSI had more limbs than the commercial clearcut and the unfenced areas had more limbs than the fenced areas. These patterns were related to the stem density in those plots and are highlighted by the unfenced clearcut with TSI plot, which was not heavily stocked and more open-grown with high numbers of branches for all species.

Table 6. Analysis of variance for total limb score (five classes) by harvesting treatment, fencing treatment, and species (R^2=0.742); only species tests are valid, so F-ratios and P-values for harvest and fence treatments are not presented

Source	Sum of squares	df	Mean square	F-ratio	P-value
Harvest	58.5	1	58.5	--	--
Fence	29.6	1	29.6	--	--
Species	29.4	4	7.4	20.4	< 0.001
Fence*harvest	17.8	1	17.8	--	--
Harvest*species	51.8	4	13.0	35.9	< 0.001
Fence*species	24.9	4	6.2	17.2	< 0.001
Species*harvest*fence	17.0	4	4.2	11.8	< 0.001
Error	91.8	254	0.36		

Four variables were measured that were not used directly in determining tree quality but are useful in further analysis: total height, height to base of live crown, live-crown ratio, and dbh. The latter was biased by the sampling technique used, so this variable was ignored (white oak always had the largest dbh). Despite being larger in dbh, white oak was consistently the shortest species in total height. Total height was greatest for northern red oak followed closely by black oak, chestnut oak, and scarlet oak, all of which were significantly taller than white oak (Tables 8-9). There were no species differences in height to the base of the live crown or in live-crown ratio. I observed that all oaks tended to have taller base of the live crown and smaller live-crown ratios in fenced as those in unfenced plots.

Table 7. Number of limbs in first 2.4 m of the tree bole, second 2.4 m, both 2.4 m sections, and total limb-count class least squares means by species and Fischer's LSD pairwise mean comparison test using the Bonferroni Adjustment (means followed by same letter within columns are not significantly different at α-level = 0.005 for five species comparisons and α-level = 0.0083 for four species comparisons)

Species	Clearcut unfenced	Clearcut fenced	Clearcut w/TSI unfenced	Clearcut w/TSI fenced
		Limb-count class		
White oak	0.16 b	0.41 b	0.05 a	0.35 b
Scarlet oak	0.00 b	0.00 b	0.00 a	0.00 b
Chestnut oak	0.33 b	1.50 a	–	0.00 b
Northern red oak	2.32 a	1.90 a	0.00 a	1.10 a
Black oak	0.00 b	0.00 b	0.00 a	0.00 b
		Limbs in first 2.4 m tree bole section		
White oak	8.1 b	5.9 b	7.3 a	6.7 b
Scarlet oak	13.4 a	12.7 a	10.0 a	14.0 a
Chestnut oak	4.7 c	2.4 c	--	6.0 b
Northern red oak	1.8 c	2.0 c	13.0 a	6.6 b
Black oak	13.3 a	11.0 a	9.4 a	10.7 a
		Limbs in second 2.4 m tree bole section		
White oak	14.3 a	12.1 a	14.4 a	11.8 bc
Scarlet oak	16.3 a	14.7 a	17.0 a	14.9 ab
Chestnut oak	13.2 a	7.6 b	--	13.5 abc
Northern red oak	4.5 b	4.8 c	17.0 a	9.3 c
Black oak	15.2 a	14.4 a	13.5 a	15.0 a
		Total limbs in 4.8 m tree bole section (first and second sections combined)		
White oak	22.4 b	18.0 b	21.8 a	18.5 c
Scarlet oak	29.8 a	27.3 a	27.0 a	28.9 a
Chestnut oak	17.8 b	10.0 c	--	19.5 bc
Northern red oak	6.4 c	6.8 c	30.0 a	15.9 c
Black oak	28.5 a	25.5 a	23.0 a	25.7 ab

Table 8. Analysis of variance for total height by harvesting treatment, fencing treatment, and species (R^2=0.992); only species tests are valid, so F-ratios and P-values for harvest and fence treatments are not presented

Source	Sum of squares	df	Mean square	F-ratio	P-value
Harvest	126074	1	126074	--	--
Fence	103297	1	103297	--	--
Species	149751	4	37438	4866	< 0.001
Fence*harvest	93043	1	93043	--	--
Harvest*species	117835	4	29459	3829	< 0.001
Fence*species	108810	4	27202	3536	< 0.001
Species*harvest*fence	92949	4	23237	3020	< 0.001
Error	1954	254	7.7		

Table 9. Total height least squares means by species and Fischer's LSD pairwise mean comparison test using Bonferroni Adjustment (means followed by same letter within column not significantly different at α-level = 0.005 for five species comparisons and α-level = 0.0083 for four species comparisons)

Species	Clearcut unfenced	Clearcut fenced	Clearcut w/TSI unfenced	Clearcut w/TSI fenced
White oak	28.9 b	29.0 b	23.9 c	28.0 b
Scarlet oak	32.1 a	31.5 ab	24.5 bc	30.2 ab
Chestnut oak	30.3 ab	34.7 a	--	32.0 ab
Northern red oak	31.3 a	29.8 b	38.0 a	32.8 a
Black oak	29.3 ab	31.2 b	30.0 ab	32.9 a

DISCUSSION

Stand development was influenced more strongly by fencing than by harvesting treatment. Heavy deer browsing, especially in the unfenced clearcut with TSI, caused lower stem densities and basal areas in unfenced than fenced areas. This created a more open-grown environment during the first 10 to 15 years. Browsing also resulted in a shift in species composition toward red maple along with reduced density of oaks and other species. Fenced plots had more pin and black cherry than unfenced plots, as well as species like birch, aspen, and hawthorn. While diversity was not calculated per se, I observed that browsing reduced the diversity of tree and shrub species in unfenced compared to fenced plots. Net growth of all the stands is similar at about 1 m^2/ha/yr, but stem densities and basal areas vary considerably. This means that mortality, ingrowth, and diameter growth probably differ between plots.

The quality of oak stems in these 15-year-old stands exhibited many of the same patterns revealed in other studies. Specifically, species is more important than many other factors in determining quality, and limb-related variables also are important (Della-Bianca, 1983;

Sonderman, 1984, 1986). Northern red oak is the most prized and valuable of the upland oaks in the United States. Its higher stem quality at this young age will carry on to older ages. White oak also is valuable, but at this age is of considerably lower stem quality as shown by Della-Bianca (1983). Its greater shade tolerance is one reason for the persistence of live limbs in white oak. It is the longevity of this species that enables it to develop into quality stems. Stem quality was reduced in scarlet and black oaks due to large numbers of dead branches that were retained on the stem. If these branches are removed by pruning, both species will gain in their potential to increase in quality. Such genetic differences in limb characteristics are the basis for most of the observed differences in stem quality it this study.

Many of the stem-quality responses observed appear to be correlated with differences in stem density and basal area of the four treatment combinations. The fenced plots were denser for nearly the entire 15 years and as a result tended to have higher stem quality than the unfenced plots as well as greater height to the base of the live crown. The unfenced clearcut with TSI had low densities with crown closure still not complete at age 15. By contrast, the other plots had crown closure at or before 10 years. This open-grown environment has resulted not only in lower height to the base of the live crown but also a much higher proportion of forks. In general, the higher the stand density, the better the quality of the stems that was present. Earlier work on the effect of thinning on stem quality showed that thinning could do little to improve stem quality, but could reduce it by encouraging epicormic branches and deeper crowns (Sonderman, 1984, 1986; Sonderman and Rast, 1987). My work supports this density relationship. The best management approach to the development of high-quality hardwoods is to maintain stand density at or above 60 percent relative density (B-level stocking) during the early years of the stand's life to encourage natural pruning, straight stems, and fewer forks. Once the stand is old and large enough to have clear stems for the first 4.8 m of the tree's bole, thinnings to reduce density to encourage growth--but not heavy enough to encourage epicormic branching--should be used. In areas where deer browsing is heavy, it may be necessary to fence to obtain densities sufficient to maintain stem quality.

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