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# Evaluation of Cleanings to Maintain Oak Forests on the Allegheny National Forest

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Ten-year results for an administrative study on the Allegheny National Forest (ANF) that examined their cleaning (precommercial thinning) prescriptions and standards for success in maintaining oak (*Quercus* spp.) composition in young stands and maintaining oak stems in a competitive position are presented. Two studies were installed. One study was in a 25- to 30-year-old stand where we released intermediate and suppressed oak species, in particular white oak (*Quercus alba*), to see if they would survive and improve in crown class. The other study was installed in two 16-year-old stands where cleanings using crown-touching crop-tree release treatments were done, with untreated control plots reserved. A total of eight treated and eight control plots in two stands were examined. In the first study, mortality of white oaks in the lower canopy (intermediate or overtopped) was 83 and 39% in control versus treated areas, respectively. The cleaning treatments were successful in keeping trees alive, but crown vigor declined and no trees increased in crown class. In the second study, the mortality of crop trees was 15 and 2% in control versus treated stands, respectively. The proportion (number of stems) of crop trees of all species in the upper canopy (dominant or codominant) dropped 22% versus 1% for control versus treated trees over the 10 years. Stand-level oak composition in control stands was 11.3% of basal area after 10 years (11.7% initially). In treated stands, it was 18.3% of basal area after 10 years (10.7% initially), a 71% increase in oak. The treatments successfully increased survival, growth, and composition of oak.

**Keywords:** crop tree release, species composition

Soon after a complete overstory harvest or other stand-replacing disturbance in a hardwood stand, a new stand begins to develop. High levels of sunlight, higher surface temperature, soil disturbance, and a flush of nutrients contribute to the production of a new community of trees. Wounded stumps and roots produce new sprouts. Seed from parent trees stored in the forest floor germinates and produces a new cohort of seedlings, often including numerous taxa, depending on the diversity of the surrounding forest. Advanced reproduction that began to develop before a stand-replacing disturbance also contributes to the species composition of the new stand. Research has shown that antecedent conditions of sprout sources, stored seed, and advanced reproduction at the time of a stand-replacing disturbance play a major role in determining the species composition of a new stand (Smith 1962, Johnson et al. 2002, Brose et al. 2008). Once the new stand begins to develop, other factors such as site quality, growth habits of the species involved, and their interactions with moisture conditions act as an environmental filter to determine which species become dominant in the new stand.

Although forest managers can take steps to prepare mature hardwood stands for desirable regeneration in the next stand, little can be done in the first 10–15 years after a stand-replacing disturbance to manipulate species composition. Tens of thousands of individual stems compete for site resources in this early stage of development. Once the new stand develops a recognizable canopy and exclusion of less competitive stems begins, silvicultural treatments may be prescribed to favor desirable trees for the future (Miller et al. 2007, Brose et al. 2008).

Cleanings are prescribed in young hardwood stands to favor the survival and growth of selected trees by felling or killing less desirable trees of the same age (Smith 1962). In general, the reduction in stand density and creation of small canopy gaps that result from cleanings allow more sunlight, soil moisture, and nutrients to be allocated to the residual trees. The residual trees use the site resources freed by removal of the less

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desirable trees to temporarily exhibit faster dbh growth and expand their crowns and root systems (Miller 2000, Ward 2008). Mortality due to overcrowding within the stand is reduced for several years. The residual trees eventually claim the growing space formerly occupied by trees that were eliminated until the stand returns to full stocking.

There are several techniques by which cleanings in hardwood stands have been applied. One approach simply reduces stand density to a given level of basal area or relative stand density by felling or killing less desirable trees without regard to their proximity to desirable trees. This approach may or may not increase the availability of site resources around the immediate vicinity of desirable trees. A more targeted approach involves felling or killing trees whose crowns touch those of the desirable crop trees (Perkey et al. 1994). This technique is referred to as a crown-touching crop-tree release, whose purpose is to increase the crown growing space around individual desirable trees (Miller 2000). It focuses effort, expense, and benefit on individual trees that contribute to accomplishment of the stand management objectives. In practice, the stand density approach and crop-tree release approach can be merged into one prescription whereby both macrosite and microsite conditions around individual trees are considered (Miller et al. 2007, Brose et al. 2008).

A common problem in managing young hardwood stands is that the species composition of the upper canopy, defined here as trees in the dominant and codominant crown classes, does not meet long-term management objectives (Ward 1995, 2008). Desirable species may be present, but they have slipped into intermediate and suppressed crown classes as the stand transitioned from the stand-establishment phase into the stem-exclusion phase of development. Research has shown that crown-touching crop-tree release of dominant and codominant trees can sustain trees in the upper canopy for decades after release (Schuler 2006, Ward 2008). Less is known about using such treatments to sustain desirable trees in the lower canopy (intermediate or overtopped crown classes) or to cause them to ascend into the upper canopy.

## Sustaining Oak Forests on the Allegheny National Forest

The Allegheny National Forest (ANF) Land and Resource Management Plan (LRMP) (USDA Forest Service 2007) provides direction to ANF land managers to maintain oak (*Quercus* spp.) forests. Oak and mixed-oak forests comprise approximately 16% of the ANF and are considered regionally important from a biodiversity standpoint, particularly in light of potentially warmer climatic conditions in the future. Oak forests on the ANF are very important to many plant and animal species (Brose et al. 2008). Of particular importance are the high amounts of hard mast that oaks produce for wildlife forage. On the ANF, oak ecosystems mainly occur along the river corridors and their major tributaries and are related to Native Americans' periodic use of fire (Ruffner et al. 1997, Abrams 2005, Black et al. 2006). Because oaks are generally considered shade intolerant, mixed-oak stands will probably transition to stands dominated by other species such as red maple (*Acer rubrum*) or black birch (*Betula lenta*) in the absence of active management or stand-tending treatments on the ANF.

To sustain these ecologically important forests on the ANF, the LRMP includes an oak restoration emphasis and specific objectives to manage oak through a combination of timber harvesting, crop-tree release (e.g., cleanings), reforestation treatments, and prescribed fire. Management of oak on the ANF emphasizes the establishment, tending, and release of oak regeneration. Treatments are designed to create favorable conditions for the establishment and development of oak seedlings and saplings that are competitive with other more rapidly growing tree seedlings. Cleaning and other release treatments enhance the competitive status of oak saplings in mixed-species young stands, thereby helping sustain oaks. The LRMP emphasizes an adaptive approach that incorporates new information and research findings to sustain oak forests on the Allegheny Plateau. To address some of the uncertainty associated with sustaining oaks on the ANF, we established an administrative study to examine the effectiveness of cleanings for enhancing the survival and development of oak species in young mixed-species stands. Tests were installed among three sites to assess the biological and economic feasibility of precommercial cleaning treatments using crown-touching crop-tree release. The treatments were intended to enhance the long-term survival of oak species in young stands that originated from harvests or natural stand-replacing disturbances. Three objectives of the study were to test the ANF standards for cleanings (precommercial thinning using crop-tree release) for their effectiveness, examine stand development and competitive patterns in young mixed-species stands, and determine whether intermediate and suppressed white oak (*Quercus alba*) can respond to release.

## Methods

Two experiments were conducted in this study. Experiment 1 addressed the third objective: whether intermediate and suppressed white oak saplings can survive and improve in crown position after treatment, considering their relatively higher shade tolerance. Experiment 2 addressed the first two objectives by comparing plots treated using ANF contractors and control plots.

### Experiment 1

The first experiment was a test of cleaning in a 15-acre stand where the oaks in the

### Management and Policy Implications

The cleaning (precommercial thinning) prescriptions and standards used by the Allegheny National Forest were successful in maintaining and even increasing the oak component of young mixed hardwood stands that resulted from natural disturbances followed by salvage logging. The success of the treatment was dependent on treating stands when oak stems were in a codominant or better crown position shortly after crown closure (15–20 years old in this system) when the stands are in the early phase of the stem exclusion stage of stand development. Treatment was done using a crown-touching crop-tree release via chain saw felling of competing trees.

When stands are older (25–30 years of age) and desired stems are not in the upper canopy, cleanings via a crop-tree release treatment could keep oak stems alive in intermediate or overtopped crown positions. The released trees did not improve in crown class during the following 10 years. Although the treatment was not successful in promoting oaks to codominant status, it did keep more released oak trees, especially white oak, alive and a component of the stand, thus providing the forest manager with options for maintaining oak forests in the future.

lower canopy (intermediate or suppressed crown classes) were released using crown-touching crop-tree release to see whether those stems could be kept alive and perhaps improve in crown class. In particular, white oak, which is more shade tolerant and perhaps more likely to survive in a subdominant position, was evaluated along with the less shade-tolerant black oak (*Quercus velutina*). The 25- to 30-year-old stand was located on the top of the unglaciated Allegheny Plateau, a few miles east of the Allegheny River in the southwestern corner of the ANF (Marienville Ranger District, compartment 607, stand 18), had a red oak site index of 65–70 ft, and is typical of Plateau top sites. It was dominated by black oak, northern red oak (*Quercus rubra*), and black cherry (*Prunus serotina*) with white oak and a number of miscellaneous species. Individual white oak and black oak stems were selected throughout the stand by species, crown class, and crown vigor. Half of the stand was treated with a crown-touching crop-tree release and half was left untreated as a control. The majority of the selected trees were suppressed stems along with a few codominant stems and some intermediate stems (Table 1). There were approximately equal numbers of treated and control trees, and the initial crown vigor did not differ between the two sets of trees. An ANF contractor applied the treatment during the winter of 2000–2001 using chain saws to fell competing trees. The selected trees were followed for 10 years to evaluate their mortality, crown vigor, crown class, and diameter growth. Crown vigor and mortality were rated annually with a four-class system of good, fair, poor, and dead (Gottschalk and MacFarlane 1993). Crown class and dbh (nearest 0.01 in.) were measured pretreatment, posttreatment, 5 years posttreatment, and 10 years posttreatment.

***Statistical Analysis.*** Additional variables were calculated from the measured variables including individual tree basal area, individual tree dbh growth, and individual tree basal area growth. Both growth variables were calculated as 10-year growth (year 10 less pretreatment). The change in crown class was calculated as 10-year change (pretreatment less year 10), resulting in values that could be positive (increase in crown class), negative (decrease in crown class), or zero (stayed the same crown class). The crown vigor and mortality data were converted to percentages of the sample trees that were in each vigor class. In addition, a variable giving live or dead status was created using the year 10 vigor code for dead. Statistical analyses were conducted with Systat version 13 (Systat Software, Inc. 2009). To test the final status of the control versus released trees, the percent distribution of trees by year 10 crown vigor classes and the distribution of the 10-year change in crown class were tested using 2-way cross-tabulation tables with Pearson's $\chi^2$ and Goodman-Kruskal's lambda measures of association. The 10-year live/dead status and 10-year dbh growth variables were both analyzed with analysis of variance (ANOVA) to test the effect of treatment on the final results.

## Experiment 2

The second experiment was a test of cleanings in two 16-year-old stands that were located on the top of the unglaciated Allegheny Plateau: one was 1 mile east of the Allegheny River and one was 1 mile west of the River in the southwestern corner of the ANF (Marienville Ranger District, compartment 717, stand 27, 43 acres and compartment 602, stand 13, 79 acres); both were

**Table 1. Number of control and released white and black oak stems by initial crown class selected in experiment 1.**

| | White oak | | Black oak | |
|---|---|---|---|---|
| Crown class | Control | Released | Control | Released |
| Codominant | 7 | 3 | 2 | 10 |
| Intermediate | 10 | 17 | 4 | 23 |
| Suppressed | 88 | 81 | 98 | 124 |
| Total | 105 | 101 | 104 | 157 |

**Table 2. Composition and distribution of initial crown class of crop trees in control and released plots in experiment 2.**

| Species | Control ($n$ = 384) | Released ($n$ = 398) |
|---|---|---|
| | (% of stems) | |
| White oak (*Quercus alba*) | 16.4 | 8.5 |
| Black oak (*Quercus velutina*) | 27.6 | 18.6 |
| Scarlet oak (*Quercus coccinea*) | 17.2 | 10.0 |
| Northern red oak (*Quercus rubra*) | 25.0 | 41.2 |
| Black cherry (*Prunus serotina*) | 1.6 | 7.5 |
| Yellow poplar (*Liriodendron tulipifera*) | 2.3 | 2.5 |
| Red maple (*Acer rubrum*) | 9.4 | 10.0 |
| Other[1] | 0.5 | 1.5 |
| Crown class | | |
| Dominant | 2.1 | 1.7 |
| Codominant | 78.4 | 77.4 |
| Intermediate | 17.2 | 17.1 |
| Suppressed | 2.3 | 3.8 |

[1]White ash (*Fraxinus americana*), cucumbertree (*Magnolia acuminata*), hickory (*Carya* spp.), and bigtooth aspen (*Populus grandidentata*).

**Table 3. Crown vigor and mortality of released and control crop trees by species across all initial crown classes in a 25- to 30-year-old stand after 10 years in experiment 1.**

| | White oak[1] | | Black oak[2] | |
|---|---|---|---|---|
| Crown vigor | Control ($n$ = 105) | Released ($n$ = 101) | Control ($n$ = 104) | Released ($n$ = 157) |
| | (%) | | | |
| Good | 1.9 | 5.0 | 1.0 | 1.3 |
| Fair | 2.9 | 28.7 | 1.0 | 26.1 |
| Poor | 12.3 | 27.7 | 2.8 | 20.2 |
| Dead | 82.9 | 38.6 | 95.2 | 52.2 |

[1]Two-way cross-tabulation table of control versus released distributions within white oak is significant (Pearson's $\chi^2$ = 46.124, 3 *df*, $P < 0.000$; Goodman-Kruskal's lambda = 0.540, $P < 0.000$).
[2]Two-way cross-tabulation table of control versus released distributions within black oak is significant (Pearson's $\chi^2$ = 55.583, 3 *df*, $P < 0.000$; Goodman-Kruskal's lambda = 0.635, $P < 0.000$).

typical of Plateau top sites. The site east of the river had a red oak site index of 70–75 ft and white oak site index of 55–60 ft, whereas the site west of the river had a red oak site index of 73–78 ft and white oak site index of 68–72 ft. The stands contained a mix of dominant, codominant, intermediate, and suppressed oaks including northern red, white, black, and scarlet oaks (*Quercus coccinea*) in competition with other species such as red maple, black birch, and black cherry along with 25 additional tree and shrub species. Both stands originated from a May 1985 tornado followed by salvage logging. A total of eight treated and eight control 2.0-acre plots with a 0.6-acre measurement area inside of the buffer were established within the two stands. Treated versus control status was assigned by a coin toss. Treatments were applied during the dormant season of 2000–2001 by a contractor using the ANF's standards for crop-tree release for which the contractor selected and released crop trees. Release entailed cutting all neighbor trees whose crowns touched those of the selected crop tree on at least three sides or were within 4 ft of the crop tree bole. Most crop trees received a four-sided release. Individual crop trees that were selected by the contractor in both the treated and untreated plots were followed for 10 years. In addition, 100% inventories of all stems on the plots were conducted to get additional data on stand development and treatment success.

The 100% inventories were conducted pretreatment, posttreatment, 5 years posttreatment, and 10 years posttreatment by measuring and recording all trees of >0.5 in. dbh by species and 1-in. dbh classes. Stems per acre (SPA, no./acre) and basal area per acre (BA/ac, $ft^2$/acre) were calculated for each plot by species groups and total. The five species groups were all oaks, red maple, black birch, black cherry, and all other species and were used to determine species composition (percentage of stems and percentage of basal area by species group) and stand development patterns.

Crop tree initial measurements were done in the dormant season of 2000–2001 immediately posttreatment since they were selected by the contractor and were not available for pretreatment measurements. Crown vigor (same scale as experiment 1) and dbh (nearest 0.01 in.) were measured annually in late summer to early fall. Crown class and tree height (nearest 1.0 ft) were measured immediately posttreatment, 5 years posttreatment, and 10 years posttreatment. Height of the clear bole (nearest 1.0 ft) was measured 10 years posttreatment. Released plots contained from 24 to 55 crop trees (40–92 per acre), whereas control plots had 50–71 crop trees per plot (83–118 per acre). The higher number of crop trees in control stands was due to the contractor selecting potential crop trees in one operation and then releasing them in a second operation. Not all selected potential crop trees were subsequently released because of contract per acre limits as well as some potential crop trees being cut to release other crop trees in the treated plots. The ANF standard was to release 80 crop trees per acre average across the stand. These crop tree numbers are higher than the recommended 40–60 per acre for mixed-oak forests (Miller et al. 2007, Brose et al. 2008) and reflect an area of potential adaptation by the ANF. The ANF guidelines have a species priority list, and oaks are at the top of the list, so the crop tree composition is heavily biased toward

**Table 4. ANOVA tables for white and black oak 10-year mortality (as live/dead status) where treatment represents control versus released trees in experiment 1.**

| | Mortality | | |
|---|---|---|---|
| | *df* | *F* | *P* |
| White oak[1] | | | |
| Treatment | 1 | 52.908 | <0.000 |
| Error | 204 | | |
| Black oak[2] | | | |
| Treatment | 1 | 68.078 | <0.000 |
| Error | 259 | | |

[1] $R^2$ = 0.206; Akaike information criterion = 246.986.
[2] $R^2$ = 0.208; Akaike information criterion = 281.613.

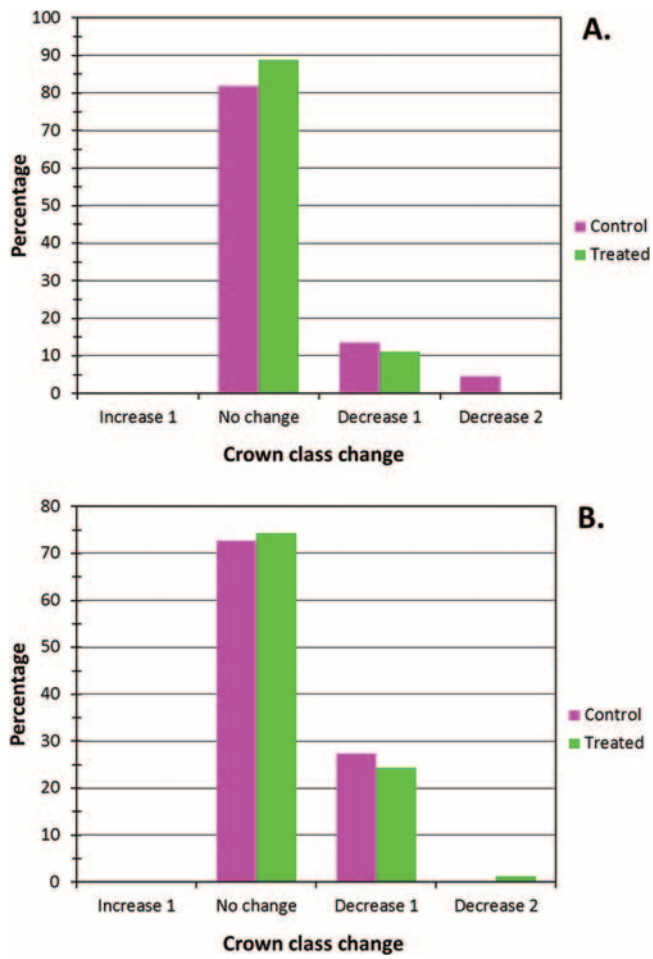


**Figure 1. Change in crown class (%) of control and released white oak (A) and black oak (B) trees after 10 years in experiment 1 (increase 1, the tree increased one class; no change, the tree stayed in the same class; decrease 1, the tree decreased one class; and decrease 2, the tree decreased two classes). Two-way cross-tabulation table of crown change classes between control and released trees is not significant (white oak: Pearson's $\chi^2$ = 3.046, *df* = 2, *P* = 0.218 and Goodman-Kruskal's lambda = 0.045, *P* = 0.928; black oak: Pearson's $\chi^2$ = 0.178, *df* = 2, *P* = 0.95 and Goodman-Kruskal's lambda = 0.000, *P* = 1.000).**

oak but along with a biodiversity objective incorporated a variety of other species including black cherry, red maple, hickory (*Carya* spp.), white ash (*Fraxinus americana*), cucumbertree (*Magnolia acuminata*), and yellow-poplar (*Liriodendron tulipifera*) (Table 2). The distribution of initial crown classes showed that codominant trees were about 80% of the crop trees, but some crop trees were selected in all crown classes (Table 2).

***Statistical Analysis.*** Additional variables that were calculated from the measured variables included individual tree basal area, individual tree dbh growth, individual tree basal area growth, height growth (all growth variables are year 10 less posttreatment), and change in crown class (posttreatment less year 10), which could be positive (increase in crown class), negative (decrease in crown class), or zero (stayed the same crown class). Statistical analyses were conducted with Systat version 13 (Systat Software, Inc. 2009). The 10-year mortality variable and 10-year height and dbh growth variables were analyzed with ANOVA to test the effect of treatment on the final results with means of the latter two variables evaluated with Tukey's honestly significant difference (HSD) to test for significant differences. To test the final status of the control versus released trees, the percent distribution of trees by year 10 crown vigor classes and the distribution of the 10-year change in crown class were tested using two-way cross-tabulation tables with Pearson's $\chi^2$ and Goodman-Kruskal's lambda measures of association. Stand development patterns of SPA, BA/ac, and species composition were analyzed with repeated-measures ANOVA and Wilks' lambda tests.

## Results

### Experiment 1

This experiment showed that the crop-tree release treatment reduced mortality of suppressed white and black oak and slowed the decline in their crown vigor ratings (Tables 3 and 4). White oak responded better than black oak, supporting the hypothesis that its shade tolerance would allow white oak to persist longer. Despite this better survival and vigor, the released trees did not increase their crown class (Figure 1). A large majority of the live trees stayed in the same crown class, and the rest of the trees dropped one or two crown classes regardless of treatment. Diameter growth 10 years after treatment (data not shown) did not differ with release for either white oak (ANOVA, $P = 0.432$) or black oak (ANOVA, $P = 0.710$).

### Experiment 2

The cleaning treatment resulted in the crop trees surviving better and either retaining or increasing in crown vigor; mortality of crop trees was 15% in control stands and 2% in treated stands (Table 5). Released crop trees improved in crown vigor compared with that of control trees (Table 5) and also increased their height growth (Figure 2A) and exhibited faster diameter growth (Figure 2B). Crown class was significantly affected by treatment as the proportion (number of stems) of crop trees of all species in the upper canopy (dominant or codominant) dropped 22% versus 1% for control versus treated trees over the 10 years (Tables 2 and 5). This difference in distribution of crown class change between control and treated crop trees was significant because treatment resulted in a few trees increasing to dominant or codominant status, but the main effect was in retention of codominant status while many codominant trees in the control plots decreased in crown class (Figure 3).

Stand development patterns over the 10-year posttreatment duration of the study plus the pretreatment status showed that the cleaning treatment did not have a significant effect on the decline in stem numbers (Table 6; Figure 4A), but time was significant. There was a significant time × treatment interaction, which related to reduced stem mortality after treatment (years 1–5), which dissipated by years 6–10. The cleaning treatment did have a significant effect on basal area growth (Table 6; Figure 4B), and time was also significant. There was a significant time × treatment interaction, which

**Table 5. Crown vigor and mortality and crown class distribution of released and control crop trees across all initial crown classes and species in 16-year-old stands after 10 years in experiment 2.**

| Crown vigor class[1] | Treatment: Control | Treatment: Released | Crown class[2] | Treatment: Control | Treatment: Released |
|---|---|---|---|---|---|
| | .....(%)..... | | | .....(%)..... | |
| Good | 59.6 | 86.5 | Dominant | 1.5 | 4.1 |
| Fair | 20.6 | 10.5 | Codominant | 57.3 | 73.7 |
| Poor | 5.0 | 1.2 | Intermediate | 5.7 | 5.9 |
| Dead | 14.8 | 1.8 | Suppressed | 35.5 | 16.3 |

[1]Two-way cross-tabulation table of crown vigor class and control versus released distributions is significant (Pearson's $\chi^2 = 81.728$, $df = 3$, $P < 0.000$; Goodman-Kruskal's lambda = 0.263, $P < 0.000$).
[2]Two-way cross-tabulation table of crown class and control versus released distributions is significant (Pearson's $\chi^2 = 37.999$, $df = 3$, $P < 0.000$; Goodman-Kruskal's lambda = 0.164, $P = 0.029$).

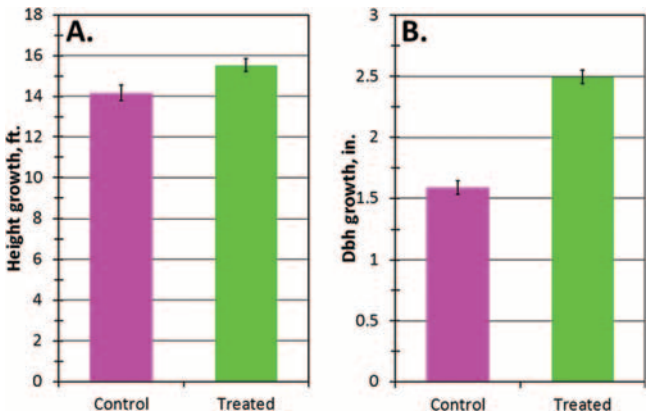


**Figure 2. Ten-year height growth (A, ft.) and diameter growth (B, dbh, in.) of control and released trees across all species and initial conditions in 16-year-old stands in experiment 2 (error bars, ±1 SE). Height growth significantly increased with release (Tukey's HSD, $P = 0.005$; ANOVA, 1, 723 *df*, *F* ratio = 7.761, $P = 0.005$, $R^2 = 0.011$, Akaike information criterion = 4,796.769). Dbh growth significantly increased with release (Tukey HSD, $P < 0.000$; ANOVA, 1, 731 *df*, *F* ratio = 124.777, $P < 0.000$, $R^2 = 0.146$, Akaike information criterion = 2,223.087).**

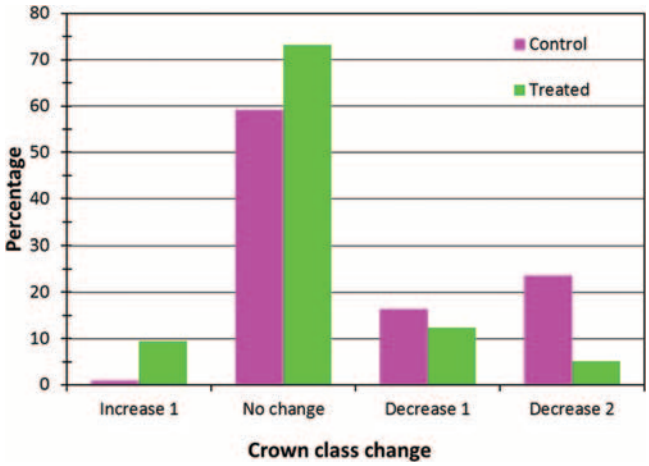


**Figure 3. Change in crown class (%) of control and released trees across all species in 16-year-old stands after 10 years in experiment 2 (increase 1, the tree increased one class; no change, the tree stayed in the same class; decrease 1, the tree decreased one class; and decrease 2, the tree decreased two classes). Two-way cross-tabulation table of crown change classes between control and released trees is significant (Pearson's $\chi^2$ = 76.674, *df* = 3, *P* < 0.000 and Goodman-Kruskal's lambda = 0.197, *P* = 0.011).**

**Table 6. Repeated-measures ANOVA for stand developmental patterns of SPA and BA/acre over the 11-year period from pretreatment through treatment to 10 years posttreatment in experiment 2.**

| | SPA | | | | BA/acre | | |
|---|---|---|---|---|---|---|---|
| | *df* | *F* ratio | *P* | | *df* | *F* ratio | *P* |
| Between subjects | | | | | | | |
| Treatment | 1 | 1.206 | 0.291 | | 1 | 4.418 | 0.054 |
| Error | 14 | | | | 14 | | |
| Within subjects | | | | | | | |
| Time | 3 | 68.917 | <0.000 | | 3 | 270.785 | <0.000 |
| Time × treatment | 3 | 3.428 | 0.025 | | 3 | 13.799 | <0.000 |
| Error | 42 | | | | 42 | | |
| Test of time | | | | | | | |
| Wilks' lambda = 0.070 | 3, 12 | 53.452 | <0.000 | Wilks' lambda = 0.019 | 3, 12 | 209.364 | <0.000 |
| Test of time × treatment | | | | | | | |
| Wilks' lambda = 0.379 | 3, 12 | 6.556 | 0.007 | Wilks' lambda = 0.250 | 3, 12 | 12.027 | 0.001 |

related to increased basal area growth after treatment (years 1–5), which declined but did not disappear in years 6–10. These patterns showed that the cleaning treatment resulted in the same endpoint in stand development in SPA and BA/ac as that for the control plots; however, the species, size, and crown class of the trees making up those totals are changed by the treatment.

The stand composition (relative basal area) response to treatment shows that the control stands are increasingly dominated by black cherry and black birch, whereas red maple and other species are declining and oak is steady (Figure 5A). Oak's rank did improve to fourth from last over other species at the end of 10 years. Conversely, treated stands show oak increasing steadily over the 10 years, whereas black cherry is steady, and black birch, red maple, and other species are declining (Figure 5B). Oak improved its rank from last pretreatment to second behind black cherry after 10 years, overtaking black birch, red maple, and other species. Despite this seemingly strong treatment difference, neither treatment nor time was significant, whereas species group was significant (Table 7). There was also a significant time × species group interaction, presumably because of the differences in the species group response to the cleaning treatment.

## Discussion

Forest managers have long recognized that promoting the development of individual trees within a hardwood forest can be a very effective approach for achieving a range

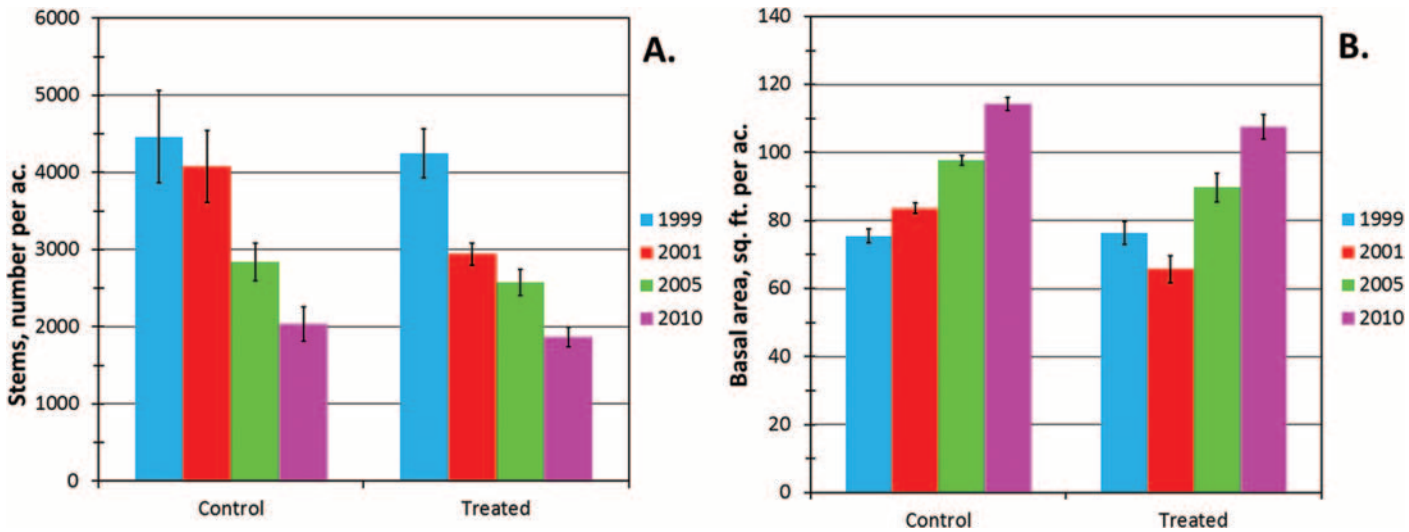


**Figure 4. Stand development of control and released 16-year-old stands after 10 years in stems (A, no. acre$^{-1}$) and basal area (B, ft$^2$ acre$^{-1}$) in experiment 2 (error bars, ±1 SE). Repeated-measures ANOVA showed that both treatment and time were significant factors in stand development (see Table 6 for details).**

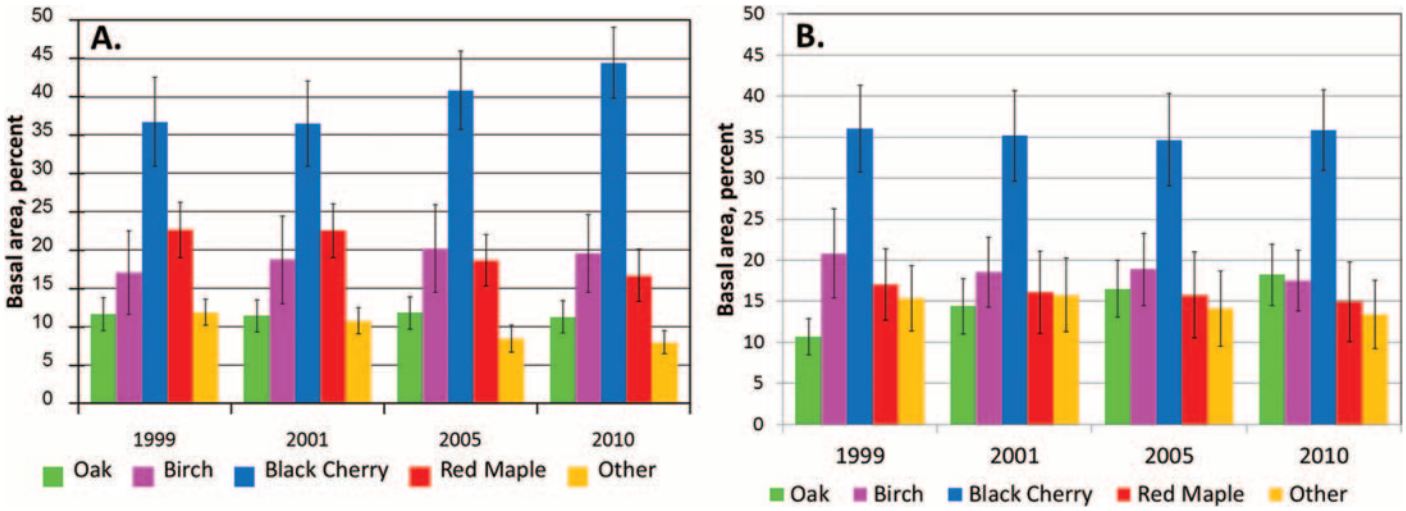


**Figure 5. Stand development of species composition (% basal area) in control (A) and released (B) 16-year-old stands after 10 years in experiment 2 (error bars, ±1 SE). Repeated-measures ANOVA showed that species group but not treatment and time was a significant factor in stand development (see Table 7 for details).**

**Table 7. Repeated-measures ANOVA for stand developmental patterns of composition by five species groups (percent of total basal area per acre) over the 11-year period from pretreatment through treatment to 10 years posttreatment in experiment 2.**

| | Composition (% basal area) | | |
|---|---|---|---|
| | *df* | *F* ratio | *P* |
| Between subjects | | | |
| Treatment | 1 | 0.000 | 1.000 |
| Species group | 4 | 12.374 | <0.000 |
| Error | 74 | | |
| Within subjects | | | |
| Time | 3 | 0.000 | 1.000 |
| Time × treatment | 3 | 0.000 | 1.000 |
| Time × species group | 12 | 6.482 | <0.000 |
| Error | 222 | | |
| Test of time | | | |
| Wilks' lambda = 1.000 | 3, 72 | 0.000 | 1.000 |
| Test of time × treatment | | | |
| Wilks lambda = 1.000 | 3, 72 | 0.000 | 1.000 |
| Test of time × species group | | | |
| Wilks lambda = 0.528 | 12, 190 | 4.345 | <0.000 |

of management objectives. Traditional thinning prescriptions, whereby stand density is reduced by removing less desirable species or trees of poor form, is an indirect way of favoring the residual trees (Pham 1985, Johnson et al. 2002). Although reducing stand density generally allocates site resources to the residual trees, it does not ensure that the microsite conditions around trees that exhibit the most desired attributes are improved. Research has shown that crown release of individual crop trees is a more direct and efficient approach to improve survival, growth, and vigor of the most desirable trees in a forest stand (Perkey et al. 1994, Miller et al. 2007).

Several studies have shown that crown release increases the diameter and crown growth of hardwood crop trees in young hardwood stands (Downs 1946, Allen and Marquis 1970, Trimble 1974, Lamson and Smith 1978, Smith 1979, Lamson 1983, Ward 1995, 2008, Miller 2000, Schuler 2006). Faster diameter growth has the desirable result of shortening the time required for crop trees to reach a target diameter, thus reducing the production period for commercial products. In mixed-species stands, increased survival and crown class retention are other important benefits of crown release treatments (Miller 2000, Schuler 2006, Ward 2008), in that they afford the forest manager some measure of control over species composition. As the stand matures, natural thinning reduces the number of stems and increases the average diameter of the residual trees. Timely application of crown release to desired crop trees when the stand is young is a direct way to influence the future composition of the overstory. Experiment 2 successfully changed the species composition of the treated plots relative to that of the control plots: oak composition increased 62% relative to that of controls, whereas black cherry composition declined 19% relative to that of controls.

The degree of crown release affects the growth response of crop trees in various ways. The maximum diameter growth response was obtained when crop trees were released by removing adjacent trees whose crowns touched that of the crop tree on three or four sides (Lamson et al. 1990, Ward 1995, 2008). In their studies, releasing crop trees on only one or two sides did not yield a significant growth response compared with growth of unreleased trees. Diameter growth increased significantly in experiment 2, showing the redistribution of growth from trees that were cut to the crop trees. Although a crown-touching release removes trees adjacent to the crop trees, removing additional trees beyond them had the negative effect of reducing height growth and bole quality of the crop trees (Miller 2000). Crown release generally has a temporary negative effect on height growth and did not prevent crown class deterioration in 9-year-old stands (Lamson and Smith 1978). Crown release of codominant oaks in 16- to 22-year-old stands did not reduce height growth compared with that of unreleased trees (Miller 2000, Schuler 2006). Our results in the 16-year-old-stands in ex-

periment 2 show a small but significant increase in height growth due to treatment, but this may be the result of the large number of trees in the sample. Further analysis by species and initial crown class will be necessary to determine whether this increase in height growth is a general trend within the study. We also showed a large increase in diameter growth with the three- or four-sided release used in experiment 2. However, in experiment 1 with intermediate and suppressed trees, release did not result in an increase in diameter growth, reflecting the fact that the released trees did not improve in crown class.

Crop-tree release can have important effects on survival and crown class dynamics, depending on the species and the initial status of the crop trees. In sapling stands in Connecticut, Ward (2008) found that 85% of codominant northern red oak crop trees remained in the upper canopy and only 6% percent died 18 years after being released on at least three sides. For crop trees initially in the intermediate crown class, 40% ascended into the upper canopy and 20% died. No suppressed trees ascended into the upper canopy and 80% died after a similar release. In Maryland, 31% of intermediate northern red oaks ascended into the upper canopy, and none died 10 years after a crown-touching release (Miller 2000). In West Virginia, 70% of intermediate oaks ascended into a codominant position 10 years after release (Schuler 2006). In each of those studies, survival of released oaks was significantly greater than that of their unreleased counterparts, regardless of their initial status. The released oaks in both experiments in this study showed this increased survival, but it was most dramatic in experiment 1 for white oaks. These older oaks in experiment 1 did not increase in crown class, but the younger oaks in experiment 2 either maintained their status or increased in crown class, while many of the unreleased stems decreased in crown class. This study shows the importance of releasing oak crop trees earlier rather than later in stand development—as soon as possible after crown closure before the oak trees are relegated to the lower canopy.

There is evidence that oaks in the overstory of old-growth forests may have undergone periods of suppression and slower growth, followed by release due to various disturbances at opportune times before they reached the upper canopy (Rentch et al. 2003). It follows that sustaining oaks through periodic release treatments in young and midrotation stands may allow forest managers to keep oaks alive for decades, even if they persist as subordinate trees for extended periods until eventually ascending into the upper canopy. Experiment 1 supports the first part of this hypothesis as subordinate oaks were kept alive without any improvement in their crown class. Periodic release treatments could involve oak crop trees in all crown classes at various stages of development as determined by the desired future composition of the overstory. In fact, crown release of mature overstory trees has been suggested as a possible restoration strategy for old-growth forests by hastening the development of large diameter trees, a key characteristic of the original forests (Singer and Lorimer 1997).

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