Crown Class Dynamics of Oaks, Yellow-Poplar, and Red Maple after Commercial Thinning in Appalachian Hardwoods: 20-Year Results

James S. Rentch, Gary W. Miller, and Kurt W. Gottschalk

ABSTRACT

Silvicultural strategies are often planned to favor the growth and survival of desired species until they reach a competitive position in the upper canopy. Once desired species reach the upper canopy, they can persist and provide a variety of benefits for decades. Later, they can serve as a source of natural regeneration for sustaining species composition. Although information is available for promoting desired advance seedlings in the understory of mature stands and culturing desired saplings in the upper canopy of young stands, additional information is needed on promoting desired species at mid-rotation, when the stand first reaches commercial size classes. Crown class transition rates for a total of 2,668 white and chestnut oaks, northern red oak, scarlet and black oaks, yellow-poplar, red maple, blackgum, and black birch were observed for 20 years in a 53-year-old central Appalachian mixed-hardwood stand. Treatments included three residual stand densities after commercial thinning and an unthinned control. In general, the thinning treatments reduced mortality, increased crown class retention rates of codominant trees, and increased the ascension rates of trees in the intermediate crown class. After thinning, codominant trees exhibited the crown class stability of dominant trees, and intermediate trees exhibited greater survival and ascension to the upper canopy compared with unthinned controls. Very few suppressed trees improved canopy position in thinning treatments; however, thinning did tend to reduce mortality of these trees. Crown class transition rates are presented to help forest managers understand how commercial thinning treatments can affect the composition of the upper canopy in the latter stages of stand development.

Keywords: canopy ascension, canopy regression, canopy persistence, crown class transition rates, oak silviculture

Sustaining oak (*Quercus* spp.) species composition in hardwood forests requires a strategy of managing stand structure at key intervals during the oak life cycle to allow young oaks to achieve and maintain a competitive canopy position until the stand is mature (Dey et al. 2008). Many years of research throughout the eastern hardwood forest have identified two basic requirements for sustaining oak species. Loftis (2004) describes these requirements as the two "laws" of oak silviculture. First, competitive sources of oak reproduction must be present in the form of advance seedlings and/or vegetative sprouts when a stand-replacing disturbance occurs. Note that the process of successful oak regeneration actually begins many years before parent trees are removed from the overstory. Competitive sources of oak reproduction are the product of antecedent occurrences such as good seed crops and vigorous development of advanced seedlings leading up to a stand-replacing event.

Second, adequate and timely release treatments to favor continued development of oaks must take place at later stages of stand development. Timely removal of the overstory when oaks are in the competitive seedling stage allows trees to flourish and keep pace with neighboring vegetation until the canopy closes in the new stand 10–15 years later (Loftis 1990). Precommercial cleanings or crop tree release treatments when oaks are in the sapling stage allows them to remain in a competitive position for decades after canopy closure (Miller et al. 2007). Finally, commercial thinning treatments when oaks first reach the commercial sawtimber stage allow them to ascend to or persist in the upper canopy until the stand is mature. Although much has been reported about the response of oak seedlings and saplings to release treatments, more information is needed about the response of mid-rotation oaks as they transition to sawtimber size classes (i.e., Ward and Stephens 1994). This study examined crown class dynamics associated with a total of 2,668 oaks, red maple (*Acer rubrum* L.) and yellow-poplar (*Liriodendron tulipifera* L.), blackgum (*Nyssa sylvatica* Marsh.), and black birch (*Betula lenta* L.) after commercial thinning in a 53-year-old Appalachian hardwood stand. This information will be helpful to forest managers who seek to sustain or increase oak species composition in mixed-species stands during the stem exclusion and understory reinitiation stages (Oliver and Larson 1996).

Survival Probabilities Associated with Oaks

Forest managers often rely on estimates of long-term survival probabilities for prescribing silvicultural treatments to enhance the competitiveness of favored species. For example, shelterwood treatments are intended to increase the microsite light available to advanced oak seedlings to enhance their growth and competitiveness several years before the overstory is removed. The size of the advanced seedling when the overstory is removed determines its dominance probability (Sander et al. 1984, Loftis 1990, Dey et al. 1996), that is, its ability to achieve at least a codominant position in the new

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James S. Rentch (jrentch2@wvu.edu), Division of Forestry and Natural Resources, West Virginia University, Morgantown, WV 26506-6125. Gary W. Miller and Kurt W. Gottschalk, US Forest Service, Northern Research Station, Forest Sciences Laboratory, 180 Canfield Street, Morgantown, WV 26505. *We thank Phil Turk, Department of Statistics, West Virginia University, for statistical assistance. This is scientific article no. 3043 of the West Virginia University Agriculture and Forestry Experiment Station.*

Table 1. Average species composition and structure of 54 mature oak stands[a] in Pennsylvania, West Virginia, Ohio, and Kentucky.

Species	Crown class				Total	Basal area (ft^2/ac)
	Dominant	Codominant	Intermediate	Suppressed		
	(Trees/ac)					
Oaks	2.9 (0.4)	37.7 (2.0)	25.0 (3.4)	16.1 (2.8)	81.8 (6.8)	75.4 (2.5)
Others	1.2 (0.2)	16.3 (2.0)	24.2 (2.4)	122.0 (15.3)	163.7 (14.9)	40.1 (3.0)
Total	4.1 (0.6)	54.0 (2.4)	49.2 (4.2)	138.1 (16.6)	245.5 (18.4)	115.5 (2.7)

Numbers in parentheses indicate 1 standard error (SE) (Brose et al. 2008).
[a] Stand age ranges from 54 to 110 years, site index base age 50 ranges from 60 to 86, and stand area ranges from 6 to 46 acres.

stand after the overstory is removed. As result, estimates of dominance probabilities provide bases for prescribing preparatory treatments to stimulate a cohort of advanced seedlings and for recognizing the appropriate time for scheduling the final overstory harvest.

After a new stand forms, estimated survival probabilities and an assessment of an oak's competitive capacity can again be used to guide silvicultural prescriptions (Spetich et al. 2002). In young sapling stands, crop tree release has been shown to increase the long-term survival of desired trees (Lamson and Smith 1978, Schlesinger 1978, Wendel and Lamson 1987, Mitchell et al. 1988, Ward 1995, 2009, Miller 2000, Schuler 2006). Note that such treatments are consistent with the second law of oak silviculture described by Loftis (2004). In general, crown release treatments increase the probability of oak saplings reaching and persisting in a dominant or codominant crown class, varying, of course, in their initial crown class and competitive status (Miller et al. 2007). Forest managers can use such information to promote the survival of desired trees, shape overstory species composition, and prioritize silvicultural treatments among multiple stands according to initial stand conditions.

As a stand grows beyond the sapling stage and into the pole and small sawtimber stages, competition among the surviving trees continues to affect the distribution of crown classes by species. For example, fewer than half of the codominant northern red oaks (*Q. rubra*) remained in an upper canopy position between ages 25 and 55 in undisturbed stands (Ward and Stephens 1994). Nearly half of all upper-canopy trees in 50-year-old stands died or regressed to the lower canopy in a span of 40 years (Ward 2005). Some red maples in Appalachian hardwood stands spent 20 years in the lower canopy before ascending to the upper canopy as a result of natural disturbances (Ward and Stephens 1993, Tift and Fajvan 1999). Although there is continual movement of trees between the upper and lower canopies in undisturbed stands, both natural and planned disturbances tend to accelerate crown class transition rates.

Thinning is a form of exogenous, gap-scale disturbance that stimulates residual trees to increase in height and expand laterally into open space in the canopy, thus increasing the probability that codominant trees will remain in the upper canopy for decades (Johnson et al. 2002). In addition, thinning treatments may also increase the probability that some subordinate trees will ascend into an upper-canopy position before the open space closes.

Forest managers need additional information about the effect of commercial thinning on crown class dynamics, particularly in mixed-species stands where sustaining oaks is a priority management objective. The upper canopy of mature hardwood stands contains a relatively small, manageable number of dominant and codominant trees. Ward (2005) reported that in Connecticut, 90-year-old second-growth hardwood stands had an average of 75 trees/ac in the upper canopy, with oak species accounting for 24 trees/ac and northern hardwood accounting for the remainder. Brose et al. (2008) found that typical mixed-oak stands in Pennsylvania, West Virginia, Ohio, and Kentucky contained 58 trees/ac in the upper canopy and 49 trees/ac in the intermediate crown class (Table 1). The number of upper-canopy oaks averaged 41 trees/ac, and the number of intermediate oaks averaged 25 trees/ac. Using these average conditions as targets for oak stocking, forest managers can then apply estimates of crown class transition rates to prescribe thinning treatments that reach or sustain the desired upper-canopy species composition.

This study had two objectives. The first was to describe the effect of commercial thinning intensity on the crown class transition rates of oaks and some of their competitors in an even-aged, small sawtimber Appalachian hardwood stand. The second objective was to provide some preliminary silvicultural guidelines for increasing and sustaining oaks in upper-canopy positions in the intermediate stages of stand development.

Methods

The study area is a second-growth mixed-hardwood forest located in the West Virginia University Research Forest, near Morgantown, WV. The most abundant overstory tree species in the study area were yellow-poplar, northern red oak (*Quercus rubra* L.), chestnut oak (*Quercus prinus* L.), white oak (*Quercus alba* L.), and red maple. The overstory also contained black cherry (*Prunus serotina* Ehrh.). Soils are characterized as Dekalb series on well-drained slopes and ridgetops, which are loamy-skeletal, moderately deep, and well-drained soils of low natural fertility (Auchmoody 1972). The stand is located on a northeast-facing upper slope position at an elevation of 2,100 ft; slope inclination ranges from 0 to 15%. Annual precipitation averages 51 in. and is fairly evenly distributed throughout the year. The average annual mean temperature is 48° F, and the growing season is approximately May to September (Fekedulegn et al. 2003). Northern red oak site index (base age, 50 years) is 75 ft (Lamson et al. 1990).

In 1982, a thinning study was installed using twenty 3-ac experimental units, with a 0.5-ac permanent plot located in the center of each experimental unit (Miller et al. 1984, Brock et al. 1986, Lamson et al. 1990). All trees ≥1 in. dbh within the 0.5 ac plot were permanently tagged, and the following variables were recorded prior to treatment: species, dbh, crown class (dominant, codominant, intermediate, suppressed), and additional remarks noting stem and crown condition. Three thinning treatments, resulting in 45, 60, and 75% of residual relative density (RD) as defined by Gingrich (1967), and an uncut control were randomly assigned to the experimental units, resulting in five plots in each treatment. Trees removed to reach the desired residual stocking were distributed as recommended by Roach and Gingrich (1968); two-thirds of the harvest basal area came from trees smaller than the mean stand diameter, and one-third came from trees larger than the mean stand

Table 2. Per-acre stand data by thinning treatment.

Inventory	Number of stems			Basal area			Volume	
	≥1.0 in.[a]	≥5.0 in.	≥11.0 in.	≥1.0 in.	≥5.0 in.	≥11.0 in.	≥5.0 in. (ft^3/ac)	≥11.0 in. (bf/ac)[b]
	..........(No./ac)..........			..........(ft^2/ac)..........				
45% RD ($n = 5$)								
Initial	387	208	78	144.4	137.5	93.8	3,124	15,244
Cut	227	144	49	97.5	93.1	63.5	2,100	10,880
Residual	160	64	29	46.9	44.4	30.3	1,024	4,344
60% RD ($n = 5$)								
Initial	424	235	81	152.5	145.6	93.9	3,255	15,260
Cut	219	148	40	86.4	83.1	49.3	1,804	8,388
Residual	205	87	41	66.1	62.5	44.6	1,451	6,872
75% RD ($n = 5$)								
Initial	488	218	69	137.5	128.3	74.5	2,835	11,056
Cut	177	107	21	57.8	54.1	24.5	1,140	3,933
Residual	311	111	48	79.7	74.2	50.0	1,695	7,123
Control ($n = 5$)								
Initial	468	205	65	136.4	126.6	80.0	2,826	13,562

[a] dbh.
[b] Sawtimber volume, International ¼-in. rule.

diameter. The thinning treatments were a form of crown thinnings described by Smith (1962), with removals distributed to release desirable intermediate and upper-canopy trees while keeping the residual stand fully stocked. Poor-quality trees and low-value species were preferentially removed to reach the desired residual density. The residual stand generally included crop trees containing high-quality wood products of preferred species such as yellow-poplar, northern red oak, and black cherry. All trees were measured before and immediately after treatment in the spring of 1983, and additional remeasurements occurred every 5 years in the springs of 1988, 1993, 1998, and 2003 ($n = 2668$). In addition, after five growing seasons, the trees in a subset of 680 crop trees were assigned free-to-grow ratings ranging from 0 (no crown release) to 4 (four-sided crown release) (Lamson et al. 1990).

Crown class is a qualitative structural assessment of the canopy position and competitive status of a tree in relation to its neighbors that is often used to guide silvicultural and mensurational activities (Nicholas et al. 1990). Crown classes are used to design thinning prescriptions (Smith et al. 1997) and determine site index (Carmean et al. 1989), and they have been correlated with growth and productive capacity (Trimble 1969) and mortality and species succession patterns (Ward and Stephens 1993). In this study, initial crown class assignments were made using traditional definitions proposed by Smith (1962). Dominant trees have crowns that rise above the general canopy and receive full light from above and partial light from the sides. Codominant trees have crowns in upper canopy but are largely blocked from receiving light from the sides by neighboring crowns. Intermediate crowns receive a little light from above and none from the side, and suppressed trees have completely overtopped crowns and receive only diffuse light.

Initial crown class for each tree was defined as that observed before treatment in 1983, when the stand was marked for thinning. To analyze changes in the distribution of crown classes, subsequent crown class classifications made during remeasurements were assigned to one of three outcomes: upper canopy (dominant or codominant), lower canopy (intermediate or suppressed), or dead. The distribution of outcomes at the end of the study period was computed using SAS (version 9.1, 2007, SAS Institute). Count data were converted at the end of the study period to crown class transition rates, defined as the proportion of trees in a given initial crown class that finished in the upper canopy, finished in the lower canopy, or died.

Twenty-year crown class transition rates were then assessed by thinning treatment and initial crown class for the most abundant and commercially valuable tree species (e.g., white and chestnut oak, northern red oak, scarlet oak and black oak, yellow-poplar, and red maple, as well as blackgum and black birch). At the time of the first measurement, no red maples were in the dominant crown class, and all blackgum and black birch began the study as suppressed trees. Because count data often had cells with values <5, Fisher's exact test (Fisher 1954) was used to compare the distribution of ending crown position (upper canopy, lower canopy, or dead) among treatments with expected values, using the statistical language R (R Foundation for Statistical Computing, version 2.7.1, accessed Aug. 18, 2008). We used Fisher's exact test first to determine whether observed transition rates differed between control and all density reductions combined for each combination of species and initial crown class ($\alpha = 0.05$). We then used Fisher's exact test to determine whether observed transition rates differed among control and each of three density reductions. Where significant differences occurred, we made post hoc pairwise comparisons (i.e., comparing treatments for a given species and initial crown class) using Bonferroni's multiple comparison method to test whether comparisons would have been significantly different if drawn from a random population, where $\alpha = 0.05/n$ and $n =$ number of pairwise comparisons. This test is very conservative when a large number of distributions are being compared.

Results

A review of the average stand data indicated that the commercial thinning treatments reduced competition around individual residual trees and provided increasing amounts of growing space as the residual stand density decreased. Total basal area, including all trees ≥1 in. dbh, averaged 143 ft^2/ac on the study site before treatment (Table 2). The overstory comprised an average of 73 trees/ac in the sawtimber size class (≥11 in. dbh), and the majority of those trees were codominant or dominant. After commercial thinning, there were 48, 41, and 29 residual sawtimber-size trees in the plots thinned to 75, 60, and 45% RD, respectively. The degree of crown release among residual dominant and codominant trees increased as

Table 3. Twenty-year crown class transition rates for dominant trees in a 53-year-old central Appalachian hardwood stand. Unthinned controls were compared with all thinning treatments combined (the first *P* value) and with 75, 65, or 45% residual relative density (RD; the second *P* value).

Species	Pairwise comparisons: Control vs. all thin	Pairwise comparisons: Control vs. RD level	Treatment	20-year status: Upper canopy	20-year status: Lower canopy	20-year status: Dead	*n*
				(%)	(%)	(%)	
White and chestnut oak	a	a	Control	93	7	0	14
$P = 1$		a	75% RD	83	17	0	6
$P = 0.223$		a	60% RD	67	17	17	6
		a	45% RD	100	0	0	9
	a		Thinning*	83	12	5	21
Northern red oak	a	a	Control	96	4	0	28
$P = 0.731$		a	75% RD	100	0	0	10
$P = 0.736$		a	60% RD	92	0	8	12
		a	45% RD	75	25	0	4
	a		Thinning*	89	8	3	26
Scarlet and black oak	a	a	Control	85	5	10	20
$P = 0.594$		a	75% RD	50	0	50	4
$P = 0.501$		a	60% RD	100	0	0	1
		a	45% RD	86	0	14	7
	a		Thinning*	79	0	21	12
Yellow-poplar	a	a	Control	79	12	9	33
$P = 0.018$		a	75% RD	92	0	8	24
$P = 0.166$		a	60% RD	94	0	6	31
		a	45% RD	80	0	20	15
	b		Thinning*	89	0	11	70

For pairwise comparisons, rows with different letters have distributions that differ significantly from expected values.
* All thinnings combined.

the thinning intensity increased (Lamson et al. 1990). The degree of release around the crowns of residual overstory crop trees averaged 7% in control plots and 34, 48, and 64% in plots thinned to 75, 60, and 45% RD, respectively.

In general, the thinning treatments did not affect the crown class transition rates or mortality of dominant trees (Fisher's exact test, $P = 0.789$, $n = 224$) (Table 3). The oaks and yellow-poplar were the only species in a dominant crown class before treatment. For oaks in all treatments combined, 88% of dominant trees remained in the upper canopy after 20 years. Another 4% descended to the lower canopy, and 8% died. Dominant northern red oak exhibited the greatest retention rate of initial canopy position over 20 years. Of 54 dominant northern red oaks, 51 trees remained dominant or codominant, 2 trees descended to the lower canopy, and only 1 tree died. Scarlet oak (*Quercus coccinea* Muenchh.) and black oak (*Quercus velutina* Lam.) exhibited the lowest retention rate. Of 32 scarlet and black oaks, 26 trees remained dominant or codominant, 1 tree descended to the lower canopy, and 5 trees (16%) died. Note that most of the mortality in dominant scarlet and black oak occurred in the control and 75% RD thinning treatment, where residual stand density was the greatest. For dominant yellow-poplars, individual density reduction treatments did not affect crown class transition rates or mortality ($P = 0.166$); however, there was a significant difference when all thinning treatments were combined and compared with controls ($P = 0.018$). This difference arose because in control plots, 12% of dominant yellow-poplars regressed to lower-canopy status, whereas none regressed in the three thinning treatments.

Among codominant trees, the effect of the thinning treatments differed by species (Table 4). Thinning did not affect the crown class transition rates or mortality of codominant yellow-poplar ($P = 0.448$). For yellow-poplar in all treatments combined (control and three density reductions), 83% remained in the upper canopy, 9% descended to the lower canopy, and 8% died. For other species, the thinning treatments decreased mortality and increased the percentage of trees that remained in the upper canopy. For northern red oak, the retention of trees in the upper canopy increased from 67% in control plots to nearly 90% in thinned plots ($P < 0.001$). For red maple, the retention of trees in the upper canopy increased from 44% in control plots to nearly 100% in thinned plots ($P < 0.01$).

There was a notable effect of thinning on crown class transition rates and mortality for intermediate white and chestnut oaks and northern red oaks (Table 5). For both species groups, the rate of ascension from intermediate crown class to the upper canopy increased and mortality decreased as the residual stand density decreased ($P < 0.0001$ and $P < 0.0001$, respectively). When controls were compared with all thinning treatments combined, scarlet and black oaks and red maple exhibited similar significant effects of thinning, with scarlet and black oaks showing a significant decline in mortality and red maple showing a significant increase in both crown class ascension and mortality as a result of thinning ($P = 0.023$ and $P < 0.01$, respectively). Thinning did not have a significant impact on the fate of intermediate yellow-poplar in this analysis ($P = 0.308$). Both scarlet and black oaks and yellow-poplar had relatively small sample sizes for intermediate trees, with most of the sample trees being located in the control plots.

Although Fisher's exact test revealed significant differences among treatments for all suppressed trees combined ($P < 0.0001$), differences occurred primarily in the distribution of stems among lower and dead classifications (Table 6). For all species observed in this study, the vast majority of suppressed trees either died or remained in the lower canopy, regardless of the thinning treatment. Only 1 of a total of 41 white and chestnut oak trees and none of the northern red oak trees improved canopy position. Among more shade-tolerant tree species, only 5 of 323 red maples and 1 of 65 black birches in thinned plots ascended to the upper canopy from a suppressed position, and no blackgum ($n = 452$) improved canopy status. On the basis of these results, it is apparent the main benefit of

Table 4. Twenty-year crown class transition rates for codominant trees in a 53-year-old central Appalachian hardwood stand. Unthinned controls were compared with all thinning treatments combined (the first *P* value) and with 75, 65, or 45% residual relative density (RD; the second *P* value).

	Pairwise comparisons			20-year status			
Species	Control vs. all thin	Control vs. RD level	Treatment	Upper canopy	Lower canopy	Dead	*n*
				(%)			
White and chestnut oak	a	a	Control	39	46	15	46
$P < 0.001$		b	75% RD	63	37	0	38
$P < 0.001$		c	60% RD	95	8	0	19
		c	45% RD	85	5	8	26
	b		Thinning*	81	17	3	83
Northern red oak	a	a	Control	67	20	12	49
$P < 0.001$		b	75% RD	92	8	0	39
$P < 0.01$		ab	60% RD	81	13	6	31
		b	45% RD	92	3	6	36
	b		Thinning*	88	8	4	106
Scarlet and black oak	a	a	Control	33	33	33	27
$P < 0.001$		b	75% RD	82	9	9	33
$P < 0.001$			60% RD				0
		b	45% RD	67	0	33	3
	b		Thinning*	75	4	21	36
Yellow-poplar	a	a	Control	76	14	11	71
$P = 0.501$		a	75% RD	96	4	0	24
$P < 0.448$		a	60% RD	76	14	10	50
		a	45% RD	86	5	10	21
	a		Thinning*	86	8	6	95
Red maple	a	a	Control	44	44	10	18
$P < 0.001$		b	75% RD	100	0	0	12
$P < 0.01$		ab	60% RD	90	10	0	10
		ab	45% RD	100	0	0	6
	b		Thinning*	97	3	0	28

For pairwise comparisons, rows with different letters have distributions that differ significantly from expected values.
* All thinnings combined.

Table 5. Twenty-year crown class transition rates for intermediate trees in a 53-year-old central Appalachian hardwood stand. Unthinned controls were compared with all thinning treatments combined (the first *P* value) and with 75, 65, or 45% residual relative density (RD; the second *P* value).

	Pairwise comparisons			20-year status			
Species	Control vs. all thin	Control vs. RD level	Treatment	Upper canopy	Lower canopy	Dead	*n*
				(%)			
White and chestnut oak	a	a	Control	7	38	56	61
$P < 0.0001$		ab	75% RD	25	50	25	8
$P < 0.0001$		b	60% RD	33	67	0	15
		b	45% RD	100	0	0	2
	b		Thinning*	53	39	8	25
Northern red oak	a	a	Control	0	44	56	34
$P < 0.0001$		ab	75% RD	23	53	23	30
$P < 0.0001$		b	60% RD	30	60	10	20
		b	45% RD	78	0	22	9
	b		Thinning*	44	38	18	59
Scarlet and black oak	a	a	Control	0	11	89	9
$P = 0.023$		b	75% RD	0	75	25	4
$P = 0.022$			60% RD				0
			45% RD				1
	b		Thinning*	0	75	25	5
Yellow-poplar	a	a	Control	5	47	47	19
$P = 0.308$			75% RD				0
$P = 0.267$		a	60% RD	38	38	25	8
		a	45% RD	0	33	67	3
	a		Thinning*	19	35	46	11
Red maple	a	a	Control	3	92	5	37
$P < 0.01$		ab	75% RD	5	85	10	20
$P < 0.001$		b	60% RD	40	60	0	15
		b	45% RD	50	33	17	6
	b		Thinning*	32	59	9	41

For pairwise comparisons, rows with different letters have distributions that differ significantly from expected values.
* All thinnings combined.

thinning as measured by crown class transition rates is the improvement in performance of trees in the codominant and intermediate crown classes. After thinning, codominant trees tended to exhibit the stability of dominant trees, and some intermediate trees tended

Table 6. Twenty-year crown class transition rates for suppressed trees in a 53-year-old central Appalachian hardwood stand. Unthinned controls were compared with all thinning treatments combined (the first *P* value) and with 75, 65, or 45% residual relative density (RD; the second *P* value).

Species	Pairwise comparisons		Treatment	20-year status			
	Control vs. all thin	Control vs. RD level		Upper canopy	Lower canopy	Dead	*n*
				(%)	(%)	(%)	
White and chestnut oak	a	a	Control	0	36	64	61
$P < 0.0001$		b	75% RD	0	94	6	17
$P < 0.001$		ab	60% RD	5	75	20	20
		ab	45% RD	0	50	50	4
	b		Thinning*	2	73	25	41
Northern red oak	a	a	Control	0	37	63	99
$P < 0.0001$		ab	75% RD	0	63	37	38
$P < 0.001$		b	60% RD	0	75	25	36
		ab	45% RD	0	57	43	7
	b		Thinning*	0	65	35	81
Scarlet and black oak	a		Control	33	0	67	3
$P = 0.2$	a		Thinning*	0	100	0	2
Yellow-poplar	a		Control	0	50	50	8
$P = 0.085$	a		Thinning*	0	100	0	6
Red maple	a	a	Control	0	74	26	227
$P < 0.01$		b	75% RD	1	84	15	135
$P < 0.05$		ab	60% RD	1	81	18	100
		ab	45% RD	3	76	20	88
	b		Thinning*	2	80	18	323
Blackgum	a	a	Control	0	87	13	142
$P = 0.164$		a	75% RD	0	85	15	247
$P = 0.071$		a	60% RD	0	76	24	97
		a	45% RD	0	78	12	108
	a		Thinning*	0	80	20	452
Black birch	a	a	Control	0	69	31	74
$P = 0.778$		a	75% RD	0	67	33	30
$P = 0.233$		a	60% RD	0	76	24	25
		a	45% RD	10	50	40	10
	a		Thinning*	4	64	32	65

For pairwise comparisons, rows with different letters have distributions that differ significantly from expected values.
* All thinnings combined.

to become more competitive and ascended into the upper canopy. On the other hand, few suppressed trees improved their canopy position, and the main effect of thinning them was a reduction or delay in mortality.

Discussion

Thinning is prescribed in hardwood stands to reallocate growth potential to the most desirable trees and increase the utilization of merchantable products by harvesting trees that would otherwise die from overcrowding. Smith (1962) suggested a general approach to thinning whereby the available growing space is allocated to an optimum number of trees on the basis of desired species composition, available product markets, and other nontimber outputs. Less desirable trees are removed to favor residual trees whose characteristics provide a greater contribution to desired woodland benefits than those removed. In addition, the reduction in competition for site resources allows the residual trees to increase in vigor and grow faster, thus reducing the time it takes to reach a given size or capacity to produce viable seed crops for future generations. The results of this study shed light on the impact of thinning on crown class transition rates of several important species in the central Appalachians, thus providing a basis for influencing the quality and composition of the upper canopy in the latter stages of stand development.

The relative shade tolerance of the seven species groups observed in this study may have had an important effect on crown class transition rates. Yellow-poplar is generally considered to be the most shade intolerant of the species observed here (Trimble 1975); thus, there were very few yellow-poplars found in the lower canopy before treatment (Tables 5 and 6). Most yellow-poplars were in the upper canopy, having reached and maintained competitive positions over the previous 53 years. Although the thinning treatments had little discernible effect on ascension of yellow-poplar to the upper canopy, the sample size was very small for lower canopy trees. Taken together, crown class retention for upper-canopy yellow-poplar was about 10% greater than that observed for controls, although the differences were not statistically significant. Apparently, upper-canopy yellow-poplar was already a strong competitor in the study area, and thinning had only a small effect on its ability to remain so.

The scarlet and black oaks are considered to be intermediate in shade tolerance (Trimble 1975). Few scarlet oaks or black oaks were found in the lower canopy before treatment (Tables 5 and 6). The thinning treatments led to a significant increase in survival and retention of codominant scarlet and black oaks (Table 4). Unlike yellow-poplar, the scarlet and black oaks in the upper canopy were able to use the added growing space to become more competitive after thinning.

Northern red oak is also intermediate in shade tolerance, but it is more shade tolerant than either yellow-poplar or scarlet and black oaks. Note that several northern red oaks were found in the lower canopy before treatment (Tables 5 and 6). None of the suppressed northern red oaks ascended to the upper canopy after thinning. An average of 44% of intermediate red oaks ascended into the upper canopy in thinned plots, compared with none in the control plots

(Table 5). About one-third of intermediate northern red oaks became codominant 10 years after crown release in 16-year-old stands (Miller 2000). For upper-canopy northern red oaks, thinning increased the survival and ascension of codominant trees, but this was not the case for dominant trees.

White oaks exhibit the greatest shade tolerance among upland oaks (Trimble 1975). In this study, thinning increased survival and ascension for suppressed, intermediate, and codominant white and chestnut oaks. Crown class transition rates in thinned and control plots were not significantly different for dominant white and chestnut oaks.

Red maple, blackgum, and black birch in the central Appalachians are usually classified as shade-tolerant species, although black birch is sometimes classified as intermediate, similar to northern red oak (Trimble 1975). Blackgum and black birch were found only in the suppressed crown class before treatment, and thinning did not bring about a significant change in their status compared with controls (Table 6). However, red maple was much more responsive to thinning. Both survival and crown class ascension of red maple were improved by thinning; significant differences from controls were observed for codominant, intermediate, and suppressed trees (Table 4).

Although the effects of several residual stand densities were examined in this study, most published guidelines recommend thinning hardwood stands to approximately 60% RD to maximize periodic wood volume production (Gingrich 1967) and to maintain full site occupancy. In this study, crown class transition rates between the 60% RD and 45% RD thinning treatments did not differ significantly for any species or pretreatment crown class (Tables 3–6). For codominant white and chestnut oaks, the 75% RD thinning treatment improved crown class retention and reduced mortality compared with controls, but even better results were obtained with the 60% RD and 45% RD treatments. Results generally indicated that crown class retention in the upper canopy, ascension of intermediate trees into the upper canopy, and survival of all crown classes was enhanced by thinning to any level of residual density compared with controls. However, there was not a pronounced improvement in performance that resulted from reducing stand density below 60% RD.

Estimates of crown class transition rates after commercial thinning may be useful to forest managers who seek to promote or sustain a given number of overstory oaks in mixed-species stands as they mature. Releasing oaks from nearby competition at key stages allows them to maintain or ascend into a codominant position, particularly on high-quality sites where numerous competing species exhibit faster early height growth (Oliver 1980, O'Hara 1986, Miller et al. 2007). The underlying management objectives for sustaining overstory oaks might include seed production for wildlife food, the accumulation of advanced future regeneration, wildlife habitat, species diversity, or wood production. A specific "number-of-trees" goal for the residual stand can serve as a guideline for planning the thinning treatment and making cut-or-leave decisions when the stand is marked for thinning. In general, the thinning treatment should provide an adequate and timely release of enough oaks in both upper- and lower-canopy positions to attain the desired future conditions as defined by the management objectives.

In this study, the percentage of upper-canopy oaks that remained in the upper canopy after 20 years improved from 64% in unthinned plots to 80% in plots with a relatively light density reduction (75% RD) and 88% in the most heavily thinned plots (45% RD). The contrast between thinned and unthinned response was more striking for oaks that began in a lower-canopy position. The percentage of lower-canopy oaks that ascended to the upper canopy was only 2% in unthinned plots, and the 75, 60, and 45% RD thinning treatments improved those percentages to 9, 13, and 36%, respectively. The observed crown class transition rates presented in this study provide a basis for applying thinning treatments to sustain overstory oaks and cause subordinate oaks to ascend to the upper canopy to meet long-term management objectives.

Oak stocking goals can vary according to long-term management objectives, and cultural treatments in immature stands can often help to achieve them. Such goals for number of overstory oaks can be derived from published stocking equations developed for upland oak and mixed-species stands (Gingrich 1967, Stout and Nyland 1986). For example, an individual oak that measures 18 in. dbh represents approximately 1.3% of relative stand density. Therefore, the mature stand must contain at least 50 oaks/ac of that average size, with most of them occupying the dominant or codominant crown classes to achieve 65% oak relative density. At any stocking level, however, some of the oaks would likely persist in intermediate crown classes until they can ascend into the upper canopy.

A good rule of thumb is to promote approximately 1 oak crop tree in the immature stand for every percentage point of oak stocking desired in the mature stand (Brose et al. 2008). For example, a goal of 65% oak stocking can be achieved by seeking to sustain about 65 oaks in the overstory as the stand matures. As shown in this study, not all immature oaks can be sustained in the overstory for several decades, even if well-planned thinning treatments are applied. Nonetheless, this rule of thumb allows for the loss of a few trees and provides a reasonable margin for error in reaching oak stocking goals.

The results of this study indicated that about one-third of the intermediate white and chestnut oaks and northern red oaks ascended into the upper canopy 20 years after thinning to 60% RD (Table 5). However, not all intermediate oaks offer the same potential stem quality after thinning. Residual oaks with good initial stem quality tend to retain good quality after a thinning treatment (Miller et al. 2008). Likewise, trees with excess branching or evidence of poor quality before thinning tend to become worse after thinning. In making cut-and-leave decisions among intermediate trees before thinning, it is recommended that preference be given to retaining oaks that exhibit better-than-average initial stem quality.

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