For. Sci. XX(XX):1–12
doi: 10.1093/forsci/fxz042

silviculture

Increased Individual Tree Growth Maintains Stand Volume Growth after B-Level Thinning and Crop-Tree Management in Mature Oak Stands

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Six study areas were established in 80–125-year-old upland oak stands on average sites to compare stand and individual tree growth response following two active treatments (B-level thinning, crop tree) with an unmanaged control. Initial stocking of 104 percent was reduced to 62 percent and 60 percent on the B-level and crop-tree-management plots, respectively. Approximately 7,200 board feet per acre (International ¼) were harvested on the actively managed plots with upland oaks accounting for 81 percent of pre- and 86 percent of residual stand. Eleven-year diameter and volume growth of oak sawtimber trees was greater on actively managed plots. Growth response increased with degree of release and was maintained for the length of the study. Because of the increased individual tree growth of oaks in response to release, stand volume growth of oak sawtimber did not differ between treatments. In contrast to an 11-year decline of poletimber stocking on unmanaged plots, poletimber stocking increased on managed plots as diameter growth increased in response to partial release. This may increase difficulty of regenerating oak in the future. For those mature red oak stands where traditional regeneration prescriptions will not be implemented or will be delayed, commercial harvests can be conducted without compromising stand volume growth of oak.

Keywords: *Quercus*, diameter growth, volume growth, crop tree, thinning

There are over 13.3 million acres of upland oak (*Quercus* spp.) forests that are 80 years old or older in northeast and north central United States (Smith et al. 2009). Recommendations rooted in optimizing economic return indicated that regeneration prescriptions should be initiated in these mature stands (Roach and Gingrich 1968, Sander 1977, Hibbs and Bentley 1983, Brose et al. 2008, Demchick et al. 2018). However, regeneration practices have not been, and will not be, initiated on the vast majority of these stands on both public and private lands. Management on public lands is hampered by a cutback in personnel and public sentiment against harvesting; particularly against the even-aged systems necessary for regenerating oak except on the lowest-quality sites. Whether measured by ownerships or acres, the top four reasons for owning a family forest in the United States are beauty, wildlife, nature, and family legacy rather than for commodity production (Butler et al. 2016). Family forest owners are not necessarily averse to management, as many harvest trees for personal use and to improve wildlife habitat, but there are few guidelines for those who own mature oak forests except for earlier recommendations to begin stand regeneration.

The causes for the paucity of management studies in mature oak stands are threefold: economic models indicating regeneration should be initiated in financially mature stands as noted above, relatively few older stands until recently, and the perception that older trees and stands do not respond to management. Many upland oak forests originated in the early 1900s after farm abandonment, loss of American chestnut, and effective wildfire control that allowed hardwood sprouts and new seedlings to develop into poles and sawtimber (Spaeth 1928, Abrams and Nowacki 1992). Therefore, there were few mature oak stands in the mid-1900s when most stand growth studies were initiated; and research focused on typical stands of that era. Other evidence for the increasing prominence of mature oak stands is

Manuscript received November 13, 2018; accepted June 10, 2019; published online July 8, 2019.

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Acknowledgments: *Special thanks to the Connecticut Department of Energy and Environmental Protection-Forestry Division, Metropolitan District Commission, and the Torrington Water Company for providing study sites, marking stand prescriptions, and conducting harvests. J.P. Barsky, M.R. Short, and S.C. Williams assisted with plot establishment and data collection. Special thanks to the Applied Research Editor, Associate Editor, and three reviewers for their through reading and insightful deep comments, and persistence that truly improved the manuscript. This material is based upon work that was supported in part by the McIntire–Stennis Project CONH-564 (Accession No. 195235).*

that that the volume of oak trees with a diameter of 19 in. or greater increased fivefold between 1953 and 2017 (Oswalt et al. 2019).

The last factor for a lack of research in mature oak stands was the perception that older trees did not respond to release. Gingrich (1971) wrote "Many oaks over 70 years of age have shown no growth response to the thinning release." Diameter growth of 80-year-old white oaks in Kentucky was not increased by thinning and only slightly increased when stocking was reduced below 50 percent (Hilt and Dale 1979). However, modeling indicated that thinning to 60 percent stocking increased annual diameter growth of 18-in. upland oaks relative to those in fully stocked stands (Hilt 1983). More recently, crop tree release was found to increase diameter growth of 80-year-old northern oak in West Virginia (Miller 1997) and 90-year-old oaks in Connecticut (Ward 2002).

No studies have directly compared stand volume growth in thinned versus unthinned stands that were at least 80 years old. Stand volume growth in 60–78-year-old oak stands in Wisconsin did not differ between those thinned and unthinned (Demchik et al. 2016). Models developed for Midwestern oak forests suggested that volume growth was greater in fully stocked than 60 percent stocked stands at age 80 years, but the reverse was true in stands at age 100 (Dale 1972). A 50-year analysis of some of the plots in the Dale (1972) study reported that sawtimber volume growth peaked between 60 and 70 percent stocking in stands older than 63 years with only a slight decrease, if any, in volume growth at higher stocking levels (Lhotka 2017). Two studies examined stand volume growth in 80-year-old unmanaged and shelterwood stands: a 20-year study in Michigan (Rudolph and Lemmien 1976) and a 15-year study in Connecticut (Ward et al. 2005). Using the shelterwood plots as a surrogate for crop-tree management, both studies reported that volume growth was slightly, but not significantly, higher in unmanaged stands.

To address the lack of research directly comparing management options for an increasingly large component of the eastern upland oak forest, this study was established to determine whether commercial harvests could be used to manage mature oak stands without negatively impacting stand volume growth. Stand and individual tree growth following crop tree release and B-level thinning were compared with growth on unmanaged controls. Crop-tree release and B-level thinning differ in how growth is allocated to postharvest residual stems. As stated by Miller et al. (2007) "Crop tree release differs from traditional thinning in that it assures that most site resources are focused on a small number of selected trees rather than being widely distributed to all residual trees." This was accomplished by fully releasing the crowns of selected trees on crop-tree release plots compared to a partial canopy release of most residual trees on B-level thinning plots.

The specific objectives of this study were: (1) to compare the influence of several management options on the stocking and volume growth of 80–120-year-old oak sawtimber stands over an 11-year period, and (2) to examine the relation of individual tree metrics and subsequent growth response to varying levels of canopy release to determine which individual tree characteristics could best be used by field foresters to predict growth response to partial and full release. The results of this study would provide forest managers with improved knowledge of how mature oak stands respond to several management options and then to optimize selection of residual trees to best achieve stand objectives.

Methods

Study Areas

During 2003–4, six oak management study areas were established in southern New England in collaboration with the Division of Forestry-Connecticut Department of Energy and Environmental Protection (study areas Ham, TuD, TuN, Win), Metropolitan District Commission (MDC), and Torrington Water Company (TWC). There was no history of prior management in these mature, fully stocked oak sawtimber stands. Soil descriptions are from SoilWeb (O'Geen et al. 2017). Soils were sandy and fine sandy loam Typic/Lithic Dystrudepts and Oxyaquic Dystrudepts derived from gneiss, schist, and granite glacial melt-out and lodgment tills, respectively (Table 1). Elevations ranged from 385 to 1,100 feet MSL. The area is in the northern temperate climate zone. Mean monthly temperature ranged from 27° F in January to 73° F in July with an average of 176 frost-free days per year. Mean annual precipitation was 46 in. per year, evenly distributed over all months.

Median age of sawtimber (≥11.0 in. dbh) oaks ranged from 79 to 125 years old (Table 1). Site indices (50 years, northern red oak) ranged from 64 to 70 ft. Stands had an average of 45 sawtimber oaks per acre with maple/beech/birch accounting for 65 percent of the remaining 30 sawtimber trees per acre. Oaks accounted for 80 percent of the average merchantable stand volume of 13.3 thousand board feet (mbf)/acre. Relative to nonoak sawtimber, individual oak sawtimber trees had larger diameters, were taller, had longer merchantable sawlogs, and had higher estimated board-foot volumes (Table 2).

Design and Measurements

Study design was a randomized complete block (study area) with three treatments. Each of the six study areas was divided into three 3–5-acre treatment areas. Approximately 10 crop trees per acre were selected on each treatment area prior to treatment assignment. Crop trees were selected prior to randomly assigning treatments to eliminate potential bias of selecting higher or lower-quality trees for a specific treatment. Selection criteria for crop trees were: red

Management and Policy Implications

Within the eastern upland oak forest, mature oak stands are an increasing component that currently occupies 13.3 million acres (5.4 million hectares) in the northeast and north central United States. Implementation of regeneration prescriptions in many, if not most, of the mature oak stands will be delayed to stand ages older than those of earlier recommendations. However, there is little information available to foresters on the feasibility and consequences of alternatives to initiating regeneration. In an 11-year study in southern New England, both traditional thinning to the B-level and crop-tree management increased individual tree diameter and volume growth in 80–125-year-old stands on average sites. The increased growth of residual trees was sufficient to maintain stand volume growth to levels comparable to that of unmanaged stands. However, both thinning and crop-tree management increased individual tree diameter growth and stand stocking of nonoak poletimber. The results of this study indicate that forest managers are not limited to initiating regeneration in older oak stands, but can prescribe an intermediate treatment to generate income for the land owner without sacrificing stand volume growth of the more valuable oak.

Table 1. Description of study area sites and preharvest stand conditions for a mature oak crop tree release study in Connecticut: site index (feet)—northern red oak base age 50.

	Study areas					
	Ham	MDC	TuD	TuN	TWC	Win
Soil type	Yale	Holy	ChCh	ChCh	PaMo	ChCh
Soil texture	FSL	SL	FSL	FSL	FSL	FSL
Elevation	385	515	1100	915	1110	1085
Median age	94 (85–98)	110 (97–119)	82 (77–106)	125 (90–136)	94 (83–105)	79 (74–84)
Site index	59	59	67	67	65	67
Density (trees per acre)						
Oak sawtimber	56	40	65	28	28	52
Nonoak sawtimber	19	31	21	36	60	14
Poletimber	196	119	76	67	160	112
Total	271	189	162	132	247	178
Stocking (percent)						
Oak sawtimber	60	50	74	53	39	63
Nonoak sawtimber	16	23	15	32	38	12
Poletimber	36	26	17	17	35	23
Total	112	99	106	102	112	98
Merchantable volume (thousand board feet International ¼ per acre)						
Oak sawtimber	8.3	9.6	12.0	12.2	7.6	13.9
Nonoak sawtimber	1.4	2.7	1.2	2.5	6.4	1.8
Total	9.8	12.3	13.2	14.6	14.0	15.7

Note: Soils: Yale-Yalesville (mesic Typic Dystrudepts—moderately deep, well-drained fine sandy loam formed in a loamy till); Holy-Holyoke-rock outcrop complex (mesic Lithic Dystrudepts—well-drained and somewhat excessively drained sandy loam formed in a thin mantle of till); ChCh-Charlton-Chatfield complex (mesic Typic Dystrudepts—well drained, fine sandy loam formed in loamy melt-out till); PaMo-Paxton and Montauk (mesic Oxyaquic Dystrudepts—well-drained, fine sandy loam formed in lodgment till). mbf, thousand board feet.

Table 2. Mean (standard error) preharvest tree characteristics in an oak management study for six study areas in Connecticut.

	Study areas					
	Ham	MDC	TuD	TuN	TWC	Win
Oak sawtimber						
dbh (in.)	16.1 (0.3)	17.7 (0.5)	16.6 (0.4)	22.8 (0.8)	19.3 (0.5)	17.3 (0.4)
Total height (feet)	78 (0.7)	82 (1.0)	83 (0.8)	86 (0.8)	85 (0.7)	90 (0.7)
Sawlog height (feet)	32 (1.1)	41 (1.3)	36 (1.2)	44 (1.3)	41 (1.2)	47 (1.0)
Tree volume (Int. ¼)	153 (9)	257 (18)	195 (12)	442 (32)	276 (17)	266 (13)
Butt log grade	2.1 (0.1)	1.5 (0.1)	1.8 (0.1)	1.3 (0.1)	1.5 (0.1)	1.4 (0.1)
N	104	74	121	52	51	97
Nonoak sawtimber						
dbh (in.)	14 (0.7)	13.1 (0.3)	13.4 (0.5)	14.0 (0.5)	13.7 (0.3)	14.4 (0.8)
Total height (feet)	73 (1.7)	76 (1.7)	70 (1.3)	75 (0.9)	77 (1.4)	81 (1.5)
Sawlog height (feet)	26 (2.3)	32 (1.8)	21 (1.7)	21 (1.2)	30 (1.8)	32 (3.0)
Tree volume (Int. ¼)	84 (15)	113 (11)	70 (10)	73 (6)	128 (13)	144 (32)
Butt log grade	3.2 (0.2)	2.5 (0.2)	3.1 (0.2)	3.4 (0.1)	2.9 (0.1)	2.8 (0.2)
N	35	57	38	67	111	26
Poletimber						
dbh (in.)	6.1 (0.1)	6.4 (0.1)	6.7 (0.2)	6.8 (0.2)	6.6 (0.1)	6.2 (0.1)
Total height (feet)	46 (1.1)	49 (1.5)	47 (1.6)	51 (1.7)	48 (1.3)	51 (1.5)
Pulpwood height (feet)	24 (1.0)	25 (1.5)	23 (1.7)	28 (2.1)	26 (1.4)	25 (1.5)
N	363	220	141	125	296	207

Note: Tree volume is merchantable volume after cull deduction. Only trees inside fixed-area plots were included in the analysis.

oak group (*Quercus rubra* or *Q. velutina*), codominant or dominant crown class, at least 17 feet to first fork, dbh >18 in., and grade 1 butt log.

After potential crop trees were selected and numbered, treatment areas on each study area were randomly assigned to one of three treatments (management prescriptions): B-level area-wide thinning to 60 percent stocking, crop tree release, and unmanaged controls. All harvests were conducted as part of a commercial thinning operation. The first growing season after harvest completion was 2004 for TuD and Win, 2005 for Ham and MDC, and 2007 for TuN and TWC.

On crop-tree release treatment areas, only upper canopy trees with crowns immediately adjacent to crop trees were harvested. Because quality potential crop trees were not uniformly distributed, this resulted in a mosaic of stand structures ranging from those similar to a shelterwood where there were many crop trees to dense unmanaged patches in areas without crop trees. On the B-level thinning treatment areas, local unit foresters marked stands to 60 percent stocking that favored leaving residual oaks and higher-value stems of other species using a combination of high thinning and removal of cull trees. Their only restriction was that preselected crop trees could not be marked for harvesting. The stands following this area-wide thinning had a uniform distribution of residual trees with small canopy gaps.

A minimum of 25 of the crop trees on each treatment area were selected for detailed measurement and then permanently marked at dbh and numbered with orange paint. The composition of measured crop trees was 94 percent northern red oak and 6 percent black oak. The diameters of the measured crop trees were recorded to the nearest 0.04 in. The following data were also recorded for these trees: species, crown class, tree-grade (Alerich 2000), total live crown ratio (10 percent), total height, height of bottom of live crown, merchantable sawlog height, and cull deduction (USDA-FS 2012). Heights (feet) were estimated using a laser hypsometer at approximately a 45° angle of total height prior to harvest and again in 2018. The degree of canopy release (DCR) was assessed within 1 year of cutting in 10 percent increments; e.g., a crown released from competition on two sides was given a DCR of 50 percent. Trees that were not released were assigned a release factor of 0. Tree ages were determined by counting rings on sanded stumps of a minimum of 15 harvested upper canopy oaks. The stand age was the median age of the sampled trees.

To assess the effect of management prescription on stand stocking and volume growth, a 164 × 64 feet (0.62 ac) fixed-area plot was permanently established within each of the three treatment areas at each study area. All trees with diameters greater than 4 in. within each fixed-area plot were permanently marked at 4.5 feet and systematically numbered with red paint. Data collected for crop trees were also recorded for these trees. A total of 2,573 stems (all species) were measured prior to treatment implementation. Thereafter, the diameters and crown classes of all live trees were measured annually during the dormant season. All stems with diameters at least 3.5 in. were banded and numbered in 2013. However, these stems were not included in the stand growth measurement until they had reached the minimum threshold diameter of 4 in. Total and merchantable sawlog height measurements were repeated for all sawlog trees in 2018.

Statistical Analysis

Because the year of harvest differed among the study areas as noted above, the preharvest stand and individual tree values were those of the dormant season prior to harvest. Final stand and individual tree values were those at the end of the 11th growing season after harvest. The site index for each study area was the median of estimates for northern red oaks that were 100 years of age or younger using the equation for northern red oak (base age 50 years) in Carmean et al. (1989, figure 48). Stocking was determined using species-specific equations in Arner et al. (2003). Board-foot volumes were calculated using species-specific equations in Turner (1994). Merchantable volume was volume after cull deduction. Volumes are reported as merchantable mbf (International ¼). For trees that grew into the sawtimber size class during the 10 years following harvest, sawlog heights measured in 2018 were used to determine tree volume. When appropriate, values are presented on a per acre basis. Live crown length was defined as the difference between the total height and bottom of the live crown. DCR was converted to the number of sides released to facilitate comparisons with earlier studies. Study areas were grouped into three stand age classes: early mature (79 and 82 years old), mature (94 years old), and late mature (110 and 125 years old) (Table 1).

Within fixed-area plots, separate analyses were conducted for oaks with grade 1 and 2 butt logs (oak FAS), all oaks, and all nonoaks. Comparison of preharvest stocking and volume levels among study areas was completed using ANOVA with plots as replicates (SYSTAT 13.2). Comparisons of total stand stocking and volume 11 years after harvesting were completed using the Linear Mixed Model subroutines of SYSTAT 13.2 with treatment as the fixed effect and study area as the random effect. Tukey's HSD test was used to test differences among treatments. Differences were considered significant at $P < .05$.

All statistical analyses of stocking, volume, and diameter growth for the 11 years postharvest were performed in R (R Core Team 2018) using the lmer package (Bates et al. 2015) and the psycho package (Makowski 2018). We used the lmer function to perform linear mixed effects model analysis to examine 11-year stand stocking and volume growth for each individual species group with treatment and stand age class as the fixed effects and study area as the random effect. When stand age class was found not to be significant, analyses were run without stand age as a factor (Supplemental Tables 1 and 2). The Kenward–Rogers approximation was used to estimate the degrees of freedom for the *F*-test (Kuznetsova et al. 2017). For all growth analyses, the initial values were those immediately postharvest, and the final values were those 11 growing seasons after harvest. We performed posthoc pairwise comparisons using the get_contrasts function in the psycho package (Makowski 2018).

For individual tree diameter and volume growth analysis, we used all trees within the fixed-area treatment plots and those crop trees outside that fixed-area plots that were numbered and measured. Inclusion of the outside crop trees provided a larger sample of larger-diameter trees. We used linear mixed effect models to examine individual tree 11-year diameter and volume growth. Trees were nested within the study site, which was the random effect. The fixed effects were stand age class, canopy class, release class, and live crown length. Again, initial values were those immediately postharvest, and final values were those 11 growing seasons after harvest. We ran these models separately on oak sawtimber, nonoak sawtimber, and poles. We also used linear mixed models to look at the effect of initial diameter and treatment on the growth of oak sawtimber trees, again with study area as a random effect. We verified the normality of residuals to meet model assumptions. Posthoc pairwise comparisons were used to test differences among treatments.

Results and Discussion

Stand Stocking

Initial stocking ranged from 98 to 112 percent and did not differ among study areas ($F_{5,12} = 0.95$, $P = .483$), treatments, or stand age classes (Supplemental Table 1). Total initial oak stocking ($F_{5,12} = 1.77$, $P = .194$) and stocking of oak FAS sawtimber ($F_{5,12} = 1.36$, $P = .306$) also did not differ among study areas. After harvesting, the average residual stand stocking was 60 percent on the crop-tree plots and 62 percent on the B-level thinning plots (Figure 1). The initial sawtimber oak density of 45 per acre was reduced by harvesting to only 21 and 23 per acre on crop tree and B-level plots, respectively.

The total stand stocking 11 years after treatment was greater on uncut control areas than on either actively managed treatment area, which did not differ from each other ($F_{2,10} = 48.6$, $P < .001$). Changes in total stand stocking over the 11-year period were not independent of treatment; i.e., stocking increased more on the crop-tree and B-level plots than on the unmanaged controls (Table 3).

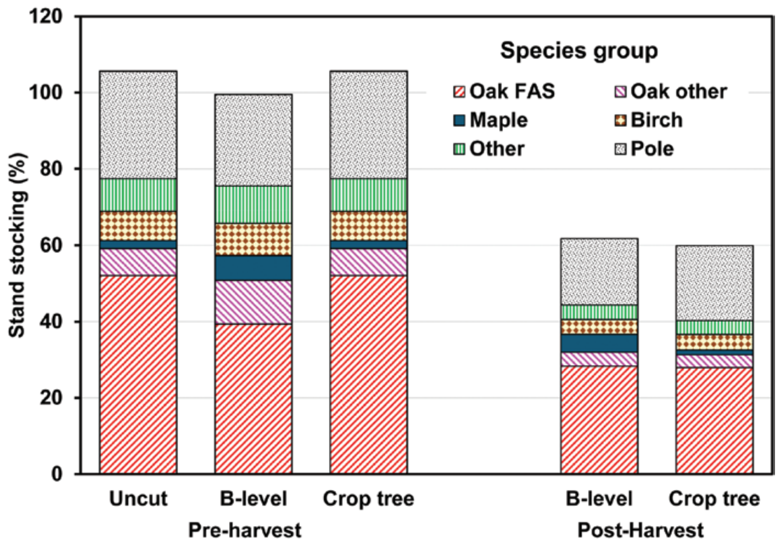

Figure 1. Distribution of stand stocking among species groups by management prescription.

Table 3. Preharvest stand stocking and 11-year stand stocking growth by cutting method for mature oak in Connecticut.

	Preharvest stocking (percent)	Stand stocking growth				
		B-level	Crop tree	Uncut	$F_{2,10}$	P
Total	104.8	16.6 a	17.3 a	8.8 b	5.2	.028
Oak sawtimber	56.3	6.9 a	5.4 a	7.2 a	0.4	.690
Nonoak sawtimber	22.8	5.9 a	6.7 a	4.0 a	1.5	.266
Poletimber	25.8	3.9 a	5.1 a	-2.4 b	7.0	.013
Oak FAS sawtimber	47.2	5.7 a	4.1 a	5.8 a	0.5	.616
Oak other sawtimber	9.0	1.2 a	1.4 a	1.5 a	0.1	.909
Maple sawtimber	5.2	1.9 a	1.2 a	1.5 a	0.3	.754
Birch sawtimber	8.1	2.0 a	2.2 a	0.4 a	2.0	.189
Other sawtimber	9.4	2.0 a	3.4 a	2.1 a	1.6	.238

Note: F-tests are for comparisons across cutting methods. Row values followed by the same letter are not significantly different at $P \leq .05$.

This increase was driven by accelerated growth of poletimber, as stand stocking growth of oak and nonoak sawtimber did not differ among treatments. In contrast, stand stocking growth of poletimber on uncut controls differed from actively managed areas, which did not differ from each other. Poletimber stocking during the 11-year interval after implementation actually decreased by 9 percent on uncut areas while increasing by 15 percent and 19 percent on B-level and crop-tree plots respectively (Table 3).

Stand Volume

Preharvest sawtimber volumes ranged from 9.8 to 15.7 mbf (International ¼) per acre and did not differ among study areas ($F_{5,12}$ = 1.04, P = .438), treatments, or stand age classes (Supplemental Table 2). Total initial oak volume ($F_{5,12}$ = 1.23, P = .355) and volume of oak FAS sawtimber ($F_{5,12}$ = 1.57, P = .241) also did not differ among study areas. On both B-level and crop-tree plots, harvesting to achieve management prescriptions reduced oak and nonoak volume to approximately 6.3 and 1.0 mbf per acre, respectively.

Total stand volume 11 years after treatment was greater on uncut control areas than on either of the actively managed treatment areas which did not differ from each other ($F_{2,10}$ = 24.3, P < .001). Total stand volume growth over the 11-year period was not independent of treatment; i.e., volume increased more on unmanaged controls than on crop-tree plots (Table 4). However, stand volume growth of oak sawtimber, and perhaps more important oak FAS sawtimber, did not differ among treatments. For the 11-year period after harvesting, both managed and unmanaged stands averaged 2.3 mbf/acre of oak sawtimber growth, of which 1.9 mbf/acre was FAS oaks. In addition, stand volume growth over the 11-year period for both total and oak sawtimber was independent of stand age class (Supplemental Table 2). This strongly suggests that stand volume growth does not decline at least through 125-year-old stands in both unmanaged and managed stands with a residual stocking of 60 percent or greater.

Previous research noted that an increase in volume growth can be maintained for at least 14 years after a complete canopy release in younger sawtimber stands (Beck 1987, Dwyer and Lowell 1988, Ward et al. 2005). Earlier studies reported that merchantable stand volume growth was unchanged or increased by area-wide thinning (Gingrich 1971, Ward 1991). However, it was recommended not to thin upland oak stands after they were 70 years old (Sander 1977, Hibbs and Bentley 1983). Managed stands in the current study maintained volume growth rates similar to that of unmanaged stands with half the number of sawtimber oaks (Table 4), suggesting that stand volume growth was reallocated to larger and generally higher-quality residual stems with the assumption that the trees we selected as residual "leave" trees were of higher quality.

There is little information on the impact of crop-tree management on stand growth. Crop-tree management increased stand basal area growth in Missouri poletimber oak stands (Dwyer and Lowell 1988), but not in Kentucky sawtimber oak stands (Miller and Stringer 2004). Stand volume growth was unchanged following multiage crop-tree management in Connecticut oak sawtimber stands (Ward et al. 2005). Residual stand structure after the first harvest of a two-step shelterwood prescription is comparable to that following crop-tree management, as many of the larger-diameter residuals are released on three or four sides. Indeed, some earlier studies reported that stand volume growth was unchanged following a deferment and shelterwood harvests (Beck 1987, Smith et al. 1989, Miller and Stringer 2004).

While not statistically significant, it should be noted that oak volume growth was lower on actively managed plots, especially on crop-tree plots, than on uncut control (Figure 2). For both treatments where trees were cut, smaller-diameter sawtimber oaks were harvested to provide additional growing space for selected residuals. Merchantable sawlog height of most larger oaks was permanently fixed by the presence of large-diameter branches or codominant forking. In contrast, merchantable height of smaller sawtimber oaks was often not fixed, but limited by diameter at the upper end of sawlog. Merchantable height on these trees increased as tree diameter increased. The volume increase from increased merchantable sawlog length on uncut plots, 1.1 mbf/acre, was double that observed on B-level and crop-tree management plots, 0.6 and 0.5 mbf/acre, respectively. This accounted for most of the increased volume growth that was observed on unmanaged plots. Two earlier studies reported nonsignificant decreases in stand volume growth on following shelterwood harvests relative to unmanaged controls (Rudolph and Lemmien 1976, Ward et al. 2005).

As noted above, both B-level and crop-tree plots had similar stocking, residual stand volume, and sawtimber oak density after harvesting. However, the stands were visually quite distinct. Trees on the B-level plots were more evenly spaced with generally small gaps between crowns. Crop-tree plots had a very irregular spatial structure with uncut sections where there were no crop trees. Immediately adjacent, there were areas resembling a shelterwood because of a concentration of crop trees.

As a result of these distinct prescriptions, the proportion of residual trees in each of the canopy release classes differed between treatments for combined species ($\chi^2 = 35.3$, df = 4, $P < .0001$) and for sawtimber oaks (Figure 3, $\chi^2 = 30.1$, df = 4, $P < .001$). Forty percent of residual oaks were released on four side on crop-tree plots compared with only 8 percent following B-level thinning. A larger proportion of oaks on the B-level plots were released on one or three sides relative to crop-tree plots.

Individual Tree Growth

Because stand volume growth was maintained after a significant reduction in stocking in managed stands (Figure 1, Table 4), it is probable that residual tree growth increased following harvesting. Analysis found that individual tree diameter growth over the 11-year period was not independent of DCR, canopy position,

Table 4. Initial preharvest stand volume and 11-year stand volume growth by cutting method for mature oak in Connecticut.

	Preharvest volumes (thousand board feet International ¼ per acre)	Stand volume growth				
		B-level	Crop tree	Uncut	$F_{2,10}$	P
Total	13.3	3.6 ab	2.7 b	4.3 a	4.7	.026
Oak sawtimber	10.6	2.3 a	1.7 a	2.9 a	2.2	.149
Nonoak sawtimber	2.7	1.3 a	1.0 a	1.3 a	0.6	.573
Oak FAS sawtimber	9.7	1.9 a	1.4 a	2.5 a	1.8	.219
Oak other sawtimber	0.9	0.4 a	0.3 a	0.4 a	0.5	.629
Maple sawtimber	0.4	0.5 a	0.2 a	0.5 a	1.1	.358
Birch sawtimber	0.5	0.5 a	0.2 a	0.2 a	1.6	.251
Other sawtimber	1.7	0.3 a	0.6 a	0.6 a	1.2	.342

Note: F-tests are for comparisons across cutting methods. Row values followed by the same letter are not significantly different at $P \leq .05$.

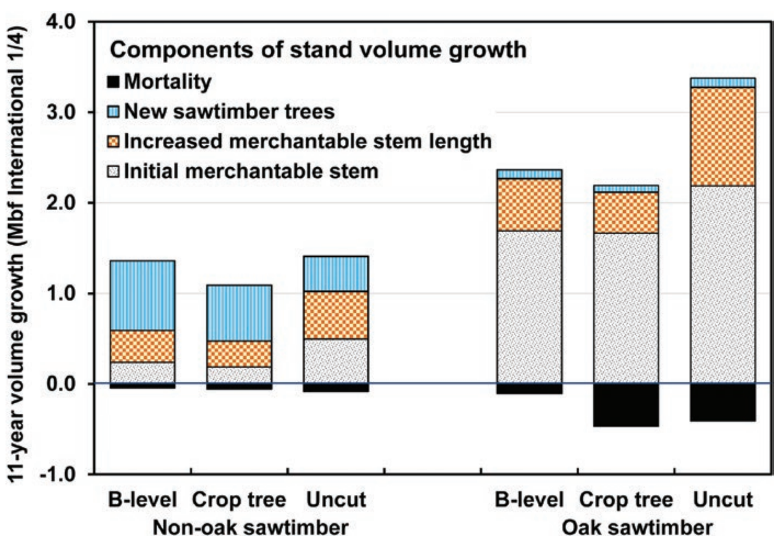

Figure 2. Distribution of stand volume growth components for the 11-year period after treatment implementation.

and live crown length for oak and nonoak sawtimber (Table 5). These factors also influenced poletimber diameter growth except for canopy position, although this may be related more to a small sample size of poletimber trees in the upper canopy than to an actual lack of factor effect. Notably, diameter growth was independent of stand age class.

Diameter growth differed by DCR, with growth increasing incrementally by slightly more than 0.25 in. for each additional side released over the 11-year period (Figure 4a). Thus, diameter growth of completely released oak sawtimber averaged 2.7 in. over the 11-year period compared with 1.6 in. for unreleased trees. Diameter growth of partially released trees was intermediate between the two. The observation that a one-sided release had a minimal effect on diameter growth is similar to reports from West Virginia (Lamson et al. 1990) and Connecticut (Ward 2008). Thus, selected residual trees should have a canopy release of two or more sides whenever possible.

Earlier research found that the growth response was directly the proportion of the DCR for oaks from the sapling through small sawtimber size classes (Lamson and Smith 1978, Graney 1998, Miller and Stringer 2004, Schuler 2006, Ward 2009). Growth responses similar to those in our study were observed for 54-year-old red oaks in West Virginia (Lamson et al. 1990), 61-year-old red oaks in Arkansas (Graney 1998), 70–75-year-old white oaks in Kentucky (Miller and Stringer 2004), 75–80-year-old red oaks in West Virginia (Smith et al. 1989, Smith and Miller 1991, Miller 1997), and 74–94-year-old red oaks in Connecticut (Ward 2008).

Diameter growth increased with diameter through the 20–23-in. diameter class on managed plots before plateauing, but continued to increase with initial size on unmanaged control plots. The 11-year diameter growth of oaks with diameters greater than 20 in. (2.7 ± 0.1 in.) was 56 percent greater than for oaks 11–14 in. (1.8 ± 0.1 in.) and 28 percent greater than for oaks 14–17 in. (2.1 ± 0.1 in.). Increased diameter growth for larger-diameter trees was also reported for Missouri (Shifley and Smith 1982) and Indiana/Illinois (Smith and Shifley 1984). Our study indicates that a positive growth response directly proportional to the DCR observed in earlier studies in smaller-diameter classes can be extended into the larger-diameter classes of mature large oak sawtimber.

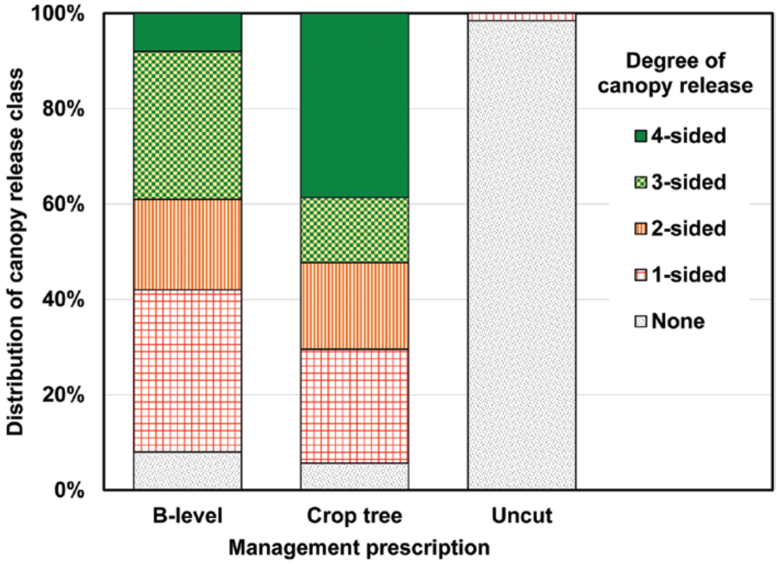

Figure 3. Distribution of canopy release classes by management prescription for sawtimber oaks following treatment implementation.

Table 5. Statistics for linear mixed model analysis of individual tree 11-year diameter and volume growth in mature oak forests in Connecticut: df—numerator df, denominator df.

Source	Diameter growth			Volume growth		
	df	*F*-ratio	*P*	df	*F*-ratio	*P*
Oak sawtimber						
Stand age class	2, 3.0	0.02	.983	2, 3.0	0.21	.821
Release class	4, 679.2	70.03	<.001	4, 679.6	15.29	<.001
Canopy class	3, 679.3	17.95	<.001	3, 679.9	6.69	<.001
Live crown length	1, 679.0	5.47	.020	1, 679.0	3.03	.082
Nonoak sawtimber						
Stand age class	2, 3.2	0.23	.805	2, 2.9	3.16	.186
Release class	4, 176.7	8.95	<.001	4, 167.3	4.45	.002
Canopy class	3, 175.7	6.35	<.001	3, 177.0	4.89	.003
Live crown length	1, 176.1	8.53	.004	1, 176.9	0.12	.734
Poletimber						
Stand age class	2, 2.9	1.09	.442			
Release class	4, 989.0	74.56	<.001			
Canopy class	2, 989.3	1.05	.350			
Live crown length	1, 988.9	9.55	.002			

Because canopy release increased diameter growth, diameter growth of residual oaks was greater on both B-level thinning and crop-tree management plots than on unmanaged controls, except in the largest-diameter classes examined, >26 in. (Table 6). Further research in stands with larger trees is required to determine whether the nonresponse at diameters greater than 26 in. represents an upper diameter limit at which oaks respond to release, or whether these trees were so large relative to surrounding trees that removal of those competitors had minimal impact on tree growth.

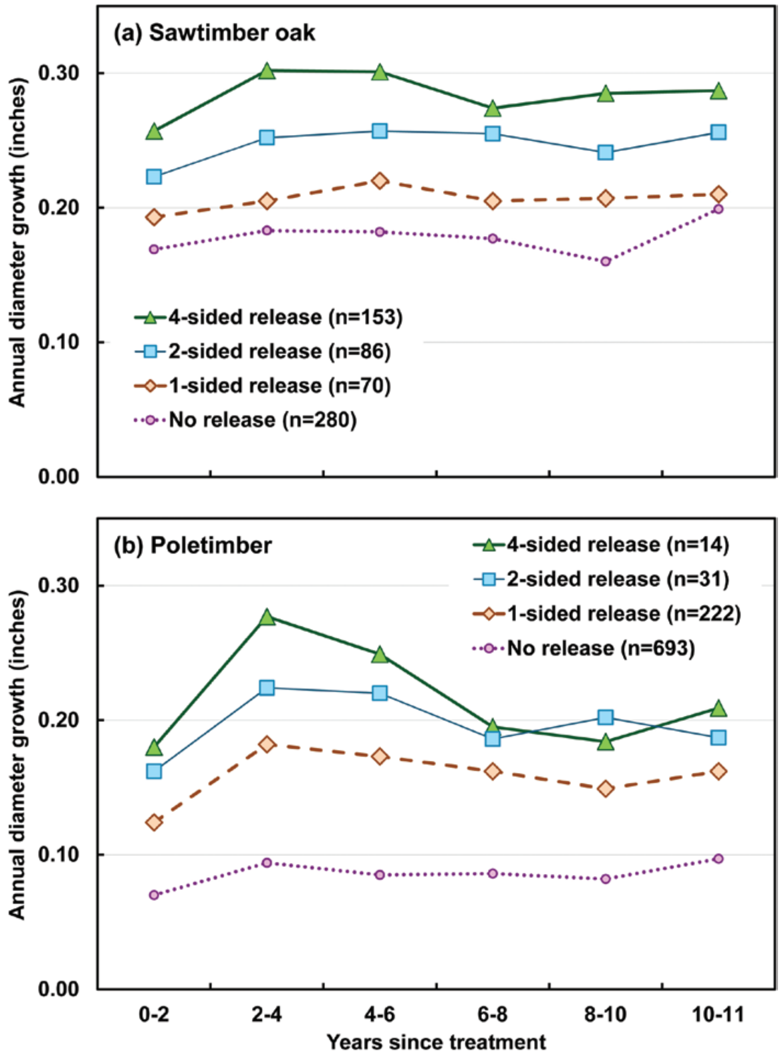

Figure 4. Annual diameter growth (in.) over 11 years by canopy release class of (a) sawtimber oak and (b) poletimber.

Table 6. Mean (standard error) 11-year diameter and volume growth of oaks by preharvest diameter class and management prescription in mature oak stands.

	Diameter growth			Volume (board feet International ¼) growth		
	B-level	Crop tree	Uncut	B-level	Crop tree	Uncut
Initial diameter (in.)						
11–13.9	2.1 (0.2) a	1.7 (0.2) ab	1.3 (0.1) b	86 (8) a	80 (14) a	34 (10) a
14–16.9	2.5 (0.2) a	2.5 (0.2) a	1.6 (0.1) b	82 (9) a	82 (15) a	60 (6) a
17–19.9	2.8 (0.1) a	2.8 (0.1) a	1.9 (0.1) b	113 (6) a	110 (9) a	77 (5) a
20–22.9	2.8 (0.1) a	3.2 (0.1) b	2.1 (0.1) c	113 (9) ab	145 (9) a	95 (8) b
23–25.9	2.7 (0.2) ab	3.3 (0.2) a	2.3 (0.1) b	112 (16) ab	153 (14) a	99 (10) b
≥26.0	2.8 (0.1) a	3.0 (0.2) a	2.6 (0.1) a	144 (19) a	139 (17) a	170 (26) a
Sample size (in.)						
11–13.9	12	8	26			
14–16.9	18	18	60			
17–19.9	73	54	82			
20–22.9	61	60	56			
23–25.9	21	38	42			
≥26.0	20	26	15			

Note: Row values followed by the same letter are not significantly different at $P \leq .05$.

It is striking that the increased growth of sawtimber oak following full and partial canopy release was sustained throughout the 11-year period of our study with no evidence of diminishing (Figure 4a). Other studies have reported that the period of increased growth for sawtimber oaks can be 10 years or longer. (Sonderman 1984, Beck 1987, Graney 1998, Perkey and Onken 2000, Ward 2008). Our study indicates that the upper age limit at which canopy release increases diameter growth of northern red oak for at least a decade can be extended to at least 125 years, with the caveat given above for those trees with diameters greater than 26 in.

While not directly targeted for release, many poletimber trees were inadvertently released when nearby sawtimber trees were harvested. Poletimber diameter growth over the 11-year period was not independent of DCR (Table 5). Although only 10 percent of poletimber trees were released on two or more sides, fully 39 percent and 33 percent were released on one side following B-level and crop tree treatments, respectively. A single-sided release was sufficient to increase poletimber diameter growth relative to unreleased trees for the first 11 years after treatment (Figure 4b). Consequently, poletimber diameter growth differed among treatments. Residual poletimber 11-year diameter growth following B-level thinning (1.6 in.) and crop-tree management (1.7 in.) was more than double that of poletimber on unmanaged controls (0.6 in.).

The increased growth in response to partial release of poletimber timbers was not unexpected, as many poletimber trees were of more shade-tolerant species such as American beech (*Fagus americana* Ehrh.), red maple (*Acer rubrum* L.), and midtolerant black birch (*Betula lenta* L.) that often persist in the subcanopy until a canopy gap provides them the opportunity to grow (Barden 1981, Hart et al. 2012). The increased growth of the nonoak poletimber trees could be a potential problem if future management goals include regenerating oak because of their ability to vigorously resprout (e.g., red maple) or produce root suckers (e.g., American beech) (Burns and Honkala 1990). Thinning increased the proportion of red maple moving into the upper canopy in a West Virginia study (Rentch et al. 2009). Regenerating oaks will require a new cohort of competitive oak seedlings to be established because only a small proportion of these older, larger oaks will develop stump sprouts

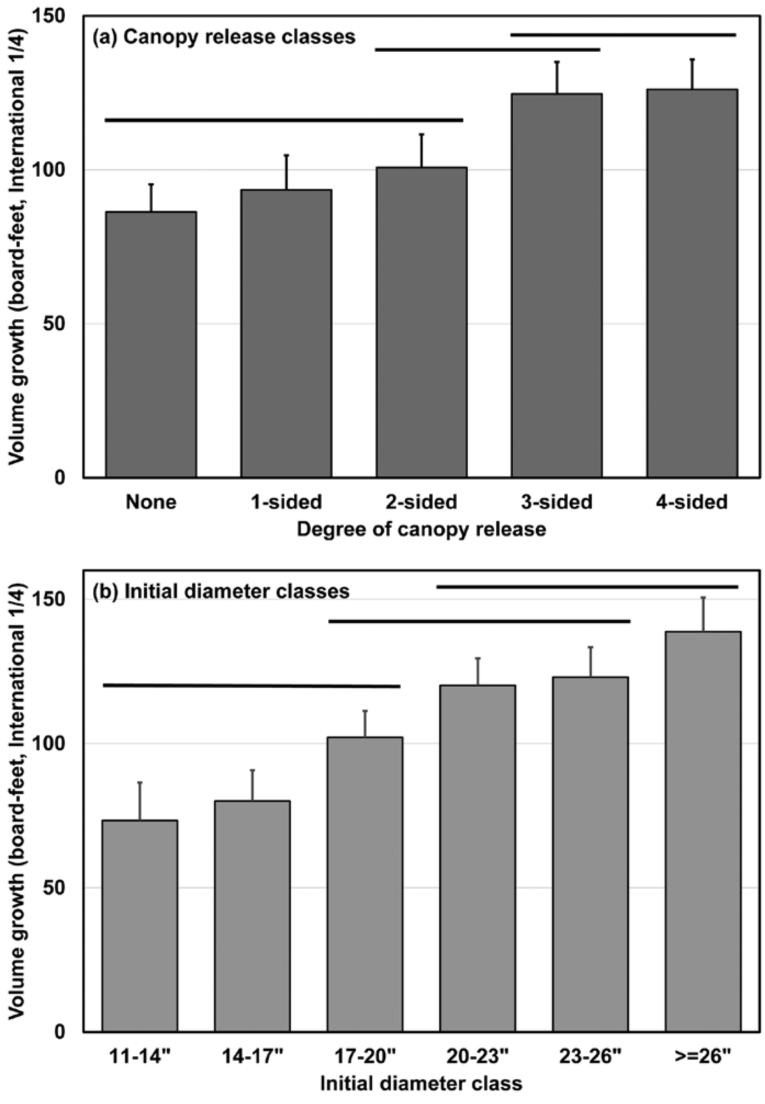

Figure 5. For upper canopy oak sawtimber, mean (standard error) 11-year individual tree volume growth (board feet/tree) by (a) degree of canopy release and (b) initial diameter class. Levels linked by horizontal lines above bars were not found to be different using Tukey's HSD test at *P* < .05.

(Ward and Williams 2018). Without aggressive implementation of practices to control competitive interference, it is unlikely that competitive oak seedlings will develop (Brose et al. 2008).

Tree Volume Growth

As individual tree volume is a function of diameter for a given merchantable height, it was not unexpected that the individual tree volume growth response followed patterns similar to those for diameter growth. Volume growth over the 11-year period was not independent of DCR and canopy position, but was independent of stand age class and live crown length for both oak and nonoak sawtimber (Table 5).

Interestingly, volume growth over the 11-year period was not independent of initial diameter for oak sawtimber, but was for nonoak sawtimber. In other words, volume growth differed by initial diameter for oak, but not nonoak, sawtimber. With study area as a random factor, linear mixed effects analysis indicated that both initial diameter class ($F_{5,664}$ = 9.9, P < .001) and canopy release class ($F_{4,664}$ = 12.5, P < .001), but not stand age class ($F_{2,664}$ = 0.1, P = .902), influenced volume growth of upper canopy sawtimber oak. Thus, 11-year volume growth of completely released oak sawtimber averaged 126 bf compared with 86 bf for trees that were not released (Figure 5a). Because release increased individual tree volume growth, both B-level thinning and crop-tree management increased the volume growth of residuals oaks relative to unmanaged controls, except for the largest diameter classes (>26 in.) (Table 6). Volume growth of oak sawtimber with diameters larger than 20 in. was 60 percent greater for trees with diameters smaller 17 in. (Figure 5b).

Conclusions

This research found that the increased growth of residual trees following complete (crop tree) and partial (B-level) release in mature oak stands up to 125 years old was sufficient to maintain stand volume growth at levels comparable to that of unmanaged stands. This extends the upper age and diameter limits from earlier studies reporting increased diameter growth following release on at least two sides in younger oak sawtimber stands with smaller diameters (Lamson et al. 1990, Graney 1998, Miller and Stringer 2004, Ward 2008, Lhotka 2017). Therefore, harvest prescriptions with the aforementioned methods can be implemented in mature oak stands to generate income without any loss of future stand volume growth. However, managers need to be cognizant that these practices will substantially increase growth of nonoak poletimber and thereby may increase the difficulty of obtaining adequate oak when a regeneration prescription is implemented.

The finding that mature oak stands up to 125 years old can be harvested using either B-level thinning or crop-tree management without loss of stand volume growth means that there are viable alternatives to regeneration prescriptions such as shelterwood or clearcut. There are several circumstances when these alternatives to stand regeneration, such as crop-tree management and B-level thinning, should be considered. The first is large forest owners (e.g., state forestry agencies) that have a balanced age structure as a management objective. Because many oak forests are even-aged, regulating forest age structure will require delaying initiation of regeneration prescriptions in some stands within the forest past their economic maturity. Crop-tree management and B-level thinning can be used to maintain residual tree health and vigor until the stands are regenerated. The second is family forest owners for whom periodic income to defray expenses such as property taxes is appreciated, but not as important a consideration as maintenance of forest cover, ecosystem services, and aesthetics. Intermediate harvests in these stands could provide some income while enhancing growth of aesthetically appealing large trees. The third is forest owners averse to harvesting on their land. Although programs such as Silviculture with Birds in Mind (Hagenbuch et al. 2011) have successfully promoted the concept of forest management as a method to enhance wildlife habitat to this group, some owners are hesitant to implement any practice that involves cutting trees beyond firewood for personal use. These owners would probably be more open to a prescription that enhanced growth of the largest, more visually arresting trees.

Supplementary Materials

Supplementary data are available at *Forest Science* online.

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