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Twenty-five year response of non-crop trees to partial release during precommercial crop tree management ☆

Jeffrey S. Ward

Department of Forestry and Horticulture, 123 Huntington Street, The Connecticut Agricultural Experiment Station, New Haven, CT 06504, United States

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ABSTRACT

An underappreciated component of precommerical crop tree release (PCTR) is the inevitable partial release of non-crop trees. While the response of fully released crop trees is increasingly understood, few studies have examined the response of non-crop trees. The effects of precommercial crop tree release at canopy closure on upper canopy persistence, mortality, and diameter growth over 25-years were examined on seven study areas established in Connecticut in 1988. Each area had nine 8 m × 8 m plots for each of two treatments: PCTR and unmanaged controls. The equivalent of 156 crop trees per hectare were completely released by cutting all stems with adjacent crowns. This resulted in the inadvertent partial release on two or more sides of 480 upper canopy, non-crop trees per hectare. Diameters and crown classes of all stems (DBH > 2 cm) were measured annually. For those stems in the upper canopy at when treated, partial release increased the proportion of oaks, but not maples or birches, which persisted in the upper canopy. Partial release increased the proportion of intermediate oaks that ascended into the upper canopy and reduced mortality. Partial release increased 25-year diameter growth of oaks. However, releasing upper canopy, sapling oaks on only one side did not increase upper canopy persistence or diameter growth. PCTR increased the proportion of oaks among the largest 300 trees per hectare twenty-five years after treatment. Where predicted oak densities are below management goals, precommercial crop tree release should be considered as a tool to increase survival and growth of quality oak saplings.

1. Introduction

A critical stage in stand development is the period immediately following canopy closure. This stem exclusion stage (Oliver, 1981) or the aggradation phase (Bormann and Likens, 1979) begins with thousands of upper canopy stems per hectare. During the subsequent decades of intense competition for growing space, upper canopy density will rapidly decrease, especially in the first few decades, to several hundred in poletimber stands and then to only a couple of hundred per hectare in mature sawtimber. Forest managers could let this process continue unabated without control of stand composition until commercial cutting is feasible in the large poletimber stage if there is a fuelwood/fiber market or else wait until the stand has reached the sawtimber size class. Delaying active management precludes the possibility of manipulating stand composition, which can be especially important when there is a wide differential of value among tree species (Miller, 1986).

Alternatively, managers could invest in precommerical crop tree release of valuable species that otherwise would likely be subordinated and lost (Zenner et al., 2012). In this paper, precommercial crop tree release (PCTR) will refer to complete crown release in sapling stands and is synonymous with cleaning (Helms, 1998) and an older definition of weeding (Downs, 1946). A subtle, but important difference, between terms is the emphasis of crop tree management is on selecting individual stems for release, while the emphasis of cleaning is on improving stand characteristics. The earliest bulletins based on practical experience recommended weeding to remove stems interfering with potentially more valuable stems (Tillotson, 1916), including as early as six years after overstory removal (Cline, 1929). The goal was to promote growth of selected species with little consideration of non-crop tree stems; perhaps because suggested spacing was 2–5 m between crop trees (400–2500 per hectare) and a second (or third) operation at 3–4 year intervals was recommended if needed (Cline, 1929; Hawley and Hawes, 1925).

Later experimental work generally confirmed that PCTR increased survival/upper canopy persistence (Trimble, 1974), diameter growth (Allen and Marquis, 1970; Della-Bianca, 1983b; Miller, 2000; Robinson et al., 2004), or both (Downs, 1946;

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E-mail address: jeffrey.ward@ct.gov

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Lamson and Smith, 1978) of upland oaks that otherwise were subordinated by less valuable species. However, crop tree release did not increase 5-year diameter growth of 7–9 year-old, upper canopy northern red oaks (*Quercus rubra* L.) and had minimal effect on upper canopy persistence in West Virginia (Smith, 1977). Another study found 5-year, but not 10-year, diameter growth of northern red oak was increased by PCTR (Lamson, 1988).

Similarly, PCTR increased diameter growth and/or survival of red maple (*Acer rubrum* L.) (Della-Bianca, 1983b; Lamson, 1988; Smith, 1977; Sonderman, 1985; Trimble, 1974), black birch (*Betula lenta* L.) (Smith and Lamson, 1983), black cherry (*Prunus serotina* Ehrh.) (Church, 1955; Smith and Lamson, 1983), and yellow-poplar (*Liriodendron tulipifera* L.) (Allen and Marquis, 1970; Miller, 2000; Sonderman, 1985).

The focus of crop tree research has been on the response of the crop trees with minimal attention paid to the surrounding forest matrix. This matrix is comprised of both unreleased trees and of non-crop trees that are partially released when the competitors of crop trees are removed (Fig. 1). While non-crop trees constitute the large majority of trees, few studies have examined either their response to partial release or how their response affects stand dynamics.

Every tree in a fully stocked stand is surrounded by several neighboring competitors. Cutting the trees neighboring a selected crop tree will inevitably cause the inadvertent partial release on two or more sides of several non-crop trees in the upper canopy; i.e., the some of the neighbors of the competitive neighbors are released. Thus, the number of partially released non-crop trees is greater than fully released crop trees and any examination of stand level effects must include non-crop trees.

Whether PCTR was considered beneficial in earlier papers depended on whether the growth and upper canopy persistence of the non-crop trees had been included in an analysis. Unfortunately, there has been a paucity of research that examined the effect of precommercial release on changes at the stand level; and stand level changes necessarily include non-crop trees along with crop trees. Previous research reported thinning 8-yr-old stands to 30% stocking, and repeating the treatment at ages 10, 17 and 22 years, had no lasting impact on composition and mean diameter of the largest 300 stems per hectare in Ohio (Hilt and Dale, 1982). Ten years after treatment, upper canopy composition did not differ between untreated control and precommercial crop tree plots of 12–16-year-old stands in the mid-Atlantic region (Miller, 2000). In a slightly older, 25-yr-old northern hardwood stand, PCTR had no significant effect on species and structural characteristics thirty-one years later (Leak and Smith, 1997).

Despite the aforementioned studies reporting that precommercial manipulation had minimal effect on future stand composition and structure, there has been a resurgence of interest in precommercial crop tree release fostered by the recognition that nearly all of a mature stand's economic value is concentrated in 150 trees per hectare (Miller et al., 2007). Thus, precommercial crop tree management provides a prescriptive tool to enhance the proportion of high quality trees by removing similar-sized trees with defects (e.g., low forks, poor form, cavities) that limit economic value, but do not limit competitive status.

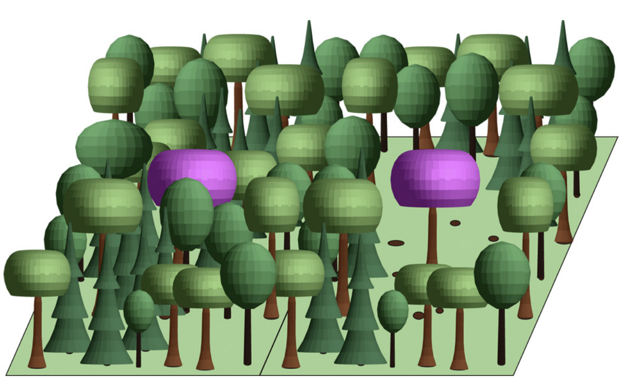

Fig. 1. Crop tree release in sapling stands provides an opportunity to release potentially valuable trees from competition. Crop tree to left was not released.

The objective of this study was to examine: (1) how partial release at canopy closure, i.e., at the beginning of the stem exclusion stage, affected subsequent growth and upper canopy persistence of non-crop trees; and (2) examine how precommercial crop tree management affected stand composition and structure. The twenty-five years covered by this study included the critical period of rapid canopy sorting and vertical stratification during the transition from sapling to poletimber stands. Because the trajectory of stand development in upland hardwood forests is largely set by the poletimber stage (Rentch et al., 2009), it is hoped the results of this study will assist forest managers to make informed decisions of whether or not to implement precommercial crop tree management in a given sapling stand.

2. Methods

2.1. Study areas

In 1988, seven study areas were established in western and central Connecticut in sapling stands where canopy closure was complete. Stands were on forests managed by the Division of Forestry, Connecticut Department of Energy and Environmental Protection (Table 1). Three study areas originated after red pine (*Pinus resinosa* Ait.) salvage harvests combined with cutting all residual stems with diameters greater than 5 cm. Remaining areas were initiated using a shelterwood cut followed by a final overstory removal. Greater detail on pretreatment stand structure is described in Ward (2013).

Soils were mesic Typic Dystrudepts; stony to extremely stony; fine sandy loams derived from gneiss, schist, and granite glacial melt-out tills that were acidic to strongly acidic (pH 3.5–6.0) (NRCS, 2016). Elevations ranged from 180 to 320 m above mean sea level. Thirty-year (1981–2010) climatic data were from Hartford, Connecticut centrally located among the plots (NOAA, 2016). The area is in the northern temperate climate zone. Mean monthly temperature ranged from −3 °C in January to 23 °C in July. There were an average of 176 frost free days per year. Average annual precipitation was 116 cm per year, evenly distributed over all months.

Table 1
Description of study areas used in precommercial thinning study in Connecticut and median initial size of northern red/black/scarlet oaks in dominant and codominant crown classes.

	Initial stand values					
	Stand age (years)	DBH (cm)	Height (m)	Stocking (%)[a]	Height in 2011 (m)	Site index (m)[b]
Tunxis	7	4.4	6.3	117	17.4	24
Hunter's Mountain	11	4.8	6.9	89	16.3	21
Overlook	12	4.1	5.9	84	15.3	20
Blueberry	12	3.9	5.4	70	16.4	22
Woodchopper	15	6.0	7.5	96	13.8	18
Mott Hill	19	6.8	8.6	100	17.2	20
Rockytop	22	6.7	7.1	102	16.1	18

[a] From Ward (2013).
[b] Site index estimated using stand ages and heights in 2011 with Table 3 in Lamson (1980).

2.2. Experimental design and measurements

Each study area had twenty-seven 8 × 8 m plots (1/63 ac) centered on a northern red, black, or scarlet oak identified as a potential crop-tree. Within each plot, a tree identification number and diameter measurement height of all stems (>2 cm DBH) was permanently marked with paint. The species, stem diameter (at 1.4 m aboveground), and crown class (Smith, 1962) were recorded. During the dormant season, diameter and crown class of all live trees were measured annually through the present. Mortality was also recorded when appropriate.

After initial measurements were completed, the twenty-seven plots at each study area were randomly assigned one of three treatments: no cutting (control plots); one removal of all stems with crowns within 1 m of the crown of a potential crop tree (crop tree plots); and two removals of all stems with crowns within 1 m of the crown a potential crop tree. Only the first two treatments were included in this report. All cutting was done after the 1988 growing season.

After cutting trees that were competing with potential crop trees, it became apparent that many non-crop trees had been partially released (Fig. 1). This provided an opportunity to examine growth response of non-crop trees to partial release. Therefore, the degree of canopy release for all non-crop trees was assessed by the number of sides released (0, 1, 2, or 3) during late spring 1989. This rating system is similar to the free-to-grow rating system detailed in Lamson et al. (1990). Trees on the crop tree plots that were not released and all trees on the control plots were assigned zero sides released (Table 2).

2.3. Data analysis

Four species groups were included in the analysis: upland oaks (*Q. rubra* L., *Q. coccinea* Münchh., *Q. velutina* Lam., *Q. montana* Willd., *Q. alba* L.), red maple, birch (*B. lenta* L., *B. alleghaniensis* Britton), and other major (*P. serotina* Ehrh., *Fagus americana* Ehrh, *Sassafras albidum* (Nutt.) Nees, *Betula papyrifera* Marshall, *L. tulipifera* L., *Carya glabra* (Mill.) Sweet, and others). Species within each group are listed in order of frequency. Species not capable of growing tall enough to form part of the upper canopy in a mature forest (primarily *Hamamelis virginiana* L., *Kalmia latifolia* L., and *Castanea dentata* (Marshall) Borkh.) were not included in the analysis.

For each species group and each initial crown class, Pearson Chi-square statistics were used to determine whether the proportion of trees found in the upper canopy 25-years after treatment differed between released and not-released non-crop trees. Because preliminary analysis (in Section 3) found upper canopy persistence did not differ between unreleased trees and those released only on one side, these two classes were combined and classified as not released. All non-crop trees released on two or more sides were classified as partially released. Pearson Chi-square statistics were used to determine whether 25-year mortality rates differed between released and not-released non-crop trees for each species group and each initial crown class. Differences were considered significant at $P < 0.05$.

At the individual tree level, when repeated measures analysis indicated a treatment effect (partial release vs. not released) on diameter growth for a species group, a two factor (study area, treatment) ANOVA with initial diameter as a covariate was used to examine the effect of treatment on final diameter. The second ANOVA was used because repeated measures analysis can indicate whether the diameter growth curves and average diameter over the study differed, but not necessarily whether diameters differed at the end of the study. Tukey's HSD test was used to test differences of final diameter among treatments. Differences were considered significant at $P < 0.05$.

At the stand level, repeated measures analysis of variance for stem density was used with year as the within subjects factor, and study area and treatments (crop tree vs. control) as the between subjects factors (SYSTAT, 2009). Reported *P*-values are those after applying the conservative Greenhouse-Geisser Epsilon correction for deviations from compound symmetry (SYSTAT, 2009). Separate analyses were run by canopy position of each species group. Differences were considered significant at $P < 0.05$. Because the difference in basal area of upper canopy oaks between treatments was trivial throughout the study, no statistical analysis was done.

To estimate future upper canopy composition in a mature forest, the two largest upper-canopy trees within each 8 × 8 m plots were identified using: (1) crown class with dominant > codominant, and (2) by largest diameter for crown class ties. The two trees per 8 × 8 m plot, equivalent to 312 trees/ha (126 trees/ac), was similar to earlier standards (Della-Bianca, 1983a; Hilt and Dale, 1982). The 8 × 8 m plot estimates of oaks and non-oaks were summed for each study area and converted to stems per hectare.

Repeated measures analysis of variance for future upper canopy oak density was used with year as the within subjects factor, and study area and treatments (crop tree vs. control) as the between subjects factors. Only one estimate per study area precluded examining study area-treatment interactions. Again, reported *P*-values are those after applying the conservative Greenhouse-Geisser Epsilon correction for deviations from compound symmetry. When repeated measures analysis indicated a treatment effect, a two factor (study area, treatment) ANOVA was used to determine if future upper canopy oak density differed between treatments. Analyses were completed for 0, 15, and 25 years after treatment. Differences were considered significant at $P < 0.05$.

Table 2
Sample size by species group and initial crown class of non-crop trees by number of sides released on crop tree release plots and of non-crop trees on untreated control plots that were not released.

Number of sides released	Crop tree release			Control	Crop tree release			Control
	0	1	⩾2	0	0	1	⩾2	0
	Upper canopy (Cod & Dom)		Number of trees		Intermediate crown class		Number of trees	
Upland Oak	66	61	86	228	101	84	42	213
Red maple	86	68	50	304	121	91	39	320
Birch	24	36	35	177	21	21	9	98
Other major	44	38	24	198	44	39	3	185
Combined (count)	220	203	195	907	287	235	93	816
Density (n/ha)	542	500	480	2233	707	579	229	2009

3. Results

3.1. Individual tree level

This phase of the analysis was limited to only those trees not selected as potential crop trees, i.e. non-crop trees that were not intentionally released. Relative to unreleased trees, upper canopy persistence was not increased by releasing the crowns on only one side for upland oaks (Pearson $\chi^2 = 0.16$, df = 1, $P = 0.692$), red maple (Pearson $\chi^2 = 2.11$, df = 1, $P = 0.146$), birch (Pearson $\chi^2 = 1.61$, df = 1, $P = 0.204$), or other major species (Pearson $\chi^2 = 0.09$, df = 1, $P = 0.767$). Therefore, as noted in Methods, non-crop trees not released and those released one side were combined and classified as not released.

Releasing the crowns of upper canopy red maple and birch on two or more sides (partial release) did not increase the proportion that persisted in the upper canopy (Table 3). In contrast, the pro-

Table 3
Twenty-five year crown class transition rates of non-crop trees by species groups, initial canopy position, and whether stems were not released or were partially released on two or more sides.

	Crown class 25 years after release					
	Treatment	Upper canopy[a]	Lower canopy	Dead	Pearson chi-square	
					Upper canopy[b]	Mortality[c]
In upper canopy when treated						
Upland oak	Partial release	56%	22%	22%	8.64	6.37
	No release	38%	25%	37%	$P = 0.003$	$P = 0.012$
Red maple	Partial release	12%	58%	30%	2.26	7.86
	No release	6%	43%	51%	$P = 0.133$	$P = 0.005$
Birch	Partial release	23%	31%	46%	0.65	1.10
	No release	30%	35%	35%	$P = 0.419$	$P = 0.294$
Other major	Partial release	46%	29%	25%	9.34	4.05
	No release	19%	35%	46%	$P = 0.002$	$P = 0.044$
In intermediate crown class when treated						
Upland oak	Partial release	21%	19%	60%	12.66	6.71
	No release	6%	16%	78%	$P < 0.001$	$P = 0.01$
Red maple	Partial release	0%	26%	74%	0.15	0.25
	No release	0%	22%	78%	$P = 0.701$	$P = 0.617$
Birch	Partial release	–	–	–	n/a[d]	
	No release	1%	25%	74%		
Other major	Partial release	–	–	–	n/a	
	No release	1%	28%	71%		

[a] Upper canopy (dominant, codominant); Lower canopy (intermediate, suppressed).
[b] Comparison between partially released and not-released non-crop trees of proportion of trees that remained or ascended into upper canopy during study.
[c] Comparison between partially released and not-released non-crop trees of proportion of trees that died during study.
[d] Too few released trees (<20) for contingency table analysis.

portion of non-crop tree oaks that remained in the upper canopy was higher when partially released than when not released, 56% and 38% respectively. For oaks that were in the intermediate and suppressed crown classes when partially released, partial release increased the proportion that were able to ascend into the upper canopy. Partial release reduced the twenty-five year mortality rate of oak in all crown classes and of red maple in the upper canopy.

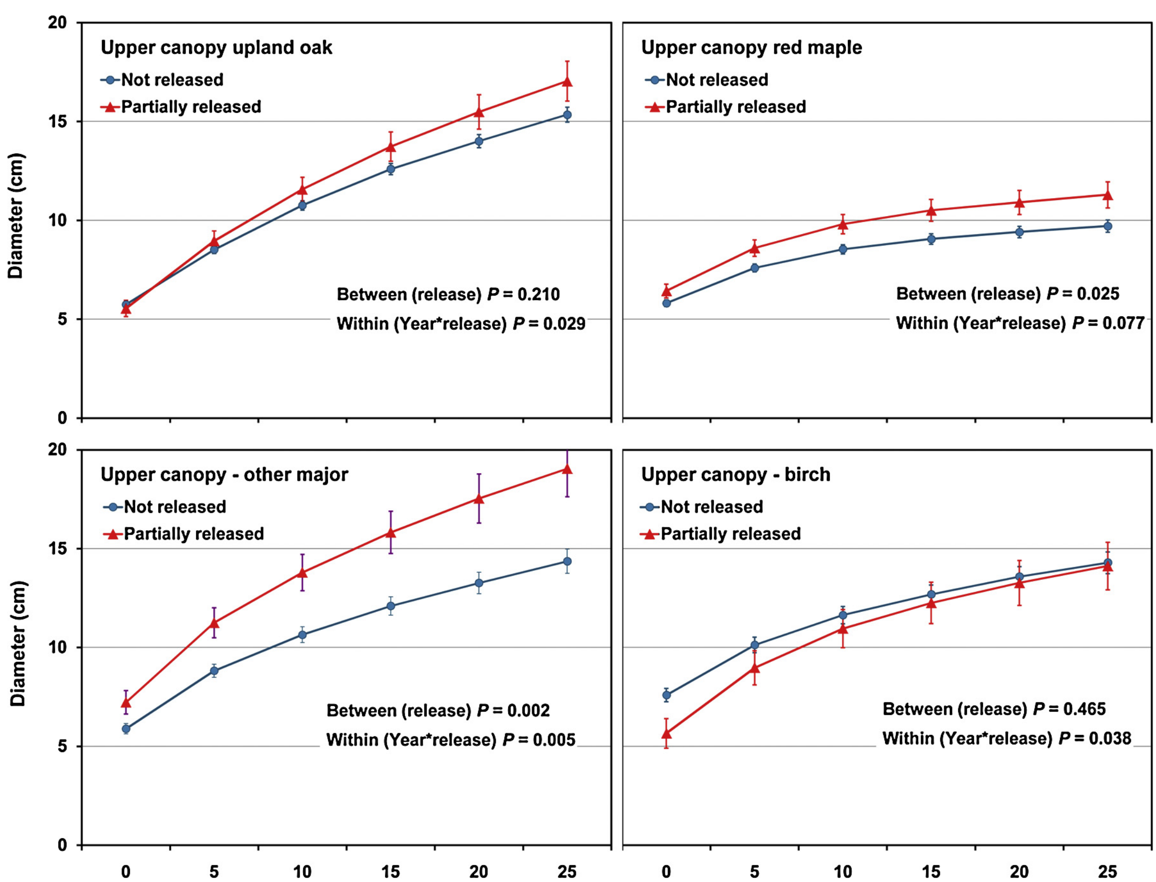

Fig. 2. Mean (standard error) diameter of non-crop trees that were in upper canopy (dominant or codominant) at beginning of study by treatment (partially released vs. not released).

The following results are for trees that were in the upper canopy (dominant or codominant crown classes) when the study was begun. Initial diameters did not differ between trees partially released and those not released for upland oaks ($F_{1,433} = 0.008$, $P = 0.927$) or birch ($F_{1,262} = 1.89$, $P = 0.170$). Partially released red maples ($F_{1,494} = 6.67$, $P = 0.010$) and other major species ($F_{1,291} = 4.38$, $P = 0.037$) had larger initial diameters than trees not released (Fig. 2).

Repeated measures ANOVA of upland oak diameters over the 25-year period indicated a significant year-by-treatment interaction ($F_{5,1390} = 4.62$, $P_{GG} = 0.029$, where P_{GG} is after Greenhouse-Geisser Epsilon correction). Diameters of partially released upland oaks were larger than unreleased trees, 17.0 and 15.3 cm, respectively, twenty-five years after treatment ($F_{1,78} = 6.43$, $P = 0.012$). For red maple diameter growth there was a weak year-by-treatment interaction ($F_{5,1235} = 3.04$, $P_{GG} = 0.077$). In contrast, partial release increased diameter growth of both birch ($F_{5,790} = 4.81$, $P_{GG} = 0.038$) and other major species groups ($F_{5,800} = 7.76$, $P_{GG} = 0.005$). However, it should be noted the increased diameter growth of birch was nominal (Fig. 2).

Table 5
P-values from repeated measures analysis of species group density by initial crown class and treatment (crop tree release vs. unmanaged control) during twenty-five period following initial treatment.

Species group	Between treatments		Within treatments (treatment * year)	
	$F_{1,6}$	*P*-value	$F_{5,30}$	P_{GG}
Upper canopy trees[a]				
Upland oak	0.98	0.360	1.30	0.306
Red maple	2.88	0.141	0.68	0.465
Birch	12.17	0.018*	4.36	0.042*
Other major	9.30	0.023*	4.84	0.051
Combined	27.536	0.002**	5.25	0.034*
Intermediate crown class				
Upland oak	1.48	0.270	4.76	0.025*
Red maple	2.25	0.184	2.68	0.123
Birch	2.75	0.110	1.21	0.336
Other major	13.1	0.011*	3.91	0.068
Combined	12.7	0.012*	2.31	0.116

* Different at $P = \leqslant 0.05$ using Tukey HSD test.
** Different at $P = \leqslant 0.01$ using Tukey HSD test.
[a] Upper canopy (dominant, codominant).

3.2. Stand level

This section of analysis includes both non-crop and crop trees. Relative to untreated control plots, precommercial crop tree release initially decreased upper canopy and intermediate densities by 32% and 25%, respectively (Table 2). Over the next twenty-five years, density of upper canopy trees decreased by 75% on plots with and without crop tree release (Table 4). The decline varied among species groups; ranging from 51% for upland oaks to 74%, 80%, and 93% for birch, other, and red maple respectively. Considering all upper canopy trees, the 5-year rate of regression from the upper canopy was greatest in the first five years, 39%, fell to 23% in the next five years, and then gradually decreased to 19% in the final five years of the study.

The difference among species groups in the rate of regression out of the upper canopy (Table 3) resulted in a shift of species dominance. Upland oaks accounted for approximately 34% of all upper canopy trees when the study began at nominal canopy closure. On the crop tree release plots, removal of many non-oaks during the initial release and subsequent canopy stratification resulted in oaks accounting for 70% of upper canopy trees twenty-five years later. However, oaks were also the predominant species group (56%) on untreated plots twenty-five years later (Table 4).

Upper canopy oak density did not differ between plots with and without crop tree management nor was there a year-by-treatment interaction (Table 5). Surprisingly, red maple density and change in density were independent of whether plots were treated. In contrast, crop tree management resulted in lower density of both birch and other species groups; for birch, crop tree management accelerated the decline in upper canopy density.

Concurrent with the expected decrease in upper canopy density during this phase of stand development (Table 4), total basal area and basal area of upper canopy oaks steadily increased (Fig. 3). Basal area of upper canopy oaks continued to increase over the twenty-five year period while total basal area of non-oak species increased by only 0.2 m^2/ha over the last decade of the study. Consequently, the proportion of stand basal area contributed by upper canopy oaks increased from 20% to 39% on untreated plots and from 24% to 52% on crop tree management plots.

The estimated number of oaks in the upper canopy of the future forest steadily increased over time ($F_{5,30} = 98.4$, $P_{GG} < 0.001$) (Table 6). There was a weak year-by-treatment interaction ($F_{5,30} = 3.36$, $P_{GG} = 0.056$). The estimate of future upper canopy oaks did not differ between crop tree release and unmanaged control plots prior to treatment ($F_{1,6} = 0.28$, $P = 0.618$) or fifteen years after treatment ($F_{1,6} = 2.76$, $P = 0.148$). However, it did differ twenty-five years after treatment ($F_{1,6} = 7.05$, $P = 0.038$). Twenty-five years after the study was established, composition of largest 300 trees per ha differed between unmanaged and crop tree release areas (Pearson $\chi^2 = 9.12$, df = 1, $P = 0.003$). Upland oaks accounted for 79% of upper canopy trees in areas managed with crop tree release compared with 61% in unmanaged areas; 246 and 191 oaks per hectare on crop tree release and untreated plots respectively.

Table 4
Mean (standard error) density of upper canopy trees (stems/hectare) on plots with and without crop tree release by years since release.

Species group	Treatment	Years since release					
		0	5	10	15	20	25
	Number of trees per hectare (standard error)						
Upland oak	Crop tree	857 (118)	564 (63)	515 (59)	492 (62)	451 (58)	411 (60)
	Control	746 (97)	556 (57)	480 (49)	463 (48)	414 (36)	372 (40)
Red maple	Crop tree	714 (132)	305 (76)	194 (56)	126 (29)	74 (25)	42 (17)
	Control	763 (167)	394 (82)	249 (49)	158 (37)	89 (23)	54 (16)
Birch	Crop tree	352 (88)	199 (62)	160 (58)	123 (39)	89 (32)	66 (26)
	Control	481 (111)	398 (98)	289 (80)	232 (63)	192 (53)	147 (35)
Other major	Crop tree	352 (197)	197 (96)	150 (64)	133 (58)	86 (29)	69 (28)
	Control	502 (211)	352 (133)	246 (83)	214 (65)	155 (41)	101 (27)
Combined	Crop tree	2405 (292)	1327 (190)	1059 (131)	894 (82)	702 (57)	591 (53)
	Control	2575 (283)	1723 (166)	1275 (125)	1068 (89)	835 (53)	660 (47)

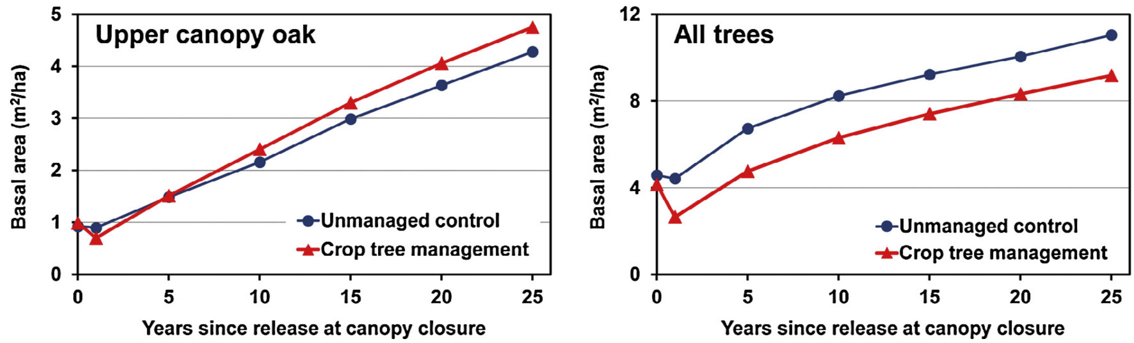

Fig. 3. Changes in stand basal area by treatment (crop tree management vs. unmanaged control) of upper canopy oaks (l) and of all trees (r). Basal area includes both crop trees and non-crop trees.

Table 6
Distribution of 312 largest trees per hectare (126 per acre) by plot treatment and species group during twenty-five year period following treatment. This provides an estimate of future upper canopy composition in a mature forest by treatment and species group.

Treatment	Species group	Years since treatment					
		0	5	10	15	20	25
Largest 312 trees per hectare (standard error)							
Crop tree release plots							
	Oak	104	166	186	208	218	246
	Non-oak	208	146	127	104	94	67
Unmanaged control plots							
	Oak	94	119	136	166	179	191
	Non-oak	218	193	176	146	134	122
Standard error of mean		13.4	13.3	16.0	17.9	16.9	14.5

Surprisingly, oak diameters did not differ between treatments ($F_{1,162} = 0.291$, $P = 0.590$).

4. Discussion

The observed stand dynamics on unmanaged control plots support the vertical stratification model of oaks maintaining height growth and eventually overtopping birch and maple during the stem exclusion stage (Hibbs, 1983; Kelty, 1986; Oliver, 1981). This was perhaps due to a more xeric soil moisture regime that occurs with the reestablishment of higher evapotranspiration following canopy closure (Bormann and Likens, 1979). Growth of mesophytic species such as birch and maple are more sensitive to soil moisture deficits than oak (Pastor and Post, 1986).

Those oaks that persist in the upper canopy during the early vertical stratification (stem exclusion) phase of stand development, i.e., the decades immediately after canopy closure, are likely to persist in the upper canopy through stand maturity (Ward et al., 1999; Zenner et al., 2012). Conversely, few oaks are able to ascend into the upper canopy once relegated to the lower canopy (Miller, 2000; Ward and Stephens, 1994; Zenner et al., 2012, but see Oliver, 1978). Because regression into the lower canopy is permanent for nearly all oaks in the intermediate and many in the codominant crown class, competition from non-oak species during the early vertical stratification phase can limit successful oak regeneration, i.e., there is "stratification bottleneck".

One potential method to increase the proportion of oaks that pass through the stratification bottleneck is precommercial crop tree release (PCTR). This study was begun in the late 1980s when it was unclear whether sapling oaks would benefit from precommercial crop tree release (Della-Bianca, 1983a; Hilt and Dale, 1982; Lamson, 1983), especially those in the dominant crown class (Smith, 1977; Trimble, 1974). Because several of the earlier studies reported that PCTR decreased height growth of sapling oaks (Allen and Marquis, 1970; Holsoe, 1947; Lamson, 1983), there was concern that early release could lead to higher rates of regression from the upper canopy. However, the height growth decrease was found to be transitory and was not observed in longer term studies of upland oaks (Lamson, 1988; Trimble, 1974; Ward, 2013) or northern hardwoods (Conover and Ralston, 1959). More recently, PCTR has been recommended to increase diameter growth and upper canopy persistence of codominant and vigorous intermediate oaks where predicted oak densities are below management goals (Brose et al., 2008; Miller et al., 2007). However, the effect of PCTR on individual partially released trees and on stand composition was not addressed.

The current study found that PCTR increased upper canopy persistence of non-crop tree oaks that were partially released in addition to increasing upper canopy persistence of completely released crop trees (Ward, 2013). Partial release also tripled the likelihood of an intermediate oak ascending into the upper canopy. However, it should be noted that releasing upper canopy, sapling oaks on only one side did not increase upper persistence (current study) or 18-year diameter growth (Ward, 2009). Similarly, for northern hardwoods in Wisconsin, PCTR doubled the proportion of intermediates that were able to ascend into the upper canopy over a sixteen year period (Conover and Ralston, 1959). The only previous study that examined partial release of saplings reported that the 5-year diameter growth of mixed species (primarily yellow poplar and northern red oak) increased with degree of release, but that the increase was only significant for complete release (Lamson et al., 1990).

In marked contrast to non-crop tree oaks, partial release did not increase long-term upper canopy persistence of red maple and birch. Indeed, twenty-five years after treatment, densities of upper canopy red maple, birch, and other major species were lower on PCTR plots than unmanaged plots. The increased diameter growth rate and decreased mortality of partially released red maple and birch that was reported for the first four years of this study (Ward, 1995) was not maintained over twenty-five years. Other studies reported PCTR increased red maple upper canopy persistence for 5–10 years in West Virginia (Lamson, 1988; Trimble, 1974) and increased diameter growth for periods of 3–14 years in North Carolina (Della-Bianca, 1983b), Ohio (Sonderman, 1985), and West Virginia (Lamson, 1988). For black birch, PCTR increased 3-year diameter growth (Smith and Lamson, 1983) and the proportion of black birch in the upper canopy 10-years after treatment (Miller, 2000). The proportion of birch in the upper canopy following PCTR in the current study did not begin to decrease until ten years after treatment, the study length of Miller (2000). The current study demonstrates the importance of extending forest management research beyond several years to a decade or longer;

and also suggests that PCTR can delay, but not stop, the process of canopy stratification where upland oaks are present (Oliver, 1981).

Ultimately, the value of a forest management practice is judged by its effect at the stand level. Our study found that precommercial crop tree release can both increase the proportion of more economically valuable oak that will be present in a mature stand and increase diameter growth of oaks. This allows for shorter rotations if trees are grown to a specific diameter limit. Similar to shorter-term studies that found precommerical crop tree release had minor effect on stand composition or structure (Hilt and Dale, 1982; Leak and Smith, 1997; Miller, 2000, but see Della-Bianca, 1983a); our study that found the density of upper canopy oaks did not differ between treatments. However, and perhaps more important, PCTR did increase the proportion of oaks among the largest 300 trees per hectare. The fifty-five additional oaks per hectare that can be anticipated to form part of the mature sawtimber stand will add to the stand's future economic value and will also provide flexibility when selecting among trees during intermediate harvests.

Not only did oaks constitute a greater proportion of the largest trees on crop tree release plots, non-crop tree oaks on release plots had larger diameters than those on unmanaged controls. The diameter increase on the PCTR plots had not reached the 2.5 cm threshold at which the treatment becomes economically positive (Miller, 1986). However, this threshold may be achieved within twenty years as diameter growth of non-crop tree oaks on released plots continued to be greater than for those on unmanaged plots. Crop tree release of older 26–40 year-old mixed-hardwoods in southern Indiana was estimated to have positive rates of returns on investment of 7% or greater over stand rotation (Morrissey et al., 2011). In summary, forest managers should consider precommercial crop tree management as a prescription to increase the proportion of oak for non-commercial goals (e.g., wildlife habitat), and as an economically viable tool to increase future stand value.

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